DEEP HOLE DRILLING WITH TWIST DRILLS

ASPECTS OF THE CNC PROCESS AND ITS

REAL TIME MONITORING AND ADAPTIVE CONTROL

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SUMMARY

The University of Aston in Birmingham

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Deep hole drilling is one of the most complicated metal cutting processes and one of the most difficult to perform on CNC machine-tools or machining centres under conditions of limited manpower or unmanned operation.

This research work investigates aspects of the deep hole drilling process with small diameter twist drills and presents a prototype system for real time process monitoring and adaptive control; two main research objectives are fulfilled in particular :

First objective is the experimental investigation of the mechanics of the deep hole drilling process, using twist drills without internal coolant supply, in the range of diameters Ø 2.4 to Ø4.5 mm and working length up to 40 diameters. The definition of the problems associated with the low strength of these tools and the study of mechanisms of catastrophic failure which manifest themselves well before and along with the classic mechanism of tool wear.

The relationships between drilling thrust and torque with the depth of penetration and the various machining conditions are also investigated and the experimental evidence suggests that the process is inherently unstable at depths beyond a few diameters.

Second objective is the design and implementation of a system for intelligent CNC deep hole drilling, the main task of which is to ensure integrity of the process and the safety of the tool and the workpiece. This task is achieved by means of interfacing the CNC system of the machine tool to an external computer which performs the following functions :

On-line monitoring of the drilling thrust and torque, adaptive control of feed rate, spindle speed and tool penetration (Z-axis), indirect monitoring of tool wear by pattern recognition of variations of the drilling thrust with cumulative cutting time and drilled depth, operation as a data base for tools and workpieces and finally issuing of alarms and diagnostic messages.

ASLIB KEY WORDS :

Twist drill, CNC Machining, Deep Hole Drilling, Process Monitoring, Adaptive Control.

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LIST OF ABBREVIATIONS

AC	Adaptive Control
ACC	Adaptive Control of Constraints
ACO	Adaptive Control Optimisation
A/D	Analog to Digital Converter
AE	Acoustic Emission
CNC	Computer Numerical Control
D/A	Digital to Analog Converter (DAC)
DHD	Deep Hole Drilling
P	Proportional Control
PID	Proportional Integral Derivative Control
PM	Process Monitoring
RPM	Revolutions per Minute
STR	Self-Tuning Regulator
ZOH	Zero-Order Hold

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 Research Context

Hole-making in general and drilling in particular is undoubtedly the most common metal cutting operation. It has been estimated that it accounts for approximately 40% of all the metal working processes, (Donahue **[94]**, Kegg**[100]**), despite the existence of alternative processes for hole making, such as Electrochemical machining (ECM), Electrodischarge machining (EDM) or Laser machining.

The production of holes has been the subject of research for the last 50 years with hundreds of papers and publications throughout the world. Despite this activity much is still not clearly understood about the process such as the mechanisms of drilling forces, chip formation, tool wear, geometrical properties of the hole produced and ultimately the control of the whole process.

A particular case of drilling is Deep Hole Drilling (DHD) of small diameter holes with a large depth to diameter ratio, typically above 10:1. In DHD the problems which are associated with conventional drilling are exacerbated, mainly because of the additional dimension of the hole depth.

During the last 10 to 15 years the manufacturing industry has entered an era of ever increasing demand for productivity, product quality and reliability. Automation, unmanned or limited manpower production, Flexible Manufacturing Systems, are replacing the more traditional methods of manufacturing. Inevitably, the process of hole making needs to adapt to the use of machine-tools or machining centres which are controlled by CNC systems of ever increasing power and sophistication.

This in turn necessitates the replacement of the traditional skills of an experienced machinist with a comprehensive knowledge of the mechanics of hole production in order to ensure the integrity and reliability of the process and product quality. These requirements are of paramount importance in a typical field of application of DHD, the Aerospace industry, where the production of small diameter deep holes in expensive components made from difficult to machine materials is quite a common operation.

1.2 Historical background to deep hole drilling

The drilling process itself is an ancient process ; hand drills consisting of a wooden sharp shaft and rotated by the aid of a crossbow cord are dated thousands of years B.C. The deep hole drilling process however is relatively new, contemporary with the appearance of guns in Germany during the 16th century.

A water mill provided the power necessary for a spade-tip cutting tool to produce the gun barrel. (American Machinist [9], Azad [16]). Two barrels could be drilled simultaneously by using two parallel spindles while feed and thrust were produced by the operator. Note that this was a process using a single edge cutting tool and so were the ones that followed the evolution of gun-drills for the next centuries.

Since then the terms deep hole drilling and gun-drilling have been synonymous and although nowadays small diameter deep holes are very common in industrial applications other than gun manufacturing, the term gun-drilling is still often used in the DHD context.

1.3 Tooling aspects of deep hole drilling

1.3.1 Definition of DHD

There are two main families of tools used for producing deep holes, the common twist drills with usually two cutting edges and the single cutting edge tools, also known as self piloting tools mainly represented by the BTA tools, ejector drills and gun drills.

In the Anglo-American terminology the term DHD implies the latter of the two groups while in the German literature there are two dedicated terms ; "Wendelbohr" for a twist drill and "Tiefbohr" for a deep hole drill. These two groups of tools for producing holes are described with more detail later in section 1.3.2.

As far as a deep hole is concerned there is no strict definition with regards to its dimensions, that is the diameter and depth of the hole. A drilled hole is usually referred to as a deep one when the ratio of the hole depth (or length) to its diameter exceeds 5:1 (Pepper [7], Trinkaus [74], or according to others, [5]-[6] lies in the range 5:1 - 20:1.

It is not the hole depth to diameter ratio however, which determines alone whether the process is classified under DHD or not. The hole diameter itself is a very important parameter since the smaller it is the more difficult the process becomes in the context of reduced tool strength and swarf extraction capability. Actually, holes smaller than 1/8" (3.175 mm) in diameter are considered as deep holes even if the L/D ratio is 4:1 or 3:1 and such holes are produced almost exclusively by twist drills, **[9]**, Gettelman **[78]**, Lishchinskii - Rabinovich **[58]**.

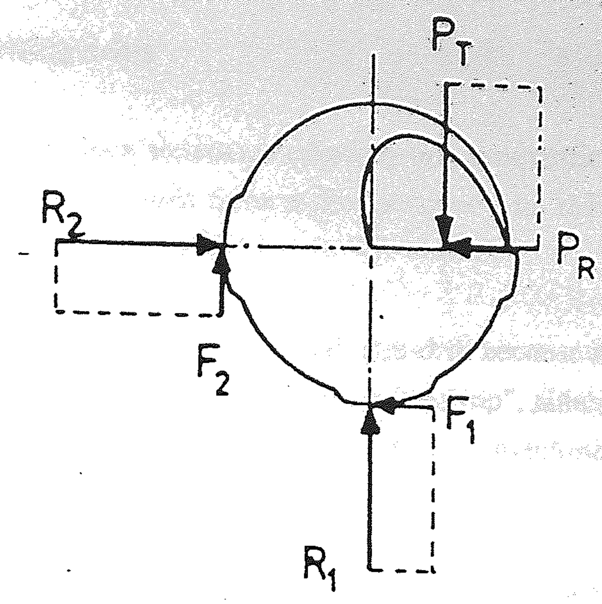
Another factor which must be also taken into account, regarding the definition of deep holes, is the material being drilled. Every material presents different machinability characteristics and mechanical properties which in turn causes certain phenomena associated with the deep hole drilling process to manifest themselves at different depths and machining conditions for different materials.

The two phenomena which are described in detail in chapter 4, are mainly a variation in the form of swarf with drilled depth and also fluctuations of the drilling torque and thrust with drilled depth. The term *instability of the deep hole drilling process* is used in the pages to follow in the context of the above phenomena.

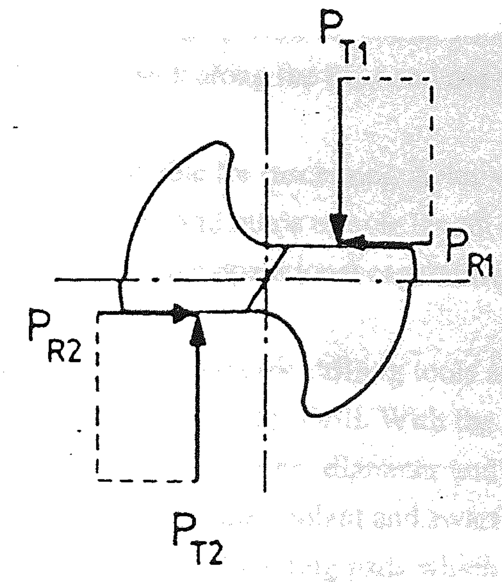
In conclusion, the two factors discussed above, tool diameter and workpiece material that is, explain to some extent the lack of a strict definition for the deep hole drilling process among various researchers. In chapters 4 and 7 a methodology is presented of an implicit definition of DHD : On-line parameter identification of the depth where the process would be described as DHD, enables to avoid the need for a rigid definition and adapts the term to the conditions of a specific drilling cycle.

1.3.2 Tools and Processes for the production of deep holes.

The drilling process involves the conversion of a workpiece material within a hole into conventional chips by the relative rotation of the cutting tool and workpiece. As mentioned in section 1.2 there are two main types of tools and two corresponding drilling processes for the machining of holes in general as well as of deep holes, the self piloting drills with non symmetric cutting action and the twist drills with a symmetric cutting action (fig. 1.1).



A



B

Fig. 1.1 : The System of Forces Acting on a :

A : Self Piloting Drill B : Twist Drill

i. Self piloting drills

These tools which are characterised by non symmetric cutting balanced by pilot or guide-pads (fig.1.1 A), form three main groups : Gun drills, BTA system drills and Ejector drills (fig. 1.2, 1.3, 1.4).

The most common is the so called gun-drill because it was originally used for the machining of gun-barrels. It features a single "tool-tip", either regrindable or throw-away type, at the end of bar with a V-shaped channel machined along its length for the extraction of the swarf.

The cutting forces Pt , Pr (fig.1.1 A) are balanced by the radial reaction forces R1, R2 and tangential ones F1, F2 generated by the guiding pads which are placed at angles of 90^{o} and 180^{o} approximately from the cutting edge. These guide pads, usually carbides, ride on the bore of the drilled hole and ensure straightness and also good finish due to their burnishing effect.

The second and very important feature of a gun-drill is the internal delivery of fluid through the tool at extremely high pressures, 300 to 1800 psi, depending on the tool diameter, which forces the chips back along the flute and out of the hole.

Standard gundrills are available for machining holes with diameters ranging from Ø2 mm (0.078 in) to Ø50 mm (2 in) and ratios of hole length to diameter up to 100:1 and as low as 1:1. Table 1 demonstrates the operational capabilities of various drilling tools.

The other two types of non-symmetric drilling tools are the BTA system (Boring and Trepanning Association) and the Ejector Drill. With the BTA system high pressure coolant is delivered between the hole internal diameter and the external surface of the tubular drill shank , while the return of the coolant and swarf is through the hollow tool. Just like the gundrill the BTA drill has 2 guiding pads which provide the guidance from the hole walls after the tool has entered the workpiece (fig.1.3).

The ejector drill bears similarities with the gundrill and the BTA drills because it consists of a set of concentric tubes that feed the cutting fluid internally and expel the swarf and used fluid externally. Additionally there is a vacuum suction in the inner tube generated by venturi shaped nozzles, in order to facilitate the extraction of the swarf and fluid from the tube.

The self piloting drills are superior tools when compared with twist drills in terms of performance and hole quality. However they require in general special machines, tooling and know-how.

Other drawbacks are their requirements for pulsating pumps, special fluid couplings and often substantial shielding and sealing in order to contain cutting fluid pulsated under high pressure (fig. 1.4), especially at the start of the operation, before the tool has significantly penetrated into the workpiece. The table below summarises the working capabilities of the various drill types for deep hole drilling.

DRILL TYPE	Twist Drill	Gun Drill	Ejector Drill	BTA Drill
DIAMETER (mm)				
Typical Range	0.5 to 50	1.4 to 25	18 to 60	12 to 200
DEPTH / DIAMETER				
Minimum Practical	no. min.	<1	1	1
Common Maximum	5-10	100	50	100
Ultimate	>50	200	>50	>100

TABLE 1 : Operational Capability of DHD Tools

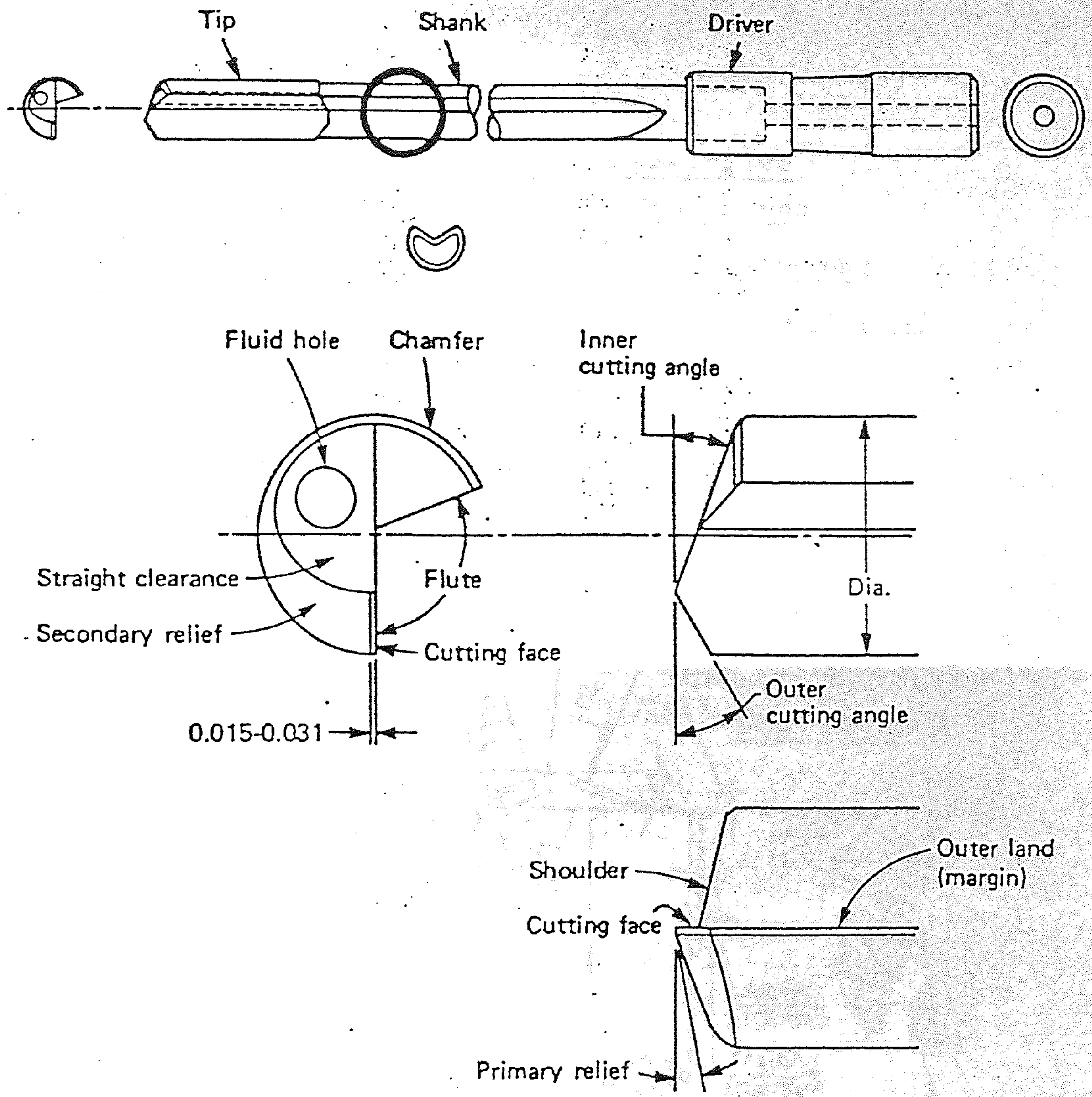


Fig. 1.2 : Gun-drill nomenclature

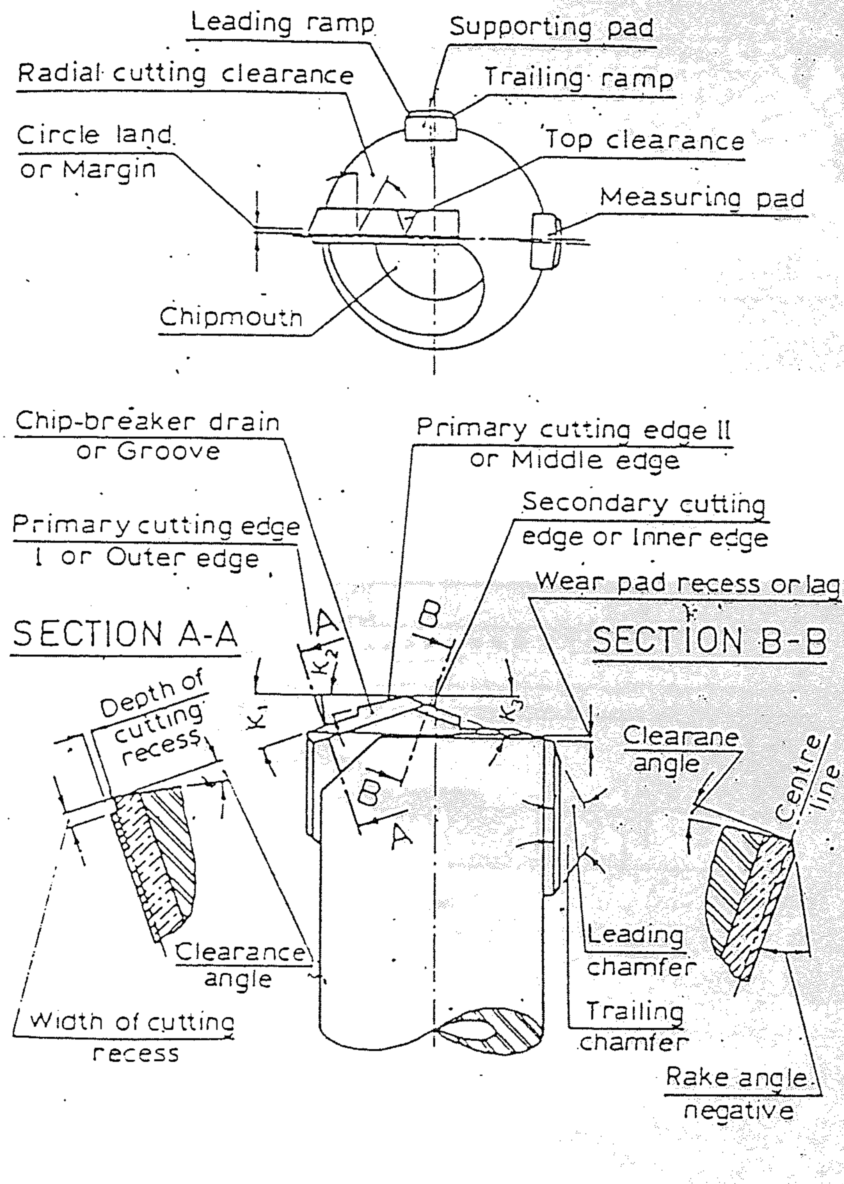


Fig. 1.3 : Geometry of BTA Solid Boring Head

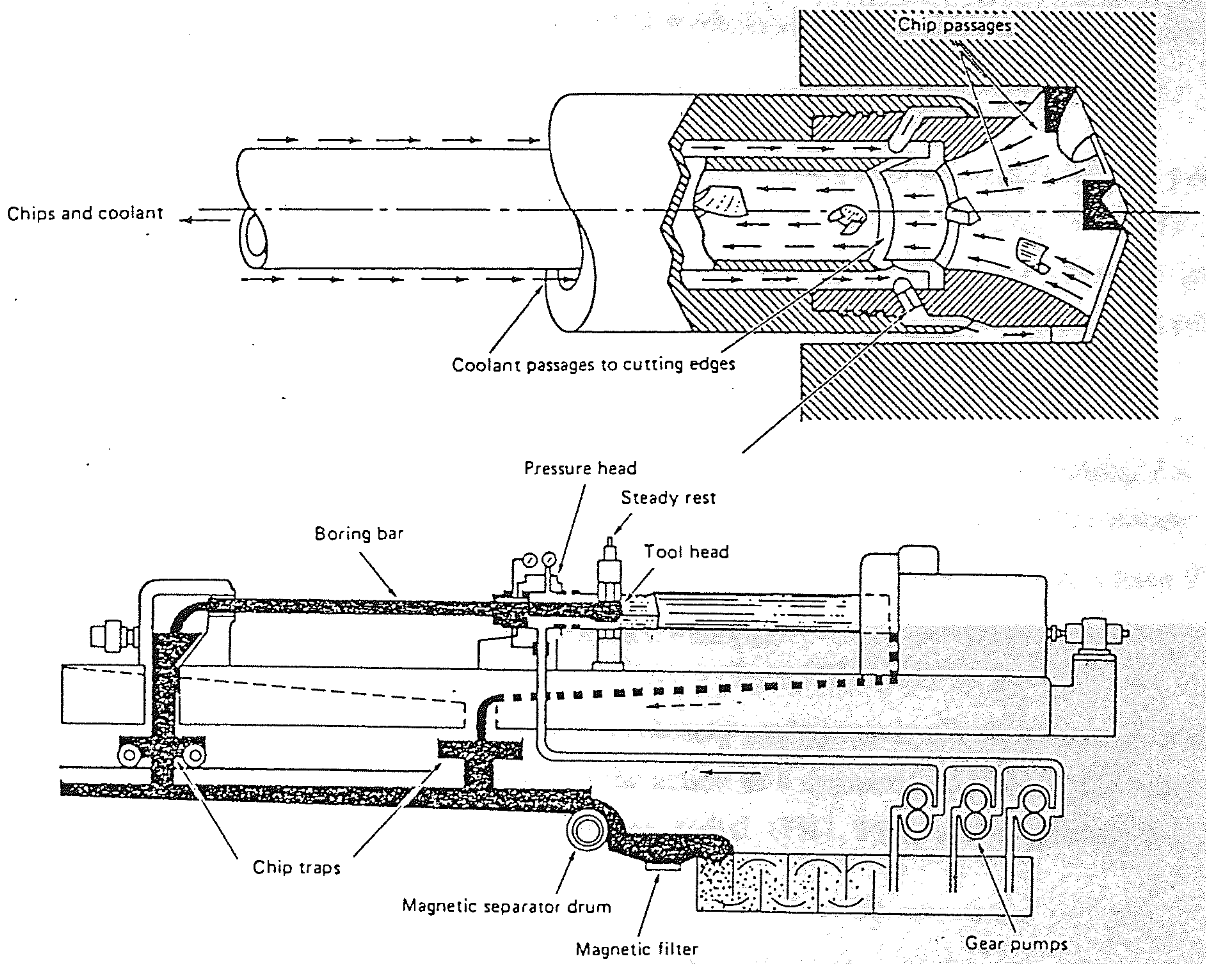


Fig. 1.4 : Horizontal Deep Hole Drilling Machine and Cutting Tool (Ejector Drill)

ii. Twist drills

Twist drills are the most common tools for producing holes in a wide range of materials and sizes. These tools have two cutting edges (lips) and are characterised by axisymmetric cutting action. The main feature of these tools is a pair of helical flutes (spirals) along the length of thge tool. The principal duty of these flutes is to extract the swarf (chips) from the cutting zone and out of the hole as the drill penetrates deeper. The basic twist drill nomenclature is given in fig. 1.5

Twist drills are manufactured to fairly close tolerances nowadays but are not precision tools because of the fact that their fluted long column body reduces rigidity, swarf removal is difficult, the speed of cutting varies from zero in the center to its maximum value at the circumference and finally the diameter determines the depth of cut (= half diameter).

The cutting edge of twist drill presents two distinct features, a pair of cutting lips and the so called chisel. The lips are essentially conventional cutting edges with positive axial rake created by the flute helix angle and relief angle (clearance) which varies from 6° to 26° according to the drill size and workpiece material.

Chip formation at the cutting lips is closely analogous to the chip-formation in turning or milling tools ; cutting is due to the action of a symmetric and balanced (when the tool is correctly ground) system of forces, radial (PR1, PR2) and tangential (PT1, PT2) as shown in fig. 1.2 B.

The chisel edge on the other hand, the short line obliquely across the web that joins the cutting lips, presents a different and more complicated mechanism . At radii near the bottom of the flutes the chisel acts as a forming tool with high negative rake but towards the centre its action is more like that of a blunt wedge which simply pushes the material. This part of the process is highly inefficient and the products are extruded into the flutes where they are mixed with the chips produced by the cutting lips.

Twist drills are very popular with industry not only because this is a long established tradition with Production Engineers but also because despite their shortcomings they feature certain advantages over the self piloting drills.

First of all they can be employed in almost any type of machine tool which can provide relative rotation and axial displacement between the tool and a workpiece.

Second is that twist drills are significantly cheaper, by a factor of 10 or more, compared with the self piloting tools, not only in terms of purchase cost but also because the use of the self piloting tools almost certainly requires capital expenditure in order to modify the cutting fluid supply system of an existing machine tool if purchase of a special purpose one is not economically justified.

Finally, there is a lot of potential for improvements in the design and application of twist drills which has not been fully exhausted. Areas of research which receive significant attention are the use of coatings, use of CAD techniques, mathematical modelling for optimisation of geometrical characteristics of twist drills, etc.

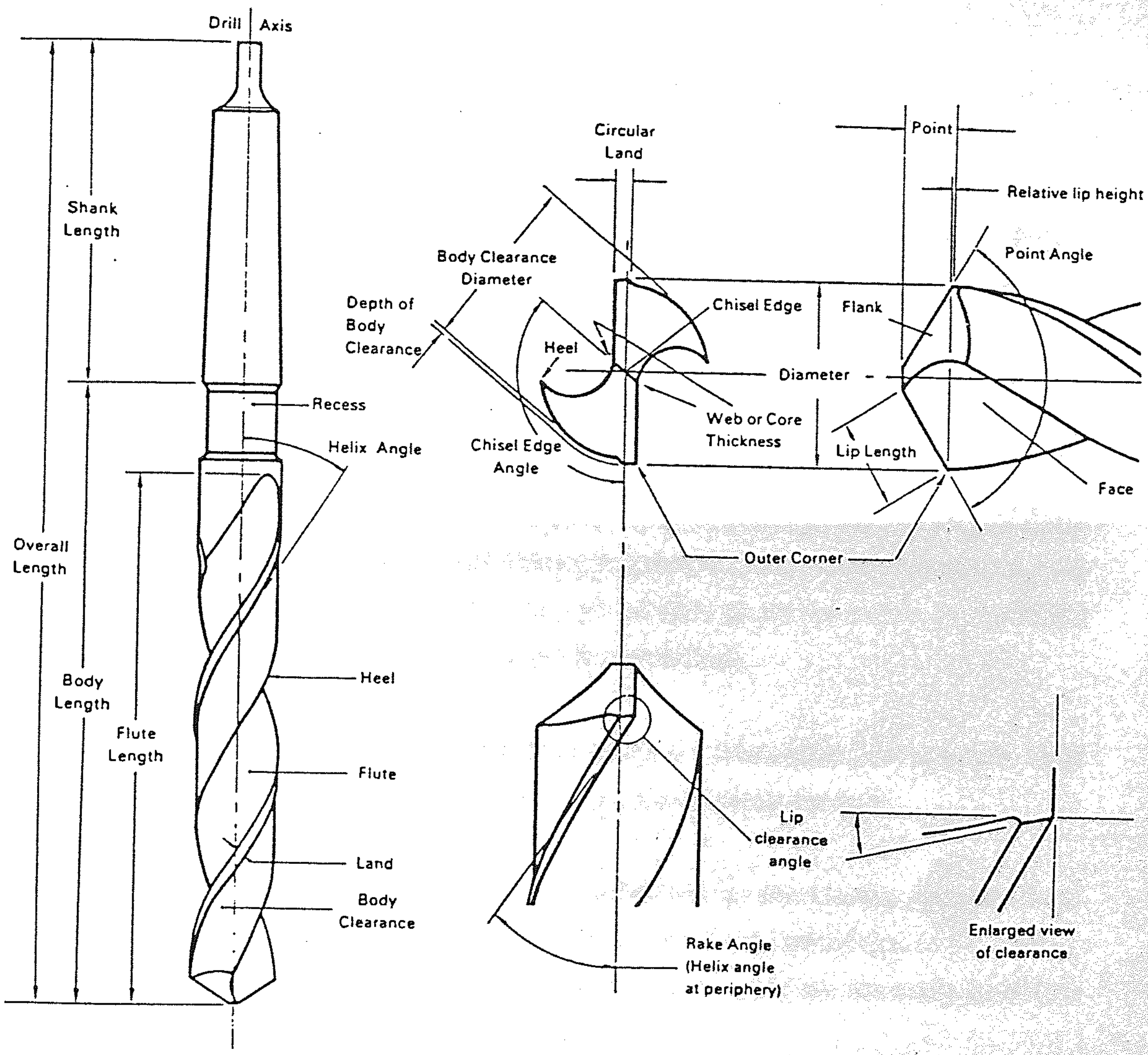


Fig. 1.5 : Typical twist drill nomenclature

1.3.3 Mechanics and quality parameters in drilling in general

One can identify the following three factors of the drilling process which are very closely interrelated :

- The metal cutting process itself.
- The cutting tool with its characteristics such as geometry, coatings, special features etc.
- The produced hole with its geometrical properties and the following general quality requirements :

1. Hole roundness to be within specified tolerances.
2. Hole straightness (runout) to be within specified tolerances.
3. Surface finish to be within specified tolerances.
4. Minimum machining time for production of a hole or a complete workpiece.
5. Maximum tool life between drill regrindings or tool replacement.

1.3.4 Mechanics and quality parameters in DHD

The comments made above are true for all types of drilling. The drilling of deep holes of small diameter exacerbates the problems and introduces an extra dimension, that of the hole depth. The following facts provide a broad idea about the nature of the DHD process and determine the framework for research in this field.

1. Drills for drilling small diameter deep holes are inherently low strength tools due to their great length (overhang) and very small cross-section.

2. In DHD the application of coolant / lubricant to the tooltip / work piece interface is gradually becoming restricted by the produced swarf due to the cutting action of the tool. (Twist drills with internal coolant supply are normally available only for diameters $D \geq \varnothing$ 10.0 mm).

3. Because of (2), swarf removal from the cutting zone, normally not a problem in other machining processes, is not ensured as the hole depth increases and the tool is subjected to overloads which in conjunction with (1) can rapidly lead to "catastrophic failure" of the tool inside the hole.

4. Variations in the composition of the work piece material and consequently to its mechanical properties are often encountered or geometrical features are

included in the design of the workpiece (e.g cross-holes). The above in conjunction with (1) can result to catastrophic failure of the tool and serious damage or even scrapping of the workpiece being machined.

1.4 Summary

Drilling of small diameter deep holes is performed by self-piloting drills and twist drills. Self piloting drills perform better than twist drills in deep hole drilling because of superior design characteristics, mainly their capability to extract the swarf from the hole very efficiently thanks to internal cutting fluid supply at the tip of the tool. They are however very expensive and require special machines, support systems and know-how.

Subject of this research is the process of producing small diameter deep holes using twist drills on CNC machine tools. The interest for research related to this tool and the coresponding metal cutting process is justified by a number of reasons :

The complexity of the process and the practical problems associated with the production of small diameter deep holes using CNC manufacturing systems where the traditional skills and knowledge of an operator are becoming increasingly absent. The DHD process with twist drills presents a major problem : frequent catastrophic failure of the tool and damage of the workpiece. The problem is exacerbated in the case of drilling expensive components made from difficult to machine materials.

Another reason is that very little research has been carried out or published to this date with regards to both a systematic examination of the mechanics of the DHD process using twist drills and also the development of a methodology and the design of a system in order to enable the drilling of small diameter deep holes with safety and reliability under CNC.

Finally, there is a strong and continuous interest and dedication to the twist drill as a tool for producing deep holes by a large number of established engineering companies, both users and manufacturers of twist drills for deep hole drilling. Some of these companies did actively get involved in supporting this research by providing aid both in materials and tools as well as incentive and guidance in terms of definition of research objectives.

CHAPTER 2

LITERATURE SURVEY AND RESEARCH OBJECTIVES

2.1. Classification of research topics

Deep Hole Drilling with twist drills is a complicated and multifaceted metal cutting process. The extended literature survey which was carried out established that there are two main, rather distinct, avenues for research in this field. The presentation which follows, has adopted this classification.

In the first approach DHD is examined in the context of being a metal cutting process; this includes a description of the process and of the problems encountered, the various working methods and techniques and finally a theoretical examination (modelling) of the mechanics of the process such as forces, tool deformation, hole quality, etc.

In the second approach DHD is examined as a process which nowadays is performed almost exclusively on CNC machine tools or machining centres and presents therefore the fundamental problem of ensuring process reliability, tool safety and product quality under conditions of limited supervision or even unmanned machining. This in turn implies that the technologies of on-line monitoring and Adaptive Control are highly applicable and offer ground for improvements in the DHD process.

Survey of the western (predominantly in English) Engineering literature has revealed the existence of a limited number of publications with regards to deep hole drilling with twist drills ; this is considered to be quite remarkable if one takes into account the fact that there are nearly 400 papers, reports, theses and dissertations about twist drills dating as early as 1904, Norris **[147]**.

On the other hand there is a large number of publications, directly related to DHD, in the Soviet, German and Japanese literature, which have never been officially translated in English. Some of these papers are included in the list of references and the author had translations of them or in most cases a synopsis in which case the reference number is accompanied by an asterisk (*).

2.2 DHD as a metal cutting process

2.2.1 Working methods in DHD

This part of the literature survey has actually been covered to a large extent in the Introduction, Chapter 1. The papers and reports from [1] to [16] cover the definition of DHD and the various methods used for drilling deep holes in general and have already been discussed.

2.2.2 Coolant-fed drills in DHD, applications and performance

A number of publications address the problem of sufficient lubrication and cooling of the tool as one of the very important aspects of DHD. In [22] (Yudovin), the pumping effect of the helical flutes is investigated and also the relationship between the cutting zone temperature and the cutting fluid delivery pressure. In [19] (Zykov), the author investigated the relationship between the flow rates of fluid and the tool-chip gap and proposed a logarithmic relationship between the two.

The potential of coolant-fed drills compared with ordinary ones is presented in works [17] (Zlatin), [18] (Rich), [20] (Prupis and Kobuladze), [23] to [25] (Trost) ; in particular it is shown that the level of the cutting forces is significantly reduced while tool life and hole quality are increased.

2.2.3 Tool deformation, rigidity and vibrations in DHD.

The publications [26], [27] discuss the problems of reduced rigidity of long drills and conclude that it is economical to use the shortest possible drills for faster production and fewer resharpenings. However if a long drill has to be used then it is beneficial to enhance its torsional rigidity by one of the following methods: Increasing the web thickness, minimising the body diameter clearance and modifying the flute shape in order to provide a larger cross-sectional area.

The works of [29] (Nekrasova) and [31] (Schaterin) are extremely interesting attempts to model the stiffness and rigitidy of twist drills by modelling these tools as helicoidal springs which can be deformed either under axial or torsional loading.

The authors identify four important properties which describe the general behaviour of twist drills under loading by axial force and torque. These are: torsional stiffness, torsional-thrust stiffness, thrust-torsional stiffness and thrust-compression stiffness. Expressions are derived for the angular and long itudinal deformations of the tool as functions of its diameter, web (core) thickness and tool length.

In [30], [32] and [33] (Garina) and [34] to [36] (Dechko et al.), the authors present the three metrological problems of deep holes, namely the displacement of hole axis (wander), the roundness errors and the parallelism errors.

They suggest that the above characteristics of hole quality are greatly dependent on the accuracy of the spindle - adaptor - tool system and to even higher extent on the characteristics of the very beginning of the penetration namely the drill rigidity, feed rate and whether a centering hole (pilot hole) is used or not.

A mathematical model in [33] (Garina) actually predicts the drill deflection in DHD as a function of the drill diameter, feed and speed and suggests that there is an optimum set of machining parameters for minimum error.

In [34] to [37] (Dechko et al.) similar mathematical models are presented which relate the hole run-out to the actual drill length cutting speed and feed. It is shown that an increase in cutting speed reduces hole run-out while an increase in feed has the opposite effect.

in [29](Nekrasova, [30] (Garina), [35] (Dechko), analytical methods are presented which determine the maximum feed at which the drill loses its axial stability. The method takes into account parameters which determine the drill stiffness such as core (web) thickness and an interesting method is proposed for the analytical calculation of the cross-sectional area and maximum and minimum moments of inertia.

The tool life of twist drills is discussed as a function of drill overhang [30] and [32] (Garina), and operating conditions [34] (Dechko), and it is shown that drill life is reduced with approximately the 4th power of the tool overhang. Corrective factors which take into account the non-dimensional length to diameter ratio are introduced in the calculation of feeds and speeds.

In [42], [44] (Burnham), the researcher concludes the following: Thrust monitoring is necessary and use of conservative feed rates, drill wandering is a problem and mainly depends on the accuracy of grinding, the primary relief angle of the cutting lips, the length and depth of the drill flutes and finally workpiece material hardness variations. In addition he remarks that pecking (periodic drill withdrawal and reentry) is necessary for controlling the process while gundrilling and the use of guide bushes are not considered to be effective techniques for accurate drilling of small deep holes.

In a very interesting work **[45]**, **[46]** (Ulsoy et al.) the authors adopt a dynamic process approach to the problem of drilling examining the drill transverse instability and how it depends on the drill rotational speed, drill length, diameter and feed rate. Mention is also made for the possibility of stabilisation of the process by means of torque control.

The most recent and extended work is a series of papers **[47]**, **[48]** (Ema, Fujii et al.) where two types of vibrations encountered with long twist drills are presented. These two types of vibration are the whirling vibration which appears in the beginning of the operation and chatter vibration which is regenerative chatter with a frequency equal to the bending natural frequency of the drill.

2.2.4 Modelling and Optimisation of the DHD process.

This part of the literature review covers reports on methods and techniques for control of the DHD process. It should be mentioned that all the techniques and methods reported rise from a comprehensive knowledge and understanding of the process and aim to eliminate some of the problems arising by a predictive corrective action, in other words an open loop control.

Apart from the use of drills of special geometry (section 2.2.5) or with internal coolant delivery (section 2.2.2) the problems of DHD are tackled by various methods used in industry :

The kinematic methods of chip breaking such as vibratory drilling and the use of special drilling cycles for cut distribution (pecking) have been investigated by various researchers :

Vibratory drilling as it appears in **[49]** (Chernichkin), **[50]** (Satel-Poduraev), **[59]** (Mansurev), refers to the use of an oscillatory motion superimposed to the main motion of the tool. This oscillatory motion is of very low amplitude (typically 10 to 20 μm) and high frequency up to 200 Hz and results in breaking up the swarf and facilitating its extraction.

The devices which produce this type of motion are electrical or mechanical devices which operate independently of the main feed drive.

Similar to vibratory drilling in principle is the use of other methods for breaking the swarf by means of periodic feed changes between a minimum and maximum value, [63] (Popovskaya-Chernyi).

Also in [59] (Mansurev), a review of all the kinematic methods known is given : the discrete method where the feed is momentarily disengaged completely ; the vibrational method where the feed is a superposition of a constant and a sinusoidally varying feed and the relaxation method in which the feed is a superposition of a constant and a tooth-saw like pattern of periodically varying feed.

Also described are mechanical devices [66]-[67] (Nagornyak), which automatically reduce the feed as the drill breaks through and being unsupported it is highly probable to fail.

In [69] (Kavaratzis-Maiden), an algorithm is presented which varies either the feed rate or spindle speed within an NC part program for DHD , in order to constantly reduce the feed (chip thickness)mas the drill advances into the workpiece. Successful results are reported when the method was employed in the place of canned pecking cycles.

Another aspect of the DHD process is the selection of optimum cutting conditions in order to satisfy various performance criteria such as cycle time, tool life, machining costs etc.

Amongst the various research efforts are the ones in which a complete mathematical model of the entire process is presented [51] (Khabenkov), [53] to [55] (Poletaev), [56] to [58] (Lishchinskii), with analytical expressions for the drilling thrust, torque, tool life and machining costs. A criterion of economic optima lity is defined and based on that is derived the optimum feed for the process.

It is worth mentioning that in [55] (Poletaev), the author addresses the problem of automatic control on the process and examines the relative merits of choosing thrust or torque as a monitored process parameter. This is one of the fundamental aspects of this research as it will be explained in the following chapters.

A similar approach is followed by the researchers [52] (Zakovorothnyi), [56] to [58] (Lishchinskii et al), where again the feed rate and spindle speed for the process are determined on the basis of a minimum cycle time by optimisation of the auxiliary motion and withdrawal feed rate (a minimum value of feed rate beyond which drilling is no longer productive and the tool has to be rapidly withdrawn) .

In [61] (Patkar), optimisation of the machining conditions is based on linear programming and the use of an objective function representing the metal removal rate while constraints are imposed by maximum values for the cutting forces and torque.

Similarly, in the works of [64] (Dobrovol'skii), [65] (Rudenko) and [68] (Kotuch), optimisation of the cutting rates (machining parameters) is based on tool life, cutting forces and torque as constraints to the process.

2.2.5 Drill geometry designs for efficient DHD.

The design and manufacturing of special, non standard, drills is one of the earliest measures taken in order to achieve more effective Deep Hole Drilling within the context of twist drills. Many researchers, [70] (Stepanov), [71] (Gribkov), [72] (Dechko), [77] (Dallas), [78] (Gettelman), [79] (Margulis) , [80] (Pleschitsev), report the satisfactory performance of special drills which, in addition to having a great overall and flute length have the characteristics described below :

- **i.** Quick helix of 35° to 40° as opposed to 30° (typically).
- **ii.** Heavy web for enhanced rigidity (reduced swarf removal capacity)
- **iii.** Open flutes for swarf removal capacity (reduced rigidity).
- **iv.** Split points with positive rake notching.
- **v.** Point angles of 135° or greater as opposed to 118° (typically).
- **vi.** Use of coatings (TiN, TiC , etc.)
- **vii.** Use of chipbreakers.

It is significant that all researchers agree that there is no universal design for efficient DHD and that the material being drilled determines which characteristics of the tool geometry are favoured.

In [75] (Vinogradov), [76] (Davidson), [79] (Margulis), some typical cases of difficult materials are examined and recommendations are made with regards to the machining conditions and special geometrical features of the tool. Empirical expressions are also proposed which determine tool life, drilling torque and thrust, etc.

2.2.6 Modelling of forces and torque in drilling in general.

This part of the literature survey was also considered as important because it is clear that up to a certain depth the characteristics of the deep hole drilling process are essentially the same as those of conventionall drilling.

Various researchers have developed an analysis of the drilling process which will give a clear understanding of the mechanism involved and which allow prediction of the cutting forces.

From this point of view one can distinguish two main schools of thought ; a deterministic one, which starts from first principles in the development of mathematical models and the other which has treated the metal cutting process in general as a stochastic one and the investigation has been orientated towards the dynamic fluctuations of the forces.

Typical representatives of the first school are Merchant, **[150]** (Shaw and Oxford), **[151]** (Galloway), **[152]**, **[153]** (Bhatcharaya et al) and others.

On the other hand very few researchers have considered the dynamic fluctuations of the drilling forces although there has been a significant number of papers for dynamic nature of the cutting forces in milling or turning.

In **[149]** (Tobias and Fishwick), it is suggested that the fluctuations of the drilling forces was a result of machine tool chatter while in **[155]** (Osman, Xistris and Chalil) is shown that the dynamic fluctuations of torque and thrust in drilling are stationary (time invariant) processes with a Gaussian density function and it is also shown that the degree of randomness could be as high as 50% of the steady state value.

2.3 DHD as a monitored and controlled process

2.3.1 Adaptive control in drilling and DHD.

The subject of Adaptive Control in metal cutting in general, has been a very popular research topic in the late 1960's and throughout the 1970's. Three main types of Adaptive Control were identified, namely Adaptive Control Constraint (ACC), Adaptive Control Optimisation (ACO) and Geometrical Adaptive Control (GAC) , **[167]** (Milner).

In Adaptive Control of Constraints (ACC) the control system is regulating one or more of the machining parameters (typically feed and speed) in order to ensure that one or more process parameters are kept within specified limits (constraints). Such parameters can be the spindle motor load, torque, feed force, tool deflection, etc.

In Adaptive Control Optimisation (ACO) systems the objective is to optimise the value of a performance index, usually a production cost function or production rate, by means of controlling one or more machining parameters, namely feed rate, spindle speed and depth of cut.

Geometric Adaptive Control (GAC) involves in-process gauging and its main objective is to ensure the surface finish and geometrical accuracy (tolerances) of the component machined. GAC is inherently the most complicated and difficult to accomplish type of AC.

As far as drilling is concerned all the research work in this area has been concentrated on the first two types of control ACC and ACO while any ACG attempts have not been reported.

In the western literature there have been only a few scientific research publications on Adaptive Control in drilling in general and a number of technical / commercial reports which are discussed later.

The first, **[82]** (Friedman), presents the fundamental problems of drilling small diameter deep holes for the aerospace industry. The paper also discusses the choice of control and controlled parameters and the control strategy required for AC.

Two methods are discussed, the variation of the feed rate under constant rotational speed and the reciprocal method, namely variation of the spindle speed while the feed is held constant. Finally the paper suggests that the AC system should be able to withdraw the drill from the hole when a minimum preprogrammed spindle speed level is reached in order to initiate chip relief action.

A more theoretical analysis of Adaptive Control and an actual AC system is presented in [93] (Bedini-Pinoti) involving drilling of holes Ø 10.75 x 30 mm in steel. This system is a blend between ACC and ACO and was based on the hard wired logic previously used by the same authors for the AC of a milling machine.

The monitored and controlled parameters in this system, fitted to an NC machining centre, are the axial thrust on the drill, the torque on the drill and the cutting power obtained by multiplying the cutting torque by the spindle speed. The control variables are the spindle speed and the tool feed rate.

From the experimental results presented in the paper it becomes evident that the need for AC arises due to the fact that the cutting forces rise with hole depth. However this AC system has been built around a static model of the drilling process in which thrust, torque and power depend only on the workpiece material, feed per rev and drill speed. The model does not account for variations in the drill diameter but even more important in the hole depth.

The ratio of hole depth to diameter which is examined is between to 2:1 and 3:1 and with drill diameters Ø 10.75 mm and Ø 15 mm the phenomena of flute clogging and torsional loading of the tool do not manifest themselves.

From this point of view the AC system described in the paper acomplishes an ACO role and to a small extent an ACC one. The fact that provision for drill withdrawal and reentry into the workpiece is not included in the control logic and that the latter is hardware based, make the system inherently unsuitable for expansion to DHD process control.

The works in [93] (Frecka), [99] and [103] (Mathias), belong to the technical / commercial literature type and are discussed in the relevant section of the literature survey.

It should be mentioned though that all agree that the most suitable parameter for control of the drilling process is the drilling torque and the drilling power ; however all systems lack the pecking facility (drill withdrawal and reentry) and the on line optimisation of the drilling cycle.

In **[100]** (Kegg), a detailed account is given of the performance and the relative merits of AC in drilling. In particular it is reported that there is a time saving of up to 33% in floor-to-floor time when comparing conventional to torque controlled drilling. Similar results are reported in Aerospace industry applications, **[94]** (Donahue), and in particular machining of structural frames and covers made from Titanium.

The German Engineering literature offers a large number of publications on AC most significant of which have been investigated in English summary form by the author. The term *Tiefbohr* in German implicitly means self-piloting drill while the term *Wendelbohr* is used for twist drills.

In **[105]** (Tuffentsammer), **[107]** (Rohs) and **[111]** (Cronjäger), the problems associated with DHD are defined ; the variation in chip formation and increase in drilling torque is reported. The effect of feed, speed and tool diameter is investigated in the context of stable and unstable drilling. Finally a system is presented for control of the drilling torque by means of varying the feed rate between a maximum and a minimum value according to a control strategy ; no description of the latter is given nor is it explained how the actual commands are given to the machine tool controller.

In **[107]** (Rohs), a review of applications of AC in DHD is presented, the use of various sensors for monitoring torque, spindle power, cutting forces (thrust and torque) and also the control strategies used.

In **[108]** (Müller-Gerbes), the principle of measuring drilling torque by means of dynamometric spindle bearings is explained while in **[110]** and **[113]** (Baijer), there is a review of other sensors available for monitoring and AC in DHD.

The Soviet Literature on the other hand offers a plethora of papers and reports on the subjects of control and optimisation of the DHD process. It is actually significant that the term Deep Hole Drilling *(Glubokoe Sverlenjie)* is explicitely used in all the referred Soviet research publications and implies the use of long small diameter twist drills.

These publications were produced mainly in the mid and late 1970's in various universities and research institutes in the USSR and only a few were officially translated in English by the MTIRA and PERA asociations in the U.K and appeared in the "*Stanki i Instrument* "(Machines and Tooling) and "*Vestnik Mashinostroeniya* " (Russian Engineering Journal / Soviet Engineering Research) publications.

Main feature of almost all the AC systems described in the Soviet literature is that they address the problem of DHD as a problem of stabilisation and control of the process because of the effect of the hole depth on the magnitude of drilling torque and thrust.

Some publications attempt modeling of the drilling forces, cutting power and drill life as functions not only of the conventionally examined machining conditions (feed, speed, drill diameter, workpiece material) but also the hole depth, **[83]** (Tverskoi), **[84]** and **[89]** (Zakamaldin), **[85]** (Poletaev), **[104]** (Bondar-Shchigelskii).

The work by V. A Poletaev in particular, is one of the most elaborate and detailed on the subject of DHD. The author examines in a series of papers **[83]** to **[85]**, the structure of a system for AC and proposes two control strategies, one on monitoring and control of the drilling thrust and one on monitoring and control of the drilling torque. The choice is based on economic optimisation of the process criteria and on a model of the two forces expressed as linear functions of the feed and the hole depth.

A similar approach is also found in work of Zakamaldin and Tverskoii, **[84]** and **[89]**, where drilling of small diameter holes Ø 1.65 x 24 mm in Steel 18H2N4VA (Soviet Specifications) is done under a system which monitors the drilling thrust and torque and regulates the feed rate.

These two systems like all the rest of the AC systems for DHD designed and used in the USSR (described in section 2.5) share a common characteristic ; they are all built around analog control devices, mainly electromechanical or hydraulic or purely mechanical. This is quite understandable because in that time (1960-1980) the state of the art was analogue control and digital techniques including the use of computers had only just started appearing in the west.

The main criticism on their research work in discussion first of all lies in the fact that the proposed models use formulae which are not suported by detailed analysis, therefore are very difficult to follow and consequently their validity is doubtful.

In addition to the above an other point for criticism is that these models predict the magnitudes of the drilling torque and thrust as explicit functions of the feed, speed, tool diameter and hole depth. This is clearly a deterministic approach, which is valid from a cutting mechanics view-point but fails to account for the dynamics of the process, namely the instability arising from friction forces, lack of lubrication, swarf breaking, etc.

In the classic approach, drilling has been investigated as a time invariant process the mechanics of which originate in the vicinity of the tool point (cutting lips and chisel) and the models proposed by various researchers place emphasis on drill geometry ignoring the effect of the hole depth and the external disturbances which arise when the depth of the hole exceeds a few diameters (see also section 2.2.6).

Only in works by **[105]** (Tuffentsammer), **[106]** (Weber), **[165]** and **[166]** (Ogawa, Nakayama) the phenomenon of variations of chip geometry with hole depth is reported, albeit for short hole drilling (Ø 6.0 mm and the ratio L/D ≤ 4:1) ; this mechanism which causes torsional vibrations of the tool at greater depths is examined in detail in this thesis, chapter 4.

2.3.2 Tool condition monitoring and tool breakage detection

During the 1980's a major change of direction in the research on metal cutting has been taking place. The popular, during the 1960's and 1970's, subject of Adaptive Control has gradually given its place to another area, that of process monitoring, tool condition monitoring and breakage detection **[115]** to **[146]**.

There seem to be two main reasons for this change ; the main and obvious reason is simply a change of priorities in the operation of manufacturing systems. The latter are moving in the well known directions of FMS, Manufacturing Cells, Unmanned Machining and ever growing Automation in general. From this point of view it becomes clear that condition monitoring, detection of breakages and other malfunctions in general is essential.

The other reason for moving the research emphasis away from Adaptive Control is that AC is such an extended research field with many simultaneous requirements (ACC, ACO and GAC).

Despite the large number of powerful algorithms developed for ACC and ACO in Turning, Milling and Grinding mainly, these could not be utilised in practice (on the shopfloor) by the NC and CNC machine tool controls of the 1960's and 1970's primarily because of lack of computing power and memory for real time calculations and control.

The ACO algorithms in particular proved an elaborate and impractical task due to the large amount of calculations involved. Also, because no universal transducer has yet been found to satisfy the various characteristics of at least the four or five major metal cutting processes.

Therefore, the research effort has been orientated to the direction of developing algorithms for rapid recognition of breakages in the automated, unmanned shopfloor environments of this decade. These algorithms **[156]** to **[160]** are still a form of ACC and indeed some very interesting pieces of research work have been produced on this field.

The above research effort is orientated towards the monitoring of processes such as turning and milling, while DHD has received very little attention or none at all. There are however a few extremely interesting proposed methods for monitoring drill wear and failure in conventional drilling.

In **[115]** (Subramanian-Cook), the authors present a simple model which relates drill flank wear with thrust and torque and hardness of the workpiece; the model however is restricted to drilling of holes a few diameters deep, where only classic wear phenomena manifest themselves and not instability due to the swarf clogging the drill flutes.

In **[119]** (Yee-Blomquist), a method is described for determining drill wear and predicting drill breakage. The monitoring of the process is based on applying time-domain analysis to the signal from an accelerometer mounted on the workpiece. Success around 98% is claimed with a high level of accuracy ; the paper however does not mention at all the algorithm or analysis used in processing the signal of the accelerometer.

In **[125]** (Heisel), it is explained how it is possible to measure accurately, in a production environment, drilling forces by means of dynamometric bearings in the main spindles of machine tools. The method is reported to be suitable for drills of small diameters down to Ø 3.0 mm

In **[127]** (Thangaraj-Wright), a rather sophisticated system is presented which not only monitors drill wear and predicts tool failure but is also capable to retract the tool from the cutting zone and avoid total failure. The monitoring and prediction strategy is based on the gradient of the drilling thrust calculated using a digital filter.

In **[130]** (Liao), another on-line method is presented for detection of breakages during drilling ; the method is based on monitoring of the spindle motor current and its variation with the drilling load. The current is measured by a current transformer (induction coil), amplified and filtered through an analogue 20 Hz bandwidth Butterworth filter. Experimental evidence shows close similarities between the torque pattern vs time and the current pattern vs time which suggests the suitability of the method for monitoring drilling operations.

In **[142]** (Lee), the method used for detection of tool breakage in the case of twist drills in the range of diameters Ø 1.0 to 3.0 mm was based on the use of an AE sensor fixed to the machine table. The system distinguishes drill breakage from normal drilling or mechanical noise not by recognition of the power spectra pattern but from the actual power magnitude (dB). It was also established that the tool breakage signal was neither affected by the tool diameter nor was it too sensitive to the distance between the AE sensor and the AE source.

In **[146]** (Li-Wu), the authors propose a method for identification of drill wear states by pattern recognition in which the drill wear conditions can be represented by four fuzzy states ; "initial", "small", "normal", "severe". The above algorithm is claimed to be more adequate than conventional techniques for drill replacement control but the hole dimensions under which it was established (Ø 6.35 x 38 mm) leave doubts with regards to its applicability in DHD.

A similar method is described in **[132]** (Moriwaki), except that the drill emits ultrasound when the tool holder slips mechanically against the spindle when torque exceeds a predetermined threshold.

A number of other systems and techniques for tool wear monitoring and breakage detection have also been surveyed although they refer to other processes such as turning **[116]** (Moriwaki), **[126]** (Matsuhima), **[142]** (Lee), and milling **[140]** (Takata), **[145]** (Atilntas). The monitored parameters again include AE, vibrations, spindle power. Among the detection algorithms discussed the Kalman filter (or time series of residuals or auto-regressive moving average) emerges as the most reliable and promising.

2.4 Commercial and Technical Research Literature
(Process Monitoring, Tool Breakage, Adaptive Control)

The significance of deep hole drilling and its complexity as a metal cutting process is shown by the amount of effort on behalf of the R&D departments of numerous companies worldwide, both machine tool builders and cutting tools manufacturers.

The first commercially available sytem for process control in drilling was the Tornetic System presented in 1962, **[81]** (Deroch) which was based on torque control under constant horsepower and its main application was drilling small diameter (0.0625" or 1.58

mm) in exotic aerospace alloys such as Vasco-Jet 1000, Titanium A-286 etc. The system was later applied to other metal cutting operations such as milling , tapping , turning and even band sawing with computer control of the hydraulic feed.

Another system was the Cincinnati Milacron presented in 1975, **[93]**, **[100]** developed for NC machines based again on torque and horsepower constraint by feed rate control. The torque limit was a three digit code punched into the NC tape while another set of codes, informed the machine that machining was non-adaptive, code 000: limitation of using the system for diameters > Ø 0.2" or 3.0 mm or code 999: horsepower constraint only for heavy drilling or face milling in order to ensure protection of the spindle motor from overloads.

Another system was the one jointly developed between Macotech Corporation and Boeing Aerospace Corporation (USA) in 1973, **[99]** and **[103]**, which is very similar to the Cincinnati Milacron System in the sense that both horsepower and torque are controlled, but in addition the system senses spindle end-deflection by means of a special electromagnetic induction sensor. Feed rate and spindle speed are the control parameters.

The Valeron Corporation System presnted in 1979, **[101]** and **[133]** is based on power monitoring for a cutting tool and typical applications are deep hole drilling using gun drills, gear and camshaft hobbing and rough milling. Its main limitation is that drilling torque is not measured directly but calculated from the power consumed and because the latter can fluctuate significantly due to various reasons (noise, mains fluctuations, etc) it is not a reliable method when powerful CNC machines or machining centres are used to drive small tools.

The Sandvik Coromant System presented in 1981, **[117]** for tool condition monitoring is based on thrust monitoring to detect tool breakages and also approach of end of tool life while for horsepower monitoring it uses electromagnetic induction rings. The system again is limited by estimation rather than direct measurement of torque and is unsuitable for small diameter drills.

The Ebbert Engineering Load Sentinel System presented in 1984, **[118]** and **[139]** based also on monitoring the phase angle between the AC current and voltage and is claimed to detect load changes as slight as 0.01% of motor rating and is capable of handling motors of fractional horsepower.

The Kennametal System presented in 1984, **[137]** for cutting tool monitoring is based on direct forces measuring for detection of tool wear or breakage and is also suitable for DHD.

The West German Promess System presented in 1979 and 1984, **[138]** is a rather unusual and very interesting system because it directly measures cutting forces including torque. This is achieved by means of strain gauges embedded in narrow grooves machined along the circumference of the outer race of the bearings of the spindle and feed motors of the machine tool. A typical application of the system is monitoring deep hole drilling using gun drills of Ø 0.100" or 6.25 mm.

All the above systems represent the commercially available technology in the West for tool condition monitoring and Adaptive Control.

There are a number of systems developed in the USSR by research establishments or technical institutes and they have been reported as applied in industry :

The system developed at the Chelyabinsk Polytechnic Institute in 1970, **[85]** is based on drilling torque monitoring by means of a balanced dynamometric drive. Feed rate control is done by means of oil flow control while trips, relays and limit switches perform rapid withdrawal and reentry. Typical application is drilling Ø 2.0 x 59 mm holes in Steel 45 (165 to 195 BHN). Significant improvements are reported in number of pecks (250 % reduction), cycle time (300 %), tool life and number of regrindings (500 %).

The system developed at the Rostov-on-Don Polytechnic Institute in 1971, **[52]** also based on torque and thrust control and regulation of the feed rate.

The system developed at the Rostov-on-Don Agricultural Machinery Institute and Kramatorsk Heavy Machine Tools Works in 1974, **[92]** based on monitoring and stabilisation of the axial drilling force during drilling of holes Ø 80 x 10,000 mm !!! by control of the feed rate.

The system developed in 1977 by OKBSA in Moscow, **[97]**, **[98]** based on monitoring of the electrical power consumed and full adaptive control of the feed rate and tool position. The report indicates that there has been a considerable theoretical analysis of the process (from a control engineering point of view) but the information on transfer functions and control algorithms is very limited.

The model 150-GSD Deep Drilling Machine of 1979, **[102]** which measures the drilling torque by a magneto-electric induction pulse-phase transducer and regulates also the feed rate of the drill. Successful drilling of holes Ø 6.5 mm x 400 mm in carbon steel is reported to have increased productivity by 22% and tool life by 27%.

The system developed in 1980 at the Kharkov Unit-Head Machine-Tool Works, **[104]** based on a system of two spindles, a drive spindle and a tool spindle. Torque is transmitted by means of a clutch coupling and the two spindles rotate at identical velocities. When the drilling torque exceeds a critical value the two spindles are disengaged and an electromechanical system withdraws the tool from the cutting zone. Typical application of the system is drilling of holes in carburettors , Ø 2.5 x 65 mm at 0.03 - 0.04 mm/rev and limiting torque of 25 Ncm.

Other systems described are those developed by **[87]** (Smagin), **[89]** (Tverskoi - Zakamaldin), **[90]** (Yumsthyk), also based on electromechanical devices for monitoring and control of the drilling forces.

2.5 Conclusions - Research Objectives - Thesis Structure

2.5.1 Conclusions

The literature survey has shown that Deep Hole Drilling is an extended field for research where two areas of Engineering Science overlap. The first one is that of Metal Cutting in its full context. The other is a blend of Control Engineering and Computer Aided Engineering. The latter actually emerges as a more dominant aspect in the literature of the mid and late 1980's.

It is clear that in the area of DHD as a metal cutting process very little work has been reported, at least in the western literature, with the exception of few isolated publications on the topics of drill deflection and hole quality.

The situation is similar as far AC and Tool and Process Monitoring is concerned despite the large number of technical and commercial literature. The numerous systems described claim success in tackling the problems of tool, work-piece and safety process but fail to present the detailed analysis of the system, the derivation of process models and finally the development of various algorithms and strategies.

A possible explanation for this situation is that such details are part of the commercial and technical confidentiality of these systems and the competition which exists in penetration of the limited market.

As far as the Soviet literature is concerned it is clear that the subject of DHD has been of great interest and importance both in terms of Engineering Science and practice despite the fact that over 80% of those have been available only in brief English abstracts form.

The few publications which have approached the subject from a fundamental analysis and process modelling point of view are characterised by arbitrary assumptions, unsubstantiated arguments and in most cases lack of references.

The merit of these publications lies in the definition of the process, the identification of the problems and the description of its mechanics. In this context they have positively contributed in the forming and clarification of the ideas contained in this thesis.

2.5.2 Research Objectives

The aim of this research is dual : an investigation of the mechanics of deep hole drilling using small diameter twist drills and the design and development of a system for Process Monitoring and Adaptive Control of the process.

The research is based on the fact that this type of drilling, although capable of being performed manually, is actually performed by CNC machine tools or machining centres which operate under unmanned machining or limited manpower conditions (typical requirements of modern manufacturing systems). The following objectives were set :

1. Carry out an experimental investigation of the relationships between the various parameters of the process such as cutting conditions versus tool performance, cutting forces, etc. Clearly choice of suitable materials and drill geometries is very important in order to obtain a representative profile of the process.

2. Define or clarify the various problems associated with the mechanics of the DHD process. Develop a process model in order to provide a theoretical explanation and understanding of the above.

3. Establish the value and limitations of conventional techniques and systems for more efficient and reliable DHD, already in use by industry ; investigate areas of possible improvements of these methods or strategies.

4. Establish which process parameters serve best as state variables (measured variables) and also which ones serve best as controlled variables (machining parameters). Based on the above develop a suitable process control algorithm.

5. Investigate the dynamics and control characteristics of the process and design a system for Process Monitoring and Adaptive Control during Deep Hole Drilling on a CNC machine tool ; the system should be based on a software rather than a hardware structure. Primary task of the system will be to eliminate the possibility of catastrophic failure of the tool and the workpiece during machining.

6. Explore the practical aspects of installing and implementing such a system on a CNC machine tool. Experimental verification of the system performance and reliability for various combinations of tools and workpiece materials will be required in order to assess its merits over conventional methods and techniques.

2.5.3 Thesis Structure

The thesis is divided into nine chapters which form two main sections ;
Section A (chapters 3, 4, 5) deals with the deep hole drilling as a metal cutting process and examines the following : theoretical investigation into the process instability, torsional vibrations and catastrophic failure of drills in DHD ; various methods for stabilisation and control of the process without the use of feedback. Such a method developed by the author for structuring NC programs with variable machining parameters is also discussed ;

Section B (chapters 6, 7, 8) is a description of the prototype system for intelligent CNC Deep Hole Drilling ; the algorithms for Adaptive Control of the feed rate, spindle speed and tool position ; the access and flow of data in the system and finally the system software and the various functions it performs.

SECTION A

DHD AS A METAL CUTTING PROCESS

CHAPTER 3

EXPERIMENTAL STUDY OF DHD

This chapter presents an experimental investigation of the DHD process with small diameter twist drills, which was carried out with the objective of establishing the influence of various parameters on the stability, integrity and product quality of the process when performed on a CNC machine tool.

A programme of drilling tests was followed, in which two workpiece materials were involved, an Aluminium and a Titanium alloy which are used in the manufacturing of components for the Aerospace industry. The range of tool diameters was between Ø 2.4 to Ø 4.5 mm and the range of hole depths between 14 to 30 times the drill diameter. Various drill flute and tool point configurations as well as drill makes were used in the tests.

The DHD process can be considered as an interaction between various input and output parameters as depicted in fig. 3.1, which of course applies in most metal cutting operations. Having selected a tool size range as well as workpiece materials according to a typical industrial application, the main objective of the tests was to investigate the influence of the three input parameters, defined in the part program. These parameters are : feed, speed and hole depth and they are clearly the main contributors to the mechanics of all metal cutting operations.

As far as the output of the DHD process is concerned, a number of parameters were investigated, including the depth at which the process becomes unstable and the variation of swarf formation with hole depth while emphasis was placed to the study of the two main forces : drilling thrust or feed force and drilling torque. (The term *'forces'* is used here in a generalised context which includes torque, not a force in absolute terms).

Cutting forces are the most important parameters of the DHD process when compared with other parameters such as vibrations, temperature, power etc. There are two main reasons in support of this argument : first is the direct link between the safe operation of a drill for DHD and the level of the forces involved, second being that forces signals are readily available for accurate measurement and relatively easy to interpret.

3.1 Experimental set-up

The drilling tests were carried out on a Torshälla CNC 160 lathe which was suitably converted for this type of operation. The lathe was chosen instead of a vertical drilling machine tool as the only CNC machine tool, available within the machine tools laboratory, capable of performing horizontal machining in the +/-Z axis (fig. 3.2).

Such practice is necessary in deep hole drilling, in order to eliminate the influence of gravity on the produced swarf which, when drilling vertically, exacerbates the extraction problems already existing due to the small hole diameter and inadequate lubrication.

The lathe uses an ASEA-SAAB controller (PDP-11 microprocessor) to perform the NC functions of the machine tool and is operated by a 16 KW D.C motor via a separate gear box to drive the spindle. It features four speed ranges of 20-600, 40-1200, 80-2400 and 160-4800 RPM. The carriage and cross-slide are located behind the spindle with the carriage above the cross slide.

The lathe is equipped with a hydraulically indexing tool post with double tool holder, each unit accommodating eight tools. A fully enclosing plate guard ensures safety of the operator while there is a conveyor for swarf extraction. There are two axes +/-Z and +/- X, each driven by a separate d.c servomotor with full velocity feedback (tachogenerators) and position feedback (encoders).

The lathe had to be slightly modified in order to perform drilling operations ; in particular the drill was held rotating in the spindle and the role of tool holder was played by special split collets of the same diameter (fig. 3.2).

The workpieces were machined into rectangular blocks 130 x 100 x 40 mm so that they could be held firmly by a vice. The vice was mounted to one of the posts of the tool turret of the lathe by means of a special adaptor plate. The relative motion between the drill and the workpiece was therefore achieved by moving the workpiece towards and away from the tool in the - Z and +Z directions respectively.

The above described set-up enabled to drill many holes in the same workpiece in a relatively short period of time in comparison to a set-up where the drill would have been non-rotating and cylindrical workpieces would have been used instead of rectangular ones.

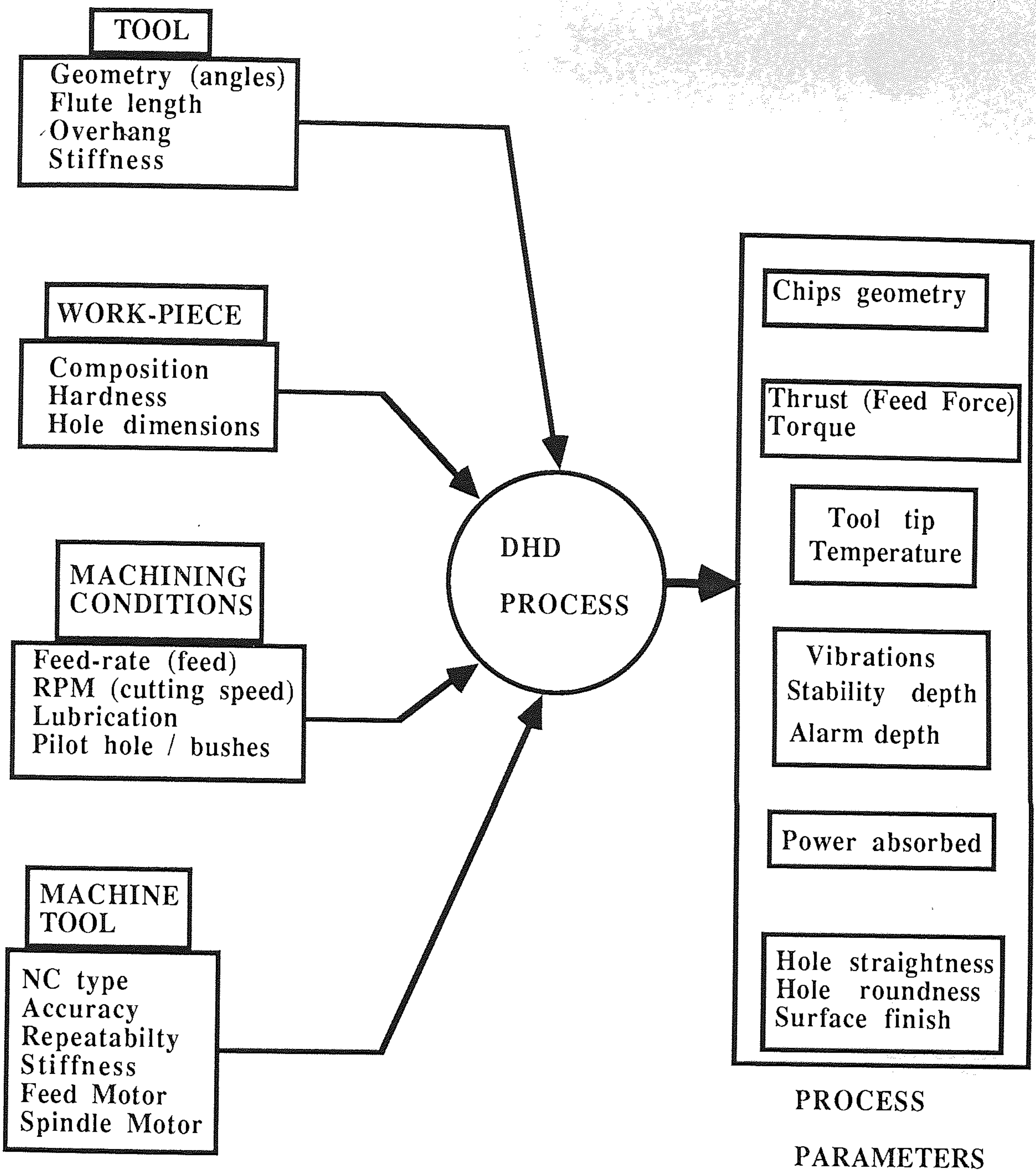


Fig. 3.1 Factors and process parameters in DHD

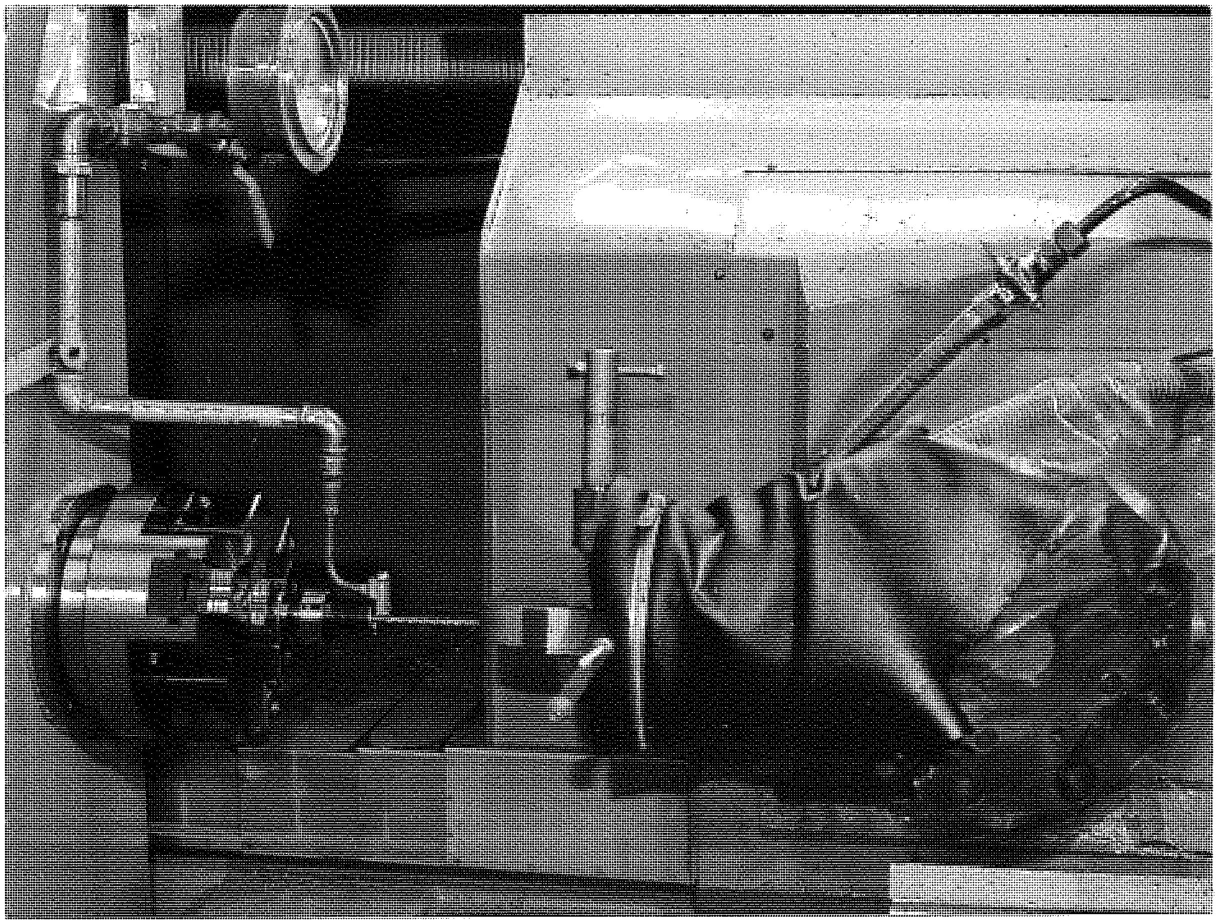


Fig. 3.2 : Experimental set-up (working area of machine tool) : Spindle, Tool, Workpiece, Vice, Tool turret, Cutting Fluid Supply

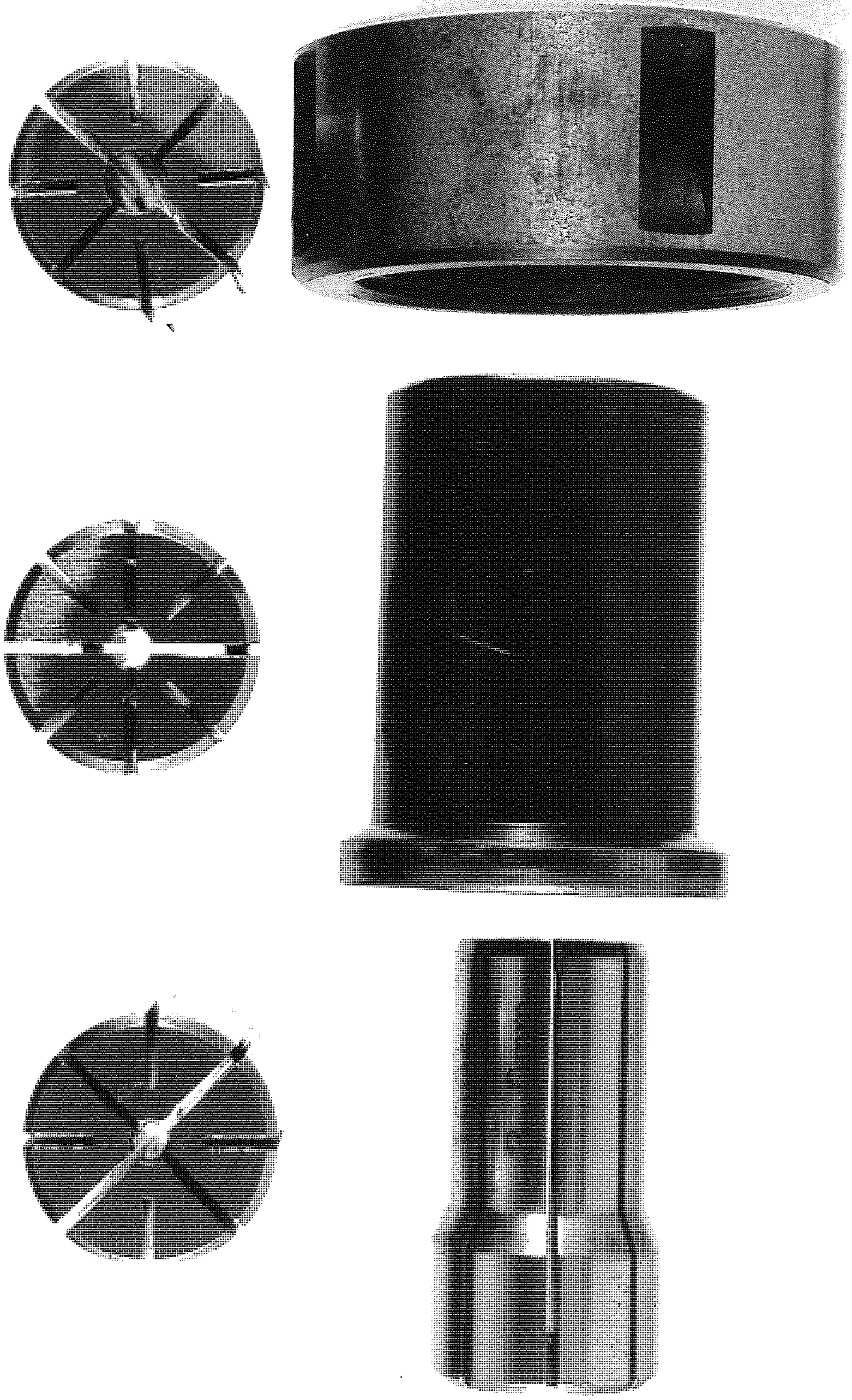


Fig. 3.3 : Bristol Ericson split collets, sizes Ø 4.5, Ø 3.0, Ø 2.4 mm and special tool holder adaptor

3.2 Cutting fluid supply system

The role of the cutting fluid in machining is clearly of great importance because it cools and lubricates the tool. In the case of DHD its performance is restricted by the fact that the cutting process is internal and the cutting zone moves all the time relative to the external supply nozzle.

From the early stages of the experimental work it became clear that a powerfull cutting fluid jet was necessary, in order to penetrate as deep as possible into the drilled hole and also to remove the produced swarf from the drill flutes upon withdrawal of the tool.

In view of this situation and also due to the fact that twist drills in the range of diameters used during tests, that is below Ø 8.0 mm, are not equipped with internal fluid supply, additional work was required in order to modify the existing cutting fluid supply system of the lathe.

A detailed investigation and analysis of the properties of cutting fluids, mix ratios, delivery pressures, etc. and their contribution to the performance of various drill types would constitute an entire research project in its own right and therefore would be outside the scope of the present work.

Instead an ad-hoc approach was considered more appropriate and the following steps were taken in order to ensure a satisfactory cutting fluid supply system suitable for DHD with non-coolant fed twist drils :

- A high pressure pump capable of delivering up to 300 psi was used in place of the standard 15 psi flood supply of the CNC lathe.

- The delivery pipe-work was fabricated with a progressively smaller diameter and followed the contour of the spindle and the tool holder so that eventually a very fine spray was delivered almost parallel with the tool axis. (fig. 3.2)

- A number of nozzle designs with different diameters were tried (fig. 3.4) and the solution adopted incorporated two jets Ø 1/16" (1.6 mm) in diameter, vertically above the drill at angles 5° and 7° to its axis respectively. Using two different angles partly solved the problem of the moving point of intersection between the jet axis and the drill axis as the work piece advanced towards the rotating drill.

- Finally the cutting fluid chosen was the commercially available general application Hocut 580 (Appendix IV) which was mixed with water in a 1: 10 ratio in order to provide a low viscosity lubricating media.

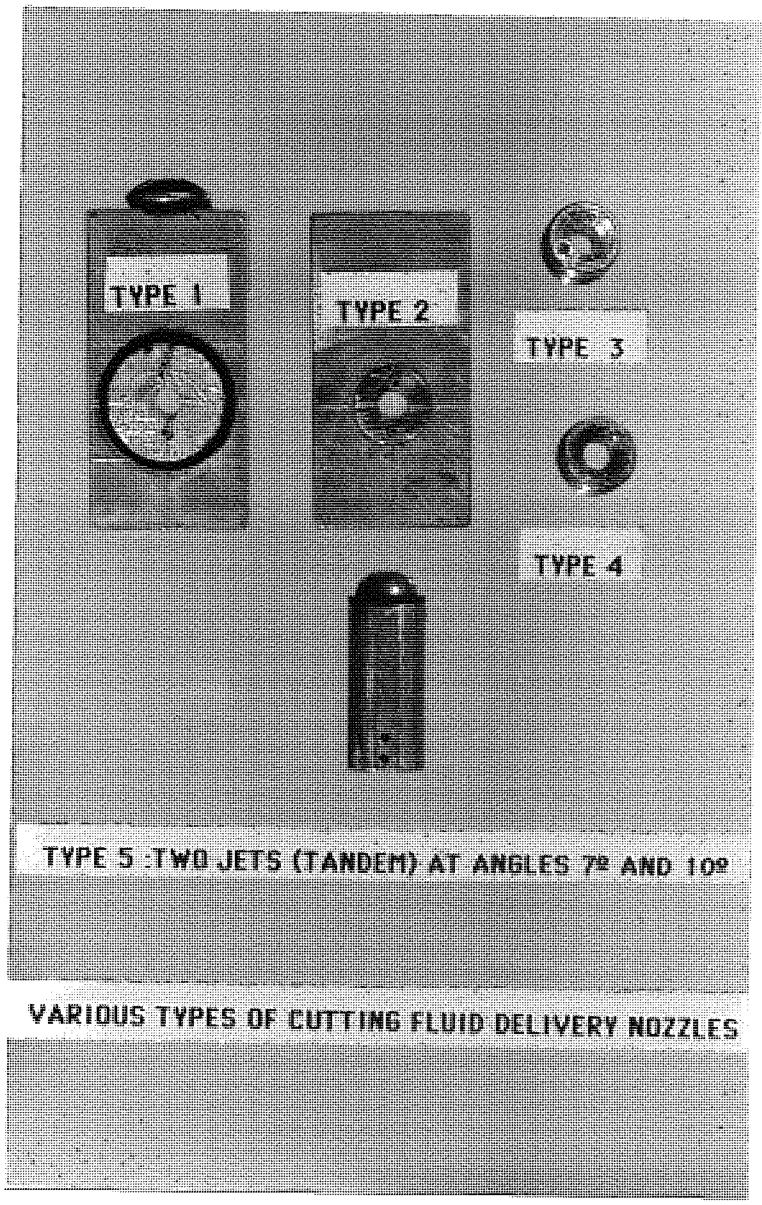


Fig. 3.4 : Various types of cutting fluid delivery nozzles

3.3 Measurement of drilling thrust and torque

The cutting forces were selected as the most suitable and reliable parameters to be recorded and used for understanding and ultimately controlling the DHD process. A number of other parameters and corresponding transducers were considered and tried indeed, such as spindle power monitoring and vibration monitoring using accelerometers.

These systems were proved incapable of providing an accurate or comprehensible picture of the status of the process and the loading of the tool. Indeed, the following situations were encountered :

In attempting to monitor the cutting power as a proportion of the total spindle power and use the signal as an indirect measure of the torsional loading of the tool, it was found that small variations of the drilling power and torque were impossible to detect. The fluctuations of the spindle power (from the mains) were in the order of $\pm$ 0.8 kW and exceeded the actual cutting power by two to three orders of magnitude; the latter was calculated using the dynamometer readings of torque and the tacho signals for rotational speed.

In the case of attempting to use accelerometers and acoustic emission signals as sources of measuring the load on the tool, it was virtually impossible to comprehend and relate the data acquired, to any of the states of loading or subsequent tool failure. It is possible that such data do indeed include a significant amount of information, but its extraction requires a more systematic approach and certainly the use of sophisticated equipment.

In addition to the above mentioned reasons, the following arguments were taken into consideration and supported the choice of direct forces measurement, using a dynamometer, as a means of fast, reliable and efficient technique for studying the DHD process :

- The study of forces in metal cutting is a well established tradition over more than 80 years of research in metal cutting.
- In drilling and DHD in particular, the low strength of a slender tool holds high cutting forces directly responsible for its catastrophic failure.
- Various researchers in metal cutting Thangaraj **[127]**, Goforth **[128]**, Li **[146]**, have shown that there is a satisfactory correlation between various types of tool wear and cutting forces or ratios of forces etc. which suggests that force monitoring is a potential source of indirect tool wear sensing.

- The signals produced from various force measuring devices are relatively easy to process for pattern recognition by a computer in real time as opposed to temperature sensing, vibration or AE signals which require more complicated algorithms (example : FFT) and a great deal of computing power and in addition are rather unsuitable or vulnerable in a shop-floor environment.
- Power monitoring on the other hand has already been successfully used in industry for nearly a decade. It provides a reliable and easy to implement method for detection and control of malfunctions during the proces but so far has been restricted to rather heavy machining applications where considerable resistance can be encountered by the feed or spindle axis motor because of a large size tool when it wears or breaks away.
- There are commercially available devices for measuring thrust, torque and radial forces in a production environment when machining with tools as small as Ø 3.0 mm **[109]** (Lehler), **[110]** (Cronjäger et al), **[113]** (Baier), **[125]** (Heisel).

Cutting forces themselves are impossible to measure exactly where they are generated but instead their reactions can be measured quite accurately at a distance from the cutting edge. The requirements for a precise measuring system have been clearly defined already in works **[163]** (Gautschi) and **[164]** (Sen-Bhattacharya).

In the present work a 4-channel piezoelectric dynamometer was used and the forces monitored were the feed force (axial thrust) and the drilling torque. Appendix III lists the main characteristics of this dynamometer.

The dynamometer was mounted onto a tool post of the tool turret by means of an adaptor plate. Mounted onto the dynamometer was a clamping vice to hold the rectangular workpiece (fig. 3.2). The rotating drill was held firmly in the spindle jaws using a special split collet adaptor. This layout not only enabled to drill many holes in the same workpiece in a short time, as mentioned earlier, but also ensured accurate measurement of the drilling thrust and torque because of the alignment of the tool axis with the axis of the dynamometer.

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In the early stages of this research the signal from the charge amplifier was fed into a U.V paper recorder and a number of experimental results are presented in photographs of U.V traces (see chapter 4). The U.V recorder is a quite traditional and reliable instrument and has been used extensively by a large number of researchers not only in the field of metal cutting but also in other areas of engineering research.

Monitoring of drilling forces by means of a U.V recorder is basically an off-line method, which combined with the very high risk of catastrophic tool failure, a dominant attribute of the DHD process, means that any drilling test can fail with consequent loss of the tool and the experimental results.

Therefore, after a number of tests, the U.V recorder was replaced by an in-house built digital data acquisition system comprising an A/D, a BBC computer and software for real time monitoring and processing of the drilling forces. The system is described in detail in chapters 6 and 7.

3.4 Drilling Tests Program

During the deep hole drilling tests the following parameters were investigated :

- **Drill diameter**	(Ø 2.4 , Ø 3.0 , Ø 4.5 mm)	
- **Maximum depth**	(85 and 95 mm, i.e up to 40 diameters)	
- **Workpiece material**	(Aluminium AMS7075 and Titanium TA11 alloys)	
- **Feed**	(mm/rev)	}Range depends on work piece
- **Cutting speed**	(m/min)	}material and drill diameter

3.4.1 Drill Makes, Types and Coding

Dormer drills (3 diameters)

A602 HSS DHD long series. Ø4.5x150 mm, Ø3.0x120 mm, Ø2.4x110 mm

TiN : (As above but TiN coated)

A603 HSS DHD rolled heel type. Ø4.5x120 mm, Ø3.0x100 mm, Ø2.4x95 mm

Titex drills (2 diameters)

TXA : A1722 Ø2.4x90 mm

TXB : A1622 Ø3.0x95 mm

Gühring drills (2 diameters)

(Gühring drills for DHD come into two types : GT50 for soft alloys (e.g Aluminium) and GT100 heavy web for high tensile strength alloys (Titanium, Stainless steels, etc.)

GT50	Gühring HSS DHD extra long No 524. Ø 2.4 mm x 125 mm. Bright (as ground) finish.
GT100	Gühring HSS DHD extra long No 502. Ø 2.4 mm x 125 mm. Bright (as ground) finish.

GT50	Gühring HSS DHD **extra long** No 524. Ø 3.0 mm x 150 mm. Bright (as ground) finish.
GT100	Gühring HSS DHD **extra long** No 502. Ø 3.0 mm x 150 mm. Bright (as ground) finish.

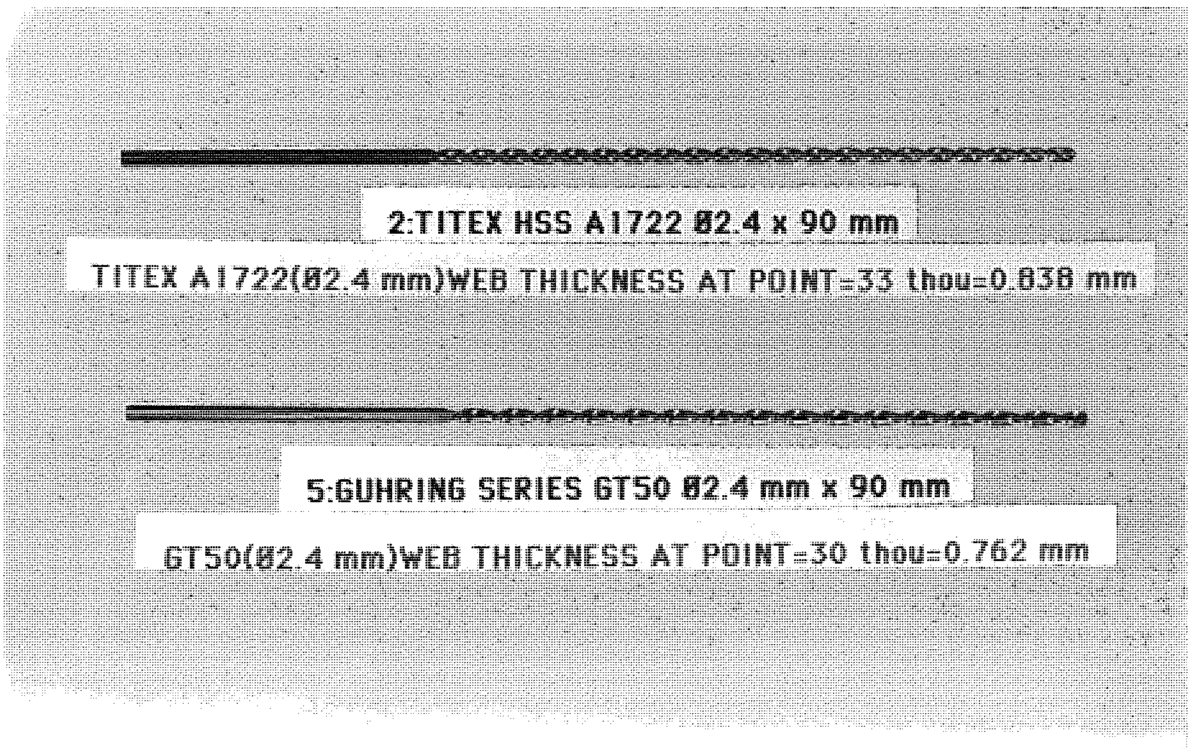


Fig. 3.5 : Drills Ø 2.4 mm used for DHD tests

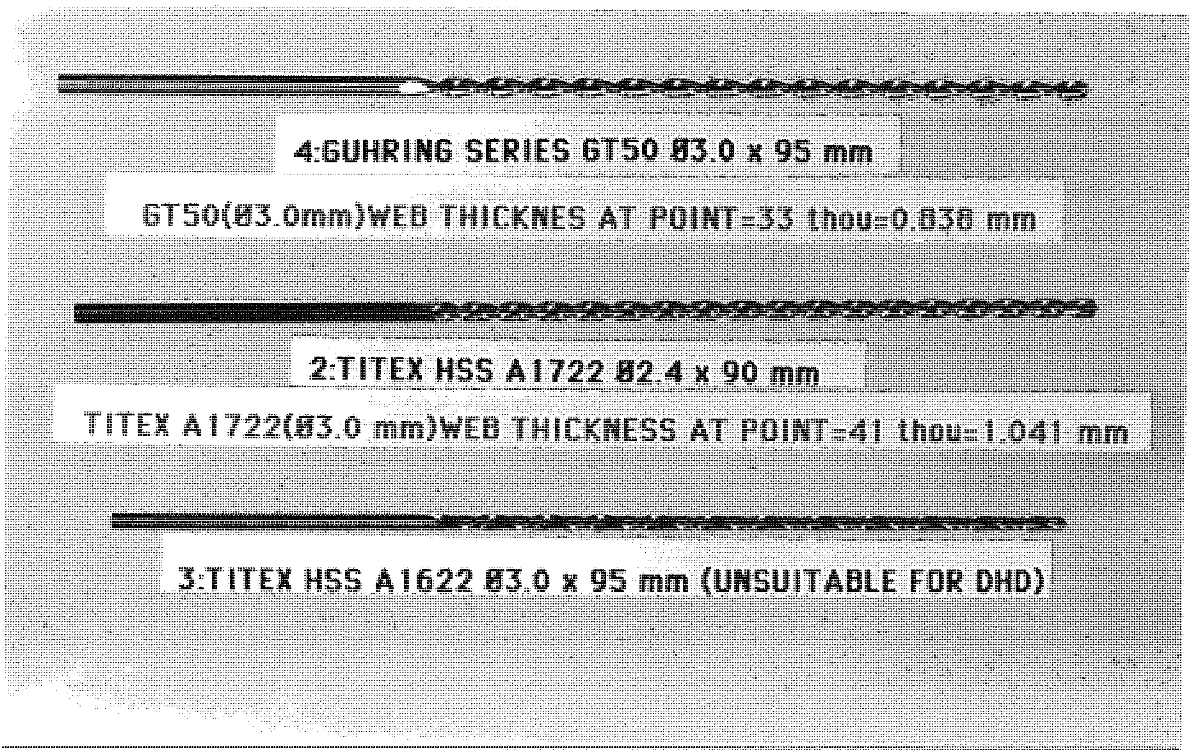


Fig. 3.6 : Drills Ø 3.0 mm used for DHD tests

3.4.2 Drilling tests

(i). **Pilot hole drilling** : The very first tests were carried out with no intermediate support or guidance of the drill, but instead right into solid metal. No drill has survived from these early tests since they all failed at various depths, the main reason being lack of support and consequently unacceptable deflection of the tool under high penetration rate.

Therefore, it was considered necessary to provide some support for the drill and reduce as much as possible the adverse effect of the overhang which for the Ø 4.5 mm diameter drills was up to 150 mm and for the Ø2.4 mm was up to 110 mm, depending on the drill make and type.

The significant effect of drill overhang to drill life has been reported by various researchers (chapter 2) and various methods for controlling it are used in practice, such as guide bushes, pilot holes as well as a reduced initial feed rate during the early penetration.

In this work, the use of a lathe instead of a special purpose drilling machine meant that guide bushes could not be easily employed without encountering technical difficulties and extensive modifications of the machine tool required. Instead, the adverse effect of drill overhang was partially reduced by the following two methods.

First by specifying a reduced feed rate during approach and early penetration (up to a depth of 2 to 4 diameters) when using long drills and second by using short jobber drills. A small part program was written for drilling pilot holes of depth equal to one diameter using very short and rigid jobber drills. After a number of pilot holes had been pre-drilled the required deep holes could be drilled using the appropriate long drill.

The pilot hole method significantly improved the hole runout and reduced drill breakages but it proved rather impractical to apply using a CNC lathe because it required the change from the jobber drill to the long sister tool of equal diameter for every row of 10 to 15 holes in a workpiece. Consequently, the very important alignment of the tool held in the spindle was disrupted. It is clear that the pilot hole method is most applicable and easy to implement when a CNC machining centre or other machine tool capable of automatic tool change.

(ii). Series A : (Ø2.4x85 mm, Ø3.0 X 90 mm, Ø4.5x95 mm through holes)

This series of tests aimed to provide an initial general vew of the nature of the DHD process and the problems associated with it. Basically it was a replica of drilling deep holes in a way similar to the one performed in the Aerospace industry for the manufacture of aircraft components from light alloys. A fixed (during the cycle) pecking depth was the main feature of these tests. Pecking, i.e periodic withdrawal and reentry of the tool is presented in detail in chapter 5.

TEST A	PECK (mm)	FEED (mm/min) (μm/rev)	RPM	No OF HOLES	COMMENTS
A1	5x18	100 (50)	2000	10	No pilot hole
Hereafter a 2 to 4 diameters deep pilot hole was introduced for all tests					
A2	5x18	150 (37.5)	4000	12	Drill damaged
A3	5x18	200(50)	4000	3	Drill damaged
A4	5x18	100(25)	3000	11	
A5	5x18	200(50)	4000	7	Drill damaged
A6	6x15	100(25)	3000	6	Drill damaged
A7	4x23	200(50)	4000	2	Drill damaged

(ii). Series B : Blind holes (continuous penetration)

This series of tests aimed to provide a detailed investigation into the drilling forces and the phenomena of instability of the process. The tests were carried out with various feeds and speeds and maximum depths for diameters Ø 2.4 mm and Ø 3.0 mm. Again very few drills survived because of catastrophic damage under various circumsatnces. U.V paper records of some of the tests performed in AMS7075 alloy are presented in chapter 4, fig.4.8 - 4.12 and 4.27 - 4.30

(ii). Series C

This series of tests were basically the same as those in series B except that the U.V paper recorder was replaced with the digital data acquisition system described in the second part of the thesis. The tests included drilling in TA11 Titanium alloy as well and selected records of the tests are presented in chapter 8.

3.5 Influence of various factors on the magnitude of steady state thrust and torque in DHD.

3.5.1 Workpiece material

It has been shown, both theoretically and experimentally, that the magnitude of the thrust and torque are directly proportional to the workpiece hardness. Confirmation of the above fact was not been established experimentally in the present work because the machining conditions for the workpiece materials used, Titanium TA11 and Aluminium AMS7075 alloys, are not comparable in principle (fig.3.7).

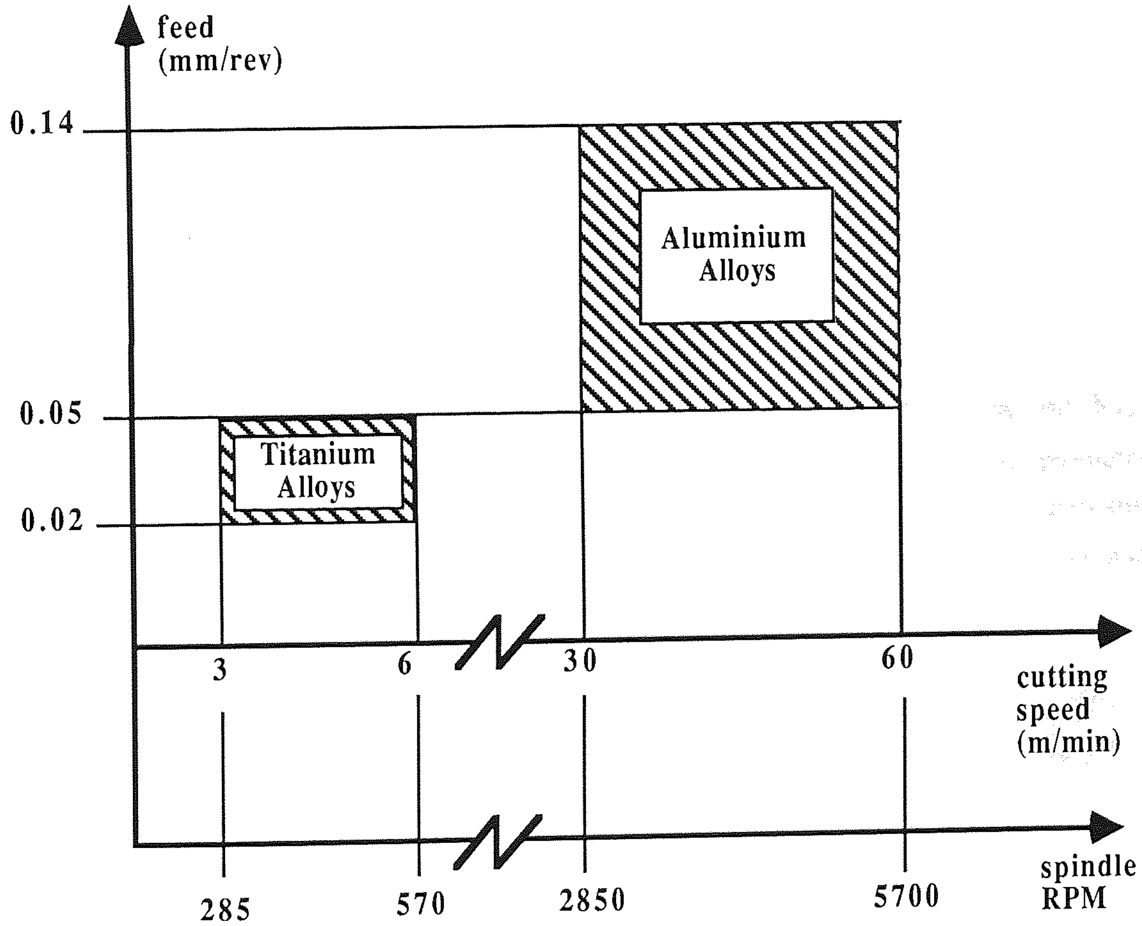


Fig. 3.7 : Comparison of recommended machining conditions for drilling Ø 2.0-5.0 mm holes in Aluminium and Titanium alloys.

(Data reproduced by permission from SKF Dormer drill user's handbook 1988)

Titanium is significantly less free-cutting than Aluminium and features a very narrow machinability window as indicated by the range of recommended cutting speeds and feeds in fig 3.7. The use of cutting speeds outside these limits results to reduced tool life as a result of high wear rate. For example high and rapidly inflicted wear or even catastrophic failure of the drill point was observed when a speed of 2000 RPM was used instead of the maximum recommended 600 RPM (fig. 4.14 - 4.18).

3.5.2 Feed

The relationship between feed and the magnitude of the steady state forces (*) in metal cutting has been shown by various researchers (section 4.3) to be logarithmic, the feed exponent being in the region of values between 0.5 to 1.0, depending on the work piece material and the tool geometry. Figures 3.8 to 3.31 show the variation of these forces for a range of feeds and speeds for both materials and confirm the above relationship.

For a given tool diameter and workpiece material the above relationships can be expressed as :

$\mathbf{M_0 = k_M f^m}$ and $\mathbf{T_0 = k_T f^{m'}}$ where $\mathbf{f}$ is the feed (mm/rev) and $\mathbf{m}$, $\mathbf{m'}$, $\mathbf{k_M}$ and $\mathbf{k_T}$, constants depending on the workpiece material and tool diameter and geometry. The values of these constants can be obtained by regression analysis of experimental results ; this is not desirable however because it presupposes a sufficient number of tests with different conditions.

On-line identification of these parameters is clearly more preferable because it automates this procedure and requires only one step change in feed rather than separate tests. The method is discussed in detail in chapter 7 and it is shown to be an important element of a system for intelligent CNC machining.

** The term steady state forces is actually used preceding its definition which is given in chapter 4. In simple terms it implies the early stages of the process when the tool has not penetrated more than 2 to 3 diameters and the two forces, thrust and torque represent the pure effort to deform the workpiece material in the region of the cutting edges.*

ALUMINIUM AMS-7075 T736

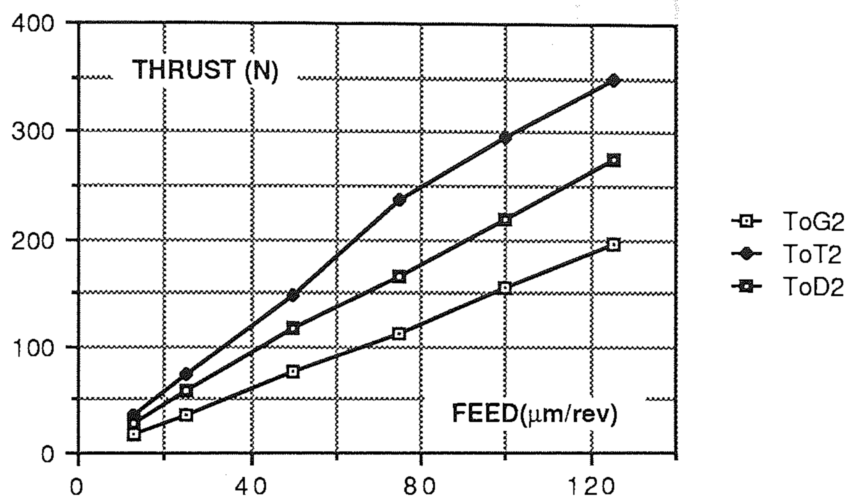


Fig. 3.8 : Drilling thrust T_0 vs feed at 2000 RPM,
Ø 2.4 x 85 mm through holes ; drills D: Dormer, G: Gühring, T: Titex ;
workpiece material : AMS7075 T736

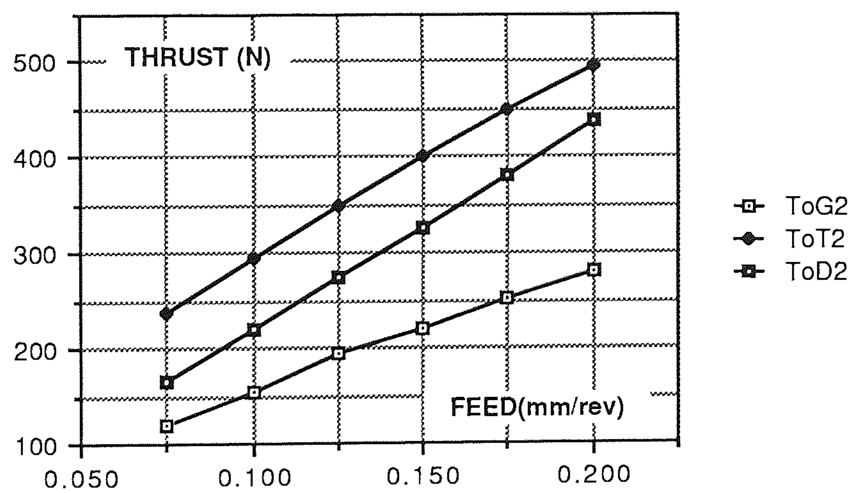


Fig. 3.9 : Drilling thrust T_0 vs feed at 2000 RPM,
Ø 4.5 x 90 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

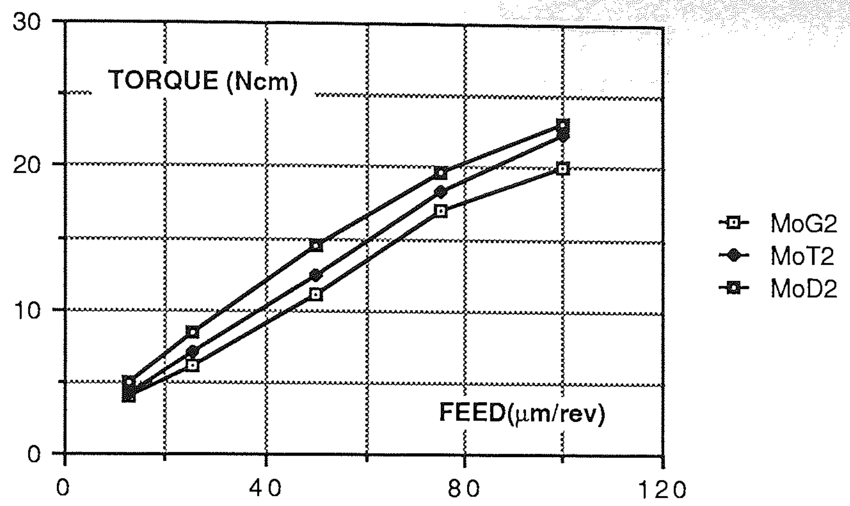


Fig. 3.10 : Drilling torque M_0 vs feed at 2000 RPM,
Ø 2.4 x 85 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

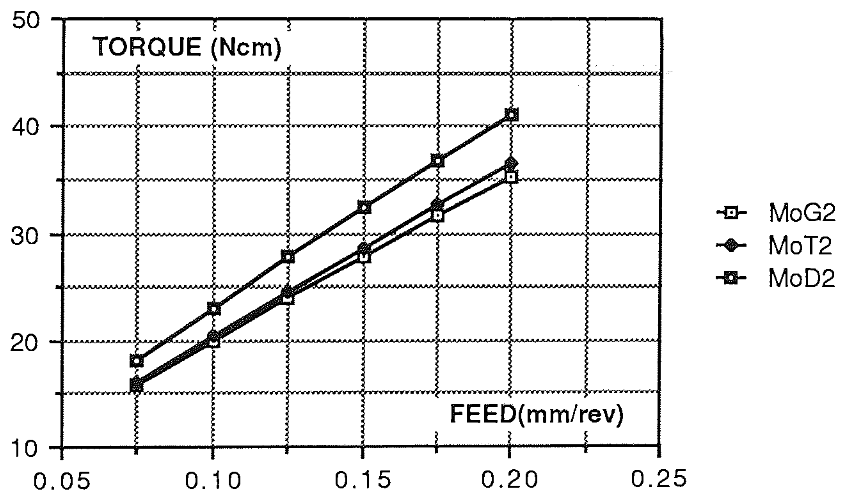


Fig. 3.11 : Drilling torque M_0 vs feed at 2000 RPM,
Ø 4.5 x 90 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

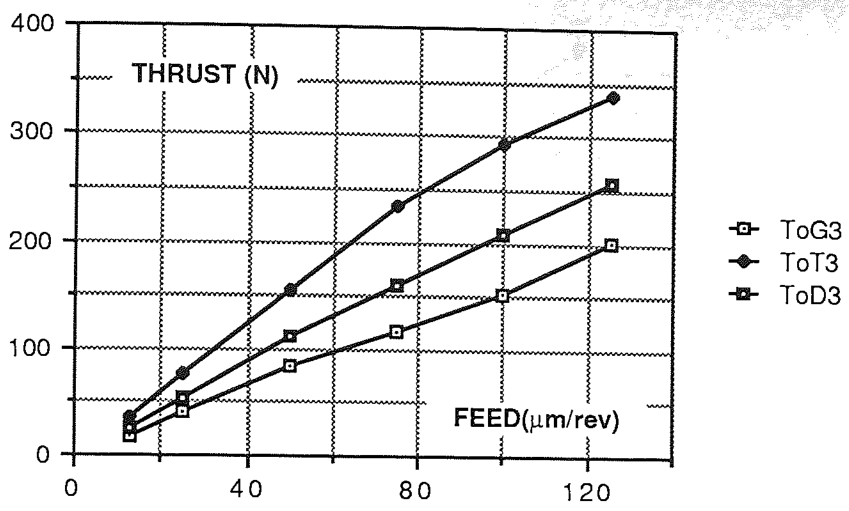


Fig. 3.12 : Drilling thrust T_0 vs feed at 3000 RPM, Ø 2.4 x 85 mm through holes ; drills D: Dormer, G: Gühring, T: Titex workpiece material : AMS7075 T736

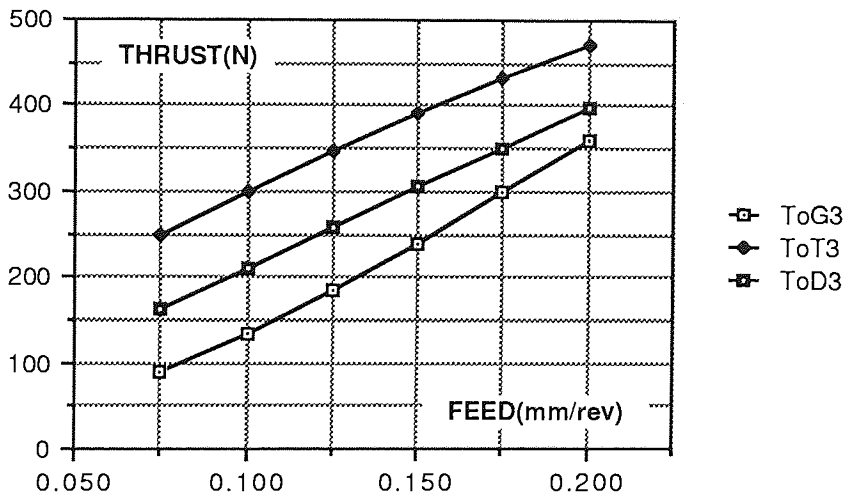


Fig. 3.13 : Drilling thrust T_0 vs feed at 3000 RPM, Ø 4.5 x 90 mm through holes ; drills D: Dormer, G: Gühring, T: Titex workpiece material : AMS7075 T736

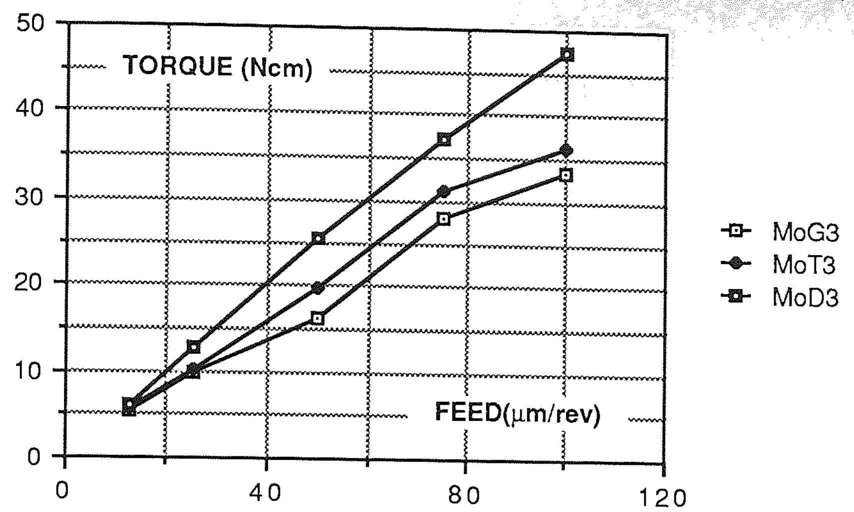


Fig. 3.14 : Drilling torque M_0 vs feed at 3000 RPM,
Ø 2.4 x 85 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

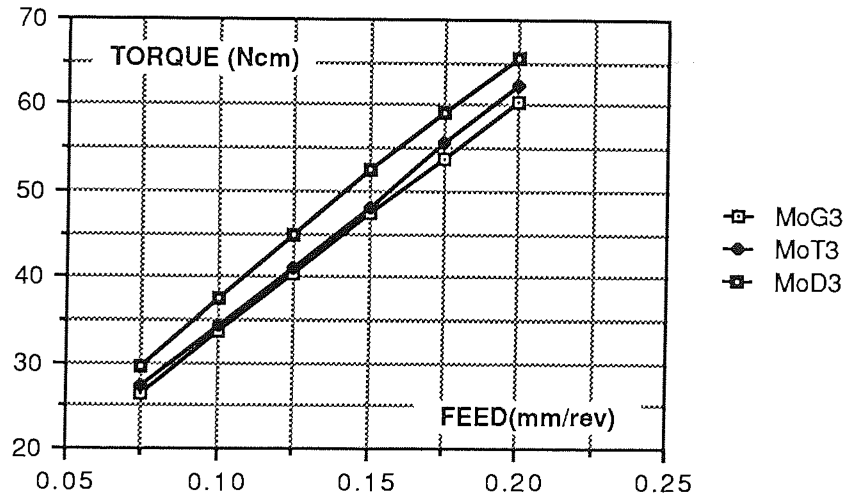


Fig. 3.15 : Drilling torque M_0 vs feed at 3000 RPM,
Ø 4.5 x 90 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

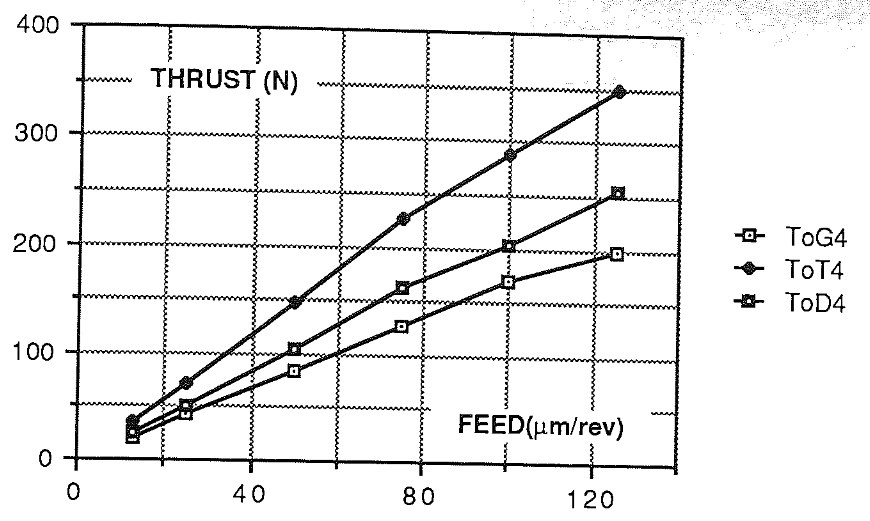


Fig. 3.16 : Drilling thrust T_0 vs feed at 4000 RPM,
Ø 2.4 x 85 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

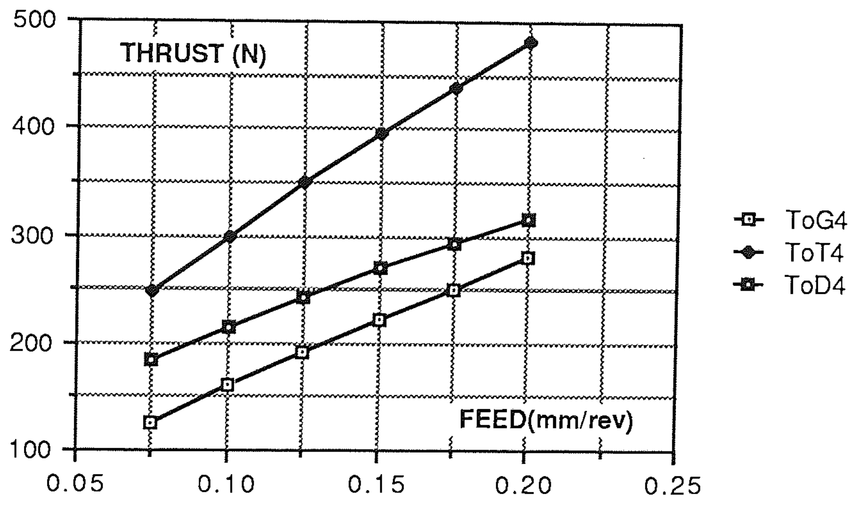


Fig. 3.17 : Drilling thrust T_0 vs feed at 4000 RPM,
Ø 4.5 x 90 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

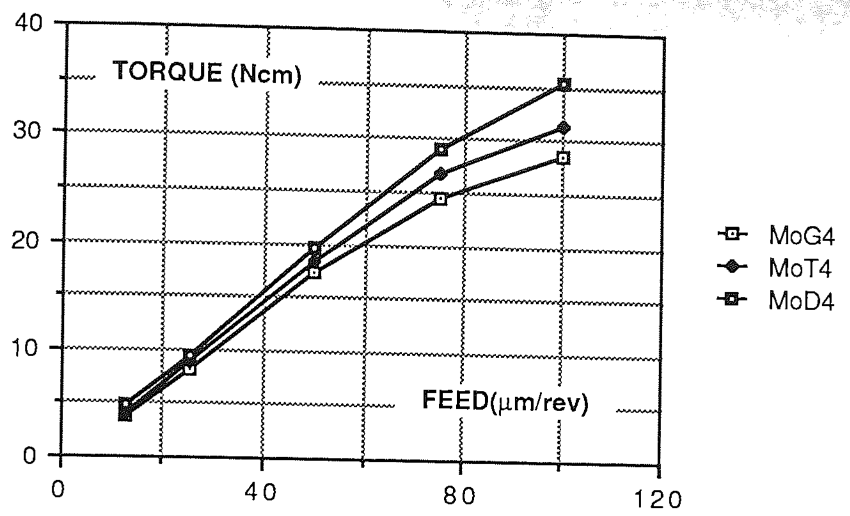


Fig. 3.18 : Drilling torque M_0 vs feed at 4000 RPM,
Ø 2.4 x 85 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

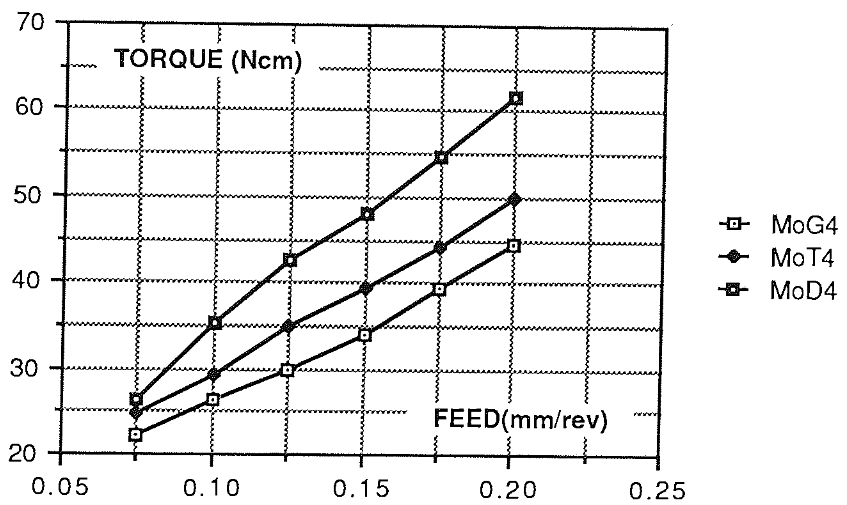


Fig. 3.19 : Drilling torque M_0 vs feed at 4000 RPM,
Ø 4.5 x 90 mm through holes ; drills D: Dormer, G: Gühring, T: Titex
workpiece material : AMS7075 T736

TA-11 DATA

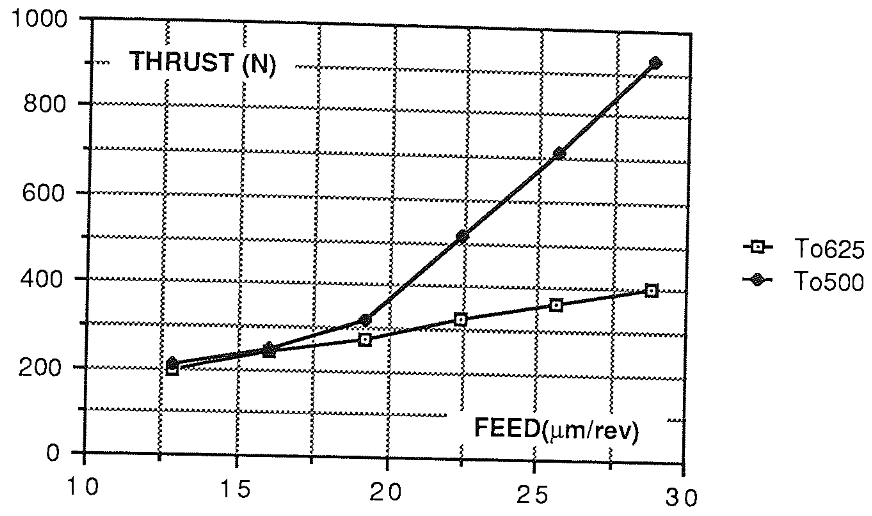


Fig. 3.20 : Drilling thrust To vs feed at 500 and 625 RPM,
Ø 4.5 x 90 mm through holes ; drill THP1 - Dormer HSS
workpiece material : TA11

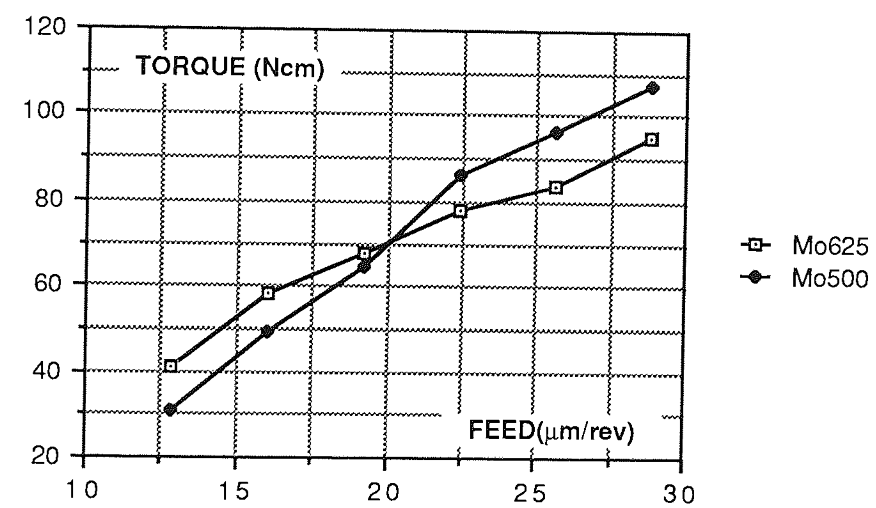


Fig. 3.21 : Drilling torque Mo vs feed at 500 and 625 RPM,
Ø 4.5 x 90 mm through holes ; drill THP1 - Dormer HSS
workpiece material : TA11

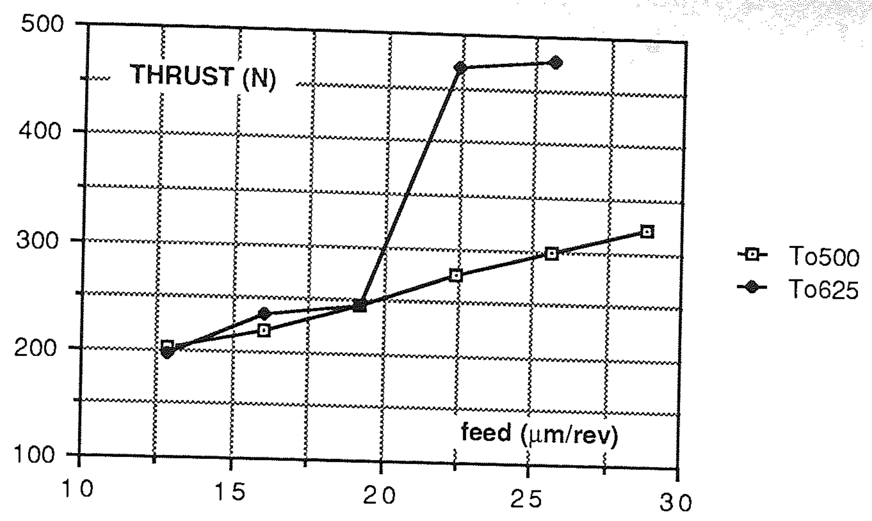


Fig. 3.22 : Drilling thrust To vs feed at 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill HW1 - Dormer HSS workpiece material : TA11

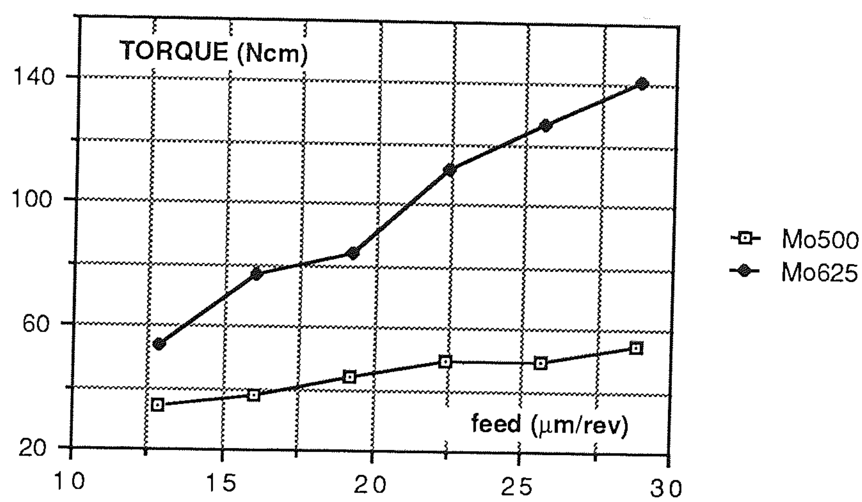


Fig. 3.23 : Drilling torque Mo vs feed at 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill HW1 - Dormer HSS workpiece material : TA11

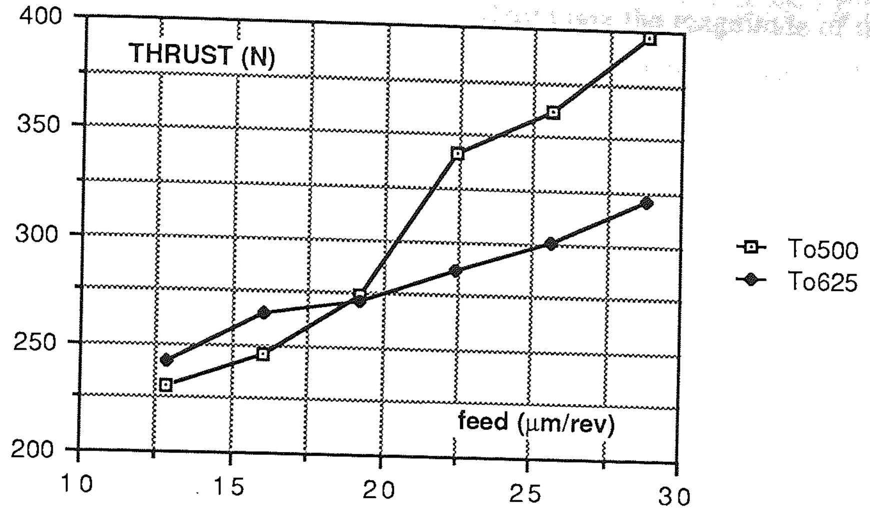


Fig. 3.24 : Drilling thrust To vs feed at 500 and 625 RPM,
Ø 4.5 x 90 mm through holes ; drill TiN - Dormer HSS
workpiece material : TA11

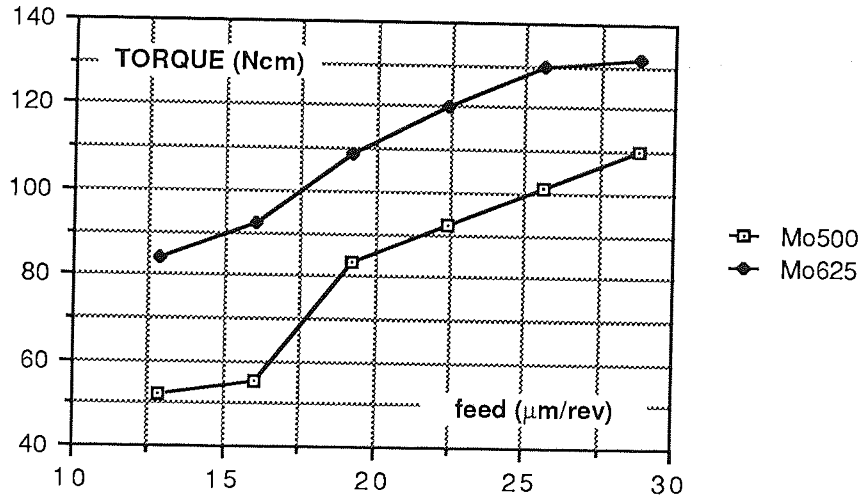


Fig. 3.25 : Drilling torque Mo vs feed at 500 and 625 RPM,
Ø 4.5 x 90 mm through holes ; drill TiN1 - Dormer HSS
workpiece material : TA11

3.5.3 Cutting Speed

Cutting speed appears to have no significant effect upon the magnitude of the drilling forces over a wide range of speeds for Aluminium and a narrower one for Titanium as indicated by figures 3.26 to 3.31 next.

AMS-7075 T736 SPEED DATA

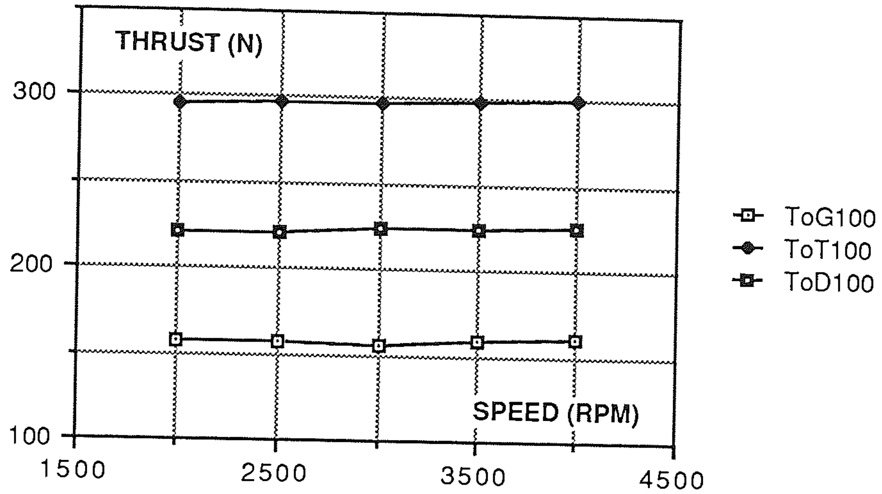


Fig. 3.26 : Drilling thrust To vs speed, 100 mm/min constant feed rate, Ø 3.0 x 90 mm through holes ; drills G : Gühring, T : Titex, D : Dormer workpiece material : AMS 7075 T736

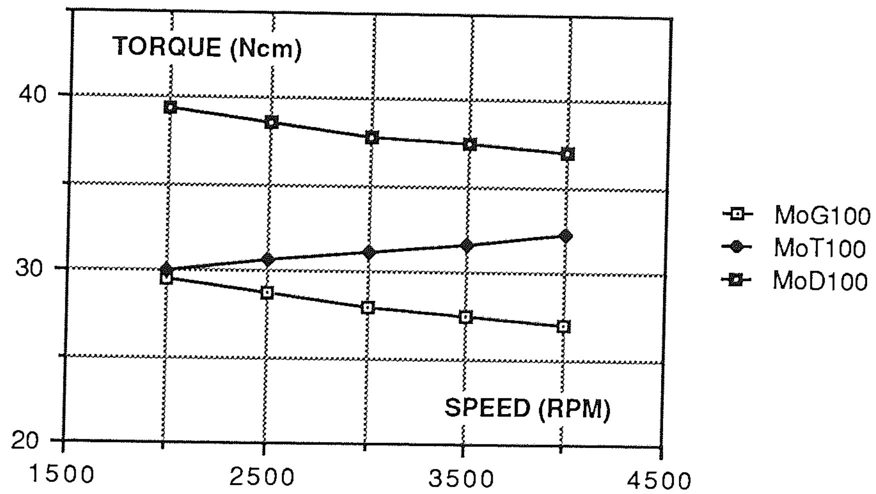


Fig. 3.27 : Drilling torque Mo vs speed, 100 mm/min constant feed rate, Ø 3.0 x 90 mm through holes ; drills G : Gühring, T : Titex, D : Dormer workpiece material : AMS 7075 T736

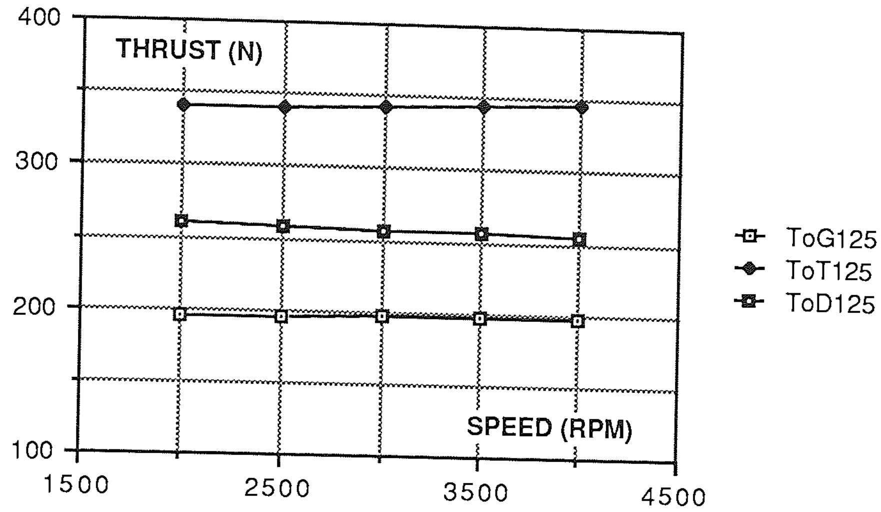


Fig. 3.28 : Drilling thrust To vs speed, 125 mm/min constant feed rate, Ø 3.0 x 90 mm through holes ; drills G : Gühring, T : Titex, D : Dormer workpiece material : AMS 7075 T736

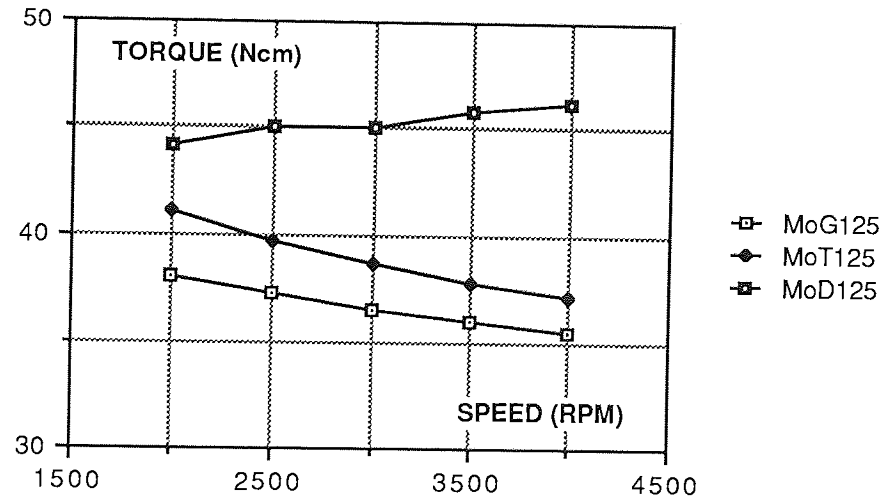


Fig. 3.29 : Drilling torque Mo vs speed, 125 mm/min constant feed rate, Ø 3.0 x 90 mm through holes ; drills G : Gühring, T : Titex, D : Dormer workpiece material : AMS 7075 T736

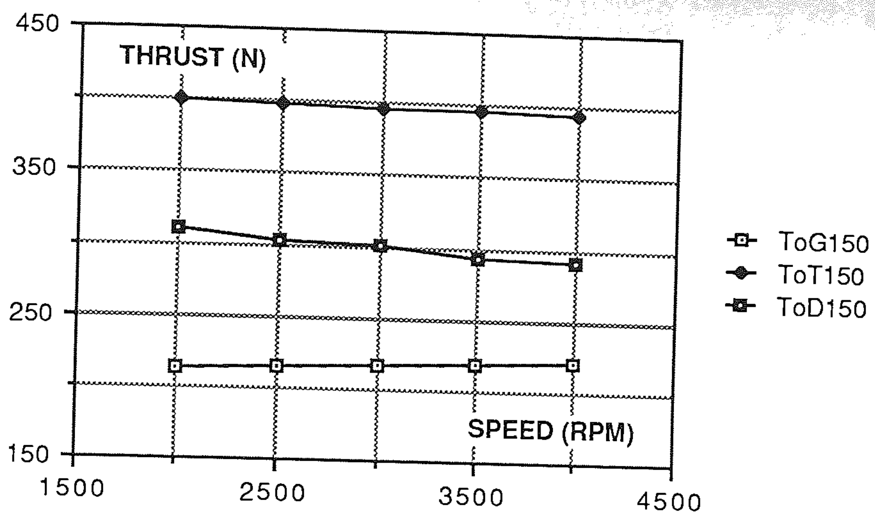


Fig. 3.30 : Drilling thrust To vs speed, 150 mm/min constant feed rate, Ø 3.0 x 90 mm through holes ; drills G : Gühring, T : Titex, D : Dormer workpiece material : AMS 7075 T736

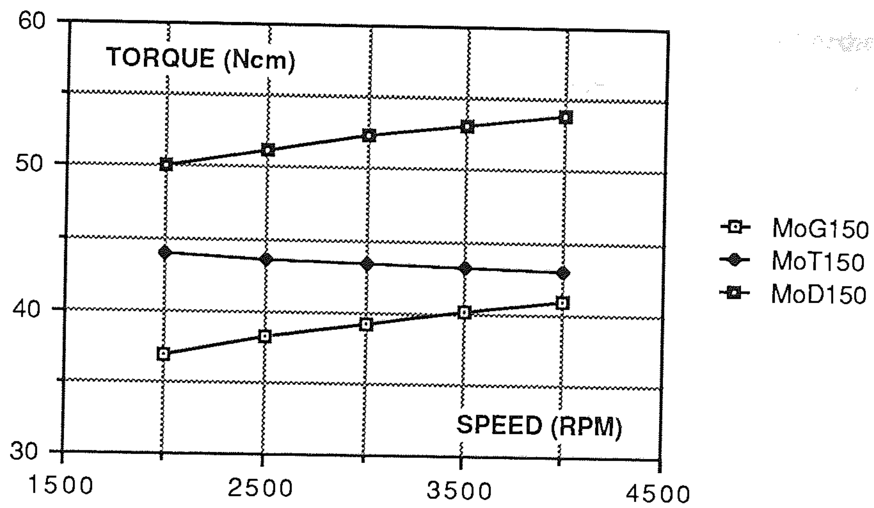


Fig. 3.31 : Drilling torque Mo vs speed, 150 mm/min constant feed rate, Ø 3.0 x 90 mm through holes ; drills G : Gühring, T : Titex, D : Dormer workpiece material : AMS 7075 T736

3.6 Instability depth Z_i (mm) and Alarm depth Z_{al} (mm)

3.6.1 Effect of feed (mm/rev)

The phenomena associated with an increase in total drilling torque and the related changes in chip geometry, as the depth of penetration increases, make the latter a fundamental parameter in DHD. The various regions in which the hole depth is divided, according to the stages of instability, are presented in detail in chapter 4. This part of the investigation examines two particular values of the hole depth, the instability depth and the alarm depth which are defined as follows :

Instability depth is defined as the hole depth beyond which the fluctuations of torque exceed by more than 20 % the steady state value. It is the depth which distinguishes conventional from deep hole drilling.

Alarm depth is defined as the hole depth at which the fluctuations of drilling torque or thrust exceed 200% of the steady state value.

The experimental determination of the two depths was based on the use of a digital system in which a computer monitored and processed the signals of drilling thrust and torque from the dynamometer. The drilling tests were carried out under constant feed rate and spindle speed and the only external control on the machine tool and the process was the ability to activate complete shut down of the machine tool when any of the two drilling forces exceeded 200 % of its steady state value.

A printout of the cutting forces was produced off-line from which the two depth parameters were determined. In the series of histograms following an attempt was made to establish any positive trends between the two depths and the feed of the tool.

As it can be seen from the graphs that follow, no such observable trend has emerged which would allow to predict in a deterministic manner the exact pattern of the instability and the magnitudes of drilling thrust and torque for any given combination of tool geometry and feed, speed.

The only element of useful information that emerges from this data, is that certain flute and drill point configurations enable one drill type to outperform another in terms of safe penetration depth. Nevertheless, such information is clearly of little importance when it is certain that both drills will fail under torsional loading before the target depth has been reached and the pertinent cycle of the part program has been completed.

Also quite significant is the fact that adjacent holes, on the same work piece block, which were drilled under identical machining conditions and by the same drill, exhibited totally different patterns of instability (chapter 8). This suggests that the deep hole drilling is a dynamic and stochastic process and therefore, a deterministic approach in attempting to predict the levels of drilling forces or pattern of instability can be of only a very limited scope.

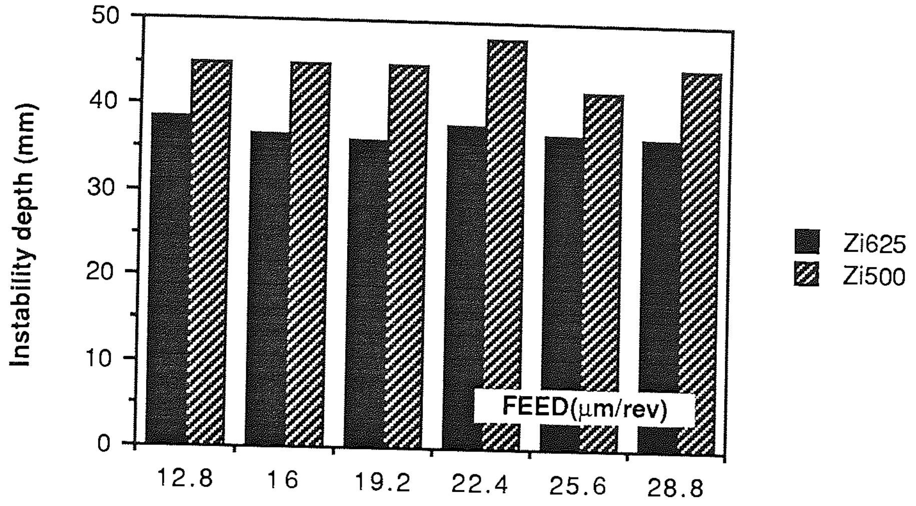


Fig. 3.32 : instability depth vs feed for two speeds of 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill : Dormer HSS THP type workpiece material : TA11

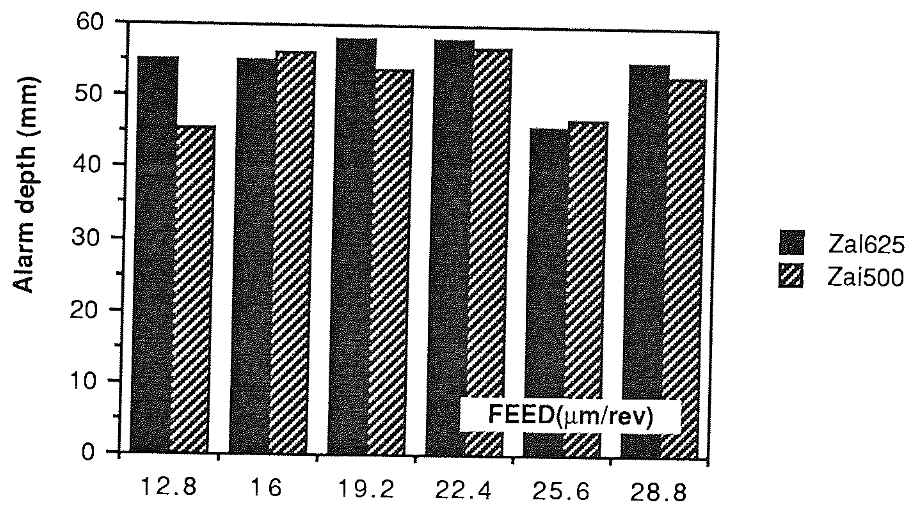


Fig. 3.33 : alarm depth vs feed for two speeds of 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill : Dormer HSS THP type workpiece material : TA11

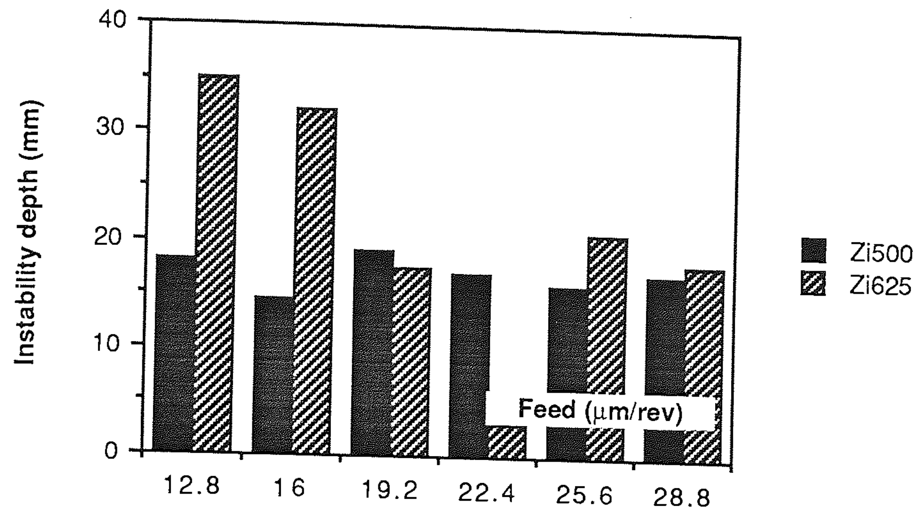


Fig. 3.34 : instability depth vs feed for two speeds of 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill : Dormer HSS HW type workpiece material : TA11

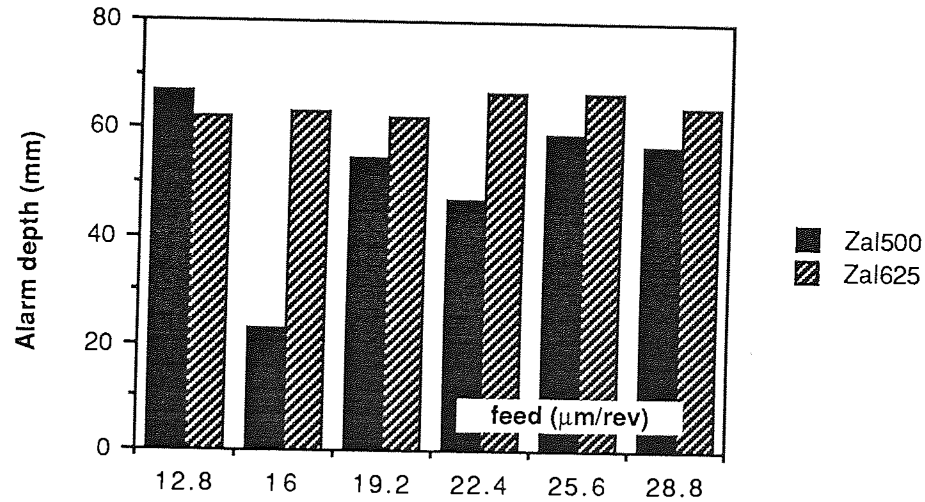


Fig. 3.35 : alarm depth vs feed for two speeds of 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill : Dormer HSS HW type workpiece material : TA11

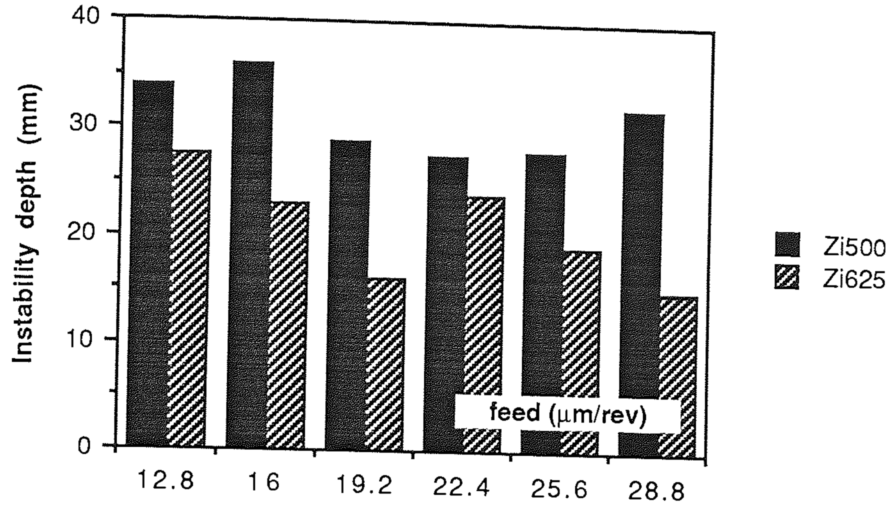


Fig. 3.36 : instability depth vs feed for two speeds of 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill : Dormer TiN coated type workpiece material : TA11

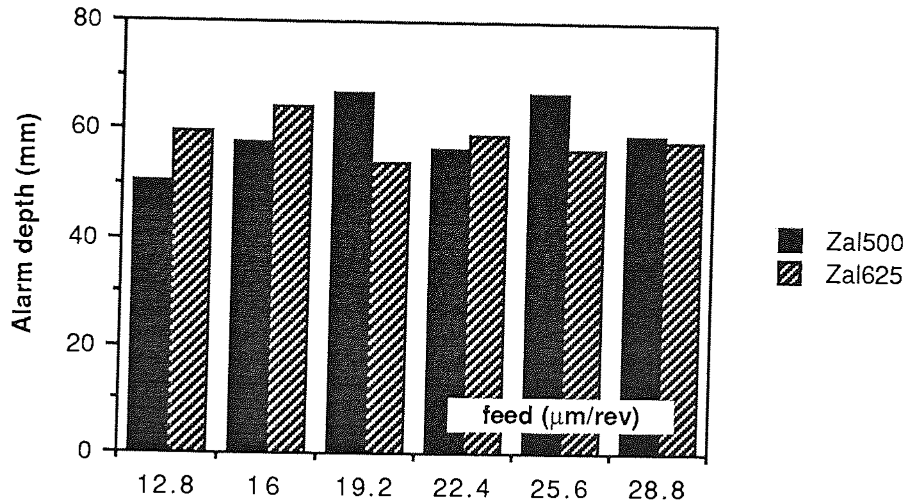


Fig. 3.37 : instability depth vs feed for two speeds of 500 and 625 RPM, Ø 4.5 x 90 mm through holes ; drill : Dormer TiN coated type workpiece material : TA11

The experimental results presented in the previous section suggest that the feed (mm/rev) appears to have no consistent effect on the instability pattern of the process. This could be explained on the hypothesis of torsional vibrations of the lower end of the drill. The CNC ensures a constant penetration rate and speed only for the rear rigid part of the tool. During instability the tool edges penetrate the work piece at a variable rate due to the twisting of the fluted part of the drill and therefore a variable chip thickness is generated ; this mechanism is discussed in detail in chapter 4.

3.6.2 Effect of spindle speed

A series of drilling tests performed under constant feed (various feed rates and spindle speeds), has revealed that it is possible to determine a spindle speed region which will ensure a longer stable penetration, that is very small increases in drilling torque. In fig. 3.38 the relative patterns of drilling torque against time are shown for different spindle speeds and feed rates.

The graphs strongly suggest that for a given combination of workpiece material, drill point, flute geometry and feed rate the pattern of instability depends on the cutting speed and penetration rate (feed rate). It is therefore possible to determine experimentally an optimum spindle speed in order to achieve a prolonged stability region. Knowledge of such data is clearly very important and useful during process planning of a DHD operation.

The region of recommended cutting speeds for a given material and hole diameter in conventional drilling is normally imposed on grounds of acceptable surface finish and tool life. This region is further restricted in DHD in the context of instability due to chip breaking and clogging of the drill flutes.

A theoretical prediction of the optimum cutting speed region would be extremely tedious because a model would require to take into account many parameters such as chip flow and breakage, flute geometry, friction characteristics, etc. and still would not be very reliable because of the element of randomness which clearly dominates DHD. In addition, a large amount of experimental work would be required in order to cover all possible combinations of workpiece materials, drill geometries and machining conditions.

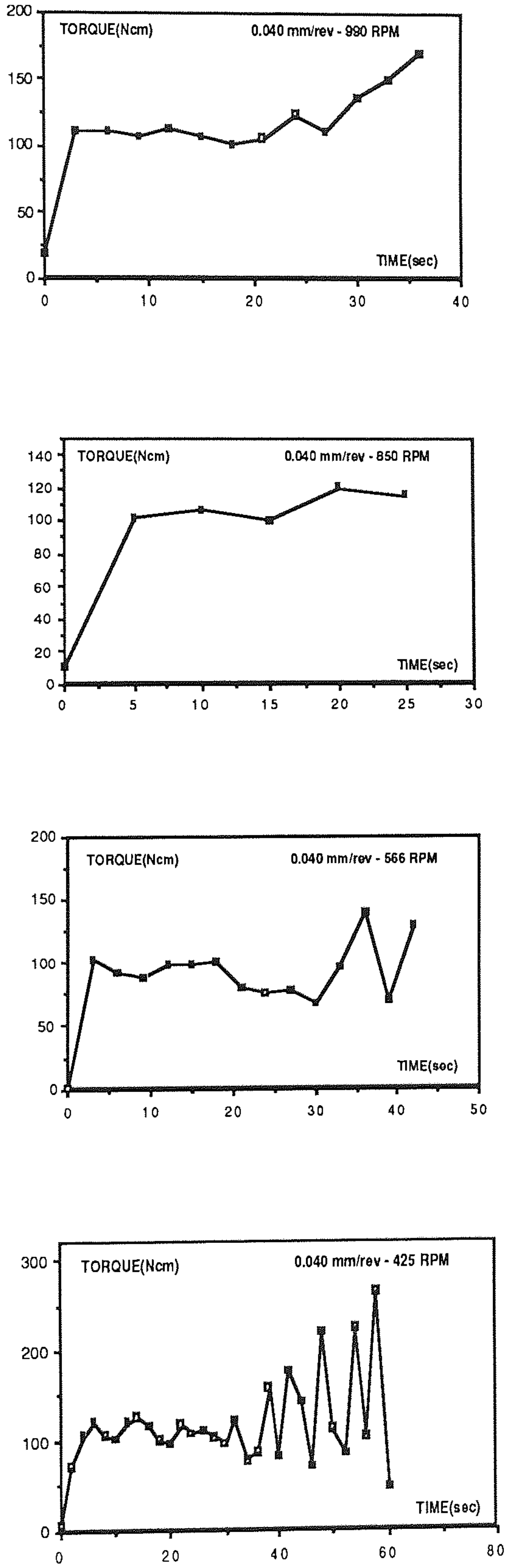


Fig. 3.38 : Drilling torque for various speeds (constant feed), Ø 4.5 x 90 mm through holes ; drill : GT100, workpiece : TA11 alloy

3.7 Tool life in DHD

A limited amount of results on drill wear and drill life were produced because the rate of catastrophic failure of drills was very high before the introduction of the monitoring and control system described in chapters 6 and 7. The tests were performed on the very hard TA11 Titanium alloy workpieces (rapid wear characteristics). Scope of the investigation was to establish whether the classic trends of increased level of feed force (thrust) and torque related to tool wear (cumulative cutting time) apply in DHD.

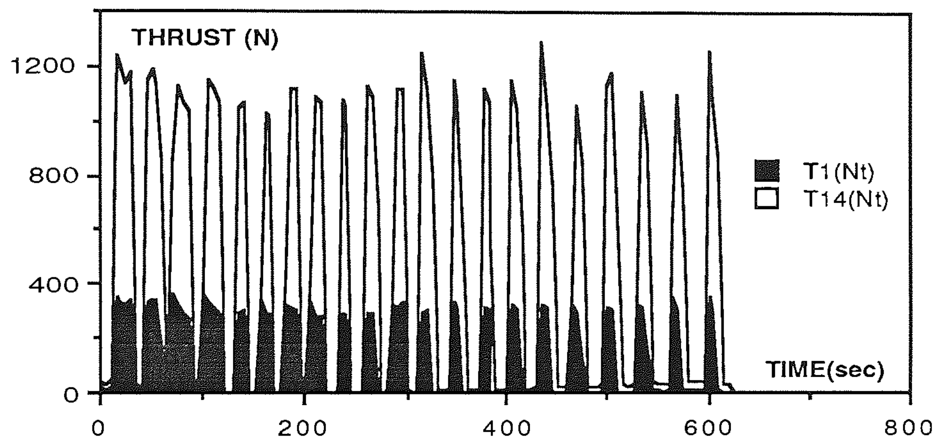


Fig. 3.39 : Comparison of thrust magnitude for 1st and 14th hole (end of drill life)

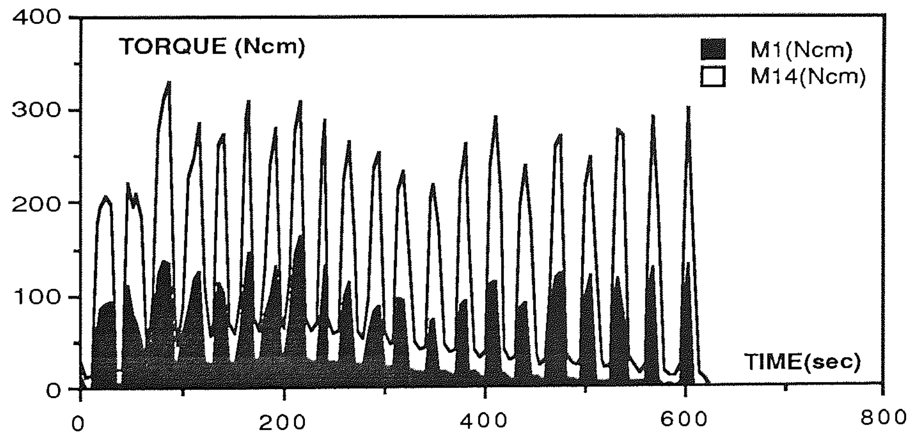
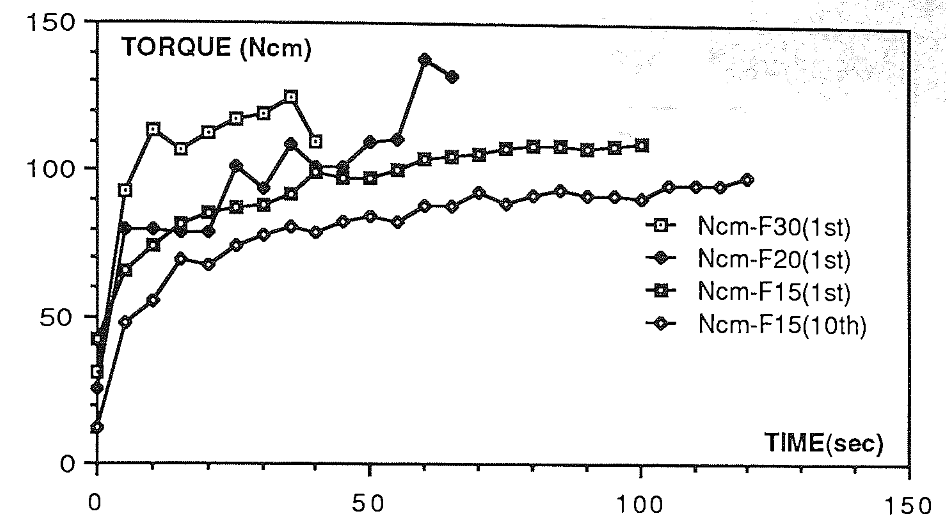


Fig. 3.40 : Comparison of torque magnitude for 1st and 14th hole (end of drill life)
Drill : GT 100 **Material** : TA11 **Conditions** : **f** = 0.030 mm/rev (15 mm/min)
V = 9.42m/min (500 RPM) **D** = Ø 4.5 mm, **Zmax** = 90 mm, 21x4.5 mm pecks



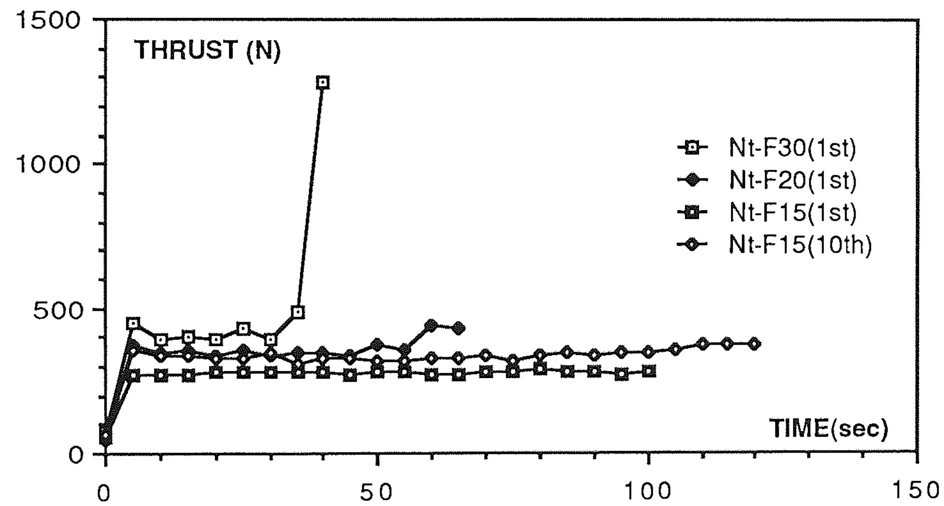
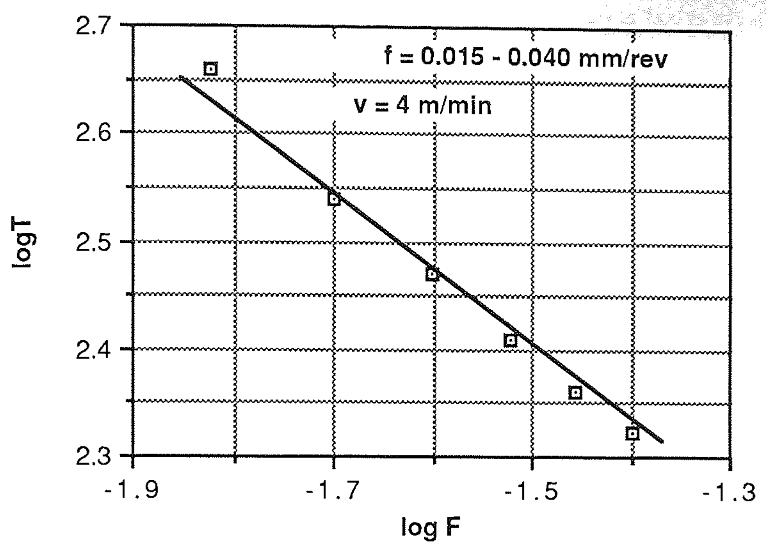


Fig. 3.41 : Variation of drilling torque and thrust with feed rate during drill life tests. Under feed rate F30 life = 45 sec, under F20 life = 300 sec, after F15 life = 1320 sec.
Drill : GT 100, Ø 4.5 x 90 mm **Material** : TA11 Titanium alloy
Conditions : F = variable (mm/min), N = 600 RPM, Ø 4.5 x 18 mm pilot hole.



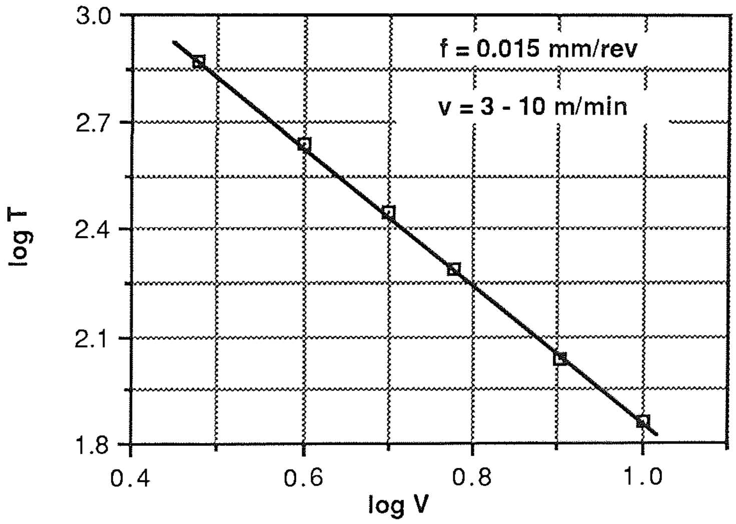


Fig. 3.42 : Effect of feed **f** and cutting speed **v** on drill life **T** during DHD
When catastrophic failure does not occur the classic tool life model (Taylor) applies :
$\mathbf{T^{0.5} f^{0.35} v = C_T}$ (C_T = 19.36, f mm/rev, v in m/min, T in minutes)
Drill : GT100 HSS Ø 4.5 x 90 mm **Material** : TA11 Titanium alloy

The results previously presented, concerning the influence of feed and speed on tool life, were obtained using the pecking technique (chapter 5) where the drill is periodically withdrawn and reenters the hole in order to clear the swarf from the flutes. This is the only method available todate in industry that ensures to some degree a successful completion of a DHD cycle and in this series of tests made it possible to reduce the effect of catastrophic failure on drill life.

The following general comments summarise the results of the investigation :

- In principle it is very difficult to retrieve a broken tool from a workpiece in DHD and by examining the tool point to establish whether tool failure was the result of wear of the cutting edges or another cause (instability).
- It is clear therefore, that the term tool life is applicable in DHD only if operating conditions exist, such that ensure a stable process and eliminate the risk of catastrophic tool failure.
- Under such conditions, the magnitude of drilling thrust and torque increase with cumulative cutting time as a result of the classic tool wear mechanism.
- Drilling thrust is by far more sensitive and increases very rapidly after a number of holes or time, hence it can be considered as an indirect tool wear index.
- Tool life is related to cutting speed and feed logarithmically .

3.8 Effect of cutting fluid pressure on thrust and torque

Figure 3.43 shows that instability in DHD, as indicated by an increase of the total drilling torque with hole depth a result of a high friction torque component (chapter 4), can be significantly reduced if a high pressure coolant jet is used even if it is applied externally. Correctly timed coolant initiation is necessary in order to avoid deflection of the tool and consequently a non-straight hole or a mismatch between the pilot hole axis and the drill axis when pilot hole drilling is used prior to the main operation. (fig. 3.44)

As far as the drilling thrust is concerned, the application of a high pressure fluid jet seems to have no significant effect since drilling is related to the action by the cutting lips and chisel edge of the tool in order to deform the workpiece material.

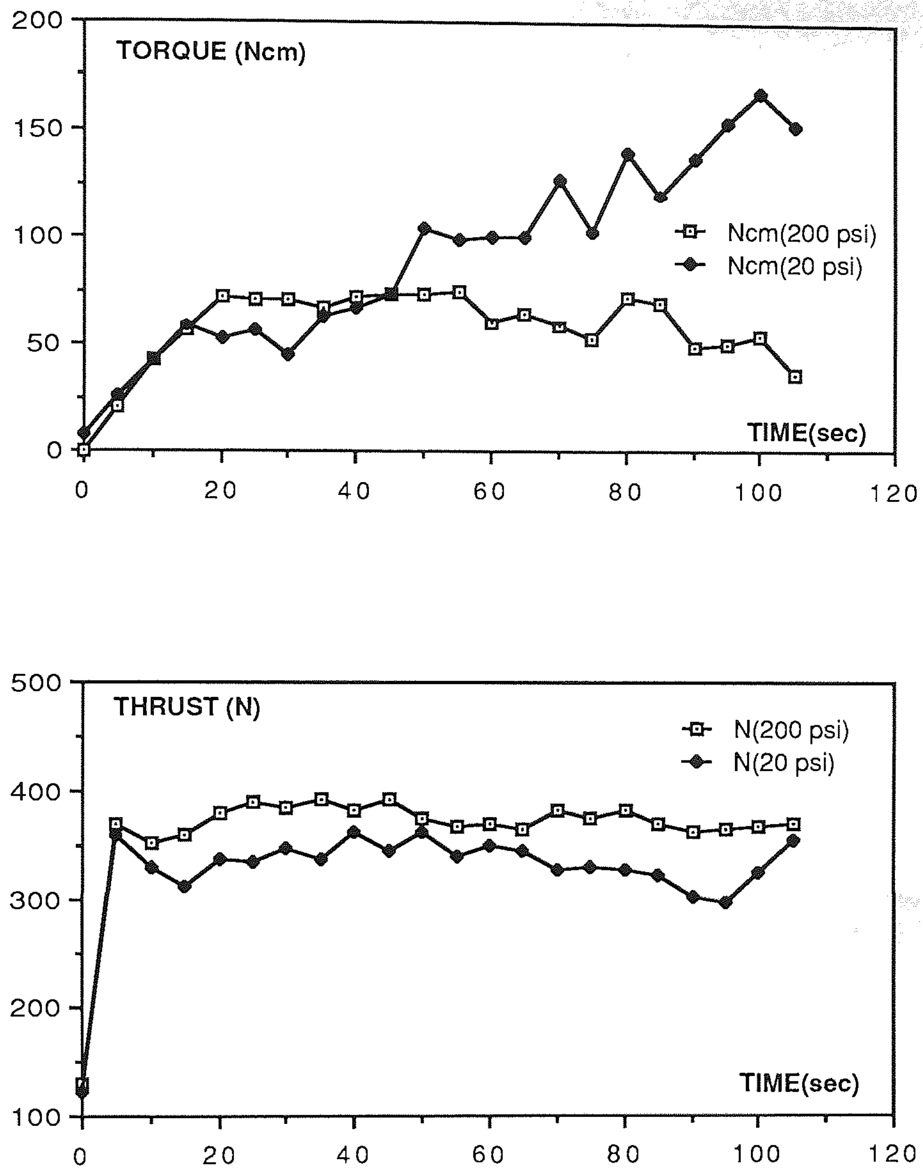


Fig. 3.43 : Effect of cutting fluid pressure on drilling thrust and torque in DHD.
Conditions : f = 0.040 mm/rev (20 mm/min) V = 9.42m/min (500 RPM)
Drill : Ø 4.5 X 90 Dormer HSS type UFL (DHD) **Material :** AMS 7075 alloy

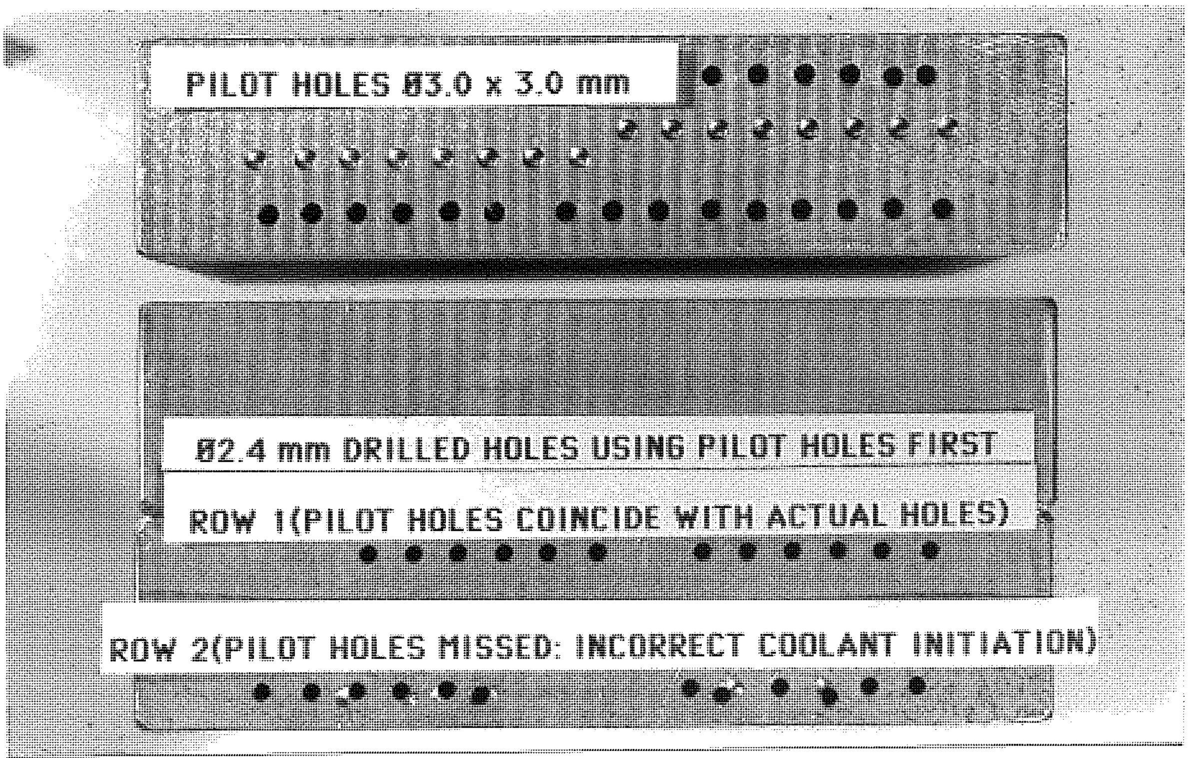


Fig. 3.44 AMS7075 workpiece with Ø 3.0 x 95 and Ø 2.4 x 85 mm through and pilot holes.
(Effect of cutting fluid correct initiation during drilling cycle)

3.9 Summary

The experimental work presented in chapter 3 has revealed the unstable and unpredictable nature and the peculiarities of deep hole drilling with small diameter twist drills and the interaction between various factors of the process. The following general conclusions summarise the results :

The DHD process is inherently unstable ; instability appears as the hole depth increases and is accompanied by two phenomena : one is the progressive change of the form of swarf from continuous and smooth into fragmented and rough form and the other is the increase in the resistance to the rotation of the tool which appears in the form of increased torque. Photographic evidence as well as a theoretical investigation of this phenomenon is presented in chapter 4.

Of the two main machining parameters in DHD, feed and speed, the latter appears to have the most significant effect on instability in the form of regions of cutting speed which allow a prolonged stable cutting. Feed on the other hand appears to have no significant effect on instability although feed in DHD has only a nominal value ; in reality feed (chip thickness) effectively changes with hole depth as the variation in the form of swarf with hole depth suggests.

Investigation of the relationship between instability depth and various feeds and speeds for two alloys, Titanium TA11 and Aluminium AMS 7075 has shown that it is not possible to determine at what depth the process becomes unstable because there is a large scatter of results. This can be accounted to a number of non-controlled factors such as the state of lubrication of the tool determining the type of friction, the mechanical properties of the swarf, the characteristics of the drill flutes, etc.

As a result of instability, catastrophic failure of the tool occurs ; it is clear that in this case the classic term tool life does not apply because failure is not related to a progressive mechanism such as wear of the cutting edges. This distinguishes DHD from conventional drilling because it adds the element of randomness to the process.

Therefore, unless the process is performed manually by an experienced operator, successful completion of a deep hole drilling operation on a CNC machine tool cannot be ensured. To control the undesired variation of chip form with hole depth and thus stabilise the drilling thrust and torque, necessitates on-line control of feed rate, spindle speed and tool position, namely periodic withdrawal and reentry.

CHAPTER 4
MODELLING AND ANALYSIS OF THE DHD PROCESS WITH TWIST DRILLS

This chapter presents an analysis of Deep Hole Drilling, based on experimental evidence as well as theoretical considerations. The nature of the particular problems associated with the drilling of small diameter deep holes using twist drills is presented. A model of the drilling thrust and torque as functions of the drilled depth addresses the problem of the process becoming unstable beyond a certain depth. The model suggests that during instability the tool is subject to torsional vibrations which result to its catastrophic failure (*). The characteristics of the torsional vibration and the tool deformation are calculated.

4.1 Fundamentals of the DHD process with twist drills

In the experimental work described in chapter 3, standard comercially available twist drills were used for drilling small diameter deep holes using a CNC machine tool. As a result of this work the fundamental characteristics of the DHD process were identified :

(i). The dominant problem in DHD is the reduced penetration of cutting fluid into the cutting zone and its total absence beyond a certain depth. This results in fragmentation of the swarf and clogging of the drill flutes (fig. 4.1, 4.2). This happens with twist drills of a diameter smaller than Ø 8.0 mm which do not have internal oil channels.

(ii). The inherent low strength of small diameter long drills combined with (i) makes catastrophic failure highly probable and severely restricts the application not only of unmanned machining but even of CNC machining ; the latter is virtually an unattended operation in the sense that the traditional skills of a machine operator are not employed during the execution of a part program.

(*) *In the pages which follow, experimental evidence of catastrophic failure of drills is presented. Failure which has either taken place or in other cases an emergency stop prevented the actual tool failure. The latter was actually achieved after the successful implementation of the monitoring and control system described in chapters 6, 7, 8.*

(iii). Catastrophic failure is highly unpredictable and manifests itself long before the classic mechanism of wear of the cutting edges and consequent failure of the tool appears (fig. 4.3 and 4.13 to 4.17). This results in failure and rejection of the component that is being drilled and waste of man and machine hours from previous operations.

(iv). Two modes of catastrophic failure of a twist drill can be identified :

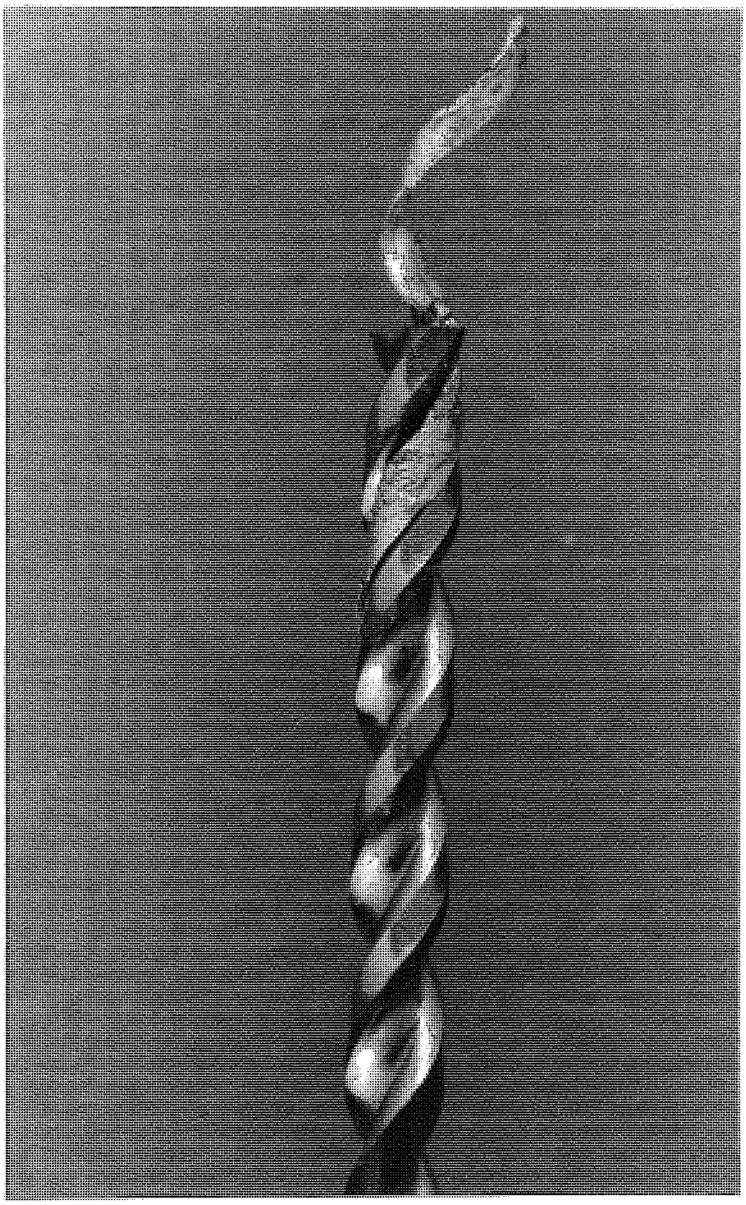
Buckling (column loading) of the drill occurs if the penetration rate (feed rate) is too high or because of hard inclusions into the work piece material. In both cases the high level of thrust generated, causes high compressive stresses which exceed the tool strength and consequently the tool fails.

The maximum value of feed which ensures axial stability of the tool depends on the tool length, the second moment of inertia of the drill cross section and the workpiece material. A methodology for calculation of this upper limit is presented in section 7.4

Torsional failure occurs because of swarf compacted in the drill flutes (Fig. 4.1, 4.2). This is a more progressive phenomenon and an accurate way of detection is by means of monitoring the pattern of the total torque applied to the tool against time or hole depth.

(v). As the drilled depth increases two phenomena manifest themselves :
Chip Formation changes ; in particular as the tool penetrates deeper into the workpiece the chips become more and more fragmented and curly as opposed to smooth and continuous during the early penetration (Fig. 4.5 to 4.7)

Drilling torque and thrust increase : Related to the changes in chip geometry is a variation in the drilling forces and in particular in the drilling torque which increases with the drilled depth. In figs. 4.8 to 4.12 are shown typical patterns of torque and thrust against hole depth (under constant penetration rate and spindle speed). Four main regions can be identified (Fig. 4.4) and are discussed in detail in section 4.2



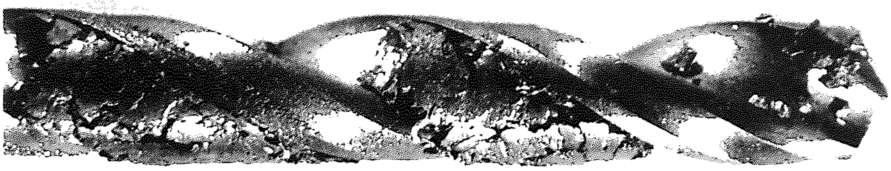
DRILL DATA : Titex A1622 HSS, type UFL, Ø 3.0 x 150 mm

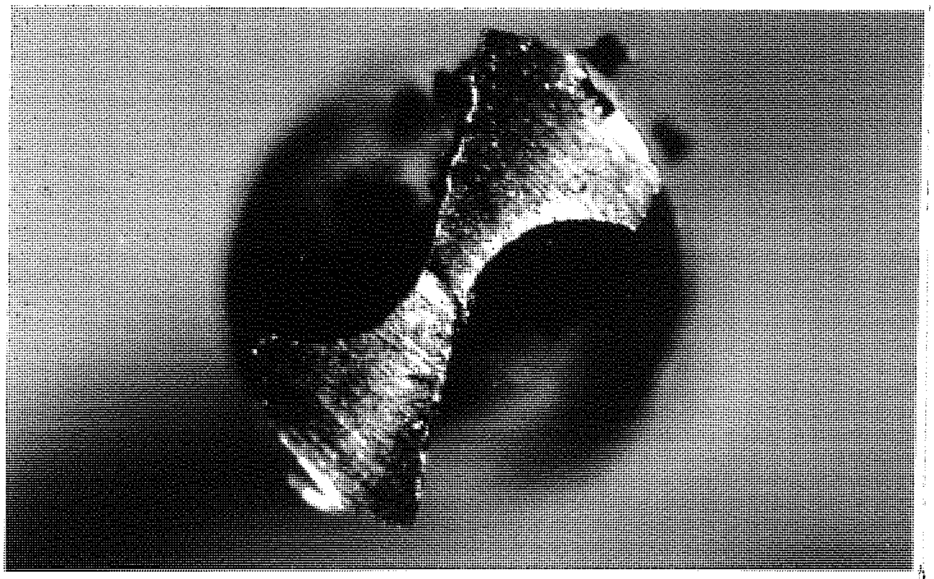
W/P MATERIAL : AMS7075 T736 Aluminium Alloy

MACHINING DATA : 3150 RPM, 120 mm/min (0.038 mm/rev)

COMMENTS : Flutes packed with swarf, 9 individual chips welded together

Fig. 4.1 : Swarf clogging the drill flutes in DHD of AMS7075 alloy





DRILL DATA : Titex A1547 HSSCo , type "Alpha X-E" , Ø 3.0 mm x 100 mm
W/P MATERIAL : TA11(IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
MACHINING DATA : 1000 RPM ,15 mm/min (0.015 mm/rev), Hocut 580 solub.oil
COMMENTS : flutes packed with swarf , cutting edges worn-out , life 4 min = 75 mm(2.5 holes), test aborted after receiving alarm signals of excessive torque.

Fig. 4.2 : Swarf clogging the drill flutes in DHD of TA11 Titanium alloy

DRILL DATA . Titex A1622 HSS, type UFL, Ø3.0 mm x 150 mm

W/P MATERIAL TA11 (IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
MACHINING DATA . 2000 RPM, 40 mm/min (0.020 mm/rev), Hocut 580 solub.oil
COMMENTS Test aborted due to alarming levels of thrust and torque, drill worn out after penetration up to 59 mm in a single pass, pilot hole Ø3 x 3 mm

Fig. 4.3 : Drill failure in DHD of TA11 Titanium alloy

4.2 Generalised model of drilling thrust and torque in DHD

The following model describes the variation of the drilling torque and thrust, the two main state variables of the deep hole drilling process, as functions of the drilled depth (or time), under constant feedrate and spindle speed.

The model is qualitative rather than quantitative and the exact pattern of variation of the drilling torque and thrust depends greatly on the initial machining conditions specified in the part program (feed-speed), the drill characteristics and of course the depth at which machining is to stop.

For this matter the model assumes a sufficiently great target depth (Zmax > 3d) in order to allow the instability characteristics to manifest themselves and to make the distinction between conventional and deep hole drilling clear. Regarding drilling torque **M(Z)** and thrust **T(Z)** as functions of the drilled depth, the following regions can be identified:

1. STEADY STATE (region 1, fig. 4.4)

Initial penetration up to depth Z_0 equal to a few diameters ; cutting action and swarf extraction from the hole are balanced. During this stage the process is practically identical to conventional drilling. The steady state values of torque M_0 and thrust T_0 represent the effort by the tool to plastically deform the work piece material. It has been shown by various researchers, both theoretically and experimentally, that the above values greatly depend on the hardness of the material drilled, the diameter of the drill (depth of cut), the feed, drill geometry and to a lesser extent the cutting speed (section 4.3).

$$M(Z) = M_0 \, , \; 0 < Z \leq Z_0 \quad \text{and} \quad T(Z) = T_0 \, , \; 0 < Z \leq Z_{max} \qquad (4.1)$$

2. INSTABILITY (regions 2, 3, 4)

The instability regions are characterised by variations of the drilling torque with drilled depth while the drilling thrust seems to be unaffected in general by the hole depth and presents no significant variations during regions 1, 2 and 3. There is only a sudden peak of thrust during the early impact with the work piece material because of the low rigidity of the slender column. After that stage the value of thrust settles to its steady state value T_0 with fluctuations which do not exceed +/- 10 % of this value.

Region 2 : Linear rise of torque with drilled depth up to 3-times the steady state value. This is due to reduced penetration of fluid to the cutting zone which causes fragmentation of the produced chips.

$$M(Z) = M_0 + aZ \; , \quad Z_0 \leq Z \leq Z_S \qquad (4.2)$$

The factor **aZ** expresses the friction component of the torque rising with the drilled depth and drilling tests indicated that **a** is practically constant within a feed rate range of 0.010 to 0.050 mm/rev (chapter 5). Clearly any attempt to stabilise the drilling torque should take place in region 2 where the additional work required to extract the swarf from the hole is directly proportional to the drilled depth.

Region 3 : Rise pattern becomes more rapid, for example a high order polynomial and values of up to 8-times the steady state value have been recorded. The shape and size of the chips has changed to even smaller values and the length of the flute packed is quite high. (Figs. 4.5, 4.6, 4.7)

Region 4 : Total absecnce of lubrication results to dry friction between the moving surfaces, namely the drill flutes, lands, hole bore and swarf. This situation leads to slip-stick phenomena as the lower end of the drill is twisted relative to its upper end.

During this final stage of the process, the drilling thrust changes significantly as well and seems to be affected by the variations in the drilling torque. In order to explain the various phenomena associated with this stage a model is proposed in which the tool is subjected to torsional vibrations which eventually lead to its catastrophic failure.

The modelling of torsional vibrations of the tool during instability in DHD has been investigated, mainly for single edge, self-pilot drills, by a number of researhers **[4]** Streicher, **[47]-[48]** Ema et al, **[41]** Thai, **[49]** Chernichkin, **[107]** Rohs, **[112]** Baier, **[166]** Ogawa ; in the present work, the proposed model is supported by experimental evidence of three types : first from the irregular fluctuations of the drilling torque and thrust recorded by means of a piezoelectric dynamometer onto U.V recording paper (figs. 4.8 to 4.12).

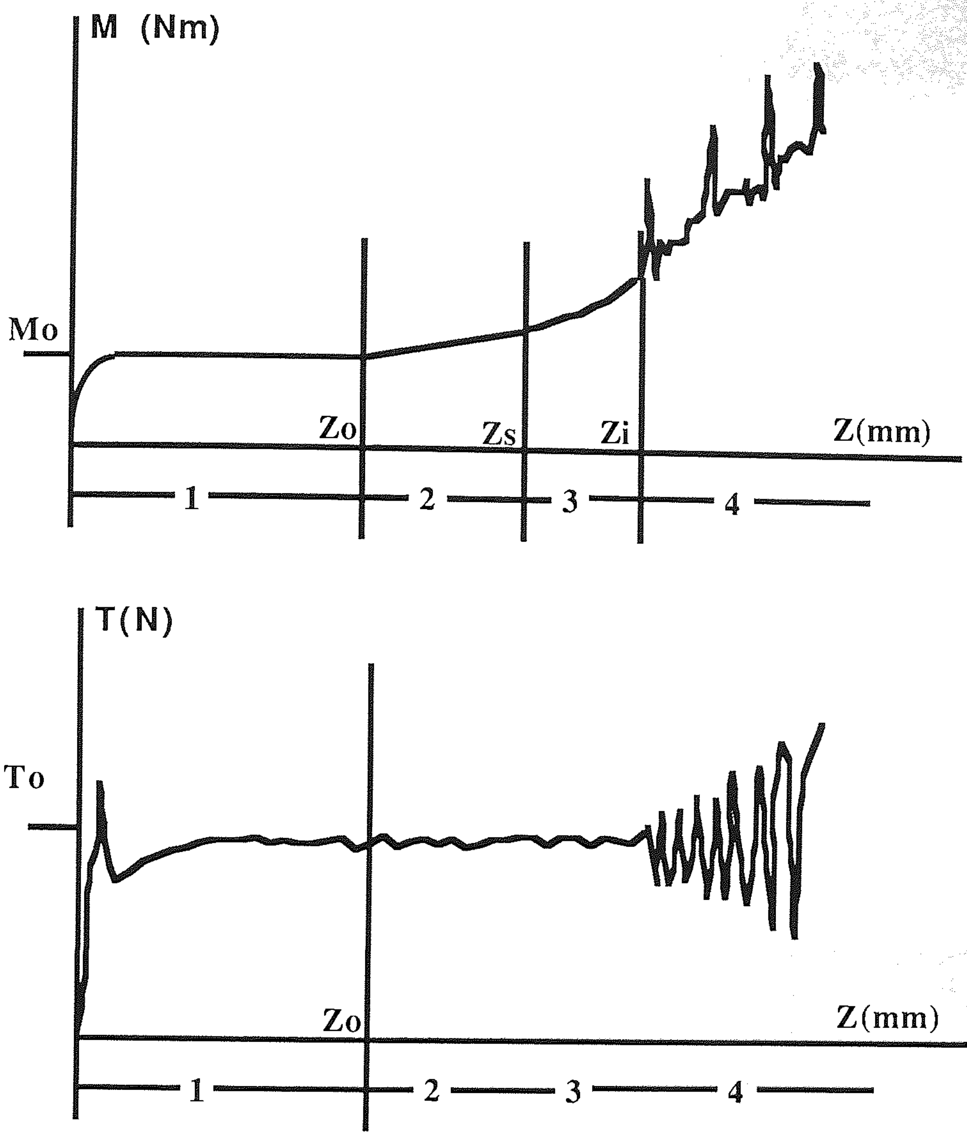


Fig. 4.4 : Drilling torque and thrust against hole depth in DHD

Next is the change in the shape and size of the produced swarf (fig. 4.5, 4.6, 4.7) ; in the event of torsional vibrations occuring, the undeformed chip thickness changes as the drill penetrates deeper into the material and this affects the drilling thrust at the drill point. The stiffness of the tool in any case is too low to cause a stall to the spindle motor (it would require a large diameter drill), therefore tool failure is unavoidable.

Final evidence is provided by examination of broken drills the lower half of which has been left in the drilled hole (fig.4.25). The gap between the tool point and the bottom of the hole which can only be explained if one assumes an elongation of the tool as a result of high torque on the one hand and the elastic properties of the tool on the other ; an attempt to model this phenomenon is presented in section 4.6.

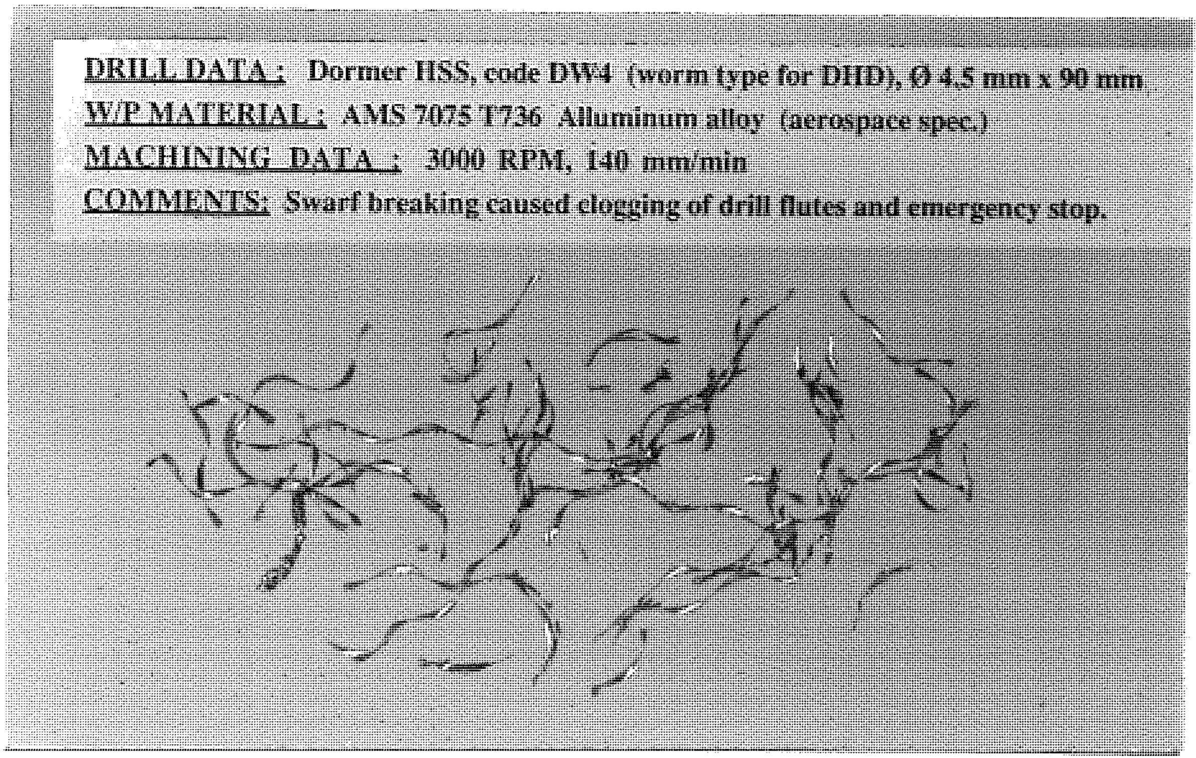


Fig. 4.5 : Variation of swarf form in DHD Aluminium alloy

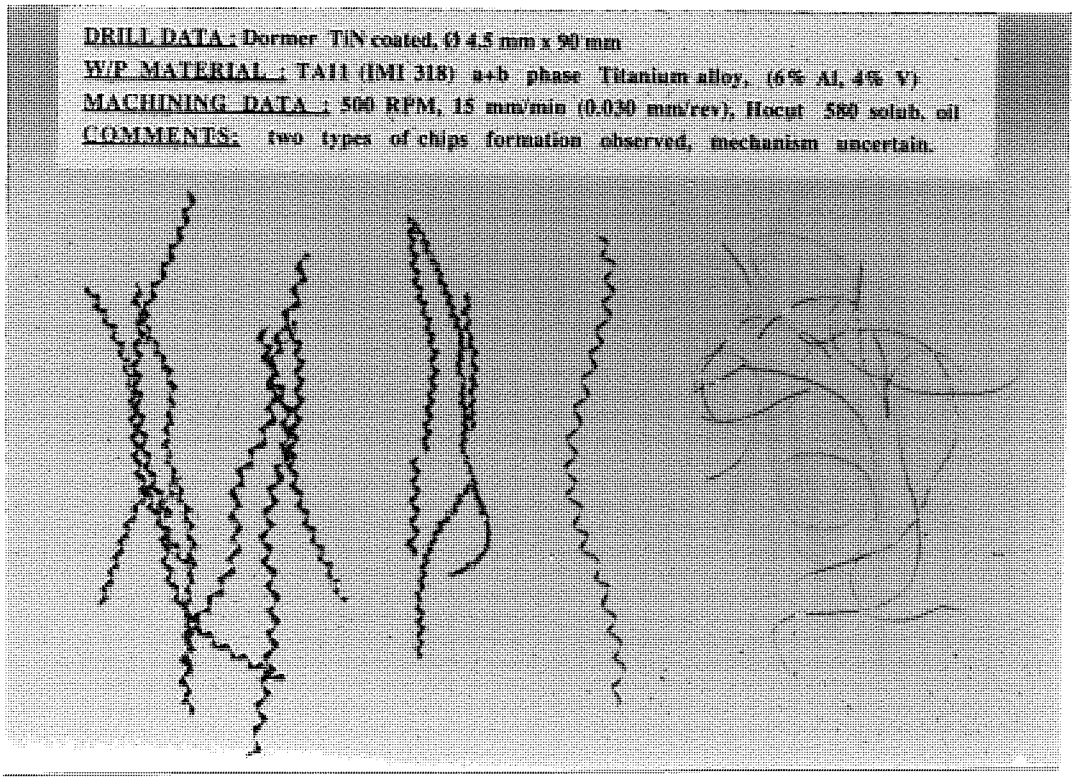


Fig. 4.6 : Variation of swarf form in DHD Titanium
Swarf changes with drilled depth from left to right
(The exact mechanism and the contributions of
speed (500 RPM), tool geometry and coating (TiN), is uncertain)

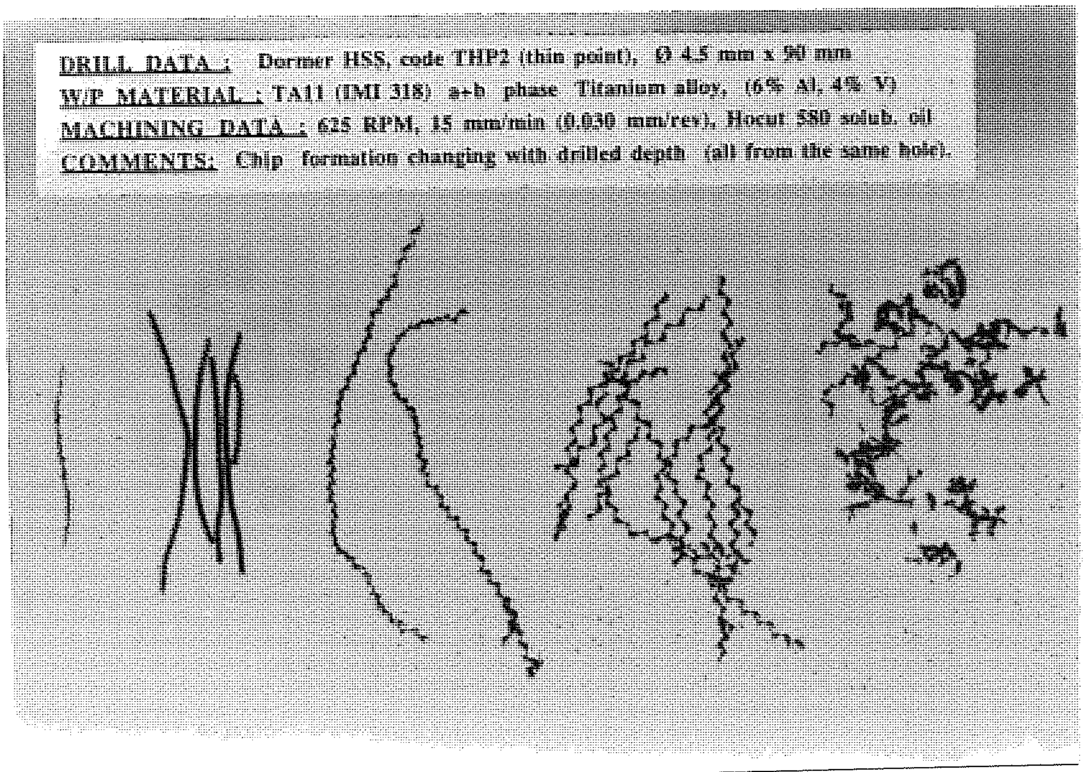
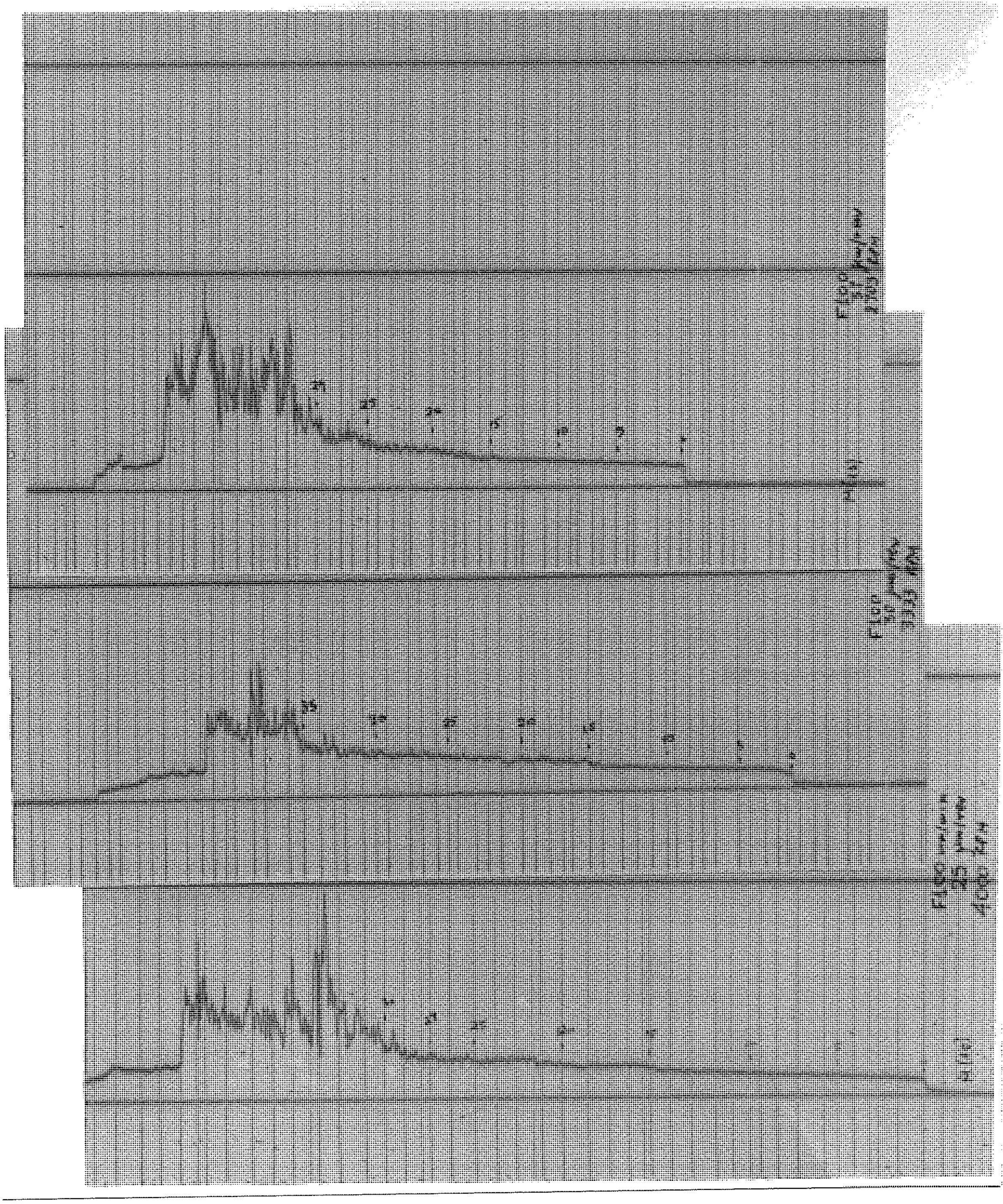


Fig. 4.7 : Variation of chip geometry in DHD Titanium
Swarf changes with drilled depth from left to right
(The exact mechanism and the contributions of
speed (625 RPM), tool geometry, is uncertain)



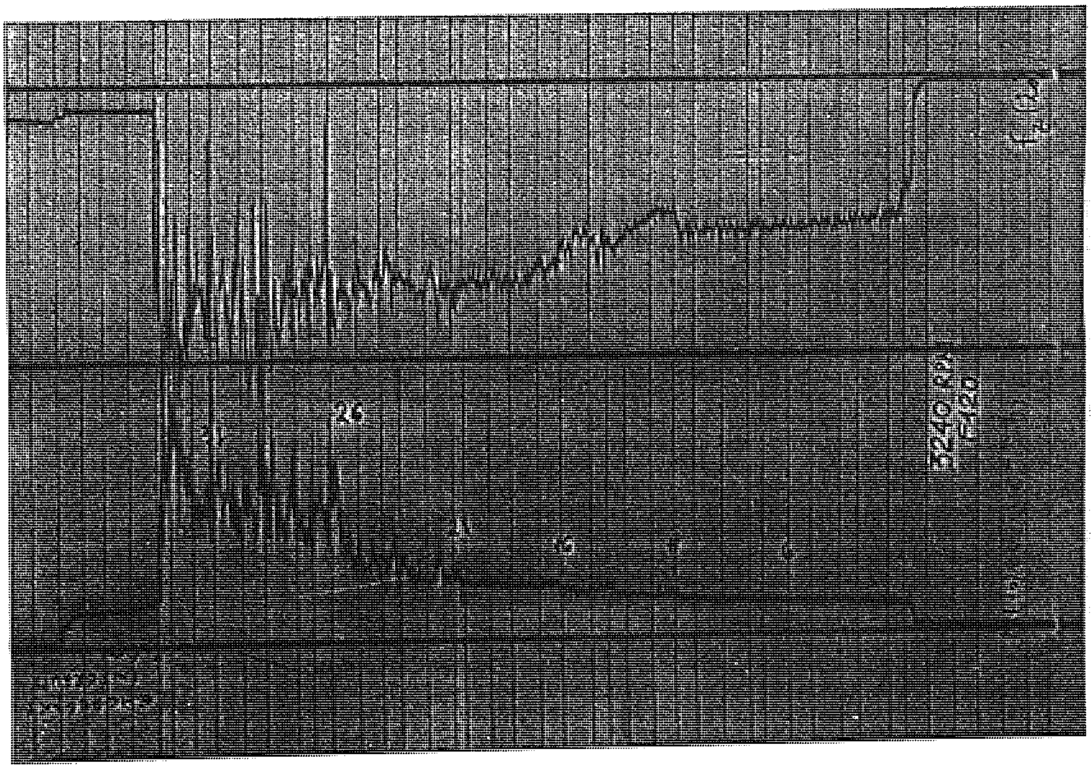
DRILL DATA : Titex A1622 HSS, type UFL, Ø 2.4 x 120 mm

W/P MATERIAL : AMS7075 T736 Aluminium Alloy

MACHINING DATA : constant feedrate 100 mm/min, various speeds/feeds

4000 RPM (0.025 mm/rev), 3333 RPM (0.030 mm/rev), 2703 RPM (0.037 mm/rev)

Fig. 4.8 : Drilling torque patterns for various feeds in DHD
Cutting speed affects pattern and depth of appearance of instability.



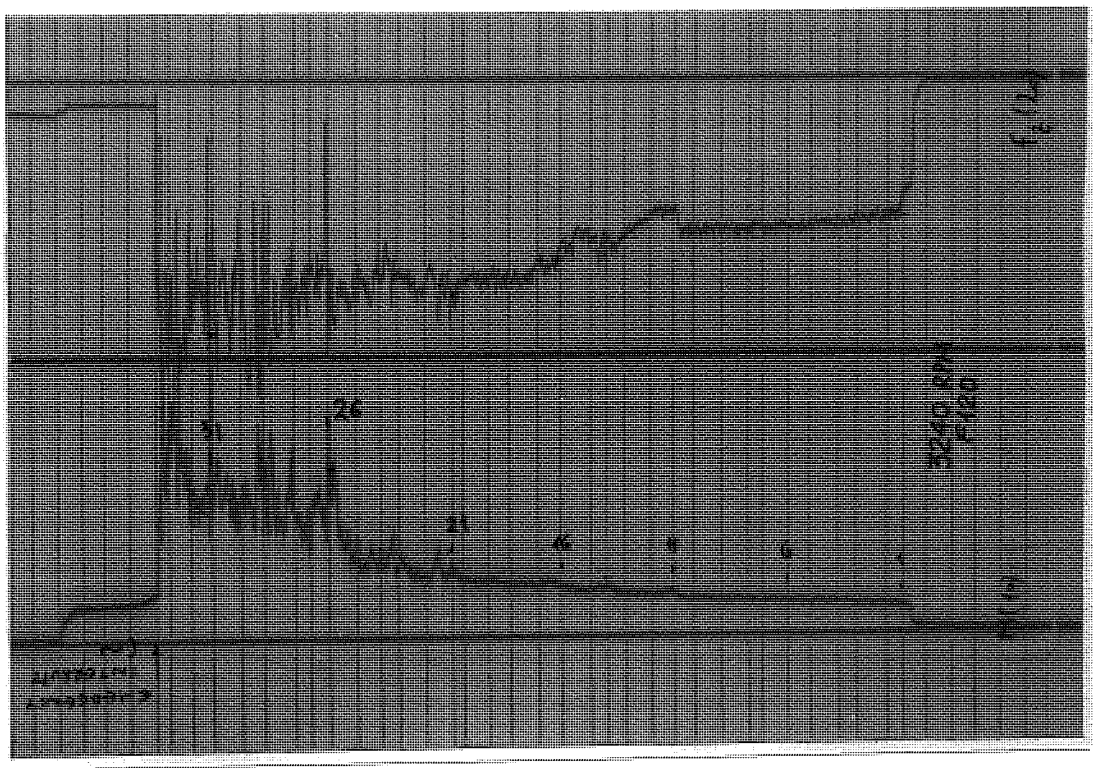
DRILL DATA : Titex A1622 HSS, type UFL , Ø 3.0 x 150 mm

W/P MATERIAL : AMS7075 T736 Aluminium Alloy

MACHINING DATA : 0.037 mm/rev , 3240 RPM

COMMENTS : Test aborted at depth 52 mm

Fig. 4.9 : Drilling torque and thrust patterns in DHD Aluminium



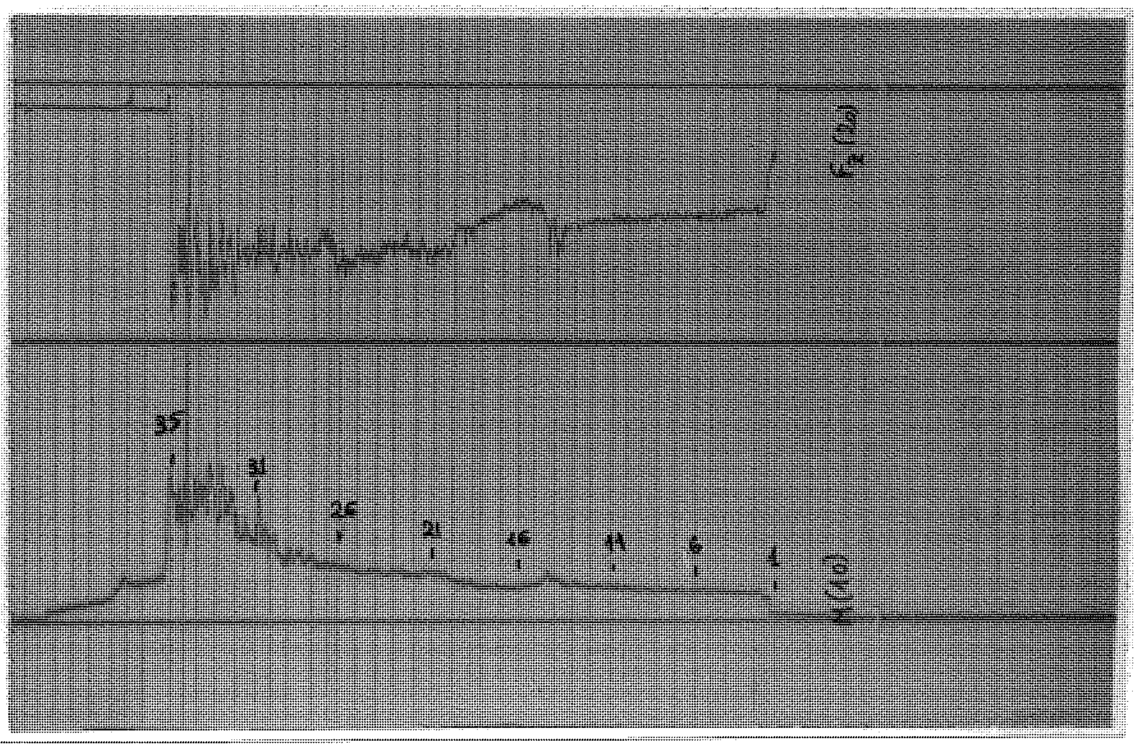
DRILL DATA : Titex A1622 HSS, type UFL , Ø 3.0 x 150 mm

W/P MATERIAL : AMS7075 T736 Aluminium Alloy

MACHINING DATA : 0.037 mm/rev , 3240 RPM

COMMENTS : Test aborted at depth 52 mm

Fig. 4.9 : Drilling torque and thrust patterns in DHD Aluminium

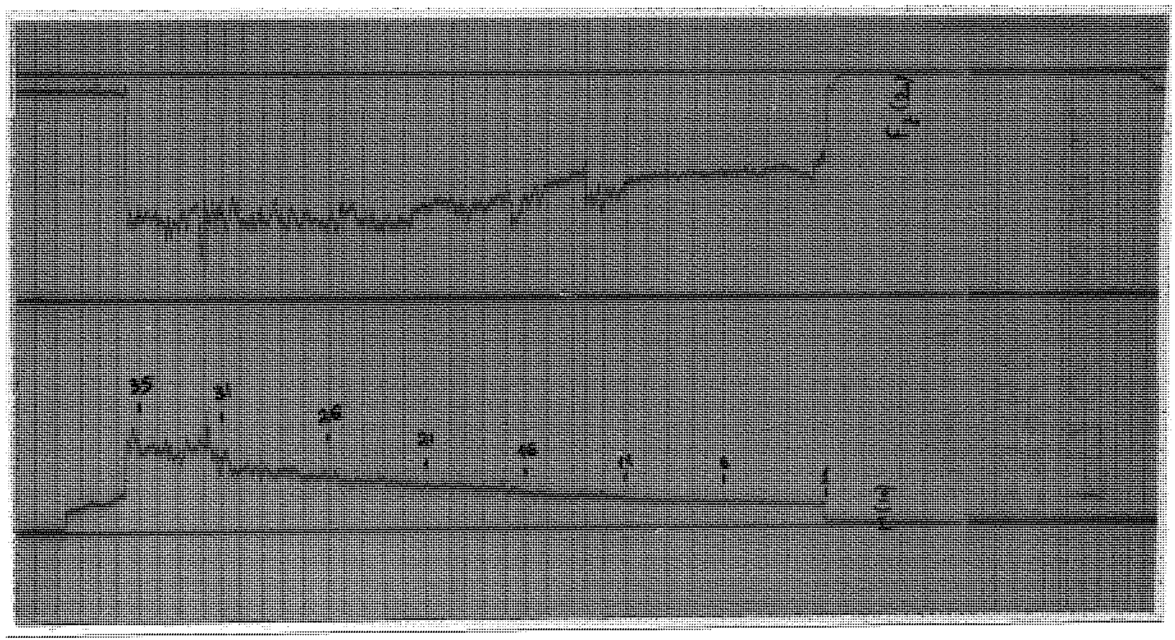


DRILL DATA : Titex A1622 HSS, type UFL , Ø 3.0 x 150 mm

W/P MATERIAL : AMS7075 T736 Aluminium Alloy

MACHINING DATA : 0.033 mm/rev, 3600 RPM

Fig. 4.10 : Drilling torque and thrust patterns in DHD Aluminium

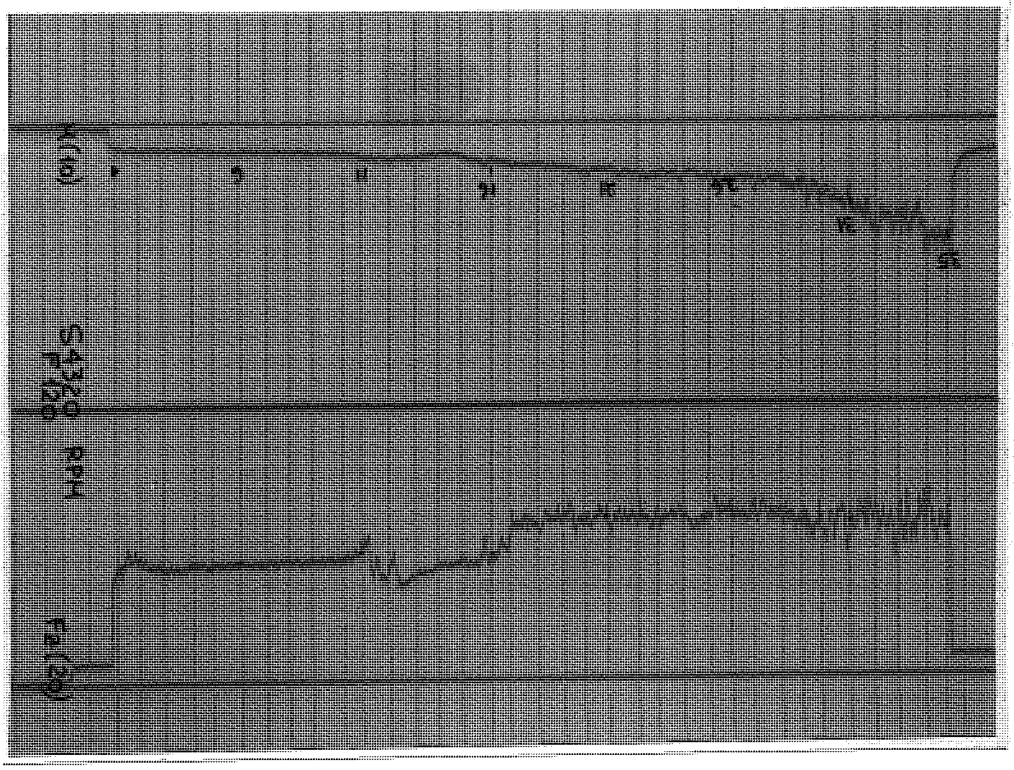


DRILL DATA : Titex A1622 HSS, type UFL, Ø 3.0 x 150 mm

W/P MATERIAL : AMS7075 T736 Aluminium Alloy

MACHINING DATA : 0.030 mm/rev, 3960 RPM

Fig. 4.11 : Drilling torque and thrust patterns in DHD Aluminium

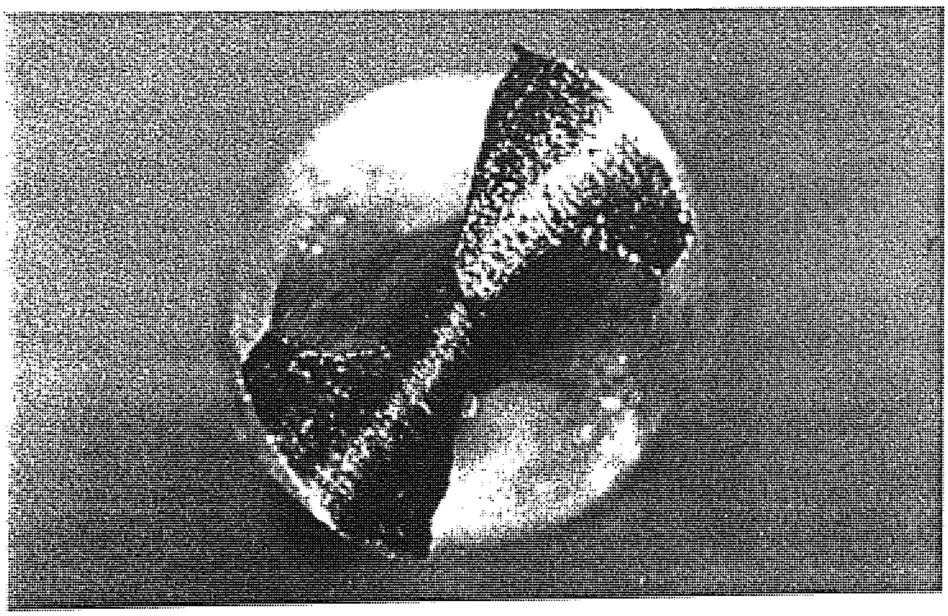


DRILL DATA : Titex A1622 HSS, type UFL, Ø 3.0 x 150 mm

W/P MATERIAL : AMS7075 T736 Aluminium Alloy

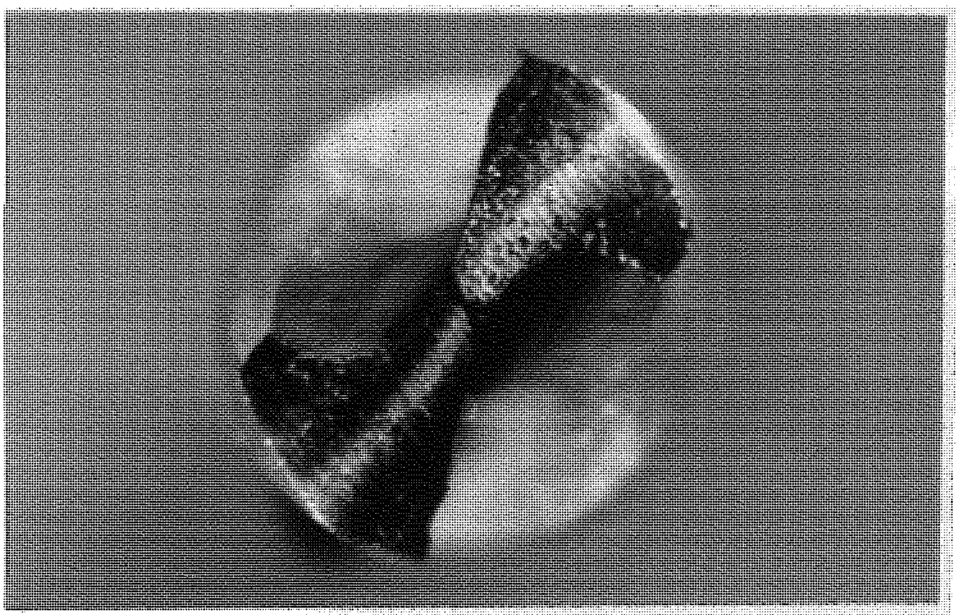
MACHINING DATA : 0.028 mm/rev, 4320 RPM

Fig. 4.12 : Drilling torque and thrust patterns in DHD Aluminium



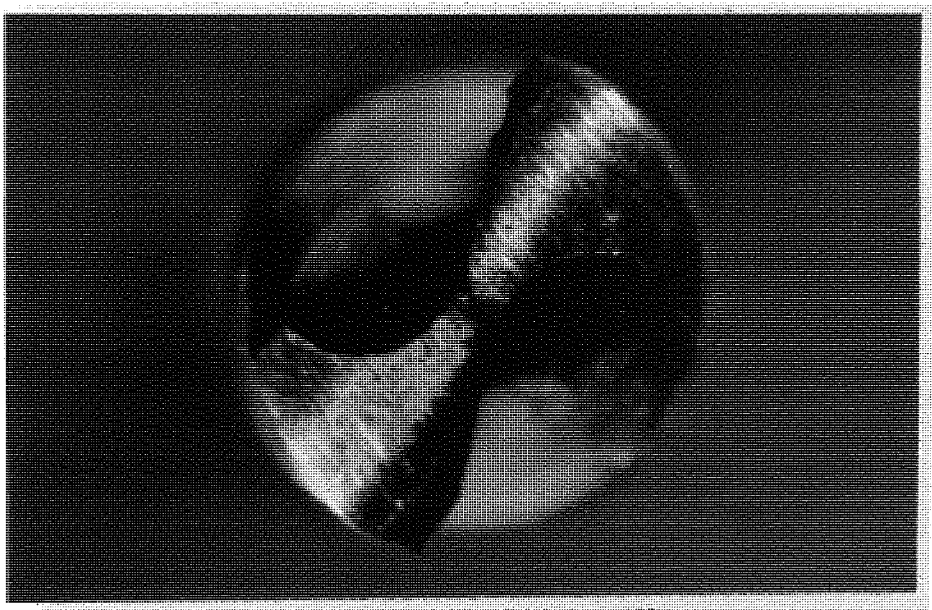
DRILL DATA : Titex A1622 HSS , type UFL , Ø 3.0 mm x 150 mm
W/P MATERIAL : TA11(IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
MACHINING DATA : 1000 RPM , 10 mm/min (0.010 mm/rev), Hocut 580 solub.oil
COMMENTS : drill worn out after 1.5 min=15 mm , pilot hole Ø3x15 mm.

Fig. 4.13 : Wear of cutting edges of A1622 drill in DHD Titanium
(very high speed - 1000 RPM -> rapid wear)



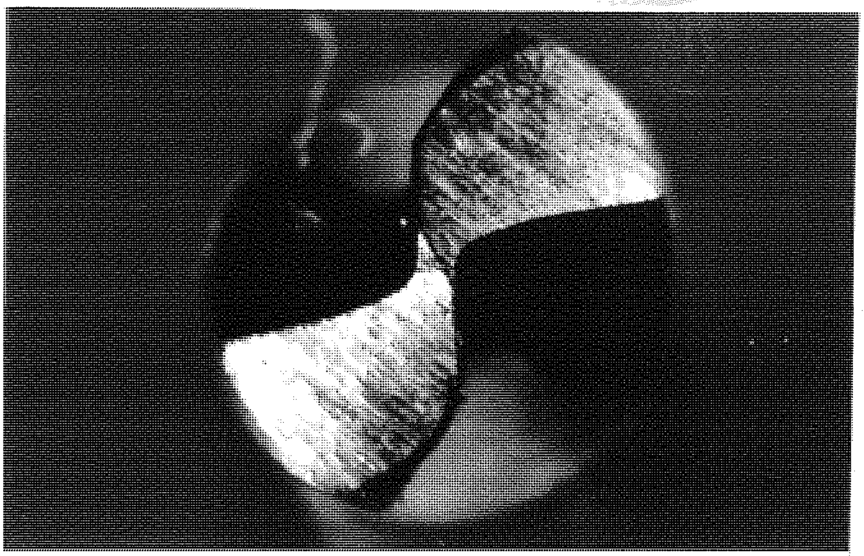
<u>DRILL DATA :</u> Titex A1622 HSS , type UFL , Ø 3.0 mm x 150 mm
<u>W/P MATERIAL :</u> TA11(IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
<u>MACHINING DATA :</u> 1000 RPM , 10 mm/min (0.010 mm/rev), Hocut 580 solub.oil
<u>COMMENTS :</u> drill worn out after 1.5 min=15 mm , pilot hole Ø3x15 mm.

Fig. 4.13 : Wear of cutting edges of A1622 drill in DHD Titanium
(very high speed - 1000 RPM -> rapid wear)



DRILL DATA : Titex A1622 HSS , type UFL , Ø 3.0 mm x 150 mm
W/P MATERIAL : TA11(IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
MACHINING DATA : 600 RPM ,15 mm/min (0.025 mm/rev), Hocut 580 solub.oil
COMMENTS : drill worn out after 6.5 min=90 mm (3 holes), pilot hole Ø3x3 mm.

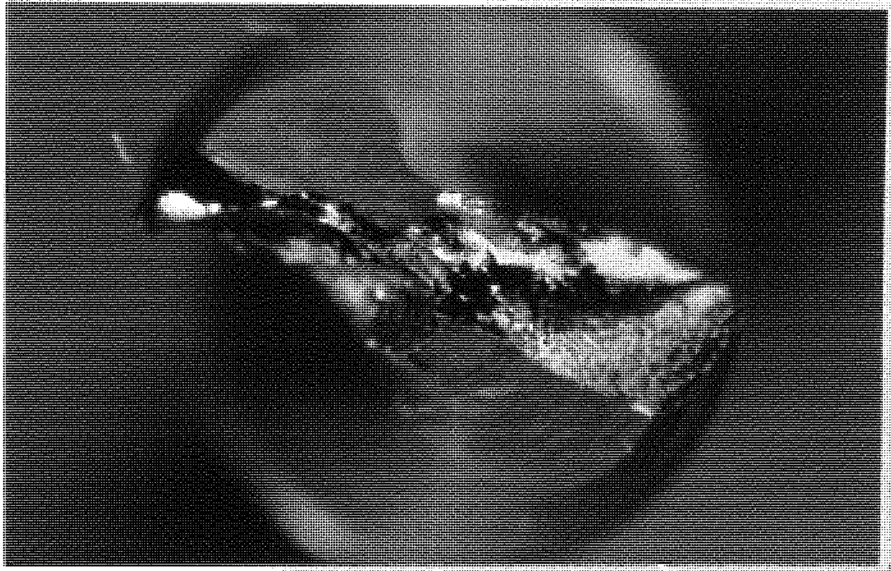
Fig. 4.14 : Wear of cutting edges of Titex A1622 drill in DHD Titanium (lower speed - 600 RPM -> longer life)



DRILL DATA Guhr ing GT100 HSS, Ø3.0 mm x 150 mm

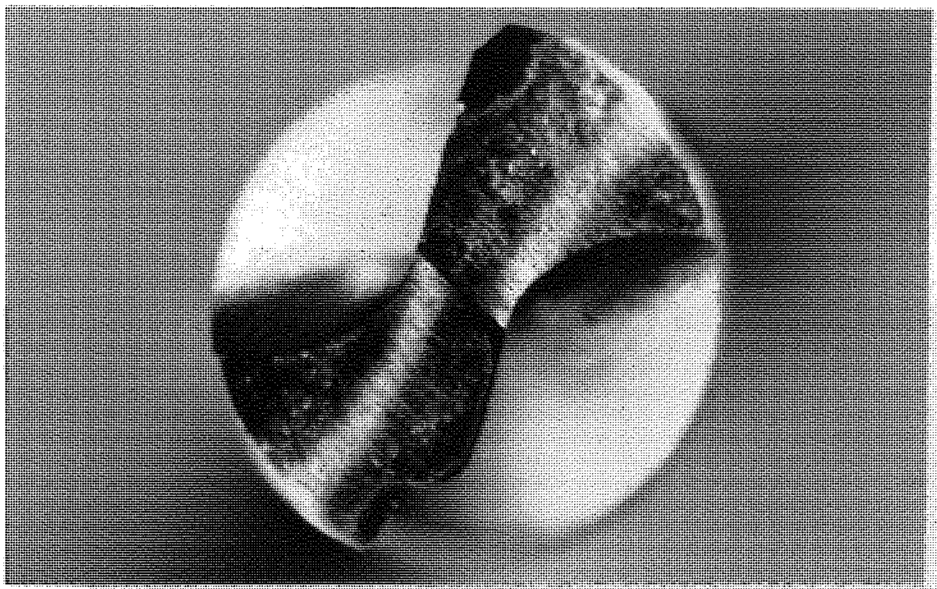
W/P MATERIAL TA11(IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
MACHINING DATA 1000 RPM, 10 mm/min (0.010 mm/rev), Hocut 580 solub.oil
COMMENTS corner wear after 10 5 min=105 mm (3 x 35), pilot hole Ø3 x 15 mm

Fig. 4.15 : Failure of cutting edges of GT100 drill in DHD Titanium (very high speed - 1000 RPM)



<u>DRILL DATA :</u> Gühring GT50 HSS , Ø 4.5 mm x 127 mm
<u>W/P MATERIAL :</u> TA11(IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
<u>MACHINING DATA :</u> 600 RPM , 16 mm/min (0.027 mm/rev), Hocut 590 solub.oil
<u>COMMENTS :</u> drill failed to enter the workpiece , immediate failure of cutting lips due to excessive point thinning (unsuitable for high tensile strength alloys).

Fig. 4.16 : Catastrophic failure of GT50 drill in DHD Titanium (unsuitable point geometry)



<u>DRILL DATA :</u> Titex plus HSS , Ø 4.5 mm x 128 mm
<u>W/P MATERIAL :</u> TA11(IMI 318) a+b phase Titanium alloy (6% Al, 4% V)
<u>MACHINING DATA :</u> 400 RPM , 10 mm/min (0.025 mm/rev), Hocut 580 solub.oil
<u>COMMENTS :</u> drill failed to enter the workpiece , immediate failure of cutting lips due to excessive point thinning (unsuitable for high tensile strength alloys).

Fig. 4.17 : Catastrophic failure of Titex-plus drill in DHD Titanium (unsuitable point geometry)

4.3 Steady state torque and thrust in DHD (region 1)

The steady state torque M_0 and thrust T_0 dominate region 1 in fig. 4.4 up to a certain depth Z_0, which cannot be defined explicitly, but depends on a number of factors, mainly the material being drilled and the tool size. Typically Z_0 is less than 5 diameters and represents the drilling depth up to which the drilling forces are generated purely from the deformation of the workpiece material while the chipbreaking and friction components have not manifested themselves.

The steady state forces are related to the process parameters **d** (drill diameter), **f** (feed), v (cutting speed) with empirical relationships of the type :

$$M_0\,(d,\ f,\ v) = k_M\, d^p\, f^m\, v^n \qquad (4.3)$$

$$T_0\,(d,\ f,\ v) = k_T\, d^{p'}\, f^{m'}\, v^{n'} \qquad (4.4)$$

Alternatively, M_0 and T_0 can be expressed in terms of feed rate **F** and spindle speed N as follows :

$$M_0\,(d,\ N,\ F) = k_M\ [\pi/1000]^n\ d^{p+n}\ N^{n-m}\ F^m \qquad (4.5)$$

$$T_0\,(d,\ N,\ F) = k_T\ [\pi/1000]^{n'}\ d^{p'+n'}\ N^{n'-m'}\ F^{m'} \qquad (4.6)$$

where k_M , k_T, p, p', m, m' , n, n' , (m>>n) are constants depending mainly on the workpiece material but also the drill characteristics **[147]** to **[155]**.

In the table which follows, a presentation of some selected published results follows, which aims to show the importance of empirical expressions but also the great diversity which exists with regards to the significance and contribution of the various factors (feed, speed, hardness, etc.) to the magnitude of these forces. The Kpcm or Ncm units of torque are not acceptable in the strict sense of the systems of units but they have been left in their original form found in the relevant publications.

DRILLING THRUST AND TORQUE (steady state)

Researcher (Ref. No)	Material and Diam.	Feed f (mm/rev) Speed v (m/min)	Torque (Kpcm) Thrust (Kp)
Oxford (150)	Steel Ø 3.5 -12.5 mm	0.25 - 1.25 6.5	C_M HB $d^{1.8}$ $f^{0.8}$ C_T HB $d^{1.0}$ $f^{0.63}$
Bedini (95)	Fe 42B Steel Ø 10.75 mm	0.09 - 1.20 10 - 30	C_M $f^{0.73}$ $v^{-0.03}$ C_T $f^{0.83}$ $v^{-0.07}$
Tverskoii (83), (89)	Chromel Ø 1.3 mm	0.015 - 0.03 3.1 - 6.1	2.81 $f^{0.55}$ $v^{0.033}$ 79.4 $f^{0.706}$ $v^{0.195}$
Davidson (76)	ML5 alloy (Magnesium) Ø 6 - Ø 14 mm	0.14 - 0.50 19 - 35	0.61 $d^{1.88}$ $f^{0.6}$ 5.73 $d^{1.04}$ $f^{0.6}$
Vinogradov (75)	VT18 alloy (Titanium) Ø12 mm	0.05 - 0.12 16 - 40	11.4 $d^{1.3}$ $f^{0.22}$ $v^{-0.08}$ 2.7 $d^{1.85}$ $f^{0.66}$ $v^{-0.12}$
Vinogradov (75)	KH18N10T (steel) Ø12 mm	0.04 - 0.084 30 - 65	10.7 $d^{1.7}$ $f^{0.55}$ $v^{-0.23}$ 508 $d^{0.53}$ $f^{0.57}$ $v^{-0.28}$
Margulis (79)	38KhS steel Ø15 - Ø 30 mm	0.058 - 0.2 20 - 35	123 $d^{1.85}$ $f^{0.87}$ $v^{-0.25}$ 1930 $d^{1.12}$ $f^{0.85}$

Pleshivtsev	AK4 -AK6-AL4U	unknown	$C_M\ d^{1.8} f^{0.6} v^{-0.01}$
(80)	(Light Alloys ?) Ø16 mm	unknown	$C_T\ d^{0.9} f^{0.5} v^{-0.03}$
Patkar	Mild Steel	0.05 - 1.3	$14.13\ d^{2.26} f^{0.78} v^{-0.07}$
(61)	Ø8 - Ø 17 mm	5 - 40	$361.2\ d^{0.45} f^{0.73} v^{-0.08}$
Zakamaldin	18X2N4BA Steel	0.01 - 0.05	$0.35 + 0.04z + (32.3 + 4.5z)f$
(84)	Ø 1.5 x 24 mm	14.5	$5 + 1.35\ z + (252 + 51z)f$
Poletaev	Steel 45	unknown	$0.003 + 1.86\ f + 0.034\ z$
(55), (85)	Ø2 x 59 mm	17	$49 + 2020\ f + 29.6\ z$

It is clear from the above table as well as from the experimental results presented in chapter 3, that the values of steady state torque and thrust are predictable once the initial conditions are given, that is workpiece material and drill characteristics. Such expressions however, are difficult to obtain because they require many experiments and are restricted to one material and tool combination.

Undoubtedly their scientific value is high ; but in view of the fact that new materials are produced and used all the time and also that automation and use of CNC systems is expanding rapidly it is necessary to avoid the dependance on such knowledge.

Identification of these parameters should become also automated with a minimum amount of off line number of tests required. A simple example of the above concept is presented in chapter 7, section 7.3.4.

4.4 Tool life in drilling in general and in DHD

A similar situation to the one discussed in the previous section also applies to the tool life against feed and speed relationships. Most researchers propose empirical relationships which determine the cutting speed as a function of tool life, feed and some times tool diameter.

There is a great deal of diversity regarding the power indices for the various parameters in the tool life expressions ; however there is one clear characteristic, the contribution of cutting speed is between two-fold to five-fold that of the feed (indices) although the exact ratio depends entirely on the work piece material.

TOOL LIFE - SPEED RELATIONSHIPS

Researcher (Ref. No)	Material and Diam.	Feed f (mm/rev) Speed v (m/min)	Tool Life - Cutting speed
Vinogradov (75)	VT18 alloy (Titanium) Ø12 mm	0.05 - 0.12 16 - 40	$v = 4.7\ d^{0.87} f^{-0.21} T^{-0.28}$
Vinogradov (75)	KH18N10T (steel) Ø 8-20 mm	0.04 - 0.084 30 - 65	$v = 20.6\ d^{0.45} f^{-0.41} T^{-0.39}$
Dechko (72)	Steel 45 Ø 3-10 mm	0.06 - 1.6 15 - 35	$v = 5\ d^{0.4} f^{-0.58} T^{-0.12}$
Garina (30)	Steel 45 Ø 3-10 mm	0.003 - 0.007 5 - 25	$v = 0.65\ d^{1.32} f^{-0.86} T^{-0.3}$

Mikhaliyuk (73)	Hardn. Steeel Ø 3-10 mm	0.05-0.07 10-18	$v = 0.19\ d^{1.6} f^{-1.2} T^{-0.5}$
Tverskoi (62)	Chromel Ø1.3x16 mm	0.05-0.07 10-18	$T = 7.24\ v^{-1.78} f^{-1.52}$

A situation analogous to the one discussed in section 4.3, regarding the importance of expressions for the steady state values of thrust and torque, occurs in the case of tool life. Expressions such as those presented above are of paramount importance because they can assist the process planner to select machining conditions, namely feed and speed, which not only belong to the machinability window of the workpiece material but also satisfy a certain tool life criterion. In cases of unmanned or limited supervision machining automatic tool replacement can also take place between intervals specified by such expressions.

The above are valid arguments if one assumes that the process runs uninterrupted from catastrophic failures and the classic wear mechanism manifests itself without any disturbances. In the case of deep hole drilling however this is the exception rather than the normal situation because the twist drill is a unique tool ; in addition to its primary function as a cutting tool it also performs the task of conveying the produced swarf out of the hole.

Therefore, the term tool life applies in DHD under the condition that the risk of catastrophic failure is eliminated and the process integrity is ensured. Under such circumstances it is possible indeed, as shown in section 3.7, to obtain a satisfactory tool life model based on a generalised Taylor equation, accounting for the effect of speed and feed on tool life.

4.5 Friction forces between the drill, hole bore and swarf

In section 4.2 and with reference to fig. 4.4, the proposed model suggested that the source of instability during DHD is the phenomenon of swarf fragmentation with drilled depth which in turn is the result of increasing absence of cutting fluid, in its dual role as coolant and lubricant, from the cutting zone and the flutes.

The greatest friction of the cutting part of twist drills is normally observed round the corner edges and also between the bore of the hole and the margins. The basic purpose of the drill margins is to guide the drill and ensure the straightness of the hole being drilled and this the reason why they are part of a cylindrical surface.

In order to reduce the high friction forces between the drill and the hole bore, a number of measures are employed, the most common of which are : the reduction of the width of the margins, an increase of the drill back taper, the use surface coatings (e.g TiN, TiC) and where possible the use of internal coolant supply. A simple two-dimensional analysis follows, which investigates the forces acting upon an elementary swarf particle of mass m and this shown in figure 4.18 below :

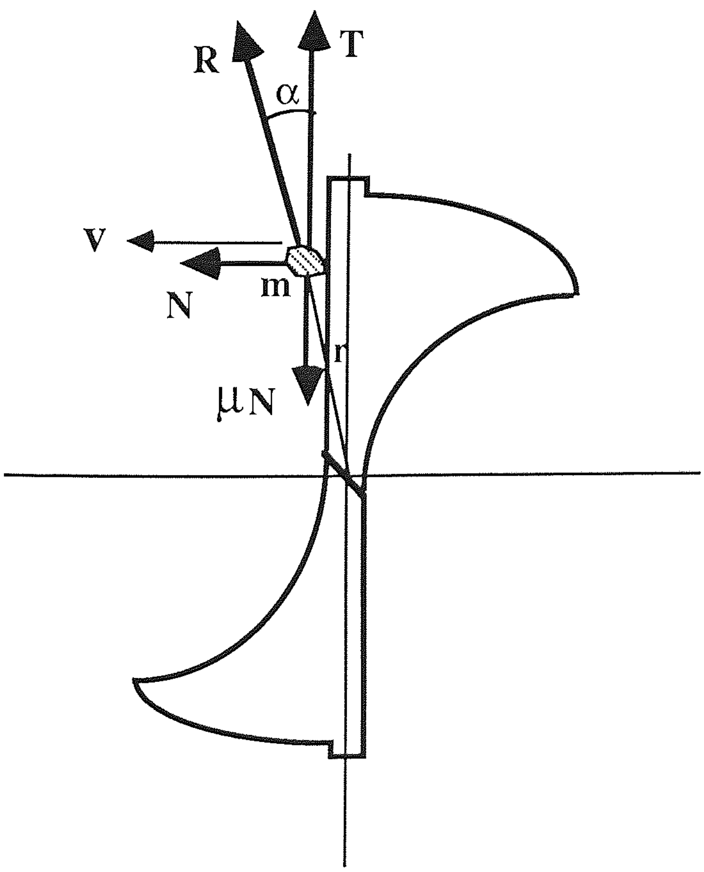


Fig. 4.18 : Forces acting upon a swarf particle (chip) in drilling (top view of drill cross section at right angles to drill axis)

The problem is clearly three-dimensional since there is a velocity component at right angles to the peripheral velocity (cutting speed) **v**. This component is equal to the feed rate (penetration rate), but when compared with **v** justifies the simplified two-dimensional approach (e.g : for DHD of AMS 7075 alloy, typical values : **d** = Ø 3.0 mm, spindle speed **N** = 3000 RPM , cutting speed **v** = π**dN** = 28260 mm/min, feed rate **F** = 100 mm/min).

The force $\mathbf{R} = \mathbf{m}\, \mathbf{v}^2\, \mathbf{r}^{-1}$ has two components **T** and **N**, where **T** is the force acting along the tangential direction to the inner flute surface and **N** is the normal to the direction of that force ; from the geometry it follows that :

$$\mathbf{T} = \mathbf{R}\cos\alpha \qquad \mathbf{N} = \mathbf{R}\sin\alpha \tag{4.7}$$

Assuming dry friction, the friction force $\mu\mathbf{N}$ lies in the opposite direction to that of the tangential force **T** and the condition for the swarf not to move towards the circumference of the tool is :

$$\mu\mathbf{N} = \mu\mathbf{R}\sin\alpha \geq \mathbf{R}\cos\alpha \qquad \mu \geq \cot\alpha \tag{4.8}$$

Clearly the above simple relationship suggests that the coefficient of friction between the drill and the workpiece material determines the optimum value for the angle **a**. Although what follows should be experimentally shown one can take as an example an arbitrary and yet typical value for μ = **0.4** considering the rough surface of the produced swarf and dry sliding friction.

(As a comparison it is worth mentioning that the coefficient of friction between engine components made of steel and without lubrication is between 0.19 to 0.21 - Marks Handbook for Mechanical Engineers - Appendix IV)

For the above value of μ = **0.4** the corresponding value of α should be : α = **68°**, the value of the angle in the commercially available twist drills however, does not exceed a few degrees or minutes for smaller diameters, this in turn causes the swarf to travel towards the circumference of the drill which eventually results in fragmentation of the swarf and the corresponding values of high torque.

This simple analysis suggests that one possible solution to the problem of chip breakage in DHD would be to redesign the flute shape somehow in order to alleviate the problem ; this is of course outside the scope of the present work.

In order to assess the effect of the drill helix angle to the above discussed movement of the swarf, the forces which act upon the same particle of mass **m** as before, in a vertical plane are shown in fig.4.19. The forces which act are the friction force $\mathbf{F_{fr}}$ and the weight **W** as a result of which a centripetal force appears in order to allow the motion of the particle in a circle.

The friction force $\mathbf{F_{fr}} = \mu\, m\, v^2\, r^{-1}$ has a direction opposite to that of the cutting speed at the circumference of the drill.

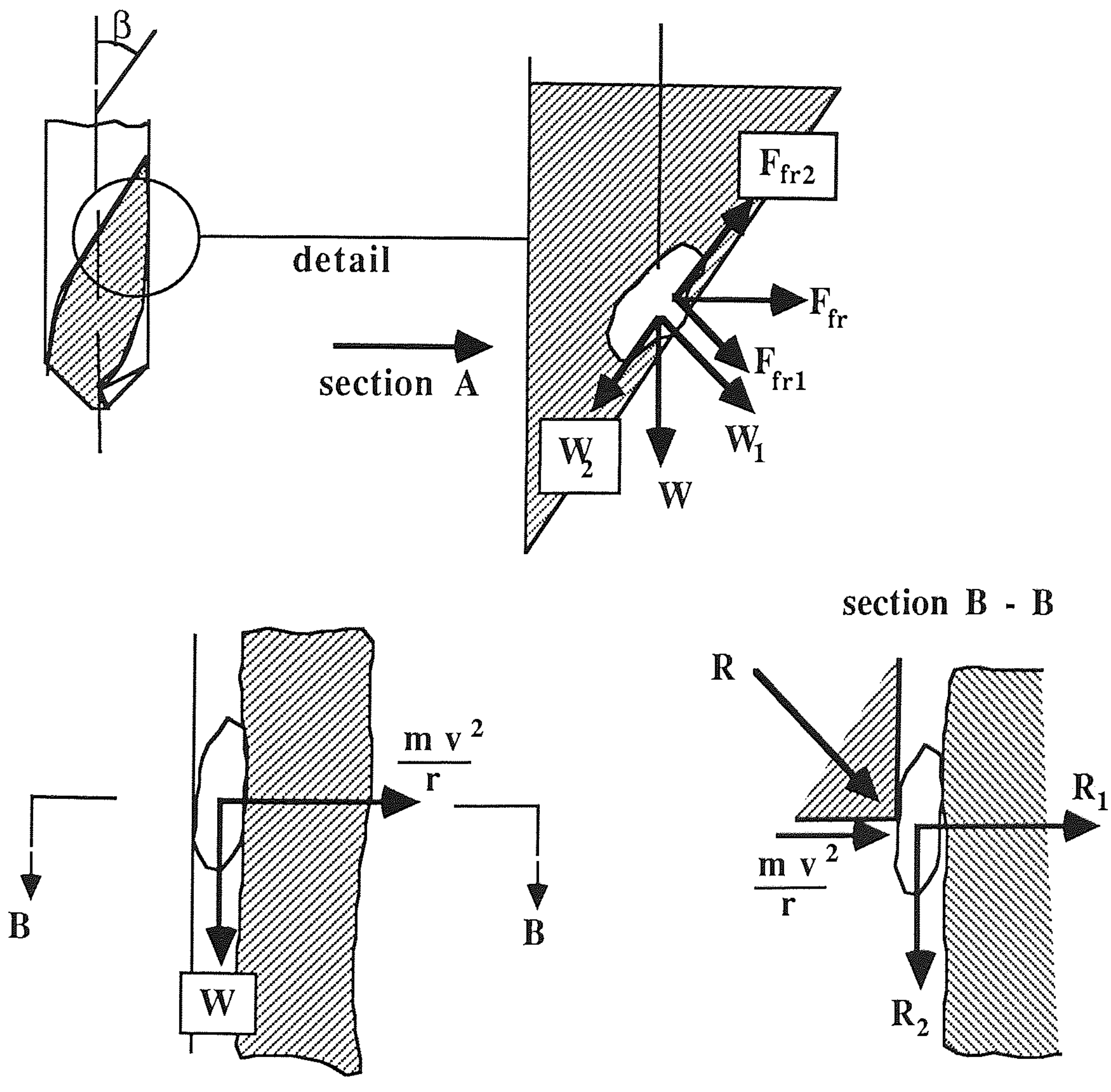


Fig. 4.19 : Forces acting upon a swarf element near the drill margin

$\mathbf{F_{fr}}$ can be resolved into two components $\mathbf{F_{fr1}}$ at right angles to the drill margin and $\mathbf{F_{fr2}}$ parallel respectivelly : these can be expressed according to helix angle β as follows :

$$F_{fr1} = F_{fr} \cos \beta = \mu \, m \, v^2 r^{-1} \cos \beta \qquad (4.9)$$

$$F_{fr2} = F_{fr} \sin \beta = \mu \, m \, v^2 r^{-1} \cos \beta \qquad (4.10)$$

The weight can be also analysed to its two components in a similar manner :

$$W_1 = W \cos (90 - \beta) = W \sin \beta \qquad (4.11)$$

$$W_2 = W \sin (90 - \beta) = W \cos \beta \qquad (4.12)$$

The above expressions show that the total force acting upon the swarf element is : $F_{fr1} + W_1$, it is clear that as the angle β increases the component F_{fr1} is reduced in magnitude while W_1 increases. It would be useful to determine when the total force becomes maximum and when it becomes minimum ;

$$F_{total} = \mu \, m \, v^2 r^{-1} \cos \beta + m \, g \sin \beta \qquad (4.13)$$

$\partial F_{total} / \partial \beta = 0$ yields : $- \mu \, m \, v^2 r^{-1} \sin \beta + m \, g \cos \beta = 0$

$$\tan \beta = g \, r \, \mu^{-1} v^{-2} \qquad (4.14)$$

Substituting $\mu = 0.4$ and $g = 9.81$ and $r = 0.01$ m and four typical values for the cutting speed : $v_1 = 10$, $v_2 = 20$, $v_3 = 20$, $v_4 = 20$ m/min gives :

$\tan \beta_1 = 9.81 \times 0.01 \times 0.4^{-1} \times 10^{-2} = 0.00245$ $\qquad \beta_1 = 0.1405°$

$\tan \beta_2 = 9.81 \times 0.01 \times 0.4^{-1} \times 20^{-2} = 0.00061$ $\qquad \beta_2 = 0.0351°$

$\tan \beta_3 = 9.81 \times 0.01 \times 0.4^{-1} \times 30^{-2} = 0.00027$ $\qquad \beta_3 = 0.0156°$

$\tan \beta_4 = 9.81 \times 0.01 \times 0.4^{-1} \times 40^{-2} = 0.00015$ $\qquad \beta_4 = 0.0087°$

The second derivative is : $\partial^2 F_{total} / \partial \beta^2 = -\mu \, m \, v^2 r^{-1} \cos \beta - m \, g \sin \beta < 0$ in all cases and it can be seen from formula (4.11) that the influence of the other parameters is such that when m and v increase F_{total} increases while when r increases F_{total} decreases.

From a point of view of practical interest it is worth examining the influence of the helix angle β when it varies between 0 °- 60 °and speed **v** when it varies between 0 - 100 m/min and this shown in the following figure.

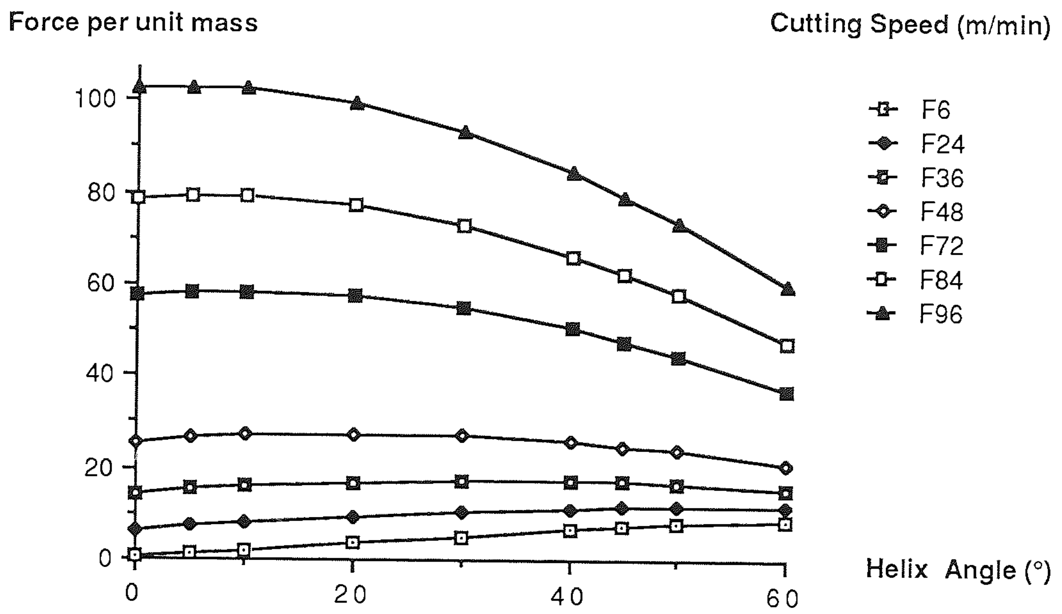


Fig. 4.20 : Total force (per unit mass) acting on a swarf element vs helix angle for various cutting speeds

The graph suggests that an increase in helix angle β between 30 °- 45 ° the total force is reduced by 20 % to 25 % for all cutting speeds, while for an increase of the helix angle between 45 °- 60 ° the corresponding reduction of the total force can be as high as 70 % .

This explains to some extent why in DHD twist drills with a quick helix exhibit a superior performance to drills with a slow helix in the context of swarf fragmentation and flute clogging, despite the fact that a high value of helix angle results in a longer travel path for the swarf extraction. This superior performance is demonstrated by the low in comparison levels of drilling thrust and torque for a given feed and speed (figs. 3.8-3.31). This has been also reported in the works of various researchers [27], [29] Nekrasova, [34] - [36] Dechko et al.

4.6 Torsional vibrations of twist drills in DHD

As mentioned in section 4.2, during stage four of the drill penetration, the process becomes unstable and this is indicated by two phenomena. Fluctuations of the drilling torque and fragmentation of the produced swarf. An explanation for this phenomenon is possible if the drill is considered as an elastic structure which is subject to torsional vibrations and the analysis which follows is on this basis.

The mechanism of torsional vibrations of twist drills can be explained as follows : Twisting of the drill due to an additional torque (friction component) causes not only a twisting of the lower part of the tool relative to its shank firmly held in the tool holder but also a longitudinal extension of the tool.

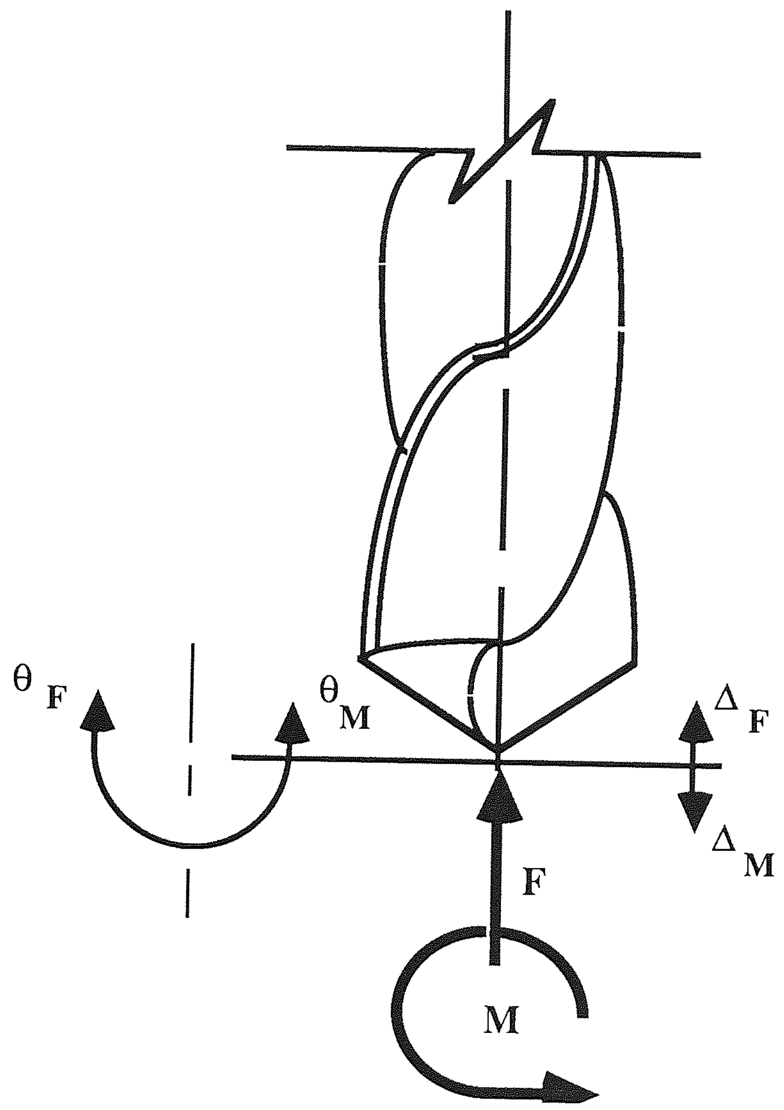


Fig. 4.21 : Torsional and longitudinal deformation of a twist drill

On the other hand, the tool is subject to additional twisting and a compressive deformation in the opposite direction due to dynamic axial loading (above the steady state value of thrust). This axial loading can be the result of rapidly propagating tool wear or the presence of hard spots in the workpiece.

Schaterin **[31]**, has defined four types of deformation and four corresponding properties which define the overall rigidity of a twist drill when modelled as a helicoidal spring :

-Torsional deformation due to an increase in torque : $\theta_{\delta M} = \delta M / C_{\theta M}$ (4.15)

$C_{\theta M}$ is the torque-torsion-stiffness of the drill

-Longitudinal deformation due to an increase in torque : $\Delta_{\delta M} = \delta M / C_{\Delta M}$ (4.16)

$C_{\Delta M}$ is the torque-tension-stiffness of the drill

-Torsional deformation due to an increase in thrust : $\theta_{\delta F} = \delta F / C_{\theta F}$ (4.17)

$C_{\theta F}$ is the thrust-torsion-stiffness of the drill

-Longitudinal deformation due to an increase in thrust : $\Delta_{\delta F} = \delta F / C_{\Delta F}$ (4.18)

$C_{\Delta F}$ is the thrust-compression-stiffness of the drill

These parameters help to explain a phenomenon observed during the tests in DHD with long twist drills ; The phenomenon could be described as a "cross-talk" between torque and thrust since the two are normally not related and expressed as following :

$$C_{\Delta M} = C_{\Delta F} / K_{\Delta} \text{ and } C_{\theta F} = C_{\theta M} / K_{\theta} \qquad (4.19)$$

(K_{Δ} and K_{θ} are coefficients)

The linear nature of the above relationships has been investigated with twist drills of small diameters (Ø 3.0 , Ø 4.5 mm) and high length to diameter ratios (L/d >> 20 : 1) and is shown next.

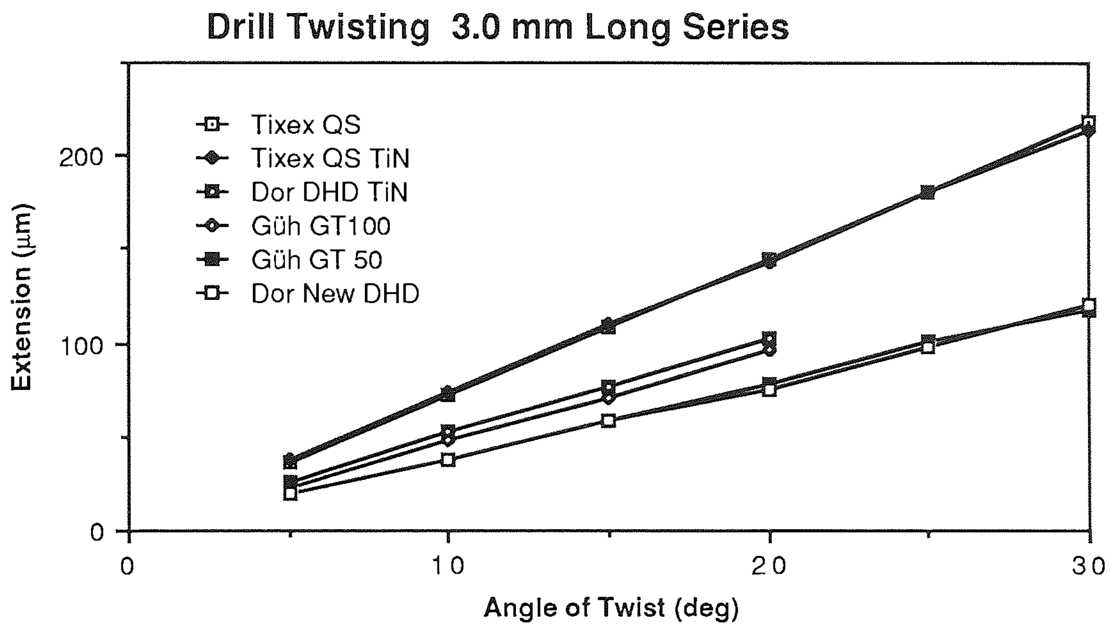


Fig. 4.22 : Angle of twist vs drill extension

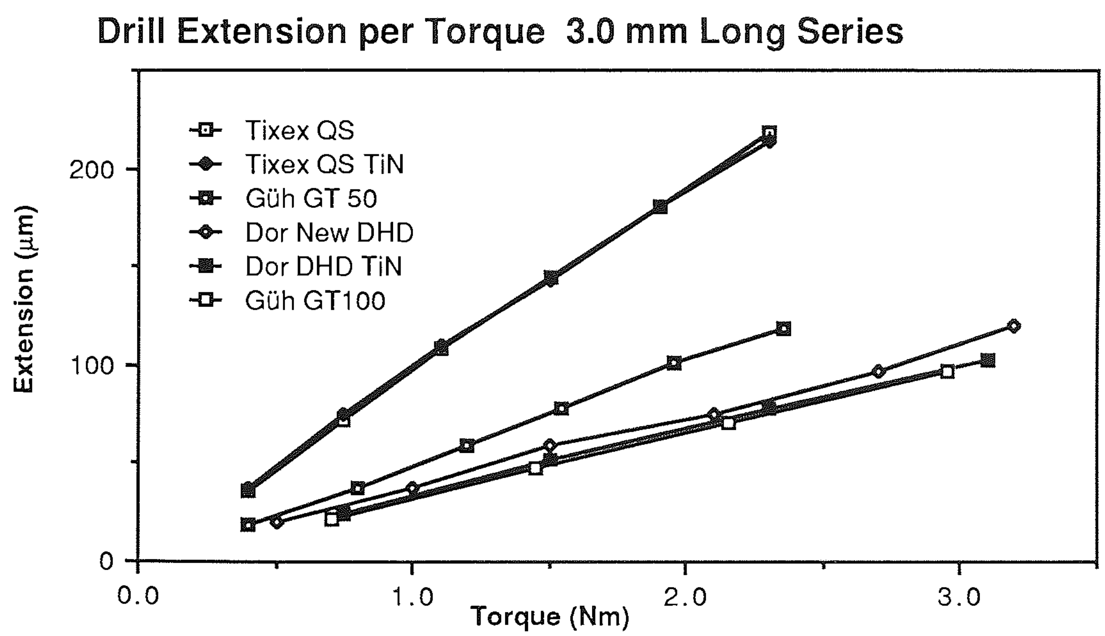


Fig. 4.23 : Drill extension vs applied torque

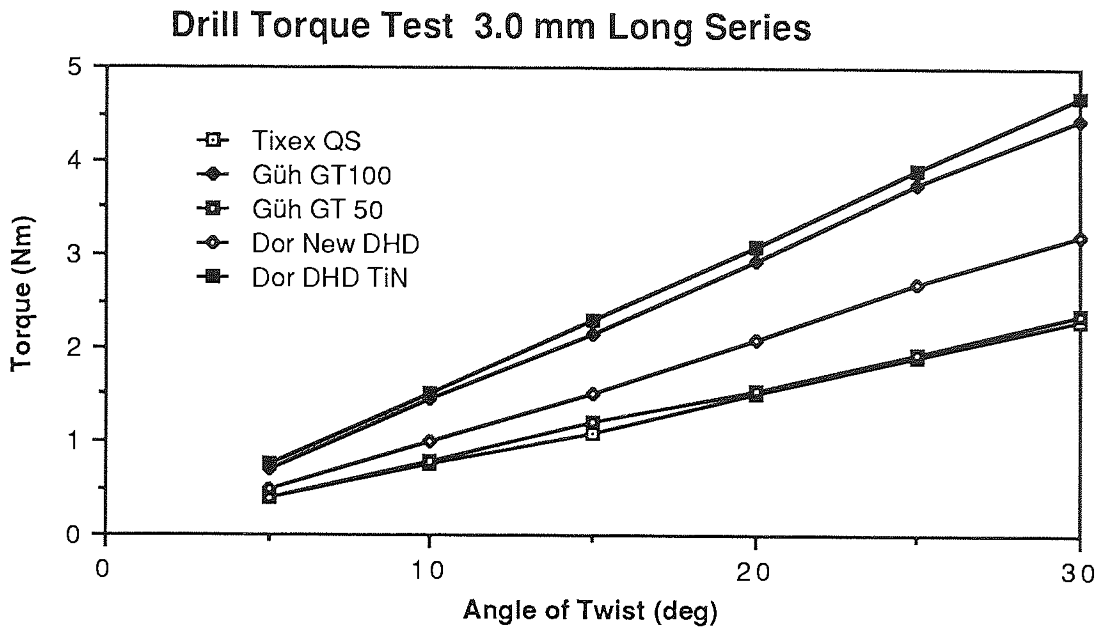


Fig. 4.24 : Torque vs angle of twist

In the series of photographs of U.V paper recordings of the drilling thrust and torque which follow this phenomenon of cross-talk between the two is shown, namely that variations of the drilling torque due to friction affect the drilling thrust. (Figs. 4.27 to 4.30)

It is reminded that the term drilling thrust refers to effort by the tool point to penetrate the workpiece material, while the drilling torque, measured by a dynamometer in DHD, incorporates both the torque generated by the cutting edges and the frictional resistance to the rotation of the tool which generated by contact with the hole bore.

Finally, additional evidence is provided from the photograph of a broken drill (fig. 4.25) where it can be seen that the tool point is well away from the bottom of the hole. This suggests that when failure occurred the drill length had actually increased and consequently the instantaneous value of feed was much higher than its nominal value.

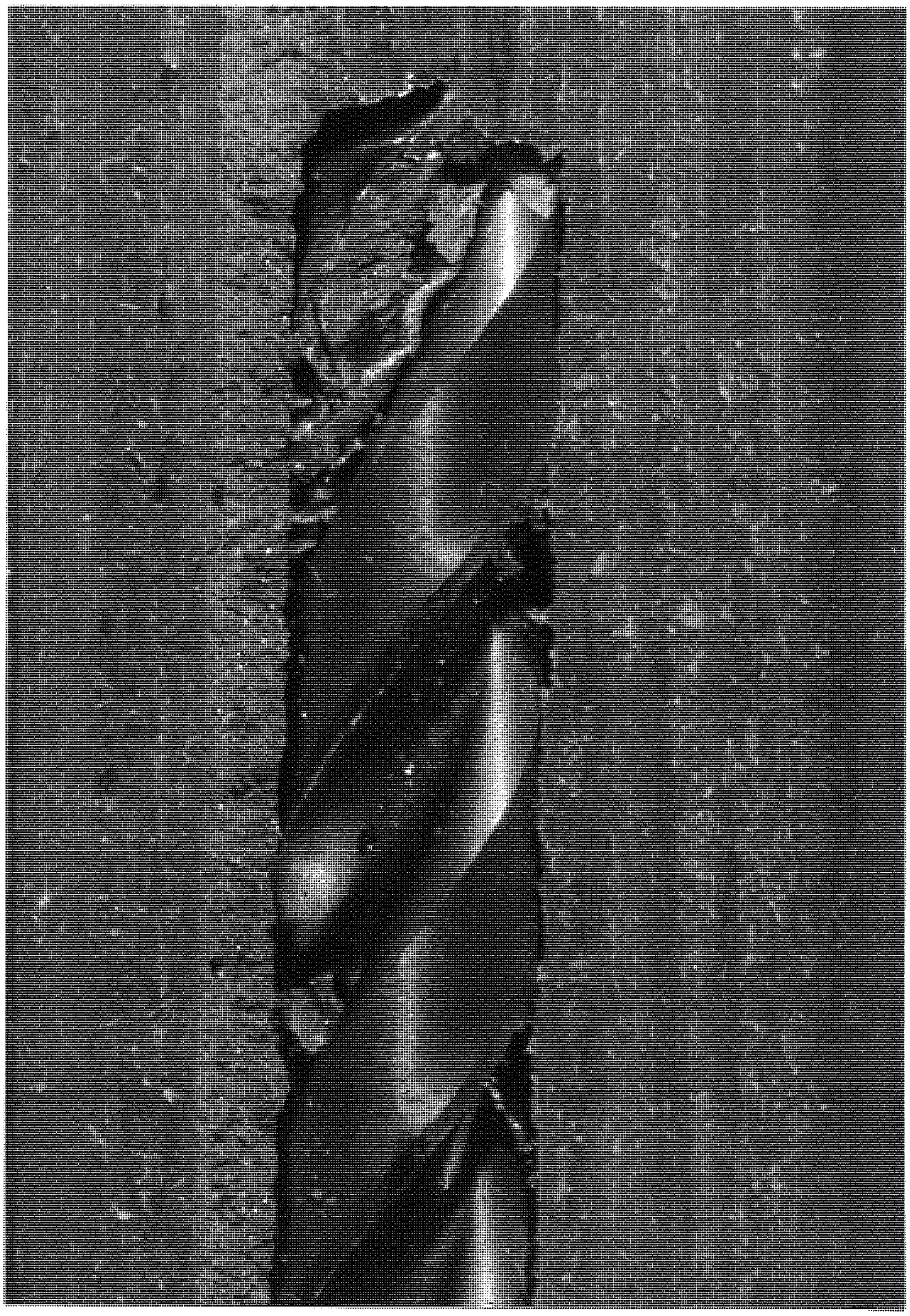


Fig. 4.25 : Drill failure as a result of change in length due to torsional vibrations and instant increase in effective feed (feed rate and spindle speed remained constant) TA11 alloy, Ø4.5 x 95 mm, 16 mm/min, 625 RPM

4.7 Calculation of the characteristics of torsional vibration

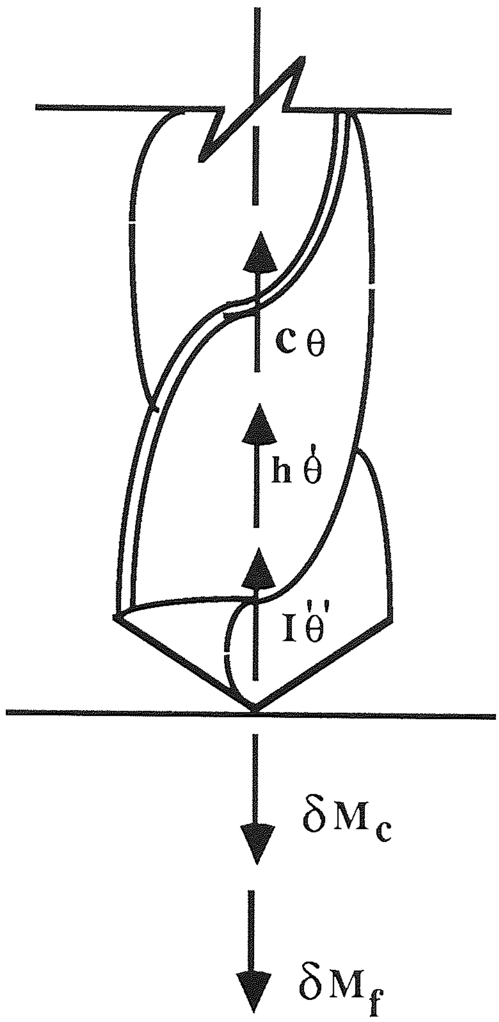


Fig. 4.26 : Equilibrium of drilling torque in DHD

In the analysis that follows it is assumed, for simplicity reasons, that the drill vibration is sinusoidal and the simplified equivalent system consists of one oscillating mass. An independent coordinate is introduced which describes the vibration, that is the angle of twist θ while it is assumed that the drill rotates with constant angular velocity ω.

The constant (invariable) part of the drilling torque exercises no effect on the drilling vibration so only the alternating part is considered. The alternating part of the drilling torque δM consists of two variable components, a frictional component δM_f and a cutting component δM_c so that :

$$\delta M = \delta M_f + \delta M_c \qquad (4.20)$$

The frictional moment is the result of the variation of the frictional forces acting on the rake face and clearance face. The varying drilling torque is due to the change in stress distribution caused by the translation frequency of the drill and consequent variation in chip thickness.

The frictional and drilling torque vary the equilibrium of the drilling working torque and cause self excited tool vibration. In fig. 4.26 the total torque is shown in a vector diagram. A one mass oscillation system is used to describe the drill vibration and this is described by the following differential equation :

$$I\theta'' + h\theta' + c\theta = \delta M_f + \delta M_c \qquad (4.21)$$

$$\theta = \theta_{\delta Mc} - \theta_{\delta F} \qquad (4.22)$$

Where **I** is the moment of inertia of the fluted part of the drill, **h** is the damping coefficient, **c** is the torsional rigidity of the twist drill and $\theta = \theta_{\delta Mc} - \theta_{\delta F}$ is the angle of twist due to the variation in drilling torque δM_c and feed force δF and θ'' θ' are the second and first derivatives with respect to time.

Equation (4.21) considers both the torsional vibration plus the vibration due to the longitudinal deformation of the drill length. The frictional force is described by the following equation by **[161]** Krivouchov and Voronev as a function of the cutting speed:

$$T_f = a\ v\ e^{-bv} \qquad (4.23)$$

Where **a** and **b** are constants depending on the workpiece material, lubrication and stress distribution while **v** is the velocity of the cutting edge relative to the workpiece surface. Assuming that the force T_f acts on the middle of the tool radius **d/2** then the frictional torque is :

$$M_f = (T_f\ d) / 4 = (a\ d\ v\ e^{-bv}) / 4 \qquad (4.24)$$

Substituting $v = (d\omega)/2$ into (4.24) gives :

$$M_{f0} = (a\ d^2\ \omega\ e^{-b\ d\ \omega}) / 8 \qquad (4.25)$$

The torsional vibration of the drill cutting edge occurs so that its absolute angular velocity $\omega_{abs}(t)$ is given by the following relationship :

$$\omega_{abs}\ (t) = \omega - \theta' \tag{4.26}$$

Substituting $r = d/4$ into (4.25) yields :

$$M_f\ (t) = 2\ a\ r^2\ \omega_{abs}\ e^{-b\ r\ \omega_{abs}} \tag{4.27}$$

$$M_{f\,0} = 2\ a\ r^2\ \omega\ e^{-b\ r\ \omega} \tag{4.28}$$

$$M_f\ (t) = 2\ a\ r^2\ (\omega - \theta')\ e^{-b\ r\ (\omega - \theta')} \tag{4.29}$$

The frictional moment is $\delta M_f = M_f\ (t) - M_{f0}$ or :

$$\delta M_f = 2\ a\ r^2\ (\omega - \theta')\ e^{-b\ r\ (\omega - \theta')} - 2\ a\ r^2\ \omega\ e^{-b\ r\ \omega}$$

$$\delta M_f = 2\ a\ r^2\ e^{-b\ r\ \omega}\ [\ e^{b\ r\ \theta'}\ (\omega - \theta') - \omega\ ] \tag{4.30}$$

Taking the Taylor series expansion of the expression $e^{b\ r\ \theta'}$

$$e^{b\ r\ \theta'} = 1 + b\ r\ \theta' + (1/2)\ (b\ r\ \theta')^2 + (1/6)\ (b\ r\ \theta')^3 + \ldots$$

Considering the first three terms and also defining **A, B** as follows :

$$A = 2\ a\ b\ r^3\ e^{-b\ r\ \omega} \tag{4.31}$$

$$B = a\ b^2\ r^4\ e^{-b\ r\ \omega} \tag{4.32}$$

Then (4.30) yields :

$$\delta M_f = (\theta')\ [A\ \omega - A\ /\ (b\ r)] + (\theta')^2\ [B\ \omega - A] + (\theta')^3\ [-B] \tag{4.33}$$

The variable part of the cutting torque δM_c has already been mentioned that it is due to variation of the chip thickness. It is known that the cutting torque M_0 in the steady state is given by equation (4.3). Ignoring the contribution of the cutting velocity (4.3) can be written as :

$M_0(d, f, v) = k_1\ d^p\ f^{\ m}$ or alternatively

$$M_0(d, F) = k_2\ d^p\ F^m \tag{4.34}$$

The variable feed **f** (undeformed chip thickness) for each cutting lip, can be considered to comprise a constant $f_0/2$ and a time-variant part $\Delta=\Delta(t)$ due to the torsional vibration :

$$f(t) = f_0/2 + \Delta \tag{4.35}$$

The periodic drilling torque according to (4.34) and (4.35) then becomes :

$$M_c\,(t) = k_f\,(f + 2\Delta)^{\,m} \tag{4.36}$$

The constant k_f incorporates a constant diameter and the material constant.
Expanding (4.36) in series gives :

$$M_c\,(t) = M_0\,(1 + 2\,\Delta\,m\,/\,f) \tag{4.37}$$

So the cutting alternating torque is expressed :

$$\delta M_c\,(t) = M_c\,(t) - M_0 \tag{4.38}$$

which is transformed into :

$$\delta M_c\,(t) = 2\,k_f\,m\,d^p\,\Delta\,f^{m-1} \tag{4.39}$$

The periodic longitudinal deformation of drills is determined by the following expression:

$$\Delta = \Delta_{\delta Mc} - \Delta_{\delta F} \tag{4.40}$$

where $\Delta_{\delta Mc}$ is the periodic longitudinal deformation of the twist drill as a result of the alternating cutting torque $\delta M_c\,(t)$ and $\Delta_{\delta F}$ is the periodic longitudinal deformation as result of the drilling thrust (feed force) $\delta F(t)$ variation. It has been shown, ([31] Schaterin), that :

$$C_{\Delta M} = C_{\Delta F}\,/\,K_\Delta \quad \text{and} \quad C_{\theta F} = C_{\theta M}\,/\,K_\theta \tag{4.41}$$

which in turn yields :

$$\Delta_{\delta F} = \delta F \,/\, C_{\Delta F} \;\; ; \;\; \Delta_{\delta Mc} = \delta Mc \,/\, C_{\Delta M} \qquad (4.42)$$

$$\theta_{\delta F} = \delta F \,/\, C_{\theta F} \;\; ; \;\; \theta_{\delta Mc} = \delta M_c \,/\, C_{\theta M} \qquad (4.43)$$

where $\theta_{\delta F}$, $\theta_{\delta Mc}$ are the angular deformations of the drill due to the alternating drilling thrust δF and drilling torque δM_c correspondingly. Also $C_{\theta M}$ and $C_{\theta F}$ are the corresponding torsional and spring stiffness of the drill, $C_{\Delta F}$ is the tension-compression-stiffness and $C_{\Delta M}$ is the torsion-tension-stiffness and K_Δ , K_θ are coefficients ; (4.40) then gives :

$$\Delta = \delta M_c \, K_\Delta \,/\, C_{\Delta F} \; - \delta F \,/\, C_{\Delta F} \qquad (4.44)$$

or $\Delta = C_{\theta M} \, K_\Delta \, [\theta_{\delta Mc} - \theta_{\delta F} \,/\, K_\Delta K_\theta \,] \,/\, C_{\Delta F}$ (4.45)

In order to simplify the differential equation (4.19) we can normalise the coefficients K_Δ , K_θ , (**[175]** by setting : $K_\Delta K_\theta = 1$ (4.46)

Therefore (4.45) becomes : $\Delta = C_{\theta M} \, K_\Delta \, \theta \,/\, C_{\Delta F}$ (4.47)

In which case the expression (4.39) for the alternating drilling torque becomes :

$$\delta M_c\,(t) = 2 \, k_f \, m \, d^p \, f^{m-1} \, C_{\theta M} \, K_\Delta \, \theta \,/\, C_{\Delta F} \qquad (4.48)$$

With the above expression it can be explained during the first half turn of the drill the phenomenon of the alternating drilling torque as long as the drill cuts a surface free of chatter marks. Let Δ_1 be the instantaneous deflection of the one cutting edge and Δ_2 the deflection for the other cutting edge, then :

$$\Delta = \Delta_1 - \Delta_2 \qquad (4.49)$$

$$\Delta_1 = \; C_{\theta M} \, K_\Delta \, \theta_0 \sin\,(\omega t\text{-}\varepsilon) \,/\, C_{\Delta F} \qquad (4.50)$$

$$\Delta_2 = C_{\theta M}\ K_\Delta\ \theta_0 \sin(\omega t) / C_{\Delta F} \qquad (4.51)$$

where θ_0 is the amplitude, ω is the angular frequency of the torsional vibrations, t is the time and ε is the phase displacement between two successive oscillations, then gives :

$$\Delta = C_{\theta M}\ K_\Delta\ [\ \theta' \sin\varepsilon / \omega - 2\theta \sin^2(\varepsilon/2)\ ] / C_{\Delta F} \qquad (4.52)$$

Combining (4.39) and (4.52) and simplifying gives :

$$\delta M_c(t) = G\ \theta' - H\ \theta \qquad (4.53)$$

where $G = 2\ k_f\ m\ d^p\ \omega^{-1}\ f^{m-1}\ (C_{\theta M}\ K_\Delta / C_{\Delta F}) \sin\varepsilon \qquad (4.54)$

$$G = 4\ k_f\ m\ d^p\ f^{m-1}\ (C_{\theta M}\ K_\Delta / C_{\Delta F}) \sin^2(\varepsilon/2)\ ] \qquad (4.55)$$

Substituting into the differential equation (4.21) gives :

$$\begin{aligned} I\theta'' + (C_{\theta M} + H)\,\theta = {} & (\theta')\ [\ A\ \omega - A / (b\ r) + G\ ] + \\ & (\theta')^2\ [\ B\ \omega - A\ ] + \\ & (\theta')^3\ [\ -B] \end{aligned} \qquad (4.56)$$

The differential equation (4.56) represents the free vibration of a system (left hand side) and the sum of internal work in the system (right hand side).

Assuming that the terms (θ'), $(\theta')^2$, $(\theta')^3$ are small when compared with $I\theta''$ and $(C_{\theta M} + H)\theta$ simplifies the equation and leads to a solution of the type

$$\theta(t) = \theta_0 \sin(\Omega\ t) \qquad (4.57)$$

with $\Omega = [\ (C_{\theta M} + H) / I\ ]^{0.5} \qquad (4.58)$

In order to determine the amplitude θ_0 of the vibration one can use the energy equilibrium of the system. The energy of the system in this case is proportional to the acting moment. The right hand side of (4.58) is nil when each term is integrated over a period T to give the work of moment.

$$0 = [A\omega - A/(b r) + G - h] \int_0^T (\theta') d\theta + [B\omega - A] \int_0^T (\theta')^2 d\theta + [-B] \int_0^T (\theta')^3 d\theta \tag{4.59}$$

The three integrals are calculated next as follows :

$$J_1 = \int_0^T (\theta') d\theta = \int_0^T [\theta_0 \Omega \cos(\Omega t)] \; [\theta_0 \Omega \cos(\Omega t) dt]$$

$$J_1 = (\theta_0 \Omega)^2 \int_0^T [\cos^2(\Omega t) dt] = (1/2)(\theta_0 \Omega)^2 \int_0^T [1 + \cos(2\Omega t)] dt$$

$$J_1 = (1/2)(\theta_0 \Omega)^2 T \;, \text{ but } T/2 = \pi/\Omega \;, \text{ so : } J_1 = \pi \Omega \theta_0^2 \tag{4.60}$$

$$J_2 = \int_0^T (\theta')^2 d\theta = \int_0^T [\theta_0 \Omega \cos(\Omega t)]^2 \; [\theta_0 \Omega \cos(\Omega t) dt]$$

$$J_2 = (\theta_0 \Omega)^3 \int_0^T [\cos^3(\Omega t) dt]$$

$$J_2 = (1/4)(\theta_0 \Omega)^3 \int_0^T [\cos(3\Omega t) dt] + (1/4)(\theta_0 \Omega)^3 \int_0^T [3\cos(\Omega t) dt]$$

and since both terms are trigonometric the integral is : $J_2 = 0$ (4.61)

$$J_3 = \int_0^T (\theta')^3 d\theta = (\theta_0 \Omega)^4 \int_0^T [\cos^4(\Omega t)] dt$$

$$J_3 = (1/4)(\theta_0 \Omega)^4 \int_0^T [1 + \cos(2\Omega t)]^2 dt$$

$$J_3 = (1/4)(\theta_0 \Omega)^4 \left[\int_0^T dt + \int_0^T \cos^2(2\Omega t) dt + \int_0^T 2\cos(2\Omega t) dt \right]$$

which can be written as :

$$J_3 = (1/4)(\theta_0 \Omega)^4 \int_0^T dt + (1/8)(\theta_0 \Omega)^4 \int_0^T [1 + \cos(4\Omega t)] dt + (1/4)(\theta_0 \Omega)^4 \int_0^T 2\cos(2\Omega t) dt$$

Again the two trigonometric terms give zero integrals which results into :

$$J_3 = (3/8)\ (\theta_0\ \Omega)^4\ {}_0\int^T dt = (3/8)\ (\theta_0\ \Omega)^4\ (2\pi\ /\Omega\ )$$

$$J_3 = (3/4)\ \pi\ \theta_0{}^4\ \Omega^3 \qquad (4.62)$$

Substituting the three integrals in expression (4.59) yields :

$$[\ A\ \omega - A\ /\ (b\ r) + G - h]\ J_1 = [B]\ J_3$$

$$[\ A\ \omega - A\ /\ (b\ r) + G - h]\ \pi\ \Omega\ \theta_0{}^2 = [B]\ (3/4)\ \pi\ \theta_0{}^4\ \Omega^3$$

solving in terms of θ_0 gives :

$$\theta_0{}^2 = (4/3)\ [\ A\ \omega - A\ /\ (b\ r) + G - h]\ [B]^{-1}\ \Omega^{-2}$$

$$\theta_0 = (2/\sqrt{3}\ \Omega)\ [\ A/B\ (\omega - 4/b\ D) + (G - h)/B]^{0.5}$$

$$\theta_0 = (2/\sqrt{3}\ \Omega)\ [\ 8/Db\ (\omega - 4/b\ D) + (G - h)/B]^{0.5}$$

$$\theta_0 = (2/\sqrt{3}\ Db\Omega)\ [\ (bD\omega/4 - 1) + 256(G - h)\ e^{-b\ r\ \omega}\ /\ D^2\ a\ ]^{0.5} \qquad (4.63)$$

The above is the ultimate expression for the amplitude of torsional vibrations of the twist drill during instability. The result can be interpreted as follows : Equation (4.58) suggests that the angular frequency $\Omega = [\ (C_{\theta M} + H)\ /\ I\ ]^{0.5}$ increases with the torsional stiffness $C_{\theta M}$ and the parameter H related to the cutting parameters. On the other hand, equation (4.58) suggests that with an increase in the angular frequency Ω the amplitude of the vibration becomes smaller while the influence of other factors is not as clear.

The expression **($bD\omega/4$ - 1)** indicates the influence of the friction component of the torque while the expression **(G-h)** determines the critical angular velocity ω_{cr} at which the torsional vibration appears ; there are three distinct cases :

(i) $(G\text{-}h) > 0$ then $\omega_{cr} < 4/bD$ (4.64)

(ii) $(G\text{-}h) = 0$ then $\omega_{cr} = 4/bD$ (4.65)

(iii) $(G\text{-}h) > 0$ then $\omega_{cr} > 4/bD$ (4.66)

The experimental work presented in chapter 3 as well as the results presented in figures 4.8 to 4.12 of this chapter, provides strong evidence which supports the above analysis. Namely the strong dependence of instability on cutting speed. However, the lack of suitable means to measure torsional deformation under cutting conditions leaves the matter open to further investigation.

In chapters 6, 7, 8 on the other hand a control system is presented which stabilises the cutting process long before it reaches the stage of torsional vibrations as described in the present chapter.

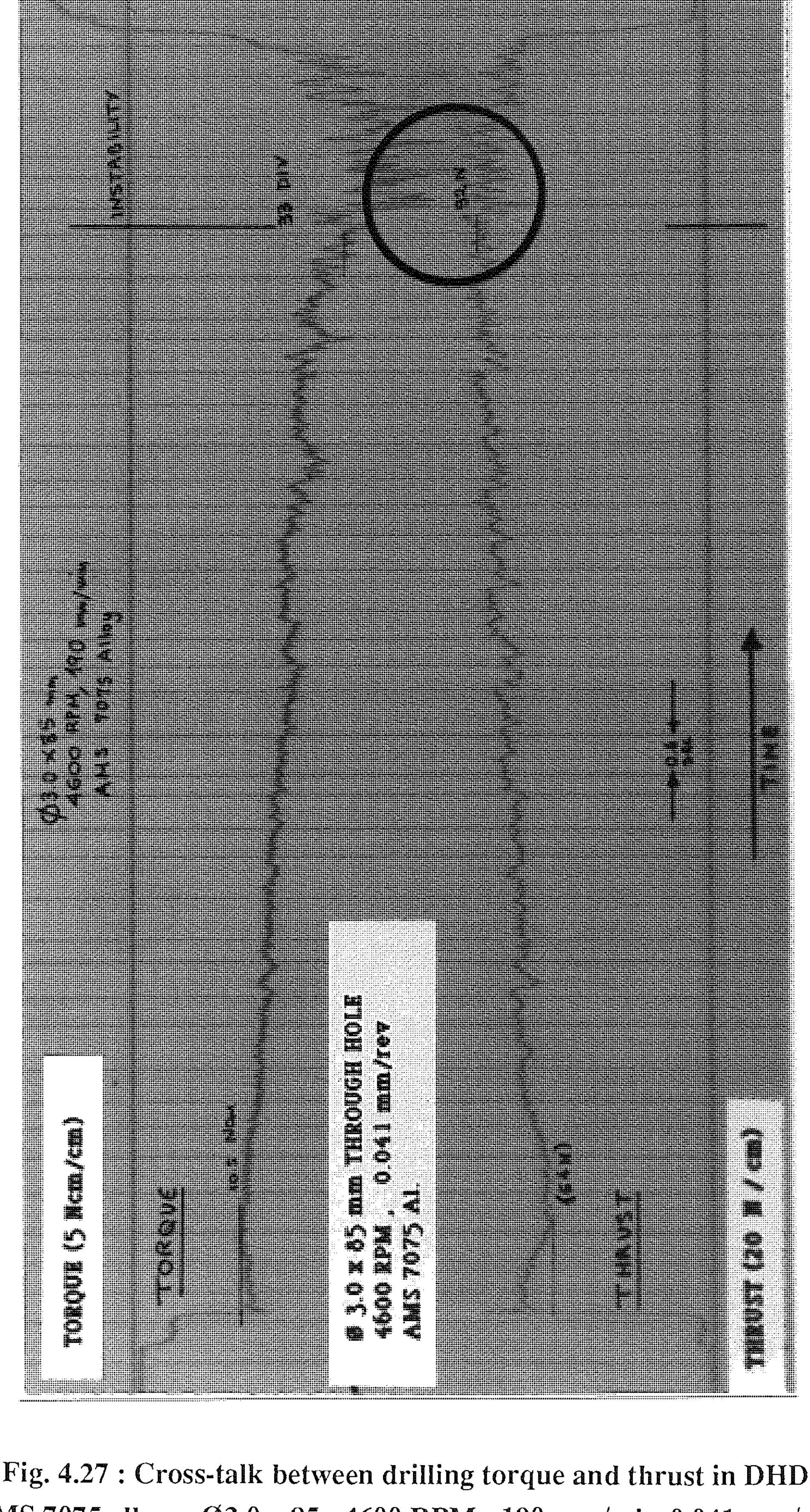


Fig. 4.27 : Cross-talk between drilling torque and thrust in DHD
AMS 7075 alloy - Ø3.0 x 85 - 4600 RPM - 190 mm/min-0.041 mm/rev

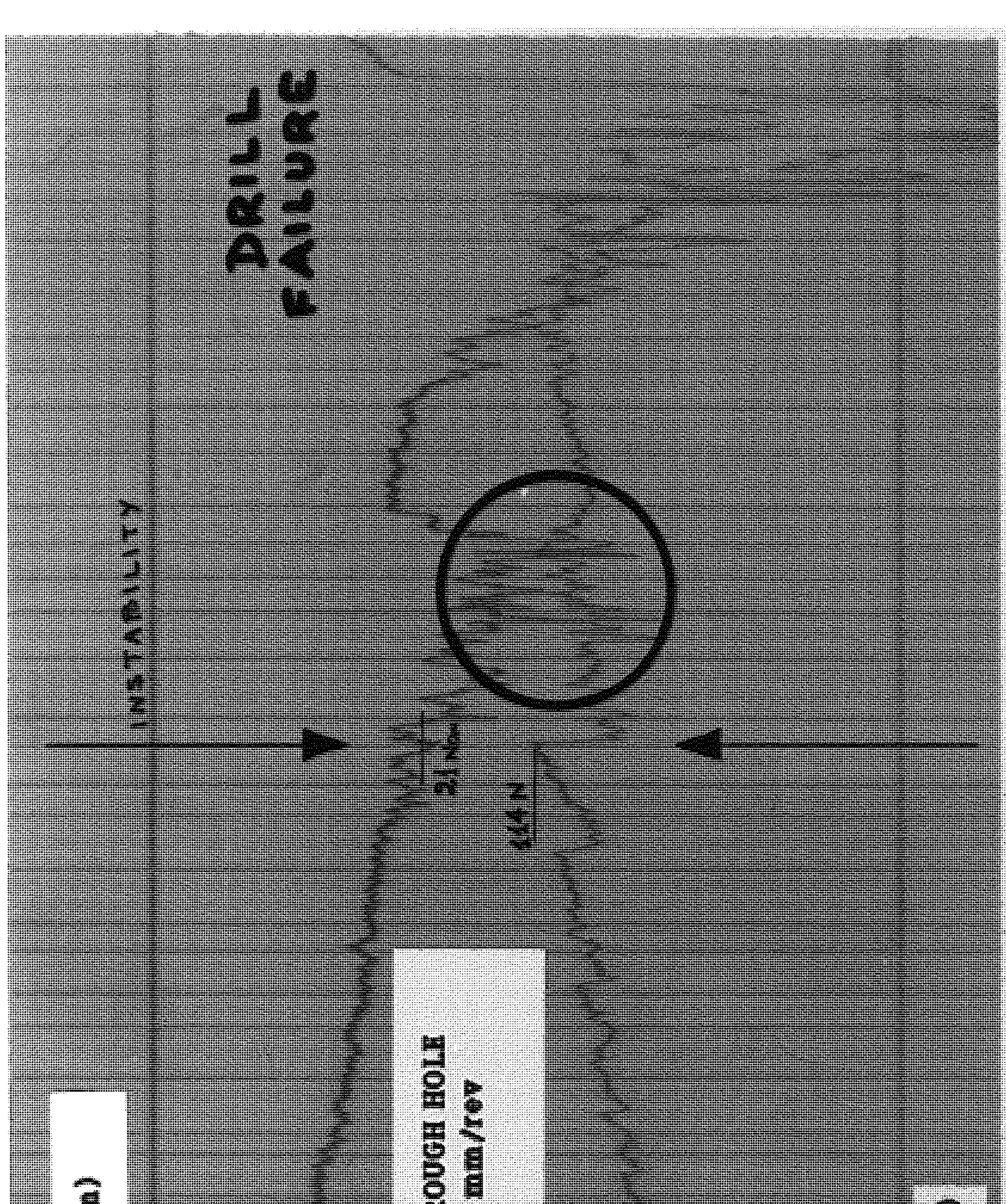


Fig. 4.28 : Cross-talk between drilling torque and thrust in DHD AMS 7075 alloy - Ø3.0 x 85 - 4600 RPM - 210 mm/min-0.046 mm/rev

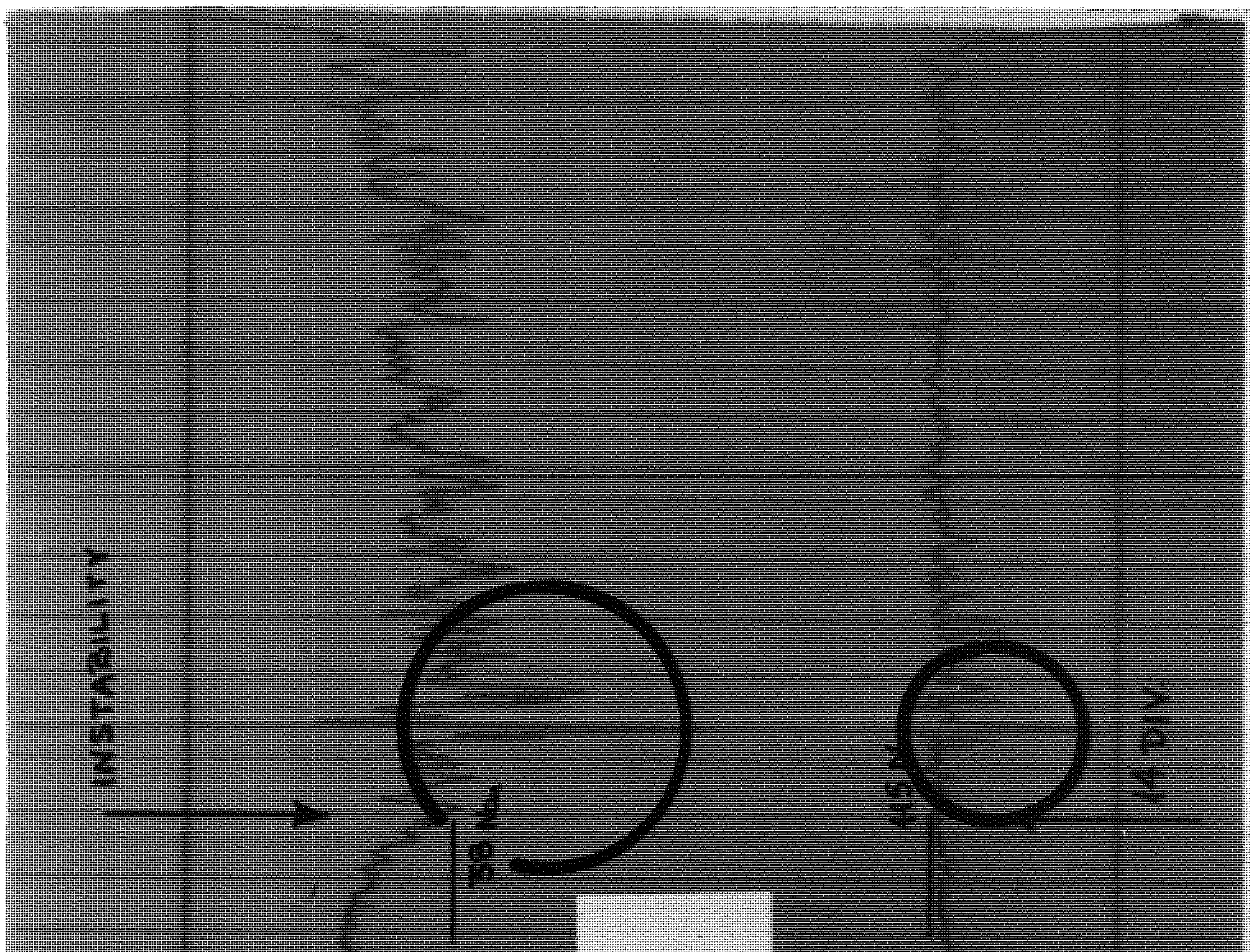


Fig. 4.29 : Cross-talk between drilling torque and thrust in DHD
AMS 7075 alloy - Ø3.0 x 85 - 4600 RPM - 240 mm/min-0.052 mm/rev

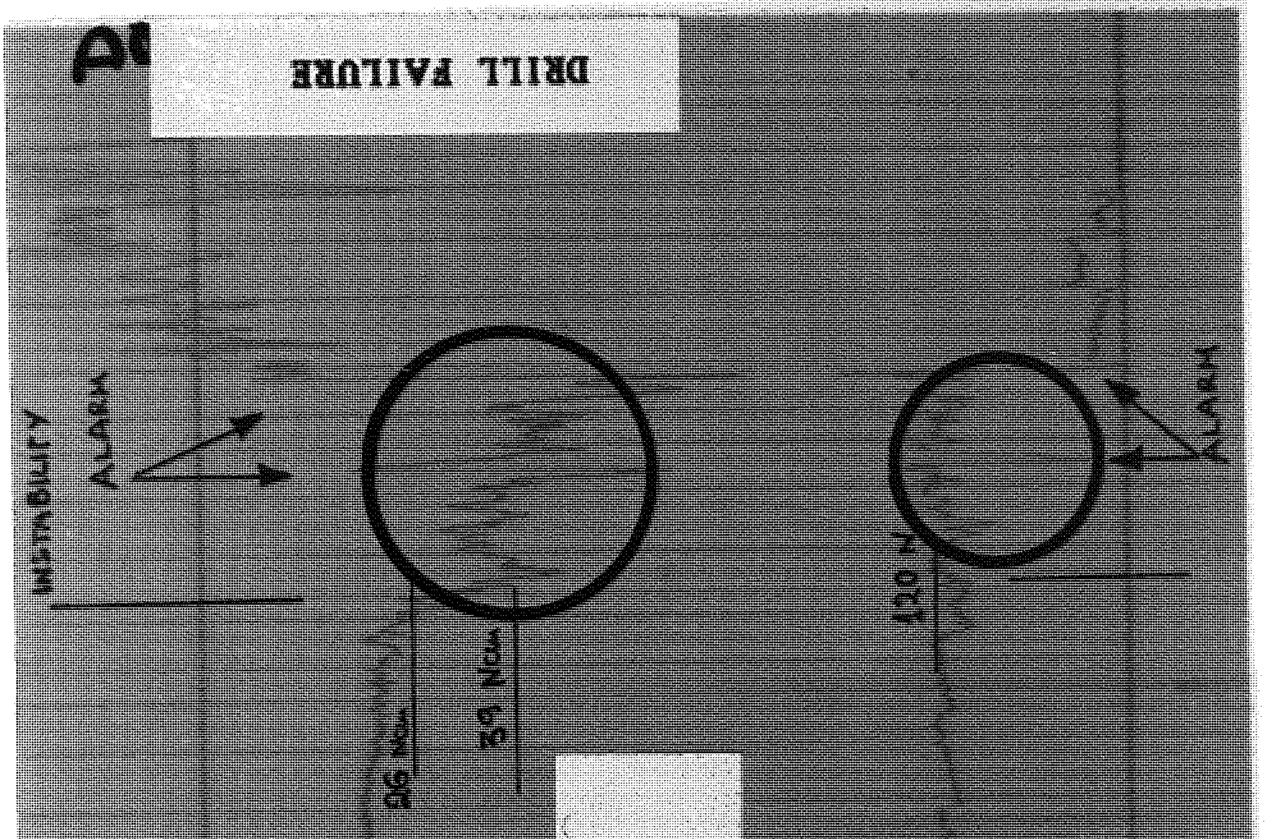


Fig. 4.30 : Cross-talk between drilling torque and thrust in DHD
AMS 7075 alloy - Ø3.0 x 85 - 4600 RPM - 248 mm/min-0.054 mm/rev

4.8 Tool deflection during Deep Hole Drilling

Tool deflection during machining of small diameter deep holes occurs because of the tool overhang and the lack of support at the working end during the early penetration of the tool. It can be argued that in all cases where deflection appears there is a system of unbalanced forces. These can originate from a number of causes such as unequal lip height, tool wear, hard or soft spots in the workpiece, etc.

As a result of the above situation geometrical errors appear which affect the quality of the hole. Out of roundness is one while the run-out or straightness error is another and in fact more important because of the functional role of small diameter deep holes in various precision engineered components.

Therefore it is desirable to be able to predict in the first place the deflection of a long twist drill and if possible to take corrective action either before or during machining. There have been some approaches to the matter the most simplistic of which is to regard the drill as a beam the deflection of which is given from the displacement integral of the elastic line equation, Kirilov **[28]**:

$$y = T_r L^3 / 3EI \qquad (4.67)$$

In reality however, the hole wall restricts the mobility of the free end of the tool so the problem can be formulated differently :

Define the deflection **y** of the end of a beam of length **L** and rigidity **EI** under a radial force ΔT_r and an axial force ΔT_a if one end of the beam is fixed and the other is freely suported by a spring of constant **k**.

The problem can be solved with the Ritz method in which case the total potential energy of the system consists of the potential energy of the drill shank under deformation:

$$E_{sh} = EI/2 \int_0^L (\partial^2 Y/\partial x^2)^2 \, dx \qquad (4.68)$$

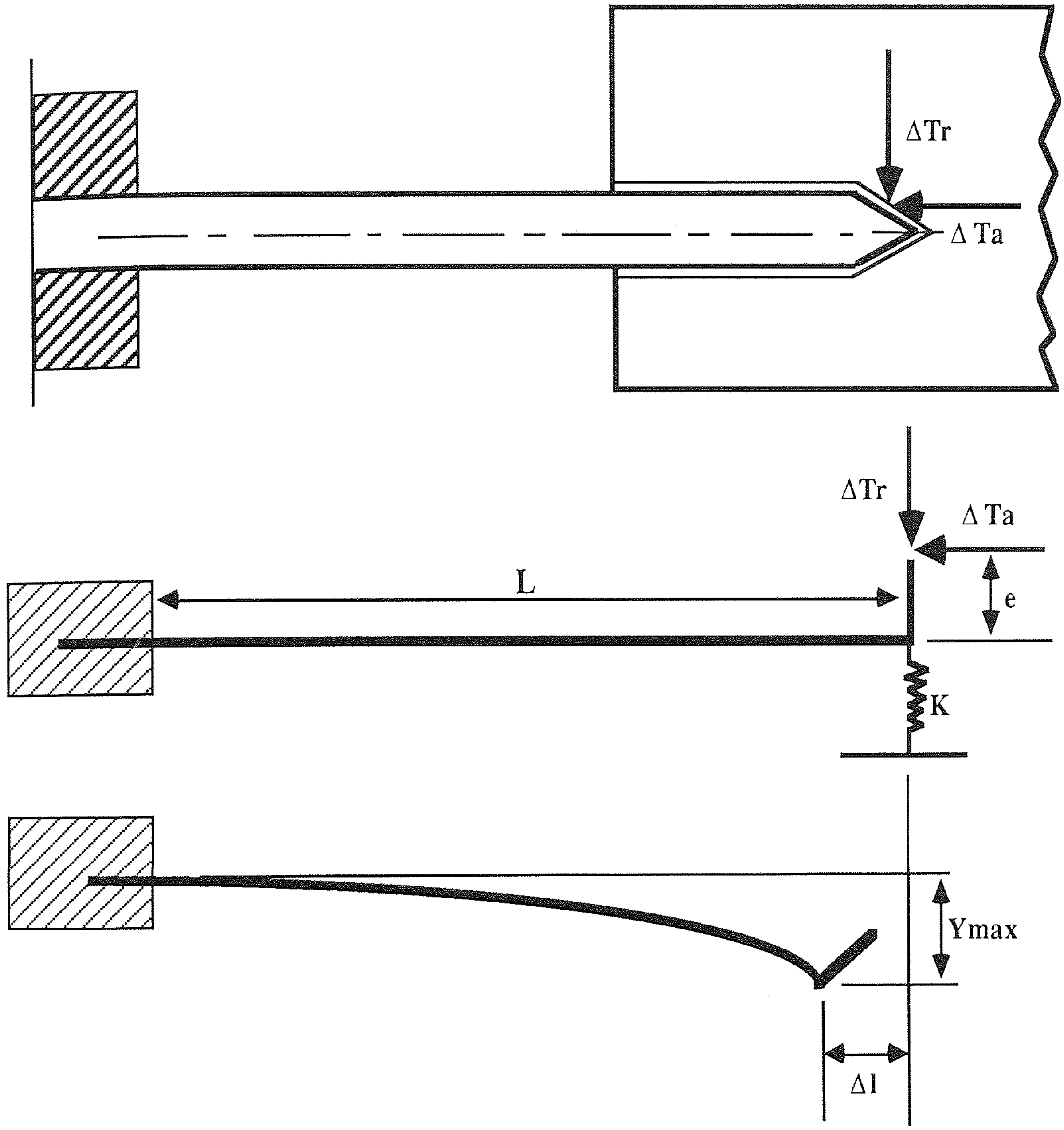


Fig. 4.31 : Tool Deflection Model in DHD

The potential energy of the elastic base :

$$E_b = k\ Y^2 /2 \tag{4.69}$$

and the work done by the forces $\Delta\ T_r$ and $\Delta\ T_a$ during the deflection

$$E_r = -\ \Delta T_r\ Y(L) \tag{4.70}$$

$$E_a = \ \Delta T_a\ [\ \Delta l\ -\ e\ (\partial Y(L)\ /\ \partial x)\ ] \tag{4.71}$$

It is known that : $$\Delta l = \int_0^L (\partial Y/\partial x)^2 \, dx \, /2 \qquad (4.72)$$

The total Potential Energy of the elastic system is then given by the following expression:

$$E = EI/2 \int_0^L \partial^2 Y/\partial x^2 \, dx + k\, Y^2 /2 \; + \; \Delta T_r \, Y \; -$$

$$- \Delta T_a \left[\int_0^L (\partial Y/\partial x)^2 \, dx \, /2 - e \, (\partial Y(L) \,/\, \partial x) \right] \qquad (4.73)$$

A solution for the elastic line $Y(x)$ is given by the equation :

$$Y = A \; (\cos \pi x/2L-1) \; + \; B \sin^2(\pi x/L) \qquad (4.74)$$

Differentiating and substituting the result for the integral expressions of the first and last term of the equations we obtain :

$$I_1 = \pi^4 \; (A^2/32 \; +2B^2 \; + \; 2AB/15) \; /L^3 \qquad (4.75)$$

and $$I_2 = \pi^2 (A^2/4 \; +B^2) \; / \; 2L \; + \; 8AB\pi \; /15L \qquad (4.76)$$

After substitution the energy expression becomes :

$$E = EI \, \pi^4 \, (A^2/32 \; +2B^2 + 2AB/15) \, / \, 2L^3 \; + k \, A^2 /2 \; - \Delta T_r \, A \; -$$

$$- \Delta T_a \left[\; -eA\pi/2l \; + \pi^2 (A^2/4 \; +B^2) \; /4L^2 \; + \; 4AB\pi \; /15L \; \right] \qquad (4.77)$$

Taking the derivatives $\partial E/\partial A = 0$ and $\partial E/\partial B = 0$ gives the stationary points :

$$A = Y_{max} = \frac{\left(\Delta T_r - \Delta T_a \frac{e\pi}{2L}\right) \frac{2EI\pi^4}{L^3} - \Delta T_a \frac{\pi^2}{2L}}{\left(\frac{EI\pi^4}{32\,L^3} + k - \Delta T_a \frac{\pi^2}{2L}\right)\left(\frac{2EI\pi^4}{l^3} - \Delta T_a \frac{\pi^2}{2L}\right) - \frac{(4\Delta T_a \pi L^2 - EI\pi^3)^2}{(15\,L^3)^2}}$$

(4.78)

Substituting the value of π and assuming for simplicity that the Δ**Ta** force is zero gives :

$$Y_{max} = T_r\, L^3 / (3.03\ EI + k\ L^3) \qquad (4.79)$$

In order to use equation (4.69) is necessary to obtain the value of **k** for the elastic base ; an analytical method exists and can be found in reference **[162]** in the work of Ryzhov.

An example which follows suggests that the deflection calculated using (4.79) is a more realistic than that of equation (4.67). Consider an HSS drill Ø3.0 x 100 mm with :

$$\mathbf{I = 0.0045d^4\ \ mm^4 = 0.3645\ \ mm^4}$$

$$\mathbf{E = 212900\ \ Nmm^{-2}}\ \ \text{(HSS)}$$

$$\mathbf{k = 2.8\ \ N/mm}$$

The radial force $\mathbf{T_r}$ (or ΔT_r for that matter) when drilling Aluminium (70 BHN) was measured experimentally and was found not to exceed a maximum value of 5 N for a feed of 0.030 mm/rev. Then according to (4.67) :

$y = (5 \times 100^3) / (3 \times 212900 \times 0.3645) = 21.4$ mm

While according to (4.79) :

$y = (5 \times 100^3) / (3.03 \times 212900 \times 0.3645 + 2.8 \times 100^3) = 1.64$ mm

which is a lot more realistic value and of the order of magnitude observed in measurements of hole run-out (chapter 5).

4.9 Summary

A simple model of the deep hole drilling process has been presented and particular emphasis has been given to certain characteristics of the process. The most dominant of these, which clearly distinguishes DHD from conventional drilling, is that the process becomes unstable as the depth increases and catastrophic failure of the tool and damage of the workpiece is highly probable.

The model identifies a general pattern for the variation of drilling torque as a function of the drilled depth and distinguishes between four main regions : steady state, linear rise, rise according to higher order polynomial of the depth and finally a stage of random , violent, ever increasing in magnitude fluctuations and total failure.

The model proposes a torsional vibration mechanism in order to account for the phenomena of the last stage and the hypothesis is further supported by experimental evidence, namely variation in chip formation, recording of forces and examination of drills either broken or quickly disengaged from cutting.

The model calculates various characteristic parameters of the torsional vibration based on equilibrium of the drilling torque. A more detailed analysis and experimentation with investigation of other parameters such as radial forces or actual vibrations (using accelerometers) would be also possible.

To proceed any further with such an analysis however, would be of limited interest ; this is justified on the basis that catastrophic failure of the tool in deep hole drilling is totally unacceptable for obvious reasons. The experimental results presented in chapters 3 and 4 have shown that even during tightly controlled experimentation catastrophic failure is highly probable.

The experimental results established that the unpredictable and dynamic nature of the process severely restricted the reliability or even the successful completion of drilling tests. It became clear that a dedicated monitoring and control system had to be designed and implemented in order to ensure the process integrity and safety of the tool and workpiece and to enable further experimental investigation. In first approach the open loop control techniques of woodpecking and series drilling were investigated and also the potential improvements in DHD resulting from the use of variable machining conditions (feed rate and spindle speed) in order to alleviate the problem of dynamic variation of the feed and the resulting instability in the process. This approach is presented in chapter 5.

CHAPTER 5

STABILISATION AND CONTROL OF DHD
(Open loop techniques and algorithms)

The experimental evidence presented in chapters 3 and 4 has made clear that the DHD process is inherently unstable as a result of the added dimension, namely the hole depth. This chapter presents a brief review of techniques used in industry that aim to stabilise and partially control the DHD process and also a novel approach to this problem by means of varying the machining conditions during a DHD cycle through the use of parametric part programming and optimisation of the pecking technique (periodic tool withdrawal and reentry).

The common characteristic of the methods used in industry so far, in order to tackle the problem of instability of the DHD process and ensure successful completion of a drilling cycle, is the attempt to control the geometrical characteristics of the produced swarf by means of modifying the three main parameters of the process, that is the feed per rev, cutting speed and depth of penetration.

By changing these parameters, the chip geometry and chip flow characteristics are effectively altered, which in turn can alleviate to some extend the fundamental problem in DHD, namely the swarf extraction from the hole.

All approaches are intuitive however and are based on judgement and experience rather than a full appreciation of the mechanics of the process. A more systematic, theoretically derived novel algorithm based on the model of drilling thrust and torque is presented in section 4.2 and 4.3. The technique aims to act as a counter-measure to the mechanism of undesired effective feed (chip thickness) variation which was described in section 4.6.

The basic objective is the same as that of the techniques used in industry, namely to control the chip flow and to stabilise the process; there is however a significant improvement in terms of process efficiency and machine utilisation when comparing the proposed method with the fixed (canned) parameters pecking cycles of CNC machine tools, as revealed by the experimental results.

5.1 The series drilling technique in DHD

This technique involves the use of more than one twist drills of the same diameter and of progressively increasing lengths in order to drill a small diameter deep hole (fig.5.1).The obvious benefit of this method is first of all the enhanced rigidity of the shorter drills which it has been shown [26], [27] to have a significant effect upon hole straightness and tool life.

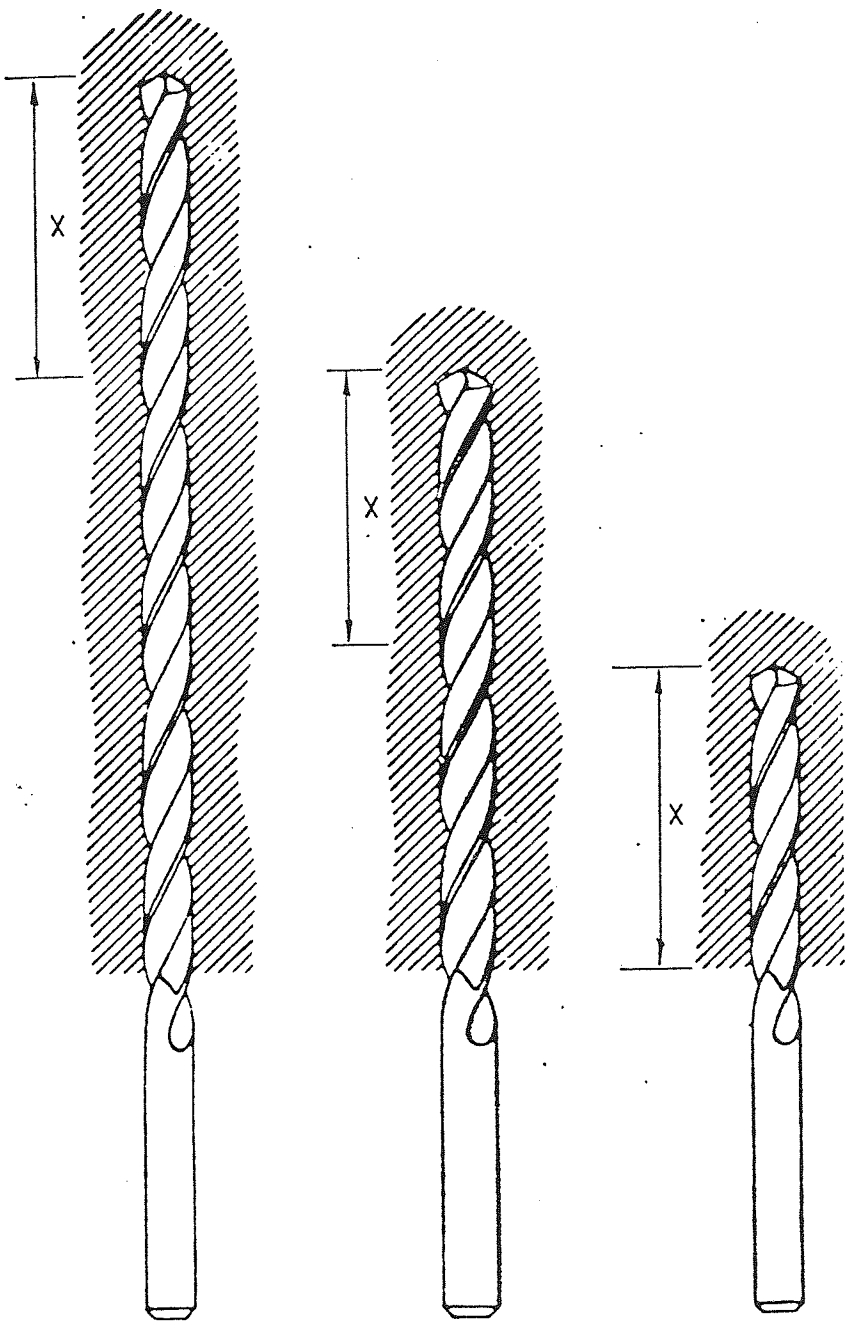


Fig 5.1 : Series drilling technique for DHD

This technique is not very practical when the machines are manually operated or when the machines are dedicated to one operation without the provision of more than one tool posts. On the contrary, modern machining centres are ideally suited since they are equipped with magazines which can hold even up to 120 tools that can be employed without changing the position of the workpiece being machined.

A limited series of DHD tests in this work were performed using pilot holes drilled by very short rigid drills before the main drill with its full working length was engaged in cutting. Pilot hole drilling is effectively a case of series drilling but it was not fully investigated as a result of the technical difficulties concerning frequent tool changes on the lathe used for the drilling tests.

5.2 The pecking technique.

The technique of pecking (or woodpecking) as the name implies involves the periodic withdrawal of the drill clear of the hole in order to extract the swarf from the hole and also to lubricate and cool the tool for the next cut (fig. 5.2).

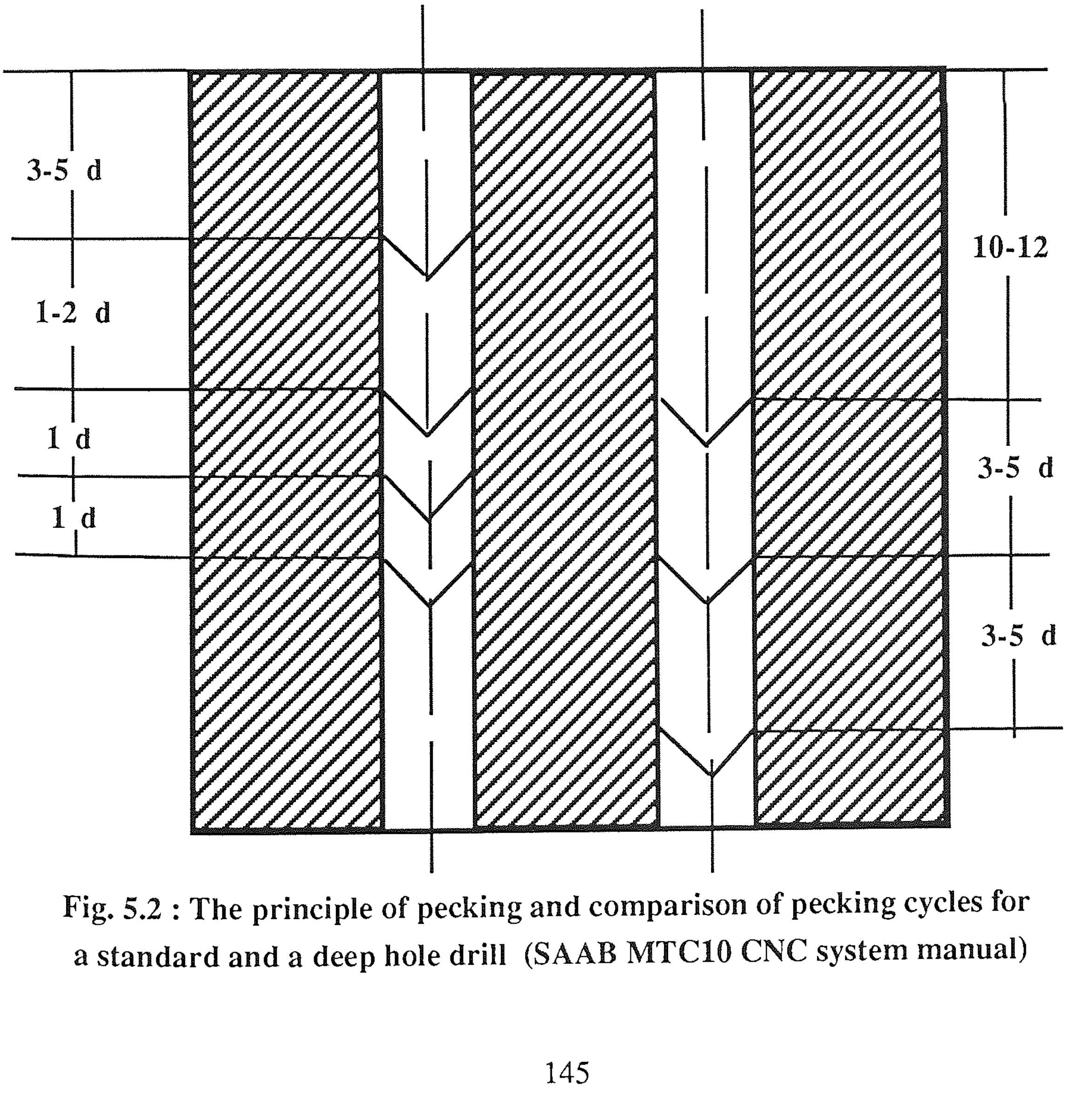


Fig. 5.2 : The principle of pecking and comparison of pecking cycles for a standard and a deep hole drill (SAAB MTC10 CNC system manual)

Pecking can be considered to be the drilling equivalent to "cut distribution" (roughing and finishing passes) in turning. Modern CNC machine tools or machining centres are equipped with standard or "canned" cycles for pecking as well as other operations suchas tapping, grid hole punching, spot drilling, chip breaking, etc.

Pecking is technique which is fundamentally important for DHD as long as the tool is not equipped with internal coolant supply. It is an efficient technique but also has the following drawbacks :

- First of all the depths at which tool withdrawal is executed are determined entirely by the judgment and experience of the part programmer. A change in parameters such as workpiece material, tool geometry or cutting conditions requires a new pecking cycle.

- If external disturbances cause instability of the process while the machine executes a block of the NC program between two consecutive pecks they will fail to be noticed and this might lead to catastrophic failure of the tool.

- Pecking is time consuming because of the auxiliary motion of the tool during rapid withdrawal and reentry. The problem has been examined in **[56]** Lishchinskii, **[64]** Dobrovol'skii.

- Certain materials such as Titanium alloys exhibit the characteristic of work hardening when the feed is disengaged and therefore require pecking action as few times as possible or none at all.

It is worth mentioning that in 1980 the researchers **[103]** Mathias, Bock, Weich, suggested that one of the improvements of DHD technology during the 1980s will be the optimisation of pecking by means of computer control.

This statement, which was made at the dawn of the appearance of powerful CNC systems and inreased automation in production, partly expresses the basic philosophy of this work : improvements in tool materials, drill point geometry, and drill flute design are no doubt of high merit in drilling in general, the most significant improvement in process performance and reliability in DHD will come from an increase in the level of intelligence of the machine tool and the application of on-line monitoring and adaptive control. The design and development of such a prototype computer control pecking system is described in chapter 6.

5.3 The step-by-step feed technique.

Step-by-step feed is a technique where the drill is held stationary in the hole (feed hold) while maintaining its rotational speed. This takes place at various depths and it results in chipbreaking which in turn can be beneficial to the successful extraction of swarf from the drill flutes (fig. 5.3).

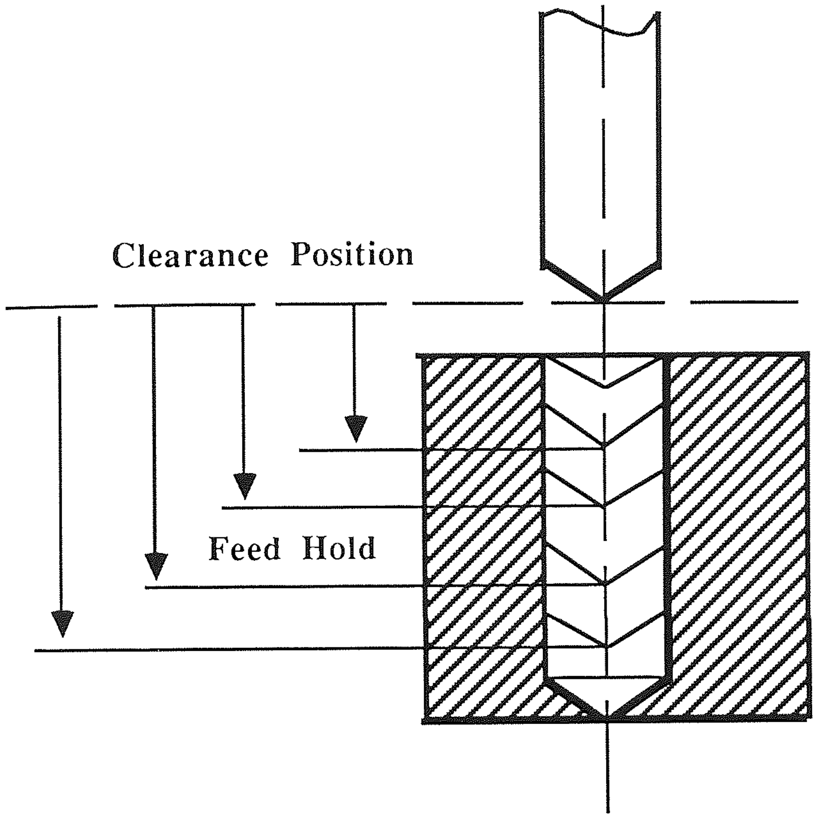


Fig. 5.3 : The principle of step-by-step feed in DHD

Almost every CNC machine tool or machining centre nowadays offers standard "canned" cycles for step-by-step feed and the operator has to specify in parametric form the main characteristics of each cycle. That is the depth of feed hold, the time dwell during which the tool stays outside the hole, the duration of the feed hold (msec) in step feed cycles, etc. It is clear that step feed is also subject to drawbacks like pecking :

- It is a predictive form of control and relies to a large extent on the judgment and experience of the part programmer.

- The latter usually adopts a very conservative attitude by specifying very low feed rates and penetration depths between withdrawals which in turn results in long cycle times and poor utilisation of the machine tool or machining centre.

- The factor material machineability is very critical in the context of chip formation, propagation of instability, work hardening and thermal distortion. For example Aluminium alloys are quite tolerable to frequent interrupts of cutting and reentry whilst Titanium alloys require a continuous positive feed all the time.

- The technique aims to alleviate the problem of swarf disposal from the hole and obviously could not cope with a case of a hard inclusion in the workpiece material or the case of very rapid wear of the tool.

5.4 Algorithm for variation of feed and speed in DHD

The following method is based on the characteristics of the drilling forces described in chapters 3 and 4 and requires specific knowledge of the linear rising pattern of the drilling torque in region 3 (fig. 4.5) and the depth at which it appears for a given workpiece material.

It was derived as a systematic approach in order to improve the technique of pecking and in additions aimes to prove that in principle it is possible to prolong stable drilling during DHD by means of dynamic variation of the machining parameters.

The specific objective of this algorithm is to maintain the drilling torque constant at the level of its steady state value $\mathbf{M_0}$ as this was described in chapter 4 ; this can be achieved if the increase in torque due to friction is compensated by reduction in the cutting component of the torque which for a given diameter and material is logarithmically proportional to feed and to a lesser extent cutting speed (depending on the workpiece material).

The feed **f** (undeformed chip thickness) can be altered by either a reduction in the feed rate or an increase in the spindle RPM. In the first method the spindle speed **N** is kept constant while a reduction in the feed rate **F** with hole depth results in reduction to the feed/rev.

In the alternative method, an increase of the spindle speed (RPM) under constant penetration rate gives the same result, provided that the drilling forces (mainly torque) for the particular material are not very sensitive in variations of the drill speed v over a range of speeds, i.e that m >> n. $[\mathbf{M_0(f,v) = k\, f^m\, v^n}]$

Typically **m** and **n** have a ratio in the order of 8:1 to 15:1 (e.g Aluminium) while the contributions of speed, feed/rev to drill life are much closer, typically 2 : 1, as presented in sections 4.2 and 4.3 of chapter 4.

For a given diameter and constant spindle speed the steady state torque is given by :

$$M_0(F) = k\,F^m \qquad (5.1)$$

The increase in torque with depth (due to friction) in the linear region is:

$$dM/dZ = a > 0 \qquad (5.2)$$

This rise can be compensated by a reduction of the cutting component so that the total torque M(z) should remain constant. A reduction in the feed rate results to a reduction in the steady state torque : $dM_0/dF = kmF^{m-1}$ therefore $F^{m-1}dF/dz = -a/k$ and by integration :

$F^m = -az/k + k^*$, condition : $F_0{}^m = -az_0/k + k^*$ therefore

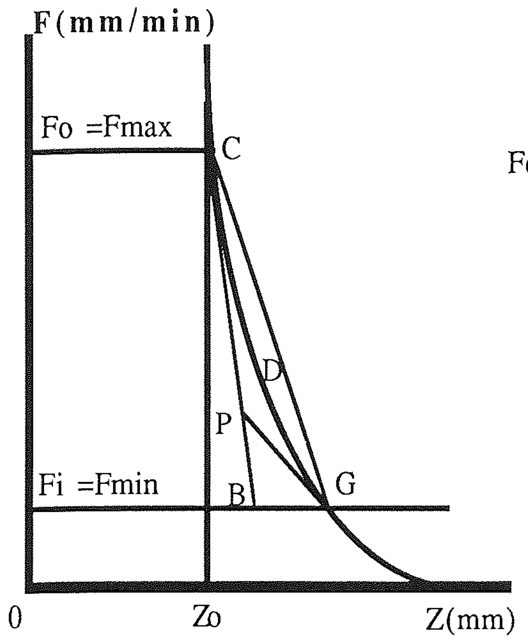
$$F^m = F_0{}^m - a(z-z_0)/k \qquad (5.3)$$

Hence the penetration rate **F** should vary exponentially with the drilled depth according to function (5.4)

$$F = (F_0{}^m - a(Z-Z_0)/k)^{1/m} \qquad (5.4)$$

F_0 is the maximum permissible feed rate and is calculated by equating the feed (axial) force on the drill (which also depends on the feed/ rev) with the force required for loss of axial stability, namely buckling failure, (section 7.7).

In practice the calculated value of F_0 is reduced by half for a safety margin and also because there is evidence that hole run-out and over-size are greatly dependent on the initial feed rate. Figure 5.4 shows a feed-depth profile according to (5.4) (line CDG) and also some linear approximations of (5.6) which are discussed next.



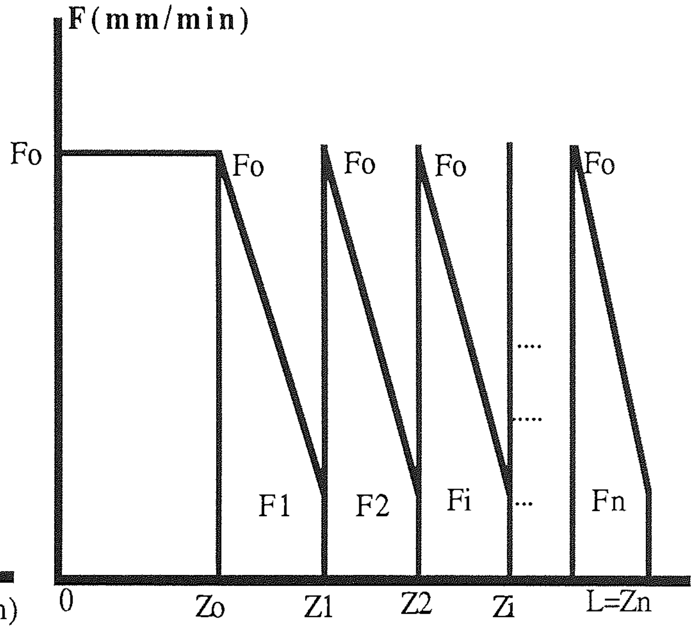


Fig.5.4 : Variation of feed vs depth **Fig.5.5 : Multi-peck drilling cycle**

Instead of reducing the feed rate with the drilled depth according to fig. 5.4, it is more practical (in terms of easier NC programming) to use some linear approximation, which in turn is an interpolation between discrete values of the penetration rate changing over discrete steps of depth (e.g 0.5 mm). Namely, instead of varying F along the route CDG use either CG or CB or CPG (fig. 5.5). The linear approximation used in tests was route CB :

$$(dF/dZ)_{Z=Z_0} = -(a/km)F_0^{1-m}$$

hence : $$F_{CB}(Z) = F_0(1-aF_0^{-m}(Z-Z_0)/km) \quad (5.5)$$

The route CG is also possible because although it maintains the feed above the theoretical safety level the difference is very small.

The safe drilling depth in this case is :

$$Z_B = mkF_0^m\,(1-(F_{min}/F_0))/a + Z_0 \quad (5.6)$$

Obviously the best route is CPG , following the two tangents of (6) at C and G which intersect at P with coordinates Z_P, F_P :

$$Z_P = [kma^{-1}(F_o-F_{min}) + (F_o^{1-m}Z_o - F_{min}^{1-m}Z_G)]\,(F_o^{1-m}-F_{min}^{1-m})^{-1} \quad (5.7)$$

$$F_P = F_o(1-aF_o^{-m}(Z_P-Z_o)/km) \quad (5.8)$$

The maximum safe drilling depth is :

$$Z_G = kF_o^m\{1-(F_{min}/F_o)^m)/a\} + Z_o \quad (5.9)$$

F_{min} is the value beyond which the feed should not drop because the drill is no longer cutting efficiently (it rubs against the hole walls) and withdrawal (pecking) is required in order to cool and lubricate the tool and clear the swarf. Drilling of a deep hole in general will require more than one pecks and such a complete drilling cycle is shown in fig. 5.5.

5.5 Optimisation of a multi-pecking DHD cycle

An analysis follows next in order to determine the value of the minimum penetration rate prior to withdrawal for each step on the basis of minimum cycle time.

When the penetration rate varies under such a law it is necessary to minimize the total cycle time in order to maximise the productivity of the process. The penetration rate for the i-th cut varies linearly between the maximum value F_0 and the minimum value (for that step) F_{0i} according to equation (5.10)

$$\begin{array}{ll}
F(z) = F_0-b_1(z-0) & F_{01} = F_0-b_1z_1 \\
F(z) = F_0-b_2(z-z_1) & F_{02} = F_0-b_2(z_2-z_1) \\
\cdots\cdots & \\
F(z) = F_0-b_i(z-z_i) & F_{0i} = F_0-b_i(z_i-z_{i-1}) \\
\cdots\cdots & \\
F(z) = F_0-b_n(z-z_{n-1}) & F_{0n} = F_0-b_n(z_n-z_{n-1})
\end{array} \quad (5.10)$$

After some transformations (5.10) yields : $z_i-z_{i-1}=(F_0-F_{0i})/b_i$

The machining time for the **i**-th cut is :

$$t(z_{i-1}, z_i) = \int_{z_{i-1}}^{z_i} dz/F(z) = \int_{z_{i-1}}^{z_i} dz/(F_0 - b_i(z - z_{i-1})) \qquad (5.11)$$

Introducing the variable $\mathbf{z = z - z_{i-1}}$ the new limits are : $\mathbf{0}$, $\mathbf{z - z_{i-1}}$ taking (5.10) into account (5.9) yields :

$$t(z_{i-1}, z_i) = \int_0^{z_i - z_{i-1}} dz/(F_0 - b_i z) = \int_0^{(F_0 - F_{0i})/bi} dz/(F_0 - b_i z)$$

$$t(z_{i-1}, z_i) = -(\ln F_0 - b_i z))/b_i \quad z: \{0, \ (F_0 - F_{0i})/bi\}$$

or alternatively : $t(z_{i-1}, z_i) = -\ln(F_{0i}/F_0)/b_i$ (5.12)

So the total machining time (without the withdrawals) will be given by the expression:

$$T = \sum_1^n t_i = \sum_1^n - \ln(F_{0i}/F_0)/b_i \qquad (5.13)$$

T is required to be minimum while there is a physical constraint which is the maximum (target) depth of the hole $\mathbf{Z = L}$. This can be expressed as following :

$$\sum_1^n (z_i - z_{i-1}) = L \quad \text{or} \quad \sum_1^n (F_0 - F_{0i})/b_i = L \qquad (5.14)$$

Introducing the Lagrange multiplier λ and taking into account the constraint (5.14) , $\mathbf{T^*}$ is required to be minimum , where :

$$T^* = -\sum_1^n (\ln(F_{0i}/F_0)/b_i \quad + \lambda\sum_1^n (((F_0 - F_{0i})/b_i) - L) \qquad (5.15)$$

Requiring $\mathbf{dT^*/dF_{0i} = 0}$ yields:

$$-(1/b_i)(F_{0i}/F_0)^{-1} + \lambda(-1/b_i) = 0 \qquad \text{or} \qquad \lambda = 1/F_{0i} \qquad (5.16)$$

$$\text{so} \ : F_{01} = F_{02} = \ldots = F_{0n} \qquad (5.17)$$

and by substituting (5.17) into constraint (5.14) yields:

$$F_{0i} = F_0 - (L/\sum_{1}^{n} 1/b_i) \qquad (5.18)$$

The significance of (5.18) is that the minimum feed rate before withdrawal of the drill can be calculated from the characteristic of the material b_i and the target hole depth L thus giving the optimum number of pecks.

The above optimisation is the easiest one to implement both in terms of analysis and actual application (section 5.6) when compared with other alternatives based on different optimisation criteria. For instance one might argue that tool life should be the criterion when modifying the machining parameters.

It is known that tool life in metal cutting depends somewhat on diameter d, feed f, and cutting speed v according to expressions : $T = C_T d^r v^{-p} f^{-q}$ where C_T, p, q, r are constants for a given material and tool geometry. Clearly variations of one or both machining parameters f, v modify the wear characteristics of the tool and therefore tool life. If the latter was to be kept constant then for every value of feed f a new cutting speed v should be used.

For a number of reasons given below this is impractical, at least when predictive control of the cutting forces is applied on the principles described in the previous sections :

- Expressions of tool life such as the one above are very difficult to obtain because they presuppose a large number of "successful" tests with various parameters.

- An equally large amount of calculations and size of NC program is required ; (see section 5.6 and Appendix II)

- In chapters 3 and 4 it was made clear that the dominant problem in DHD when performed under CNC or totally unmanned conditions is the catastrophic failure of tools and consequent failure of the workpiece. In this case there is hardly any comparison between the cost of an expensive component plus time losses from breakdowns when compared to the cost of a twist drill (typically < £10 in current figures).

5.6 Example of NC program for DHD under variable feed rate

The limitation of the NC ISO-code, or even more advanced coding of part programs for CNC machining, is that they do not include functions which would permit the variation of a machining parameter between specified limits and a number of repetitions (e.g DO loops of other languages).

Namely to vary a parameter **A**, representing either **F**(mm/min) or **N**(RPM) or **Z**(mm axis position) , by an amount $\pm \Delta A$ for **I** times :

$$A_{max/min} \geq A_0 \pm I\,\Delta A \geq A_{min/max} \tag{5.19}$$

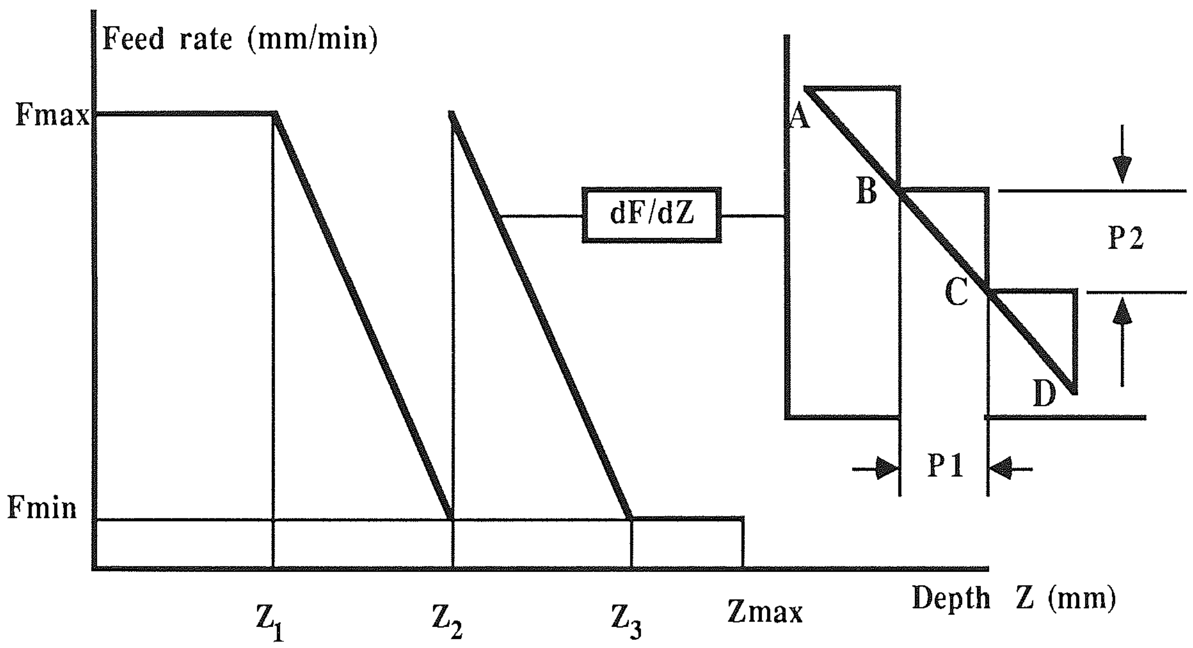


Fig. 5.6 : Variation of feed rate with drilling depth
(Linear approximation)

The method described earlier clearly requires variation of feed rate inside an a part program ; a possible solution to the problem is the following : In a space of the CNC memory are given all the discrete values of **A** between $A_{max/min}$ and $A_{min/max}$. Each one is identified by its block number N and a group can be called by a subroutine (& prefix to the block number), in this way any variation loop is possible. The complete program is shown in Appendix II.

e.g : G91 INCREMENTAL MODE

DEFINE P1=500	{ &N10 Z-P1 $A_{min/max} \pm \Delta A$
EXECUTE N30 to N120	{ &N20 Z-P1 $A_{min/max} \pm 2\Delta A$
. . . .	. . . .
REPEAT	{ &N150 Z-P1 $A_{min/max} \pm 15\Delta A$

The depth step **Z** during which the current value of **A** remains constant is defined by the parameter $\mathbf{P_1}$ (negative sign indicates advancing into the workpiece) while the reduction in feed rate (mm/min) is defined by parameter $\mathbf{P_2}$.

The total number of steps is an integer number **I** , related to the maximum hole depth **L** = **Zmax** and the limit values of **A** with the following formula :

$$\mathbf{I\text{-}1} = (A_{max} - A_{min})/\Delta A = L/P_1 \qquad \textbf{(5.20)}$$

Obviously the greater the value of I the more accurate is the interpolation while limitations are imposed by the following factors :

(i) The amount of memory available to store the different values of **A.**

(ii) The values of $\pm \Delta A$ and the minimum value of $\mathbf{P_1}$, depending on the positioning accuracy and feed, speed resolution of the CNC machine tool.

5.7 Drilling tests with variable feed

SERIES V : (Ø3.0 X 90 mm THROUGH HOLES)
TITEX QUICK HELIX (40°) DHD DRILLS)

Spindle speed : constant 3000 RPM, Feed rate variable 30-105 mm/min (10-35 µm/rev). The same drill performed the whole range successfully (V1.1 to V1.6) but it was observed that as the feed increased , i.e the undeformed chip thickness, the form of the produced swarf changed from springy and flexible and self removed from the flutes (feeds up to 20 µm/rev) , until it became brittle and compact and had to be removed manually thereafter.The drill failed before a second hole was completed using the maximum feed (35µm/rev) and without removing the swarf compacted in the flutes after the first hole.

SERIES B24 : (Ø 2.4 mm BLIND HOLES
TITEX QUICK HELIX (40°) DRILLS)

The purpose of this series of tests was to investigate the phenomenon of swarf packing in the flutes as the hole depth increases and from the knowledge gained to optimise penetration at maximum feed and depth prior to drill withdrawal (pecking). It was decided to keep the number of parameters as small as possible, so a fixed spindle speed of 3000 RPM (22.6m/min cutting speed) was used. The parameters investigated were feed and hole depth expressed in diameters (L/D ratio). Feed varied as following: 30-45-60-75-90-105 mm/min penetration rate, equivalent feed (at 3000 RPM). 10-15-20-25-30-35 µm / rev = 0.4-0.6-0.8-1.0-1.2-1.4 thou / rev.

As far as hole depth is concerned blind holes were drilled between 12D to 36D(max) increasing the depth by 1D at a time. So each (blind) hole was drilled with 6 different feeds and forces were recorded (torque and thrust). The drill performed the tests up to B24.6 (depth = 24D, max feed) without failure, then in series B25 it performed tests B25.1 to B25.5 when failure occured the feed was 90 mm/min (1.2 thou /rev) at the time. Successive attempts to drill deeper with that feed rate or smaller ones failed and the drills suffered catastrophic failure.

TITEX A 1622 , SLOW HELIX (26^o)

Tests with these drills were very unsuccessful from the very beginning, all 3 drills failed at approximately 5D depth . It was also noticed that the rise in cutting forces was much more sharp than the quick helix drills .

SERIES B30: (Ø 3.0 BLIND HOLES)
TITEX QUICK HELIX (40^o) DRILLS)

Series B30 was a replica of B24 except that Ø3.0 mm drills were used.

SERIES D30 : (Ø3.0 X 90 mm THROUGH HOLES)
TITEX QUICK HELIX (40^o) DHD DRILLS)

In this series of tests through holes were drilled with variable feed and a single peck (series 2, 3) and two pecks (series 4). The objective of this type of drilling was to simulate the action of an adaptive control system achieving torque stabilization. From series B it was found that up to a certain depth the rise in magnitude of the drilling forces is smooth and practically linear (see conclusions) and therefore a predictive control of this would be feasible if the feed was reduced with depth in a linear manner.

SERIES D 30.1 : (no pecking)

F_I =126 mm/min (35 µm/rev at 3600 RPM)
$z_I = 0$ mm , $z_0 = 90$ mm, $z_L= 95$ mm
$F_0 = 36$ mm/min (10 µm/rev at 3600 RPM)
P8 = 6 mm steps in feed drop (90÷6 -1=14 steps)

After 3 tests the drill failed so the NC program was modified and incorporated 1 peck at 52 mm (49 mm actual depth+3 mm clearance)

SERIES D 30.2 : (pecking)

peck at 52 mm, improved linearity of feed drop rate
$F_I = 126$ mm/min (35 µm/rev at 3600 RPM)
$z_I = 0$ mm , $z_{01}= 52$ mm , $z_{02} = 90$ mm , $z_L = 95$ mm
$F_0 = 36$ mm/min (10 µm/rev at 3600 RPM)
P8 = 1 mm steps in feed drop (52÷1-1 = 51 steps)

SERIES D 30.3 : identical to 2 but feed drop was not initiated until $z_I = 12$ mm (9 mm in metal) this was found to be the depth beyond which packing of the swarf in the flute occured for this feed and obviously the deeper drilling can be achieved with the maximum constant feed the shortest the cycle time. This value of Z_I is not necessarily the optimal but a rather conservative one in view the primary strategy pursued: control (predictive-open loop) of the process by torque stabilization , drill safety and obviously workpiece safety, necessary in a highly automated production line.

SERIES D 24.3 : identical to 30.3 but using Ø2.4 mm drills

SERIES D 30.4: one more peck was introduced in order to further stabilize the drilling torque fluctuations still occuring with series 30.3

SERIES L 30.1: This series of drilling tests was based on the same principle as series D , i.e variation of the feed rate/rev with the hole depth in order to stabilise the load on the drill. In series L the variation was achieved by maintaining a constant penetration rate of 120 mm/min and varying the spindle between 2400 to 4800 RPM (50 µm/rev to 25 µm/rev) and the stabilisation of the drilling torque with minimal fluctuations was achieved.

5.8 Experimental results and conclusions

In order to examine the effectiveness of the algorithm, a case of DHD from the aerospace industry was chosen : Horizontal drilling of through holes Ø 2.4 and Ø 3.0 mm in diameter and depth ratio L/d = 35 : 1, in AMS 7075 T736 Aluminium alloy. In industry this type of drilling is carried out using an 18 x 5 mm "canned" pecking cycle on a CNC machining centre. Swarf "nesting" in the drill flutes, even after successful drilling of one hole, restricts the application of unmanned machining.

Before attempting to drill with stabilised drilling torque, using variable feed or speed as described earlier, tests were carried out on the Torshälla CNC lathe in order to determine :

1. What depth can be reached before instability arises for a range of feeds ; this depth was established on the basis of torque rising linearly with drilled depth.
2. Which combination of feed rate / cutting speed ensures best chip breaking.
3. Minimum, maximum feed rates for productive drilling and drill safety.
4. Comparison between two drill types : (Titex HSS, A 1722) with little flute space and high rigidity which incidently was the drill used in industry for this particular case. A Drill (Gühring GT 50) with unusually deep flutes and smaller torsional strength. The Gühring drill was selected because of its better performance in terms of depth it reached before instability (fig. 5.7).

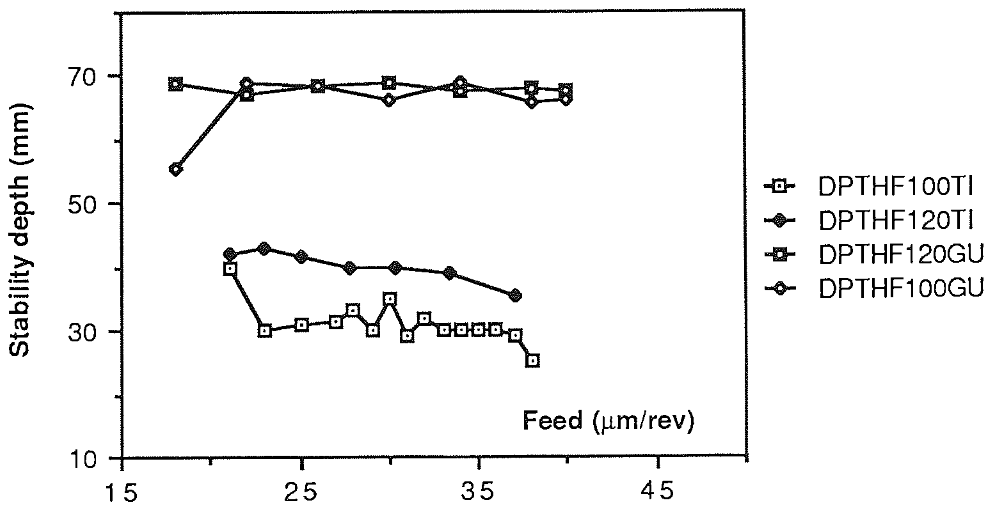


Fig. 5.7 : Stability depth vs feed (μm/rev) in DHD
Drills compared : TI = Titex A1722 GU = Gühring GT50 series
Feed rate : 100 mm/min, 120 mm/min **Material** : AMS7075 Aluminium alloy

5. Establish the parameters which describe torque as a function of hole depth. A quadratic polynomial was found to provide a satisfactory approximation of torque **M(Z)** as function of hole depth **Z** during the first three stages of the process before instability (fig. 4.4) :

$$\mathbf{M(Z) = M_0 + aZ + bZ^2}$$

The second order term has actually been omitted in the algorithm presented in the previous section because its contribution to the torque magnitude is very small compared with that of the first order term (fig. 5.8).

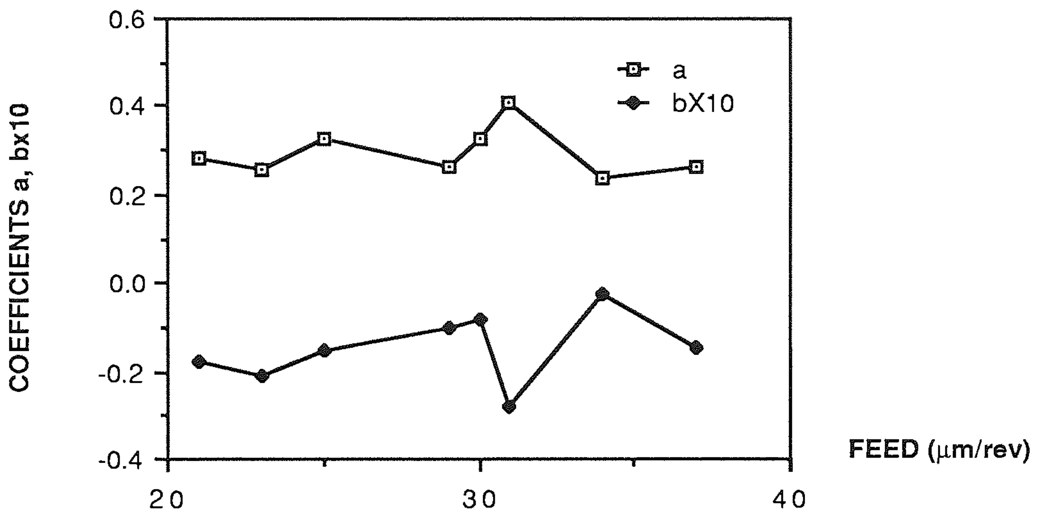


Fig. 5.8 : Coefficients of quadratic torque - depth model

The experimental results suggest that torque rises linearly (approximately) withhole depth and the rate of increase **a = dM/dZ** , is independent of the feed of the tool for a range of feeds.

Based on the above knowledge NC programs were written for drilling under variable penetration rate or RPM. Recording the drilling forces, torque and thrust, with a piezoelectric dynamometer into a UV recorder, suggested that it is possible to control the torque levels in deep hole drilling with small diameter drills, by varying the machining conditions. This also results to effective chip breaking so that the drill comes out of the drilled hole free of swarf in the flutes. Photographs of U.V paper records of the drilling forces are shown in figures 5.9 - 5.13.

When drilling was performed using NC programs with varying feed rate the following improvements were observed over the standard pecking cycle :

- The levels of drilling forces have been kept within acceptable limits without uncontrollable fluctuations. (fig. 5.9 to 5.13)

- The number of pecks, hence the total cycle time, was also reduced : the drill GT50 (open flutes) required no pecking at all, while the more rigid drill (Titex) required two pecks for a depth of 90 mm. Although full drill life tests were not conducted, both drills completed successfully 120+ holes.
- Metrological inspection of the drilled holes has suggested that hole run-out (parallelism error) was at least within the same limits as with fixed pecks, while the roundness error was reduced because fewer drill withdrawals and reentries were used.

5.9 Hole quality characteristics when using variable feed rate

In the graphs 5.14 to 5.25 a metrological inspection of a number of holes drilled with both methods, fixed feed rate pecking and variable feed rate, is given.

The parameters which have been investigated are hole roundness, hole straightness over a number of holes and the same parameters for a range of feeds.

In the tests two drill sizes have been used, Ø2.4 mm and Ø3.0 mm, Gühring GT50 while the cutting speed was kept the same at 30 m/min in order to allow for direct comparison of results.

It should be mentioned that the hole quality (roundness, runout) has been in general below average in terms of tolerances. The reason mainly lies with the fact that drilling has been performed on a lathe rather than a drilling machine and the tool being held in the spindle by means of a split collet. Such a set-up presents great problems as far as ensuring that the tool always runs true.

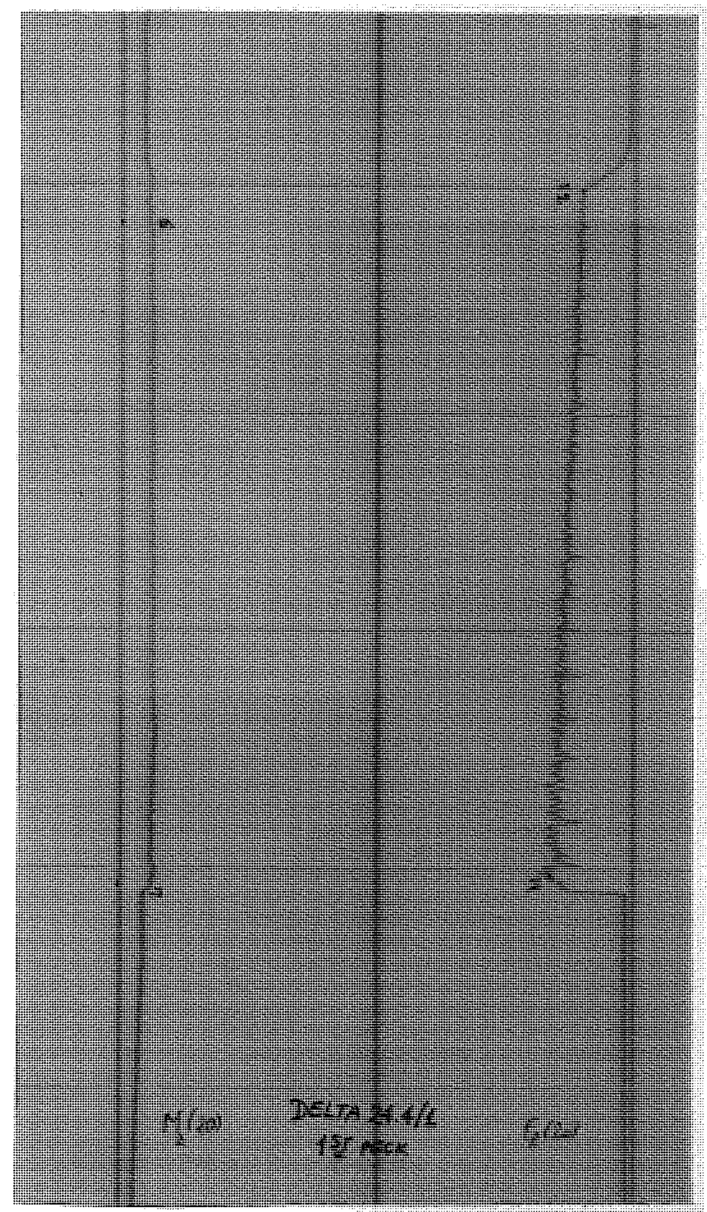


Fig. 5.9 : Drilling with variable feed rate (mm/min) using two pecks
Test from series D 24.4 (first peck),
Left trace : Mz = torque stabilised, Right trace : Fz = thrust dropping

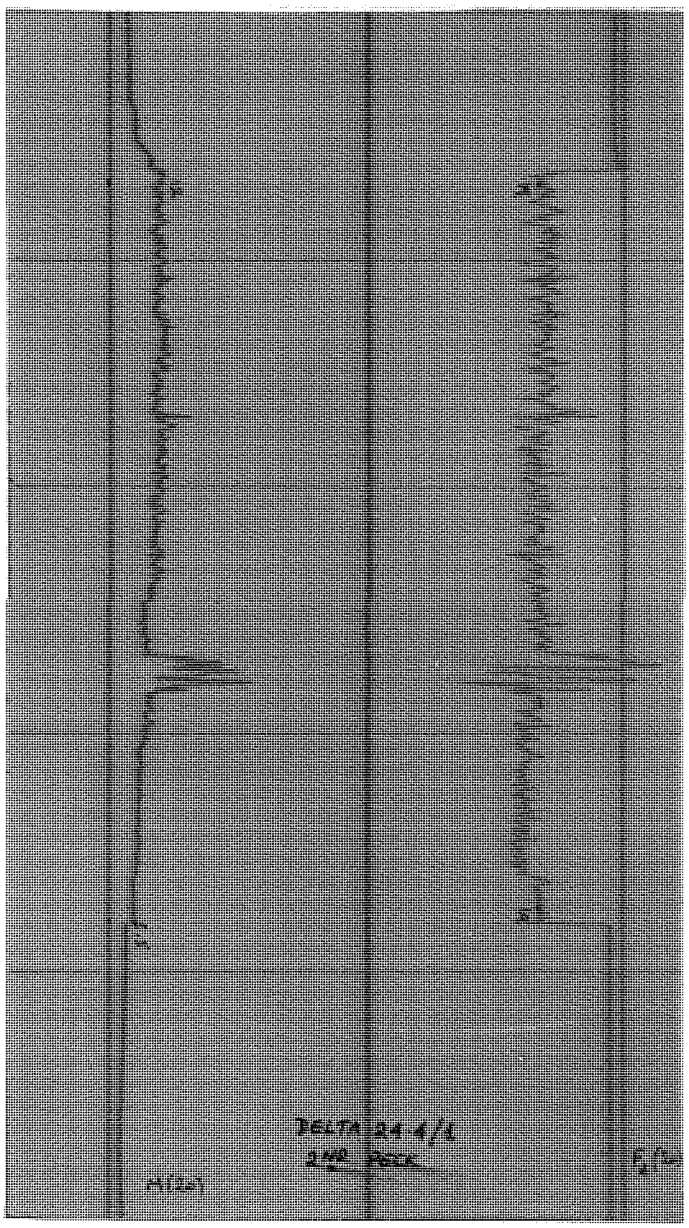


Fig. 5.10 : Drilling with variable feed rate (mm/min) using two pecks
Test from series D 24.4 (second peck),
Left trace : Mz = torque almost stabilised, Right trace : Fz = thrust stable
(observe cross talk due to twisting of tool during instability)

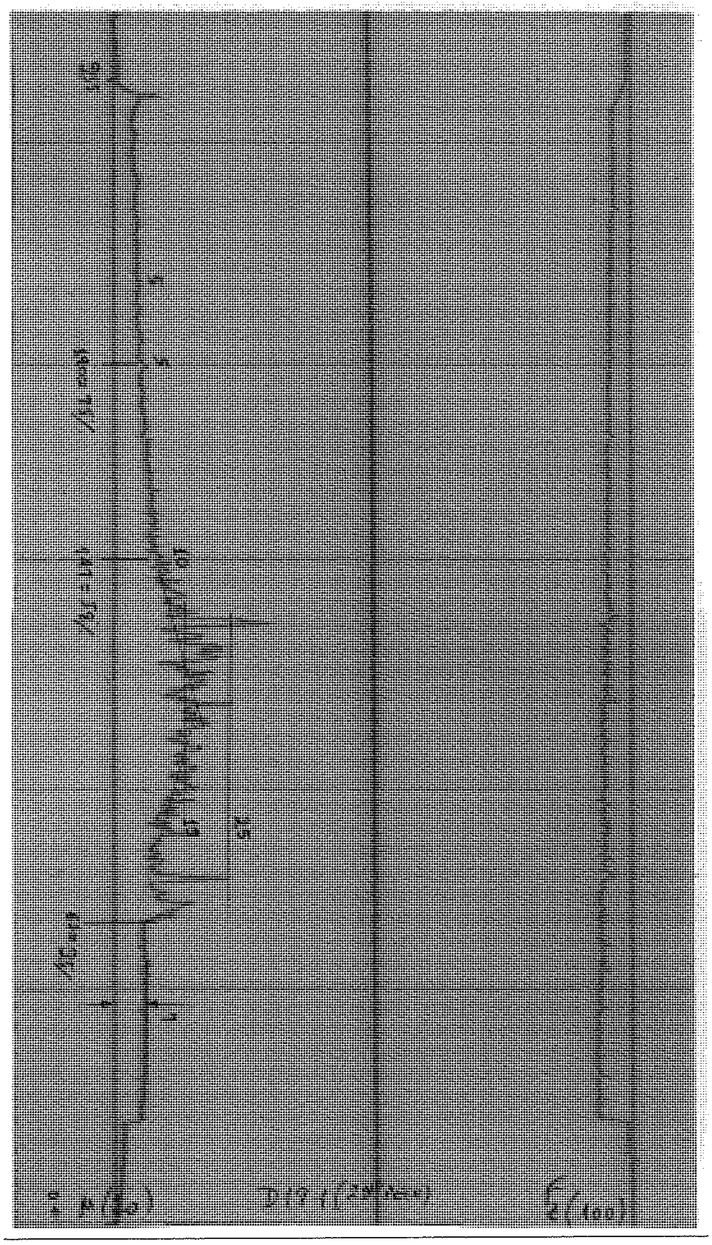


Fig. 5.11 : Drilling with variable feed rate (mm/min) using two pecks

Test from series D 19.1 (second peck),

Left trace : Mz = torque almost stabilised, Right trace : Fz = thrust stable

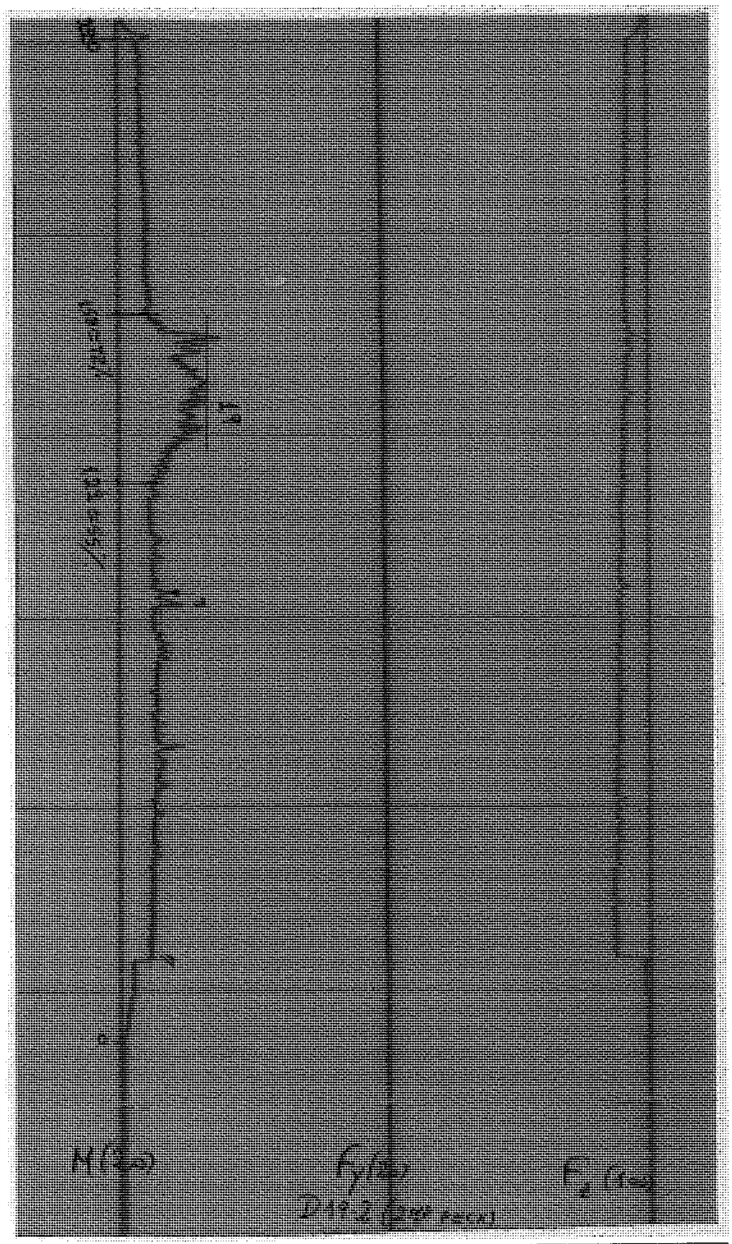


Fig. 5.12 : Drilling with variable feed rate (mm/min) using two pecks
Test from series D 19.2 (second peck),
Left trace : Mz = torque almost stabilised, Right trace : Fz = thrust stable

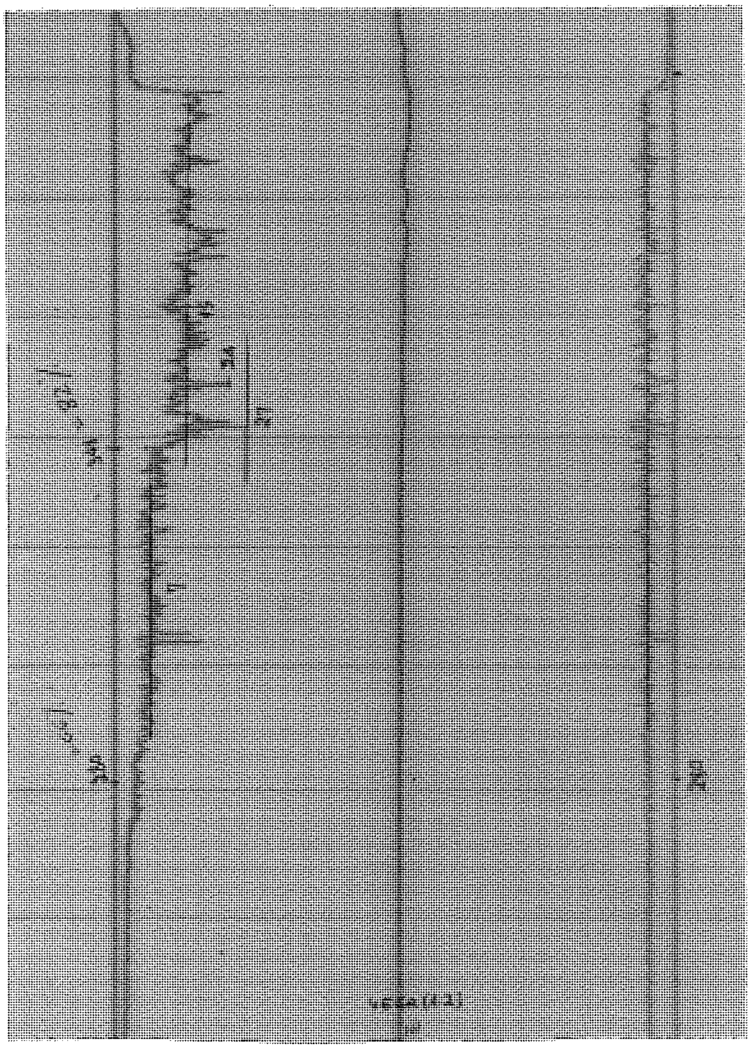


Fig. 5.13 : Drilling with variable speed using two pecks
Test from series L (variable speed RPM),
Left trace : Mz = torque almost stabilised, Right trace : Fz = thrust stable

5.9.1 Hole roundness error graphs
(Comparison of variable feed / pecking techniques)

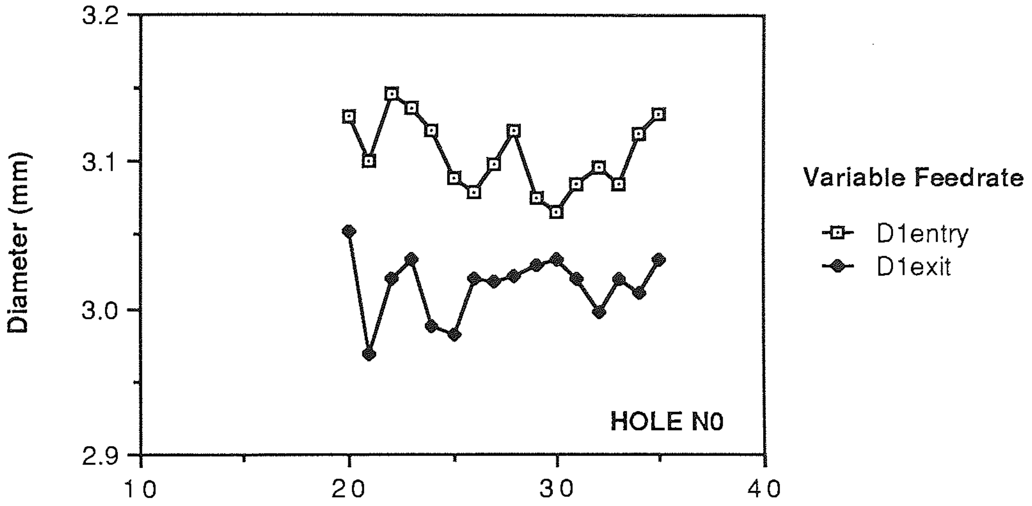


Fig. 5.14 : Hole roundness at entry and exit, nominal diameter Ø3.0 mm,
Drill : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 3150,
Feedrate variable : 120 - 30 mm / min, dropping by 2mm / min / 2 mm.

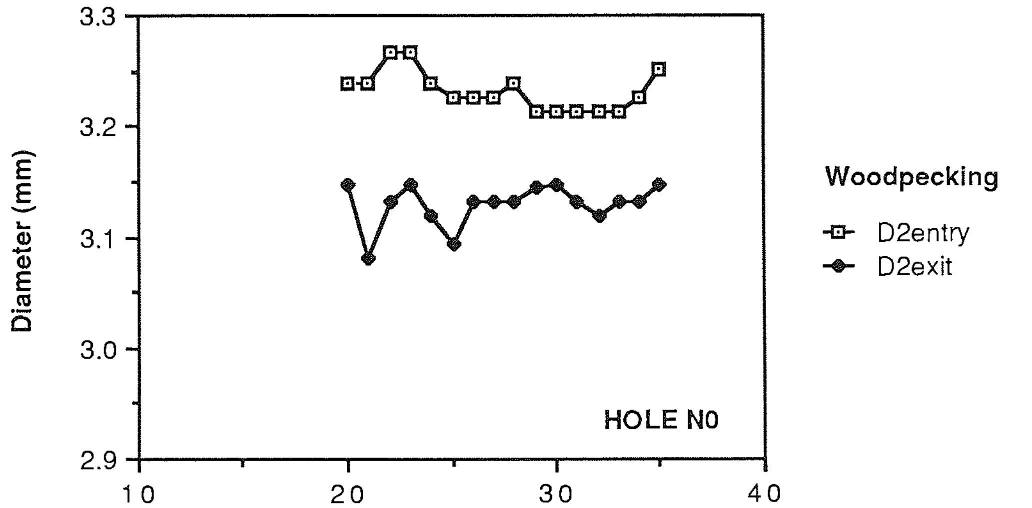


Fig. 5.15 : Hole roundness at entry and exit, nominal diameter Ø3.0 mm,
Drill : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 3150,
Feedrate constant : 90 mm / min **Pecks** : 18 x 5 mm each

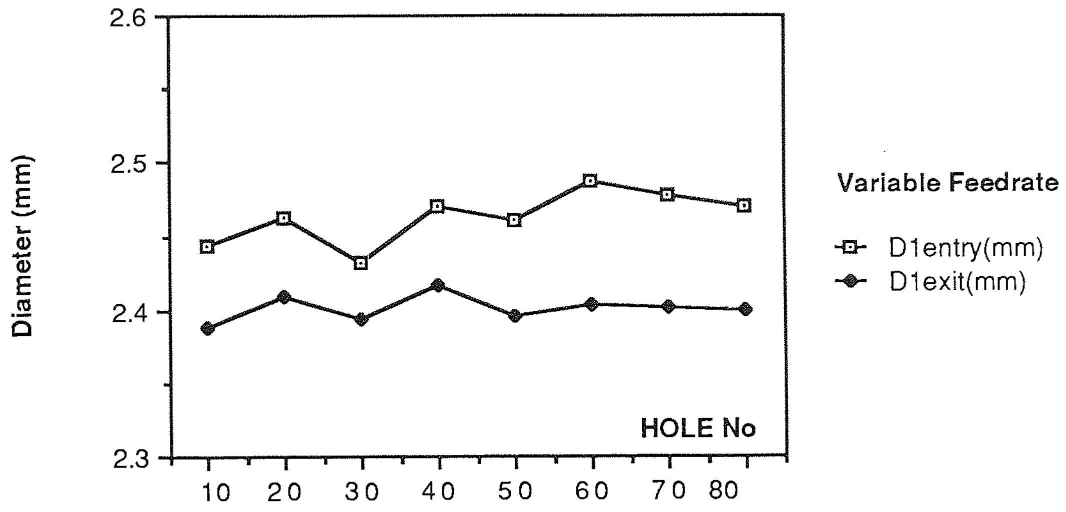


Fig. 5.16 : Hole roundness at entry and exit, nominal diameter Ø2.4 mm, **Drill** : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 2520, **Feedrate variable** : 120 - 30 mm / min, dropping by 2mm / min / 2 mm.

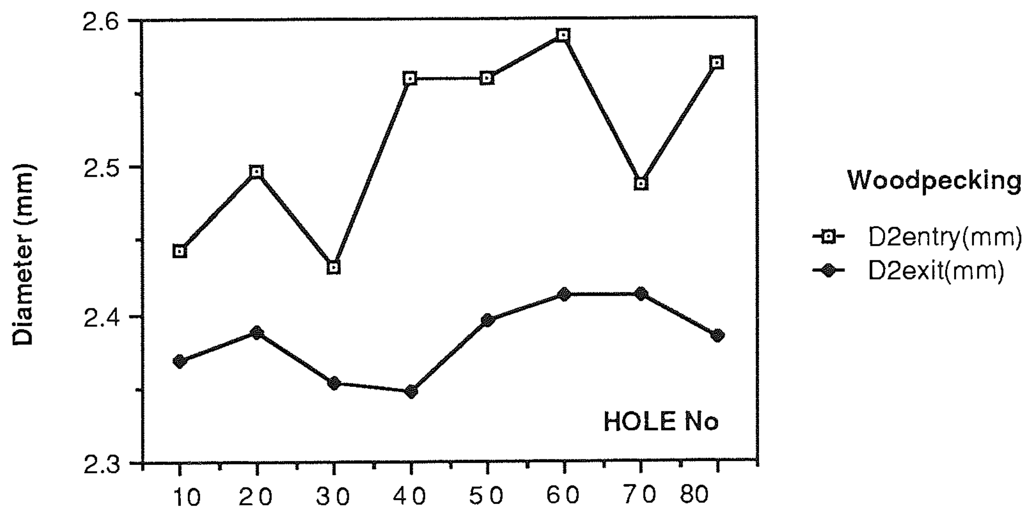


Fig. 5.17 : Hole roundness at entry and exit, nominal diameter Ø2.4 mm, **Drill** : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 2520, **Feedrate constant** : 90 mm / min **Pecks** : 17 x 5 mm each

5.9.2 Hole roundness vs feed graphs

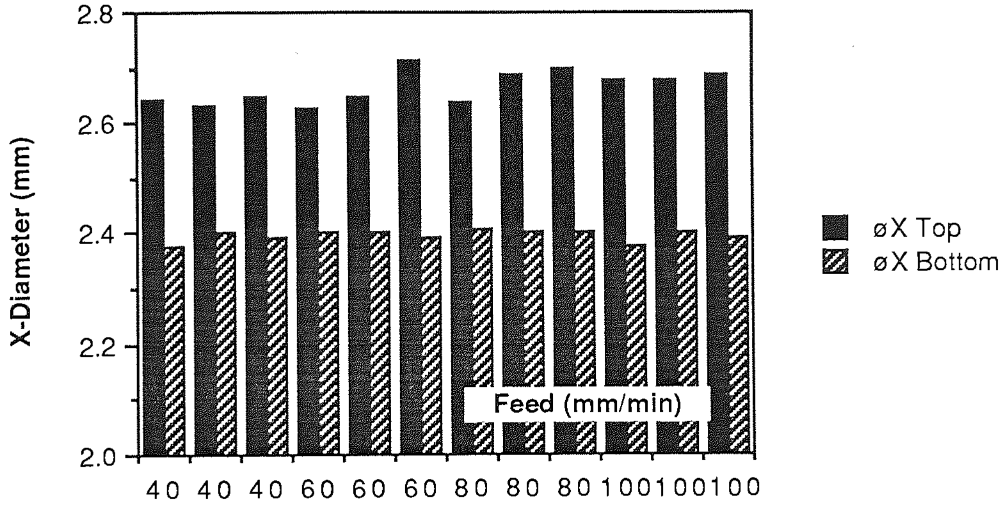


Fig. 5.18 : Hole roundness at entry and exit X, nominal diameter Ø2.4 mm, **Drill** : GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 2520

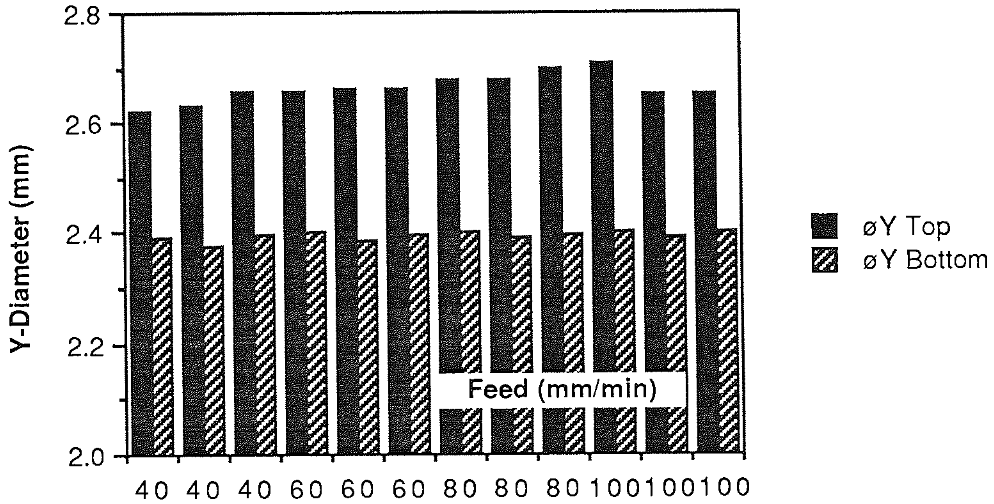


Fig. 5.19 : Hole roundness at entry and exit Y, nominal diameter Ø2.4 mm, **Drill** : GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 2520

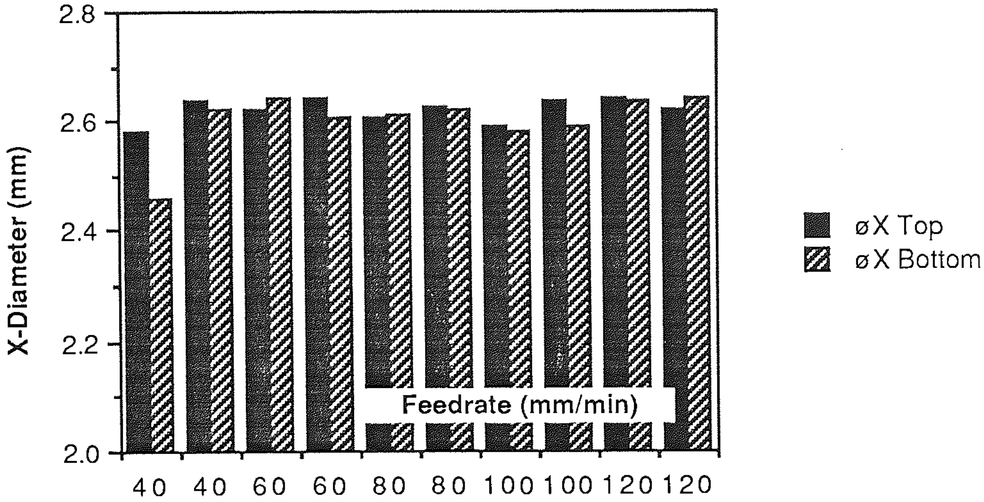


Fig. 5.20 : Hole roundness at entry and exit X, nominal diameter Ø2.4 mm, **Drill** : Titex A1622, **Material** : AMS7075 Aluminium Alloy, **RPM** : 2520

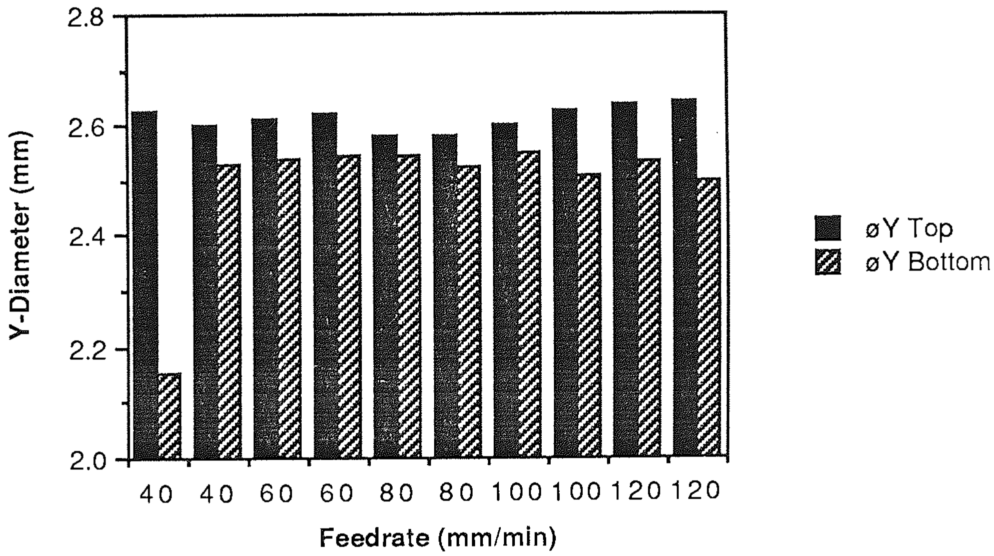


Fig. 5.21 : Hole roundness at entry and exit Y, nominal diameter Ø2.4 mm, **Drill** : Titex A1622, **Material** : AMS7075 Aluminium Alloy, **RPM** : 2520

5.9.3 Runout Graphs
(Comparison of variable feed / pecking techniques)

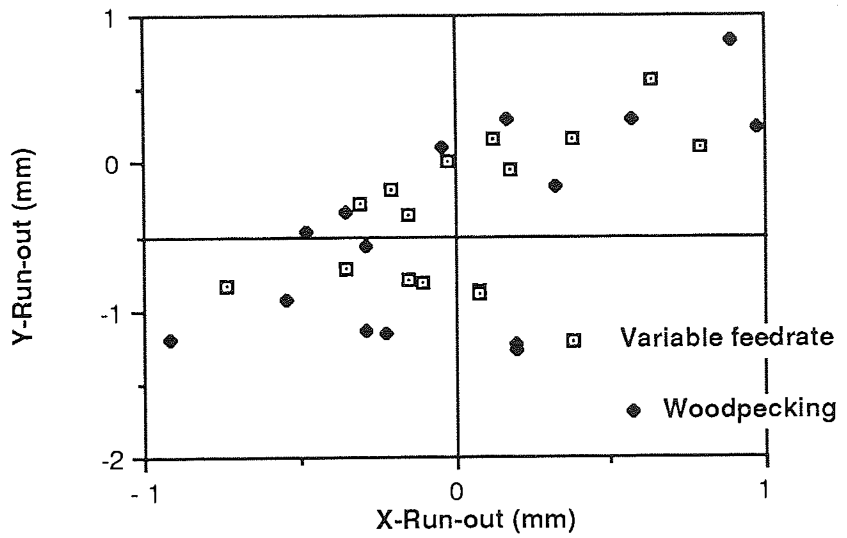


Fig. 5.22 : Hole runout, nominal diameter Ø3.0 mm,
Comparison : between variable feed rate and pecking techniques,
Drill : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 3150,

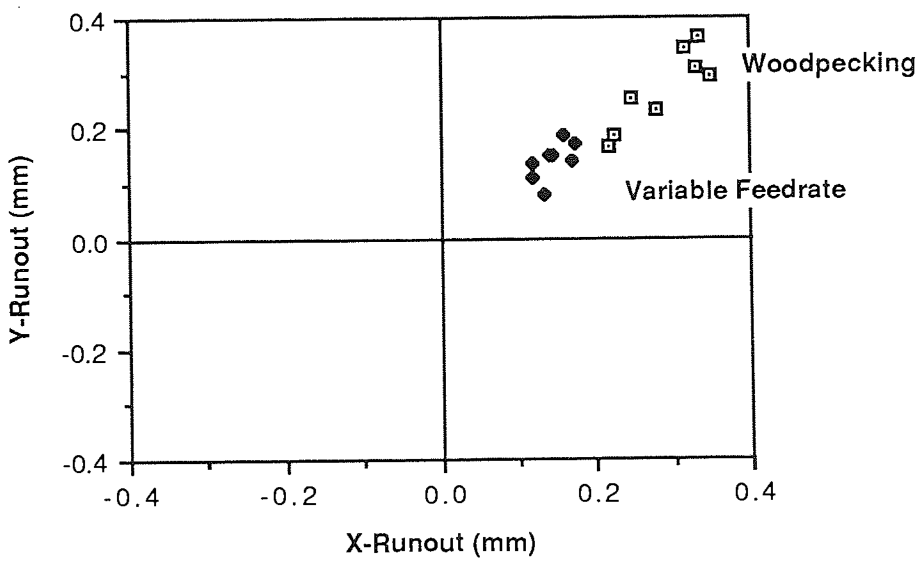


Fig. 5.23 : Hole runout, nominal diameter Ø2.4 mm,
Comparison : between variable feed rate and pecking techniques,
Drill : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 3150,

5.9.4 Hole runout vs feed graphs

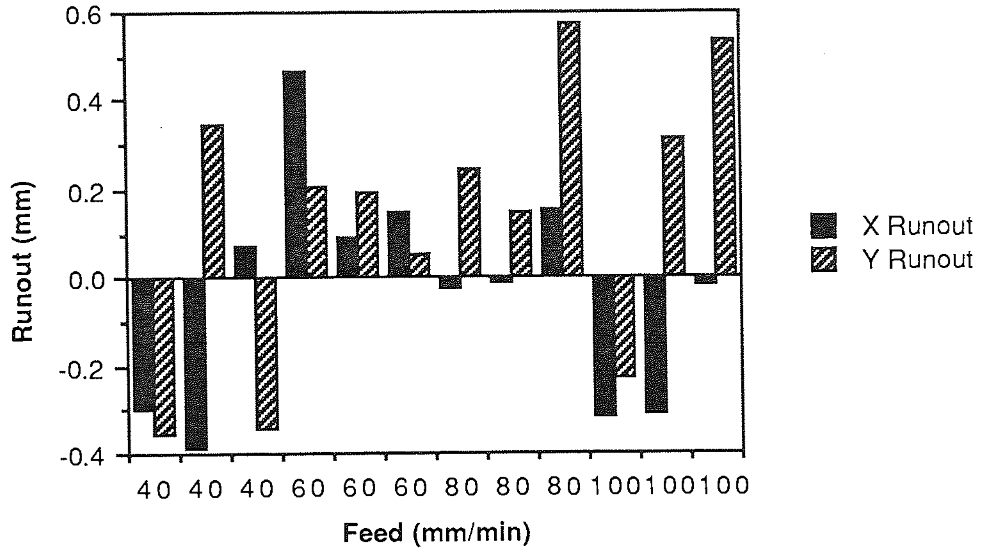


Fig. 5.24 : Hole runout vs feed rate, nominal diameter Ø3.0 mm,
Drill : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 3150

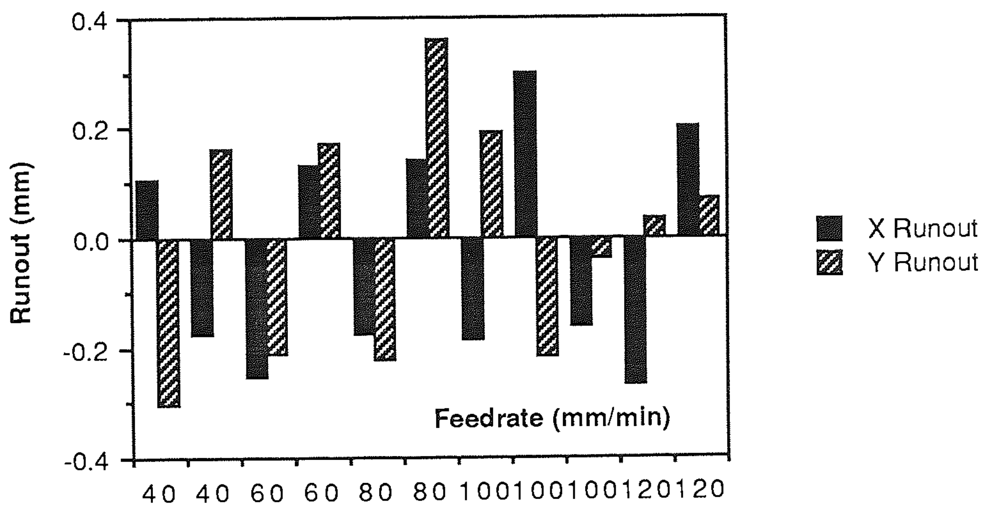


Fig. 5.25 : Hole runout vs feed rate, nominal diameter Ø2.4 mm,
Drill : Gühring GT50, **Material** : AMS7075 Aluminium Alloy, **RPM** : 2520

5.10 Summary

The problems associated with the extraction of swarf from the cutting zone and the drill flutes and consequently the problem of instability of the deep hole drilling process can be tackled in principle by effective variation of the machining parameters on line.

In industry, such an objective is partly achieved by using drills of variable length and/or using systems and devices which control the chip formation in such a way that its extraction from the hole is made easier. Most common is the technique of pecking, namely the periodic withdrawal and reentry of the tool in the drilled hole.

A more systematic approach to fixed pecking has been presented in this chapter, based on variation of the feed in a predictive corrective manner according to the rising pattern of the drilling torque with drilled depth. A simple analysis has shown that it is possible to compensate for the ever increasing friction component of the drilling torque by reducing the cutting component by means of reducing the chip thickness. When a minimum value of feed is reached, withdrawal of the tool is necessary and repetition of the cycle.

A series of tests of drilling small diameter deep holes using a variable feed during the drilling cycle has confirmed that the fluctuations of drilling torque can be successfully controlled, while the number of tool withdrawals is kept to a minimum (optimisation of pecking). On the other hand, hole quality is kept at the same level or in many cases improved over conventional techniques.

This method however, despite its promising results, remains an open loop type of process control and relies to a large extent to a priori knowledge of the pattern by which instability appears as a function of the drilled depth and the machining parameters. The integrity of the process and the safety of tool and workpiece cannot be guaranteed and in order to further reduce the risk of catastrophic failure, very conservative machining conditions would have to be specified in the part program, resulting in turn in time losses and under-utilisation of both the tool and the machine tool capabilities.

Therefore it is necessary to fully automate all the intermediate steps including the on-line identification of the control parameters. The introduction of a closed loop digital system for monitoring and control of instability is the next logical step in the context of improving the capability of producing small diameter deep holes with twist drills under Numerical Control.

SECTION B

PROCESS MONITORING AND ADAPTIVE CONTROL OF DEEP HOLE DRILLING ON A CNC MACHINE TOOL

CHAPTER 6

PROCESS MONITORING AND ADAPTIVE CONTROL IN DEEP HOLE DRILLING

This chapter starts with the definitions and a general description of Process Monitoring and Adaptive Control in the context of metal cutting and the way in which these technologies constitute fundamental elements of modern manufacturing systems. A description follows of the hardware of the prototype system for Process Monitoring and Adaptive Control (AC) in Deep Hole Drilling. The system comprises the machine tool, the drilling thrust and torque sensor, the computer based data acquisition and analysis system and the loop is closed by the software based controller and the computer-CNC interface.

The two main control loops are described next : the first is the standard position and velocity control loop (CNC) of the machine tool and the second is the AC loop. An analysis is presented of the dynamics of the position and velocity feedback loop based on technical data of the CNC lathe around which the system was developed. The analysis of the AC loop which follows is based on a first order model of the cutting process and the dependence of the stability of the loop on the control algorithm is shown. The structure of a multi level control strategy and the rationale behind its development is also presented.

6.1 Process Monitoring and Adaptive Control

6.1.1 Process Monitoring

Process Monitoring is the front-line function of the proposed system and the successful and reliable performance of any control system obviously depends on how robust and reliable is its data capturing and analysis module. As it will be made clear in chapters 7 and 8, Process Monitoring can be a stand alone function within a manufacturing system as opposed to Adaptive Control which presupposes the existence of the former. Process Monitoring (PM) has a broad context in adavanced manufacturing and two major areas can be identified :

- Machine tool monitoring, namely monitoring of the performance of important functional parts of the machine tool such as gearbox, slides and bearings, lubrication system, electrical or hydraulic motors etc.

- Process monitoring which includes also tool monitoring involves monitoring of one or more process parameters susch as spindle motor power, torque, cutting forces, noise or vibrations levels, tool breakage detection etc. (Thorneycroft **[123]**, Ridley **[124]**, Manack **[135]**, etc.)

Unlike Adaptive Control, during Process Monitoring no attempt is made to optimise or modify any of the machining parameters and the only type of responsive action that the system may take is to issue alarms to an operator in case of malfunction, or in certain cases to command a feed hold or even emergency stop of the process.

The objective of such a system is to ensure the integrity of the process and the safety of the tool, the workpiece and often the machine tool. Emphasis is also given to the diagnostic capability of the system in order to be able to provide data for off-line fault interpretation. The relative cost of implementation and maintainance, the reaction time and finally the degree of complexity of a Process Monitoring system are far superior to those of an Adaptive Control system and this explains to some extent why the former has received a much wider acceptance in the shop-floor environments.

6.1.2 Adaptive Control

Adaptive Control (AC) is a term used in the Engineering literature in two different contexts. In the Manufacturing and Industrial Engineering literature the term means the on-line manipulation of the machining parameters (mainly feed rate and spindle speed) according to some objective. Two main types of AC have been identified by various researchers, Cronjäger **[110]**, Milner **[167]**, Koren **[170]** :

- Adaptive Control Optimisation (ACO) involves optimising the value of some performance index such as a minimum cost, minimum cycle time or maximum productivity, etc. ACO has not been commercially accepted because it requires on-line measurement of tool wear and also because it requires knowledge of parameters for each combination of tool and workpiece material while the complicated ACO algorithms require lengthy on-line computations. (Poletaev **[53]** - **[54]**, Lishchinskii **[56]** - **[57]** - **[58]**, Tverskoi **[62]**)

- Adaptive Control of Constraints (ACC) has the objective of maximising the metal removal rate within the constraints of process parameters such as tool deflection, cutting forces, spindle or feed motor power, temperature etc. ACC systems have already been successfully applied in industry for ACC in milling, turning and to some extent drilling. (References [81] to [114])

In the Control Engineering literature on the other hand, the term AC is used to describe feed back control systems in general, which vary the controller characteristics in response to changes in the controlled process in order to maintain a stable performance, Masory [159], Tomizuka [160], Åstrom [169] and [171]. This is achieved by various AC schemes such as the Self Tuning Regulators (STR), Model Reference Adaptive Schemes (MRAS) and the Gain Scheduling approach which is an open loop compensation.

6.1.3 Justification for the use of Adaptive Control in Deep Hole Drilling

The use of AC, as the latter is defined in the Control Engineering literature, is not always justified and this results in abuses of AC in the sense that a well designed classic controller with constant gain can perform very satisfactorily with no need for a complex AC scheme.

In the work presented in this thesis, the controller aims to control a metal cutting process which is inherently non-linear in general, as it has been shown by many researchers of AC for turning or milling. In addition, as shown in chapters 3 and 4, the deep hole drilling process is inherently unstable and with catastrophic failure of the tool highly probable. As the literature survey has shown, the current effort is certainly a first attempt to implement an AC scheme in the drilling and DHD process in particular.

In this case, the complexity of the process, the need for detailed analysis of the CNC and AC loops, the inability to specify a priori the exact functions of the controller in quantitative terms and thus select fixed parameters and finally the essential need to design and build a reliable system, which should allow the use of fragile tools with a high level of safety on a CNC machine tool, has lead to the development of a performance related controller which could be classed as an hybrid type between the two definitions.

As will be shown in chapter 7, the controller was designed with a maximum built-in flexibility in order to be able to improve its performance as knowledge and experience of the process increases. This resulted from the need to keep hardware requirements as low as possible and concentrate the effort onto the implementation of successful control performance in the system software.

6.1.4 Computer Integrated Manufacturing Flexible Manufacturing Systems

Fundamental element of a Flexible Manufacturing Sytem (FMS) is the Flexible Manufacturing Cell (FMC) ; this concept originated towards the end of the last decade as a means of meeting frequent changes in market trends and customers demand by means of producing smaller batches and increased variety of products. An FMC produces a family of parts with similar fetures. It comprises a number of CNC machines or machining centres and robots or other manipulators for parts transfer.

A number of FMC's under the master control of a central computer constitutes an FMS which also requires other systems for transport, stock control, scheduling etc. The concept of CIM is based on FMS linked to databases and CAD/CAM systems via a central powerful computer and therefore requiring minimum human intervention on the shop floor.

Despite the successful implementation of FMS and CIM by a number of manufacturing companies, there are still many problems to be overcome including social and economic implications which have to be considered. It is clear however that more intelligent machine tools and reliable monitoring systems are of paramount importance to the successful operation of these systems.

6.2 Sensors for Process Monitoring and Adaptive Control

The sensors for Process Monitoring and Adaptive Control can be classified in the following two groups:

6.2.1 Off-line sensors.

The first group includes sensors which check between successive machining operations whether a tool is present or not and hence can detect tool breakage. These systems operate either on the basis of direct contact with the tool using probes equipped with flexible stylii or indirect sensing based on electromagnetic induction effects. The latter are applicable only in drilling because of the shape of the tool, while the direct contact ones are applicable to a greater range of machining operations such as milling, turning, boring etc.

A task other than tool breakage detection performed by these sensors is checking the workpiece surface. This is a very useful function in terms of dimensional off-line inspection of a surface or in order to confirm that the set-up has been correct, the workpiece is orientated as it should be and therefore machining can continue with the next operation.

The concept intelligent machining requires the existence of a multi sensor environment around a machine tool and it is clear that sensors for post-process (off-line) data acquisition and analysis should be present. Many manufacturers of CNC machine tools and machining centres have identified the need for such systems and the latter are offered either as standard or optional features in specific models.

6.2.2 On-line sensors.

More closely to the concept of intelligent machining are on-line sensors the functioning of which has received a considerable research effort during recent years. These sensors perform two main functions, tool wear/breakage detection and Adaptive Control. According to source and type of information they convey for monitoring and interpretation to the outside world (normally a computerised alarm system) they are classified into the following groups:

Acoustic Emission (AE) : Several publications have presented the applicability of AE signals mainly for detection of tool breakage during machining, Moriwaki **[116]**, Inasaki **[141]**, Lee **[142]**. Despite the promising results there are certain limitations in the use of AE :

- AE still remains a method for post mortem corrective action which might be perfectly acceptable in some cases or too little too late in others.

- The reliability of AE is sensitive to the location of the sensor and the presence of hostile agents such as cutting fluids, swarf or even workpiece materials.

- The dependence of AE on a large amount of data, the elaborate calibration technique required and in some cases the difficulty or total inability to interpret the received data.

Power Monitoring : This is one of the most commonly used methods in industry for process monitoring and Adaptive Control of various machining operations. Pikovskii **[91]**, Artamonova **[97]** - **[98]**, Mathias, Beer **[101]**, **[120]** Ridley, Matsuhima **[126]**, Mueler **[133]**, **[139]**. The method is based on measurements of the armature voltage, current and power factor of the spindle motor.

The above parameters determine the values of the total, tare and cutting horsepower and torque of the metal cutting process and by using a dedicated microprocessor and a suitable algorithm, tool wear or tool breakage can be detected and corrective action be taken.

Power Monitoring is a cheap, reliable and efficient method but its applicability is rather restricted to operations of heavy cuts, where the order of magnitude of power and torque encountered are kilowatts and Nm respectively, rather than watts and Ncm as in the present work.

Forces and Torque Monitoring : This has been by far the most common method of monitoring the metal cutting process with very high precision and reliability in both laboratory and shop floor conditions. The various types of force transducers and techniques for processing force signals in metal cutting have been described already in various works such as **[129]** Tlusty, **[131]** Lister-Barrow, **[137]** Powell, **[138]** Stockline, so no further mention will be made here.

6.3 Description of the prototype system for PM-AC in DHD

A prototype system for Intelligent Machining (IM) was designed and built around the CNC lathe which was used for the experimental study of the DHD iprocess described in chapter 3. The term IM incorporates the two main functions of the system, namely Process Monitoring and Adaptive Control. A schematic representation of the prototype system is shown in fig. 6.1. The prototype system comprises the following elements :

6.3.1 Machine Tool

A CNC lathe was used rather than a vertical drilling machine in order to achieve drilling of holes horizontally. This is a necessary requirement in order to facilitate the swarf extraction from the hole during DHD. The lathe uses an ASEA-SAAB controller (PDP-11 microprocessor) to perform the NC functions of the machine tool.

The Torshälla Numerically Controlled production lathe, type S-160, is operated by a d.c motor via a separate gear box to the spindle. It features four speed ranges of 20-600, 40-1200, 80-2400 and 160-4800 RPM. The carriage and cross-slide are located behind the spindle with the carriage above the cross slide.

The lathe is equipped with a hydraulically indexing tool post with double tool holder, each unit accommodating eight tools. A fully enclosing plate guard offers extraction of swarf via a conveyor and safety to the operator. There are two axis +/- Z and +/- X, each driven by a separate d.c servomotor with full velocity feedback (tachogenerators) and position feedback (encoders).

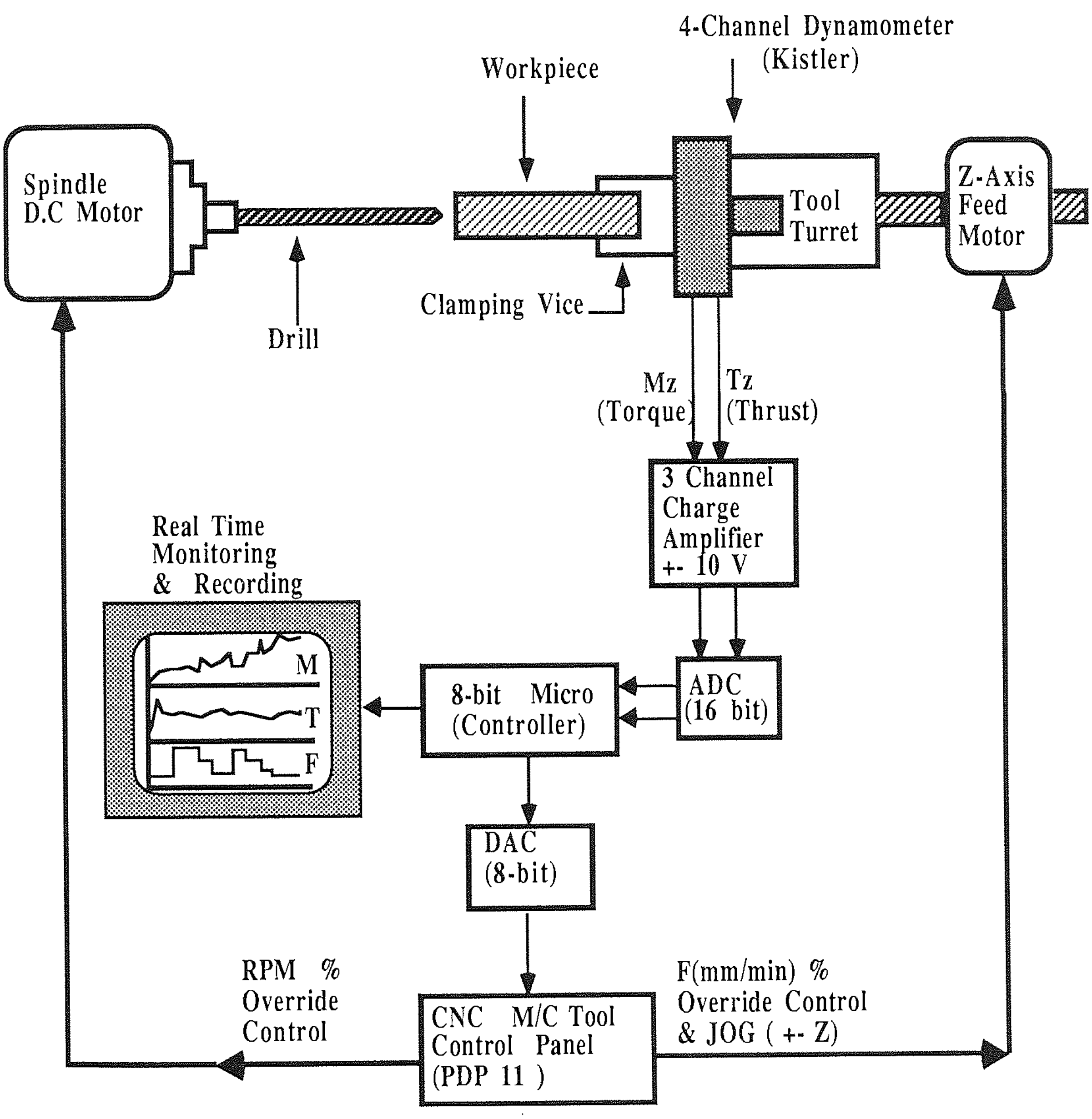


Fig. 6.1 : Schematic diagram of the system for Process Monitoring and Adaptive Control in CNC Deep Hole Drilling

6.3.2 Dynamometer and charge amplifier

The cutting forces were selected as the most suitable and reliable parameters to be monitored and be used for understanding and controlling the DHD process after a number of other transducers were considered such as a spindle power monitor and accelerometers for vibration monitoring (see also chapters 3 and 4 and Appendix III)

6.3.3 Computer (master control)

A BBC model B computer equipped with a second processor (6502) was used as the external computer to perform the tasks of data acquisition, real time monitoring and master control of the machining parameters, namely the feed rate, spindle speed and the $\pm$Z axis JOG control. The BBC-B computer was chosen for the following reasons :

- Inherently capable to perform Analogue to Digital conversions (built in 16-bit A/D) as well as to be interfaced with external devices simultaneously such as D/A (1 MHz data-bus), line-printer, etc.
- User friendly and easy to program.
- Readily available at low cost.

It should be mentioned that the code used (Basic and 6502 Assembly language) is not ideal for the complicated tasks of real time monitoring and control as well as data files handling; instead a high level language such as "C" or Pascal would be more appropriate. However, the main purpose of this research effort has not been the development of software for commercial purposes requiring state-of-the-art operating systems and high level languages.

The main effort was placed upon a general system analysis, identification of the particular problems encountered in DHD in an unmanned or limited manpower environment, availability and choice of the most suitable parameters to be monitored (e.g forces vs power or AE monitoring), data flow and access, and finally the investigation and development of suitable strategies (algorithms) for control of the process.

The CNC machine tool was interfaced with the BBC through the operator's control panel where the feed and spindle override controls reside (variable resistors) as well as the manual control of the +Z- axis (solid state or pulse coded switches). It is clear that in the case of designing an intelligent NC controller from the drawing board, the same computer which performs the basic NC functions should also perform the IM ones;

in the present system an external computer was adopted for the following reasons:

- Great difficulty in tracing circuitry and modifying the host CNC (PDP 11 microprocessor)
- Risk of damage as the PDP 11 lies away from the Machine Tool in an isolated cabinet.
- Minimal modifications required for interfacing the BBC to the Machine Tool and at a low cost.
- Design easily adopted for retrofitting to a CNC Machine Tool or Machining Centre.

6.3.4 Digital to Analogue Converter (D/A)

This in-house built device (fig. provides the feed-forward part of the control loop along with the other three elements: the computer, the feed drive servo, the spindle motor and the cutting process (fig. 6.8). It comprises three channels, each one with a $2^8 = 256$ resolution and controls the feed rate override, spindle speed override and a bank of solid state or pulse coded switches.

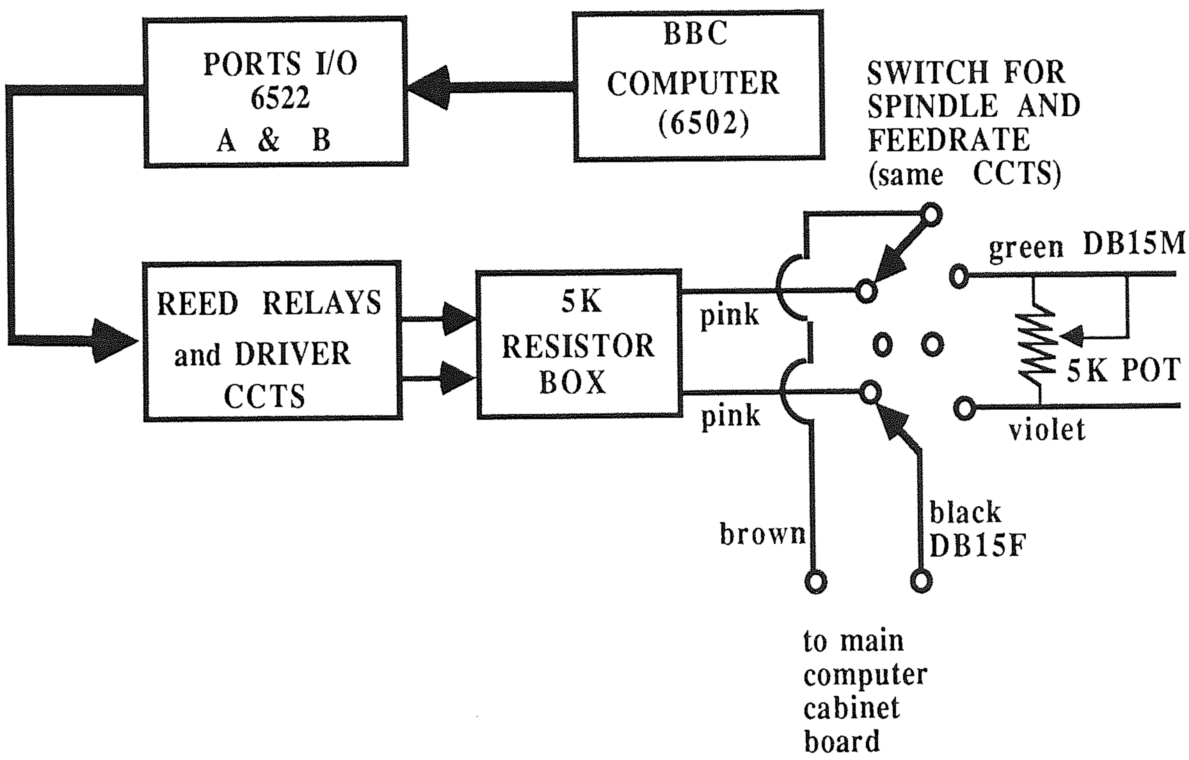


Fig. 6.2 : Schematic diagram of connections between A/D and CNC

(i). Feed rate and spindle speed control channels

The feed rate and spindle speed control channels are identical ; each has 8 resistors connected across the 5 volt supply of the override potentiometers giving a maximum of 5 kΩ when all connected or 0 kΩ when open. Thus, the sequence of digital values from 0 to 255 is mapped between 5000 to 0 Ohms.

For feed control this corresponds to the range from 200% to 0% of the nominal value (100%) in the NC program (F-word) and for the spindle speed override corresponds to the range form 75% to 125% of the NC programmed spindle speed (S-word).

In this way variations of the feed rate in steps of less than +/-1% and variations of less than +/- 0.25% for the spindle speed are possible. In practice, the nature of the cutting process and in particular the sensitivity of the drilling forces to variations of feed and cutting speed require adjustments of no less than +/- 10% for the purposes of AC. Of course the particular machining characteristics of each material also play a significant role in this matter.

Each one of the 8 resistors is controlled by one of the 8 bits of the binary value of the number between 0 = 00000000 to 255 = 11111111 (e.g a digital value of 134 = 10000110 corresponds to 94.9 % for the feed rate or 98.72% for the spindle speed.

The following example explains how feed rate control is achieved via the D/A. Assume a nominal value of penetration rate of 100 mm/min in the NC program, also assume that the control algorithm calculates a new value for the feed of 73.6 mm/min in order to reduce the chip thickness and hence the load on the tool accordingly. Then, the software is going to send to the D/A the following value produced by linear interpolation.

Digital value of feed rate = Integer {255x(1-73.6/200)} = 161

This in turn corresponds to a true feed rate of

True feed rate = 200x(255-161)/255 = 73.72 mm/min.

A similar method applies on the control of the spindle speed.

In the above analysis it is assumed that variations of feed rate of 100% in the range of 0% to 200 % are sufficient for AC purposes and indeed this has been the case with the present research work where variations of feed have actually been limited between 25% to 140% of the nominal value.

However the range 5000 to 0 Ohms can be mapped to the range between 0 % to any percentage required, simply by "misleading" the CNC, by means of specifying in the part program a feed rate value higher or lower than the one that drilling will actually take place.

Assume again that 100 mm/min is an experienced part programmer's choice of feed rate for a particular application and that for AC or any other purpose (e.g investigation of machineability parameters) the range over which the feed rate is variable should be well above the corresponding standard 200 mm/min limit, say 500 mm/min ; obviously 0% will always be the bottom limit since the feed rate cannot be negative.

Then, in the actual NC part program the value F250 is programmed rather than F100; on the other hand before machining starts, the computer sends via the D/A to the control panel the digital value 204 which will restrict the nominal feed rate to a value :

True feedrate = 500x(255-204)/255 = 100 mm/min

while a digital value of 0 (nil) would allow a feed rate of 500 mm/min to be achieved.

In practice, the wires which connect the computer with the CNC panel cause losses along the line, so a special calibration sequence was followed in order to find exactly what percentage of the feed rate or spindle speed is achieved for each one of the digital values 0 to 255 sent out.

(ii). Other functions of the D/A

A third 8-bit channel permits control of the following functions on the CNC panel by means of pulse coded or solid state switches (0 or 1) :

Bit 1 (value = 1) -Z : Motion of the workpiece towards the tool.

Bit 2 (value = 2) +Z : Motion of the workpiece away from the tool.

Bit 3 (value = 4) JOG : Disables AUTO / I and enables manual positioning in the ±Z and ±X axis. Under JOG mode the last position in the NC program is remembered and activating AUTO / I will permit machining to be resumed. Under JOG mode the spindle maintains its speed.

Bit 4 (value = 8) I : Starts the NC program.

Bit 5 (value = 16) AUTO : Enables the machine tool to execute an NC program.

Bit 6 (value = 32) SHIFT : Enables access to certain functions with two address levels such as INIT

Bit 7 (value = 64) INIT : Initialises the machine tool for another NC program.

Bit 8 (value = 128) STOP : Emergency stop which shuts down the machine tool.

Control functions 4, 5 and 8 are solid state switches in the CNC panel, the rest of the controls are pulse coded. This means that when operated manually a touch and release will activate the corresponding function; when controlled by the external computer the same effect is achieved by sending the corresponding signal through a variable OP, waiting for a few msec and sending back a zero.
For example, the sequence which follows enables the following :

?OP = 0 :	Clean up data bus for next command.
?OP = 4 :	Enable **JOG**
FOR J = 0 to 20	
NEXT J :	Send pulse for 1.3 milliseconds.
?OP = 2 :	Move away from drill along +Z axis.
FOR J = 0 to 2000 :	For 1.30 sec or 1.3 x F/60 mm in distance.
?OP = 0 :	Stop and be ready for next instruction.
?OP = 16 :	Enable **AUTO**.
FOR J = 0 to 20	
NEXT J :	Send pulse for 1.3 milliseconds.
?OP = 8 :	Enable **I** and start NC program where last left.

6.4 Position and velocity control (CNC)

6.4.1 General description

The analysis which follows refers to the Z-axis of the lathe but also applies to the X-axis although the latter is not used during drilling except for pre-process positioning (set-up). The control system for the two axis of the machine tool is of a "Sampled Data CNC system", **[157]**, **[168]** Koren, and the schematic diagram is shown in fig 6.3 while a simplified version of the loop, used for control analysis, is shown in figure 6.4

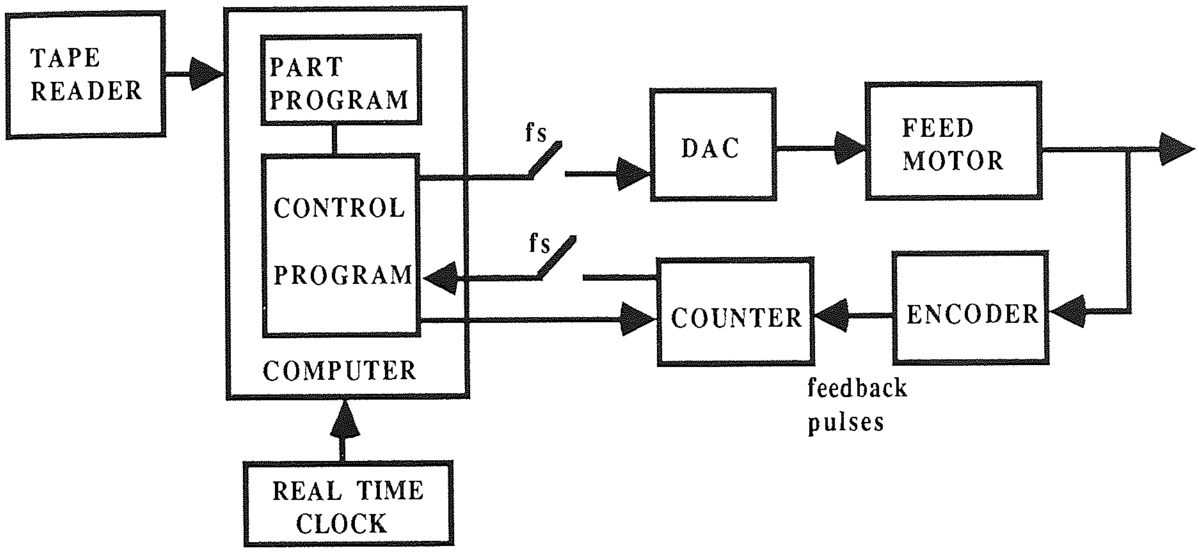


Fig. 6.3 Sampled-Data CNC system

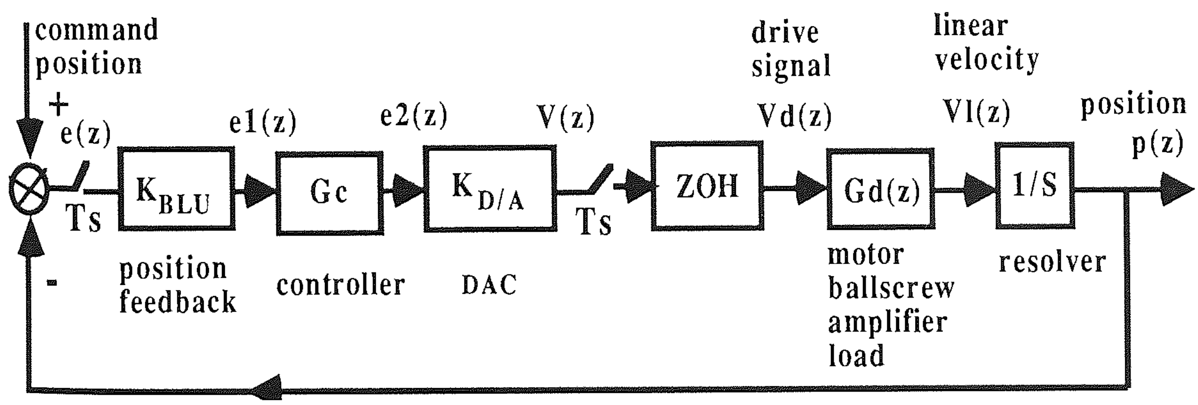


Fig. 6.4 : Simplified Block diagram of Sampled-Data CNC system

Referring to the block diagram (fig. 6.4) the following elements contribute to the CNC control loop :

I. Position Feedback

The feedback device used is a position encoder whose main feature is the Basic Length Unit (BLU) which is termed as the resolution of the feedback. From the technical data of the S 160 CNC it is taken 2μm for each axis equipped with a ball screw of 40mm diameter x 10 mm/rev pitch. The position encoders with which the CNC lathe has been fitted have a resolution of 5000 pulses/rev. According to the definition in works [157] and [170] Koren, it is found that :

$$1 \text{ BLU} = \text{pitch / pulses per rev} = 10/5000 = 2\ \mu m \qquad (6.1)$$

while the feedback gain is given by :

$$K_{BLU} = e_1(z) \,/\, e(z) = 5000/10 = 500 \text{ BLU/mm} \qquad (6.2)$$

II. Computer Control

In a Sampled Data System the position and velocity control is performed in the software. The computer samples the feedback signal at a sampling intervals of T_s (ms) and compares it with the reference signal. The resulting error is transmitted at a uniform rate through a signed 12 bit D/A to the feed servo motor. The corresponding proportional gain, referring to fig. 6.2 is :

$$G_c = e_2(z) \,/\, e_1(z) = K_c = 1 \text{ pulse/ BLU} \qquad (6.3)$$

The sampling interval for the system examined is given in the technical specifications of the CNC is : $T_s = 10$ msec (6.4)

The signed 12-bit D/A ($2^{11} = 2048$) outputs a drive signal of ± 12 V which results in a gain

$$K_{DAC} = V(z) \,/\, e_2(z) = 12/2048 = 5.86 \text{ mV/pulse} \qquad (6.5)$$

Because the system operates in a discrete time it is required to include in the analysis a zero order hold (ZOH) whose transfer function is $G_{ZOH} = (z-1)/z$

The overall gain then is given by :

$$G_{pc} = V(z) \,/\, e(z) = K_{BLU}\, K_c\, K_{DAC} \qquad (6.6)$$

III. Feed drive servomotor / amplifier / load

Type Inland TT 2923 motors are used for both axes equipped with a tachogenerator for velocity feedback and pulse-width modulated DC amplifier. Although a detailed analysis would result in a complicated system, various researchers have proposed the applicability of a second order open-loop transfer function for the system

(Koren **[158]**, **[159]**, **[170]**), and the corresponding open loop transfer function is :

$$G_{Do}(s) = \frac{K}{s(\tau s+1)} \tag{6.7}$$

and the corresponding closed-loop transfer function is :

$$G_D(s) = \frac{K}{\tau s^2 + s + K} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{6.8}$$

Where **K** is the feed drive constant (amplifier-motor-load-gain) with

K= (max. velocity) / (max.input voltage)

$$K = 10.0 \text{ m/min} / 10 \text{ V} = 1 \text{ m/min /V} = 16.7 \text{ mm/sec / V} \tag{6.9}$$

$$\tau = 5 \text{ ms} \tag{6.10}$$

The mechanical time constant τ was measured by applying a square-wave to the amplifier input and measuring the response of the tachogenerator output on a storage oscilloscope.

6.4.2 Overall analysis of the position feedback loop

The corresponding discrete-time transfer function of the ZOH-amplifier-feed motor is then given by the following expression referring to fig. 6.5 :

$$G_D(z) = p(z) / v(z) \qquad (6.11)$$

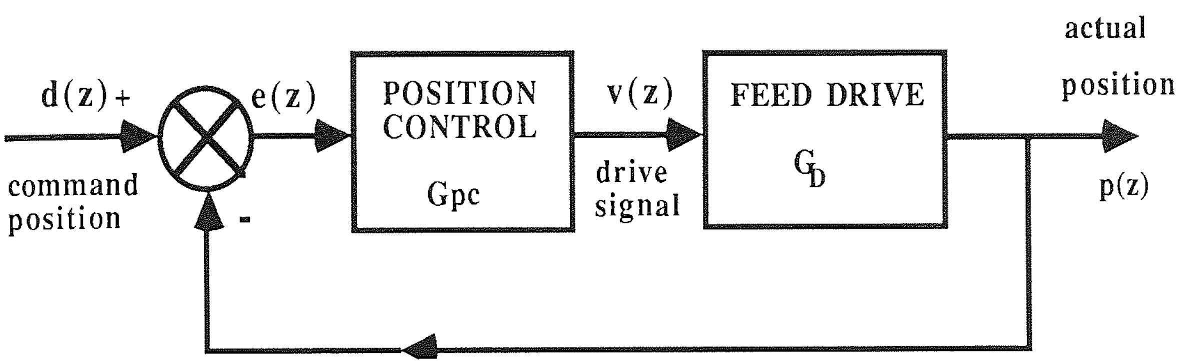


Fig. 6.5 : Simplified position control block diagram

applying the z-transform the two elements (ZOH and the feed drive) gives :

$$G_D(z) = Z\left[\frac{1-e^{-sT}}{s^2}\,\frac{K\tau^{-1}}{s+\tau^{-1}}\right] = K\ Z\left[1-e^{-sT}\right]\ Z\left[\frac{\tau^{-1}}{s^2(s+\tau^{-1})}\right] \qquad (6.12)$$

using standard tables of the z-transform we obtain :

$$G_D(z) = K\ (1-z^{-1})\ \left[(Tz/(z-1)^2\ -\ (\tau\ (1-A)z\ /\ (z-1)(z-A))\right] \qquad (6.13)$$

$$\text{where}\quad A= e^{-T/\tau} = e^{-10/5} = 0.1353 \qquad (6.14)$$

$$G_D(z) = K\left[\frac{T(z-A) - t(1-A)(z-A)}{(z-1)(z-A)}\right] = K\frac{(5.67\ z + 2.97)}{(z^2-1.135z - 0.135)} \qquad (6.15)$$

therefore, the closed-loop transfer function of the position feedback loop is:

$$G_p(z) = \frac{p(z)}{d(z)} = \frac{G_{nc} G_D}{1 + G_{nc} G_D} \tag{6.16}$$

K_{op} is the overall position gain :

$$K_{op} = G_{nc}\ K = K_{BLU}\ K_c\ K_{DAC}\ K \tag{6.17}$$

K_{BLU} = 5000 / 10 = 500 BLU / mm
K_c = 1 pulse / BLU
K_{DAC} = 12 / 2048 = 5.86 mV / pulse
K = 10.0 / 10 = 1 m/min /V = 16.7 mm/sec / V

$$K_{op} = K_{BLU}\ K_c\ K_{DAC}\ K = 500 \times 5.86 \times 1 \times 16.7 / 1000 = 49\ \text{sec}^{-1} \tag{6.18}$$

(The above value is the theoretical one and in practice is expected to be slightly different)

The closed-loop transfer function of the position loop in (6.16) can be written as :

$$G_p(z) = K_{op} \frac{[\ a z + b\ ]}{[\ z^2 + cz + d\ ]} \tag{6.19}$$

where $a = T - \tau (1-A) = 10 - 5\,(1 - 0.1353) = 5.67$ (6.20)

$b = \tau (1-A) - TA = 5\,(1 - 0.1353) - 10\,(0.1353) = 2.97$ (6.21)

$c = K_{op}\,a - (1+A) = 49\,(5.67) / 1000 - (1 + 0.1353) = -1.075$ (6.22)

$d = K_{op}\,b + A = 49\,(2.97) / 1000 + 0.1353 = 0.281$ (6.23)

substituting the above values into (6.19) then gives :

$$G_p(z) = 49 \frac{[\ 5.67\, z + 2.97\ ]}{[\ z^2 - 1.075\, z + 0.281\ ]} \tag{6.24}$$

From the denominator of the closed loop transfer function above the poles of the discrete time transfer function can be calculated :

$$Z^2 - 1.075\ Z + 0.281 = 0 \quad \text{gives :} \quad Z_1 = 0.626\ , \quad Z_2 = 0.448 \qquad (6.25)$$

Both poles are real, which suggests that the system is overdamped with no oscillatory response to a step input. The equivalent system representation in the Laplace domain is obtained by the transform $Z = e^{ST}$ which gives :

$$S_1 = 1000/10\ \ln\ (0.626) = -46.8 \quad (\text{rad /sec}) \qquad (6.26)$$
$$S_2 = 1000/10\ \ln\ (0.448) = -80.3 \quad (\text{rad / sec}) \qquad (6.27)$$

the natural frequency is $\omega_n = (S_1 S_2)^{0.5} = 61.3$ (rad / sec) (6.28)
and the damping ratio $\zeta = - (S_1 + S_2) / 2\ \omega_n = 1.036$ (6.29)

The corresponding second order transfer function of the position-loop in the s-domain is given by the following expression :

$$G_p(s) = \frac{\omega_n^2}{(s^2 + 2\zeta\omega_n s + \omega_n^2)} \qquad (6.30)$$

Since the system is overdamped (z > 1) and has one dominant pole the above expression can be further approximated with a first order system

$$G_p(s) = p(s) / d(s) = [1 + \tau_1 s\ ]^{-1} \qquad (6.31)$$

i.e the time constant $\tau_1 = -1/S_1 = 1/46.8$ sec = 21.4 msec, of the first order system is approximately equal to that corresponding to the dominant pole. This assumption was checked experimentally (fig. 6.6 and 6.7) by examining the the response of the demand position to step input and the rise time of 25 msec was found to be in good agreement with the expected value.

6.5 Drilling torque and thrust feedback loop

The feedback loop for the monitoring and control of the two forces is represented schematically in the block diagram of figure 6.6 below.

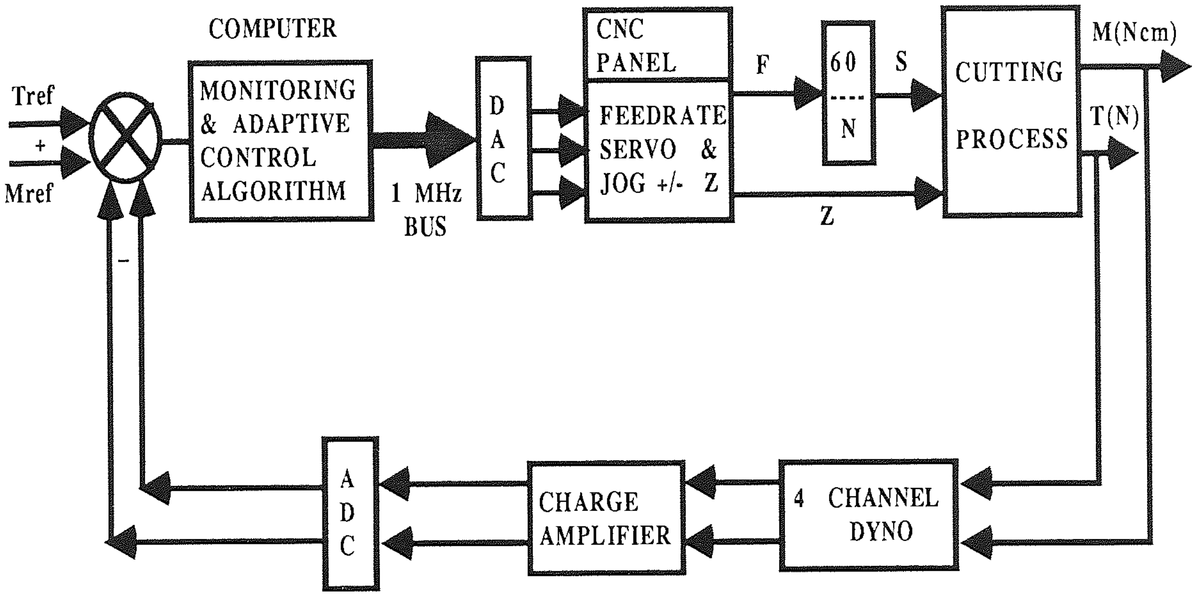


Fig. 6.6 : Overall block diagram of the forces feedback loop

With reference to the above diagram the feedback loop for the thrust and torque (actually two loops) comprises the following elements :

6.5.1 Cutting Process

A number of researchers have proposed the applicability of a first order model [158] Koren, [159] Masory, in order to describe the dynamics of the metal cutting process with a time constant τ_c proportional to the frequency of the spindle speed.

Other researchers have proposed a second order model, [156] Stute-Goetz, [160] Tomizuka, with a damping ratio of 0.8 and a time constant inversely proportional to the spindle speed.

Experiments carried out (examples shown in figs 6.7, 6.8), where a step input in feedrate was used in order to investigate the dynamics of drilling torque and thrust, suggest that a first order system could be used in first approximation, if drilling is to be considered as a process rather similar to turning than milling. A first order system also simplifies the analysis and reduces the overall order of the system.

For a first order system the following relationship exists between the cutting force at time t and the steady state force Δ_{ss}, the symbol Δ being used for both the drilling thrust (T) and torque (M) :

$$\Delta(t) = \Delta_{ss} \left(1 - \exp\left(-t / \tau_c\right)\right) \tag{6.32}$$

the time constant of the lag is: $\tau_c = (60/N) / 2$ equal to the duration of half a revolution of the spindle.

The steady state values for the drilling thrust and torque are related to the feed f and cutting speed v of the tool with relationships of the type:

$$T_{ss} = C_T f^a v^x d^p = C_1 F^a N^{x-a} = C_2 F^a \tag{6.33}$$

$$M_{ss} = C_M f^b v^y d^q = C_3 F^b N^{y-a} = C_4 F^b \tag{6.34}$$

where $C_1 = C_T \pi^y d^{p+x} 10^{-3x}$ and $C_2 = C_1 N^{x-a}$ are constants for a given diameter and spindle speed, C_T, C_M correspond to the specific cutting thrust, torque, f is the feed/rev $f=F/N$, v is the surface speed of the tool , $v=\pi dN/1000$, and d is the diameter of the tool (depth of cut).

From the expression $T_{ss} = (K_1 F^{a-1}) F$ and similar one for torque $M_{ss} = (K_2 F^{b-1}) F$, (with $K_4 = K_3 N^{y-b}$, $K_3 = K_M \pi^y d^{q+y} 10^{-3y}$) the transfer functions for each one of the two forces of the cutting process is given by the following expressions :

$$G_T(s) = \frac{T(s)}{F(s)} = \frac{C_2 F^{a-1}}{\frac{30}{N} s + 1} \tag{6.35}$$

$$G_M(s) = \frac{M(s)}{F(s)} = \frac{C_4 F^{b-1}}{\frac{30}{N}s + 1} \qquad (6.36)$$

6.5.2 Dynamometer - Charge Amplifier - A/D

These elements of the forces feedback loop contribute only as pure gains ; unlike strain gauge dynamometers which have a first order transfer function between the actual and the measured cutting force a piezoelectric dynamometer has only a gain contribution to the loop. The combined gain of the force transducer, charge amplifier and A/D is given by :

$$KT_{tr} = 1 \,/\, (\text{A/D resln}) \times (\text{Thrust Amplif. Scale})$$
$$KT_{tr} = 1 \,/\, (10 \times 2^{-15} \times 200) = 16.38 \text{ dig. inc.} \,/\, N \qquad (6.37)$$

$$KM_{tr} = 1 \,/\, (\text{A/D resln}) \times (\text{Torque Amplif. Scale})$$
$$KM_{tr} = 1 \,/\, (10 \times 2^{-15} \times 200) = 16.38 \text{ dig. inc} \,/\, Ncm \qquad (6.38)$$

(200 N/Volt and 200 Ncm/V were the amplification scales for thrust and torque respectively in the series of tests conducted).

The gain of the process in expressions (6.36) and (6.37) contains the terms F^{a-1} and F^{b-1} for thrust and torque respectively and it can be seen that the process is actually non-linear, while the indices **a, b** depend on the workpiece material and to the tool point geometry.

From the experimental work carried out and presented in chapters 3 and 4 it was made possible to identify values for the coefficients **a**, **b**, C_3, C_4 ; the approach however which is followed during the application of the system is one in which the above values are considered unknown and are identified on-line by the system (section 7.3.4).

The rationale behind this approach is two-fold : first of all the system is designed to achieve reliable process monitoring and control with any combination of drill type and workpiece material. In this case a-priori knowledge of these parameters implies a great amount of experimental work in production environment which is clearly not practical or even desirable.

Second is that even with the availability of resources and time to carry out the experimental work one could not consider the derived data as totally reliable since variation in the workpiece hardness from one batch to another can go undetected and in addition, as the tool wears these parameters are also bound to change. The need therefore is clear for a sytstem which would be independent of such data and would automatically modify the machining parameters in a manner very similar to that of an experienced operator performing the process manually, on a drill press or a conventional lathe for example, using his eyes, ears and hands as sensors.

Various researchers have described such systems for Adaptive Control and Process Monitoring in DHD Tuffentsammer **[105]**, Lehler **[109]**, Cronjäger **[110]**, and some of the characteristics of these systems, such as digital control, use of force and torque monitoring are present in the proposed system. There is one fundamental aspect however which appears to have received little attention in DHD.

This is the capability to perform pecking (tool withdrawal and reentry) when necessary. Pecking is the equivalent of automatic cut distribution in turning and milling and it was made clear in chapters 3 and 4 that it is an essential element of any control strategy which attempts to eliminate the instability of the DHD process.

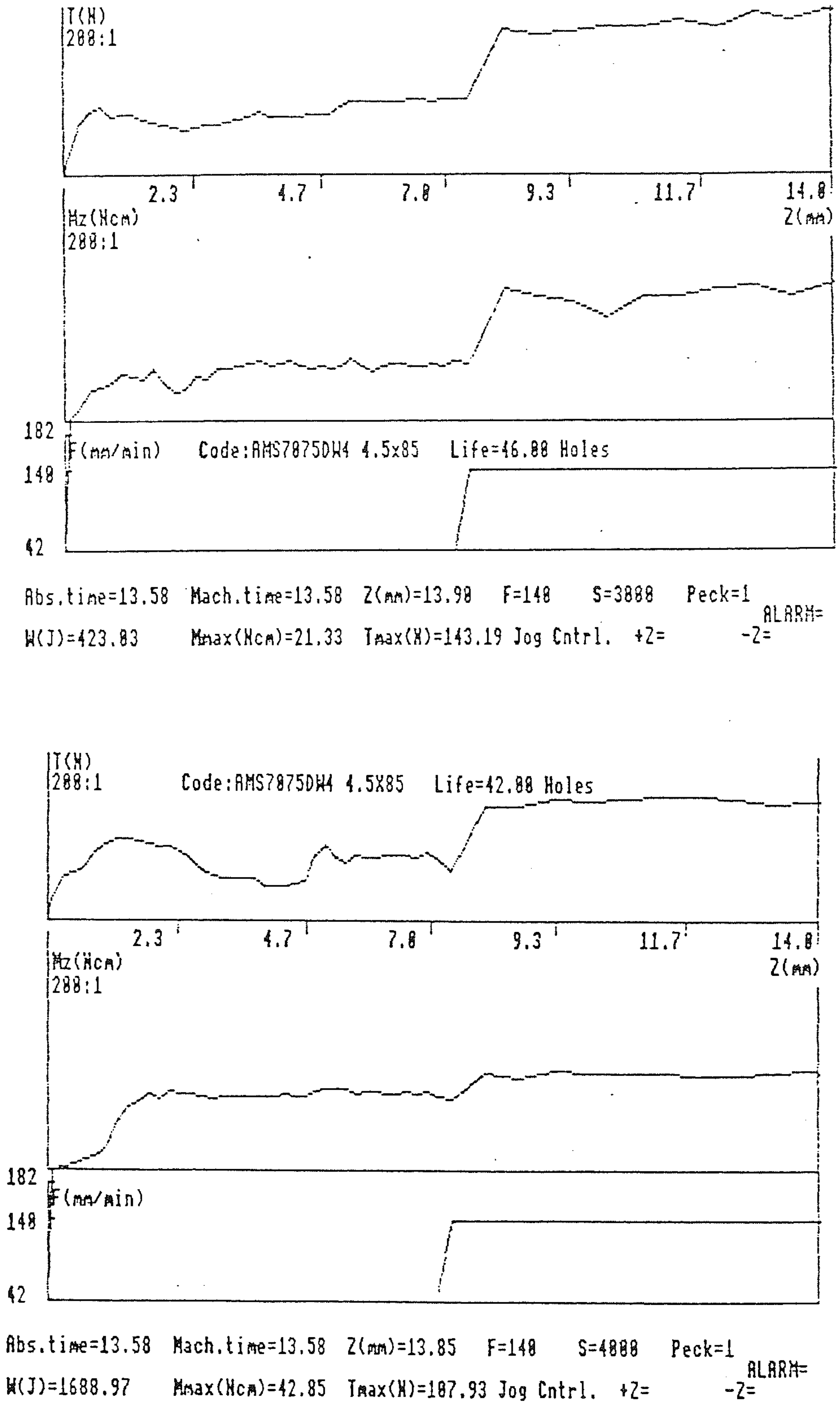
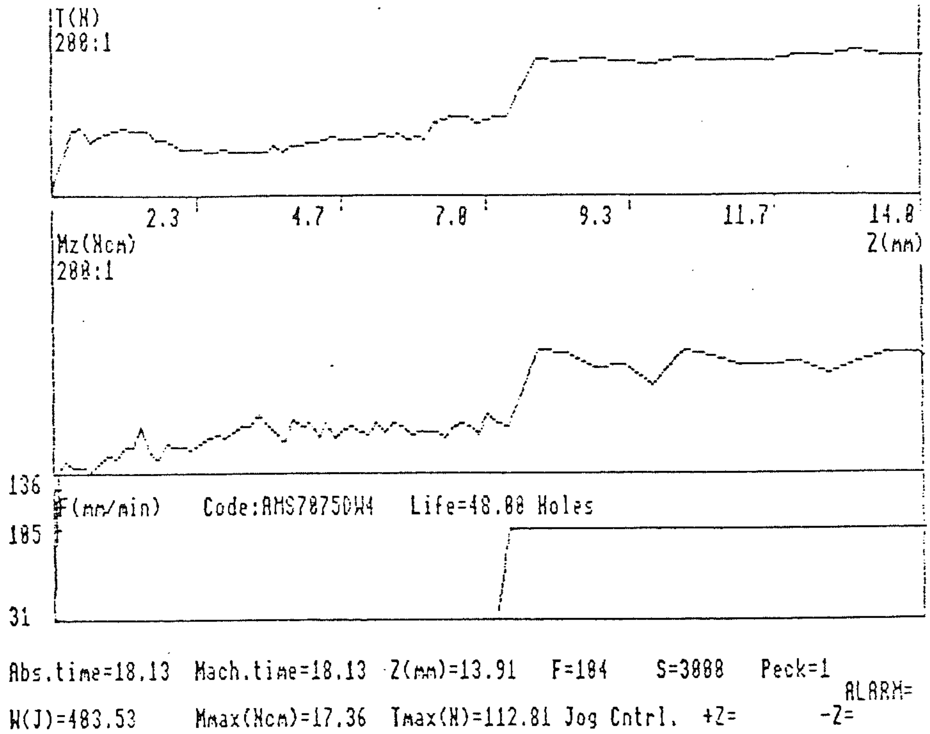


Fig. 6.7 : System response to step input of feedrate (42 to 140 mm/min)



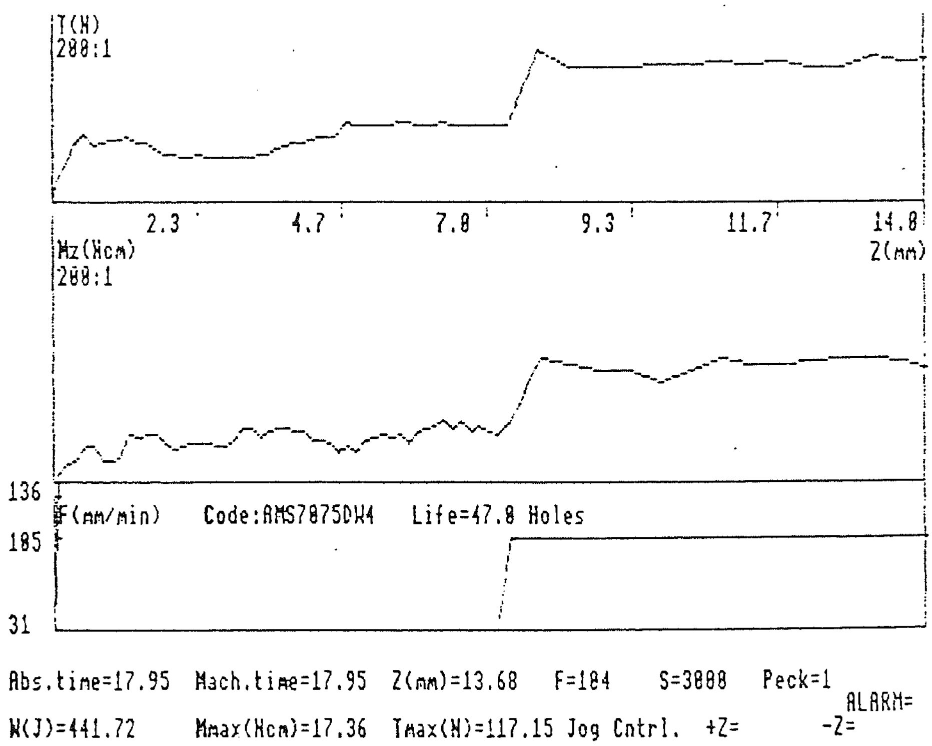


Fig. 6.8 : System response to step input of feedrate (31 to 105 mm/min)

6.5.3. Digital Controller and Control Algorithms

Control is implemented mainly by the software on the microcomputer. At each sampling period the error is computed for each of the two monitored parameters, thrust and torque, manipulated according to the control strategy (algorithm) and then the digital feed rate and spindle speed is output to the CNC via the D/A and the 1MHz data bus of the microcomputer.

The simplest controller is one of proportional type P while the most complete controller is a PID controller where the corrective action is proportional to the current value of the error as well as the integral of the error in order to achieve a zero-steady state error.

Since various controllers have been implemented and tested the general notation $G_c(s)$, $G_c(z)$ will be used to denote the software controller's transfer function in the s and z domain respectivelly ; this helps to simplify the analysis.

(i). Algorithm P (proportional control)

The simplest strategy for a proportional non linear controller is to command a new feed rate such that the new steady state plus the error will equal the reference value.

For the thrust : $$T_i - T_{ref} = T_{ref} - C_2 F_i^a \qquad (6.39)$$

and for the torque : $$M_i - M_{ref} = M_{ref} - C_4 F_i^b \qquad (6.40)$$

Hence the new feed rate value is : $$F_{pi} = [(2\,\Delta_{ref} - \Delta_i)/K_\Delta]^{1/\delta} \qquad (6.41)$$

The parameters Δ, δ represent either torque or thrust. It is obvious that the theoretical minimum possible feed rate with this algorithm is nil, corresponding to a two-fold increase of either the thrust or torque. In practice however a realistic higher value is implemented, for example 25% of the nominal value.

(ii). Algorithm PID (proportional-integral-derivative)

The equation describing the action of a PID controller for a time domain input $x(t)$ and output $y(t)$ is :

$$y(t) = K_p\, x(t) + K_i \int x(t)dt + K_d\, dx(t) / dt \qquad (6.42)$$

or $$y(t) = K_p \left[x(t) + (1/T_i) \int x(t)dt + T_d\, dx(t) / dt \right] \qquad (6.43)$$

where $$K_p, \quad K_i = K_p / T_i, \quad K_d = K_p T_d \qquad (6.44)$$

are the proportional, integral and derivative gains respectively and T_i, T_d are the integral and derivative action times. In a discrete time analysis the above equation is conveniently replaced by taking $t = n\, T_s$ where n is an integer and T_s is the sampling period (msec).

The discrete time output then is : $y(n) = y_p(n) + y_i(n) + y_d(n)$ (6.45)
where the three terms are :

$$y_p(n) = K_p\, x(n) \qquad (6.46)$$

$$y_i(n) = (K_p / T_i)\, T_s \, {}_1\sum^n x = y_i(n-1) + (K_p / T_i)\, T_s\, x(n) \qquad (6.47)$$

(trapezoid rule)

$$y_d(n) = (K_p T_d / T_s) \{x(n)-x(n-1)\} \qquad (6.48)$$

(difference quotient)

substituting into (6.45) gives :

$$y(n) = K_p \left[x(n) + (T_s/T_i)\, x(n) + (T_d/T_s) \{x(n)-x(n-1)\right] + y_i(n-1) \qquad (6.49)$$

the last term can be expressed as :

$$y_i(n-1) = y(n-1) - y_p(n-1) - y_d(n-1) \qquad (6.50)$$

substituting (6.44) into (6.50) gives :

$$y_i\,(n-1) = y(n-1) - K_p\,x(n-1) - (K_p T_d / T_s)\left\{x(n-1) - x(n-2)\right\} \quad (6.51)$$

which when substituted into (6.49) gives:

$$\begin{aligned} y(n) = y(n-1) + K_p \Big[& x(n) \; \{(T_s/T_i) + (T_d/T_s) + 1\} - \\ & -x(n-1)\{(T_d/T_s) + 2\} + \\ & +x(n-2)\{(T_d/T_s)\} \Big] \end{aligned} \quad (6.52)$$

or the equivalent simplified expression :

$$y(n) = y(n-1) + P_1\,x(n) + P_2\,x(n-1) + P_3\,x(n-2) \quad (6.53)$$

where $P1 = K_p\,\{(T_s/T_i) + (T_d/T_s) + 1\}$ (6.54)

$P_2 = -K_p\,\{(T_d/T_s) + 2\}$ (6.55)

$P_3 = K_p\,\{(T_d/T_s)\}$ (6.56)

The three important parameters K_p, K_i, K_d which determine the performance of the controller are derived from the characteristics of the transfer function for the control loop.

The differential equation for a PID controller was derived earlier as follows :

$$y(n) = y(n-1) + P_1\,x(n) + P_2\,x(n-1) + P_3\,x(n-2) \quad (6.57)$$

The corresponding z-transform is obtained by means of using standard z-transform tables.

The shift to the right is given by :

$$Z\{f(n - r)\} = z^{-r}\,f(z) \quad (6.58)$$

Then : $y(z) = y(z)\,z^{-1} + P_1\,x(z) + P_2\,x(z)\,z^{-1} + P_3\,x(z)\,z^{-2}$ (6.59)

$$y(z)\,(1 - z^{-1}) = x(z)\,(P_1 + P_2\,z^{-1} + P_3\,z^{-2}) \quad (6.60)$$

and the transfer function for the PID controller is given by :

$$G_c = y(z) / x(z) = (P_1 + P_2\,z^{-1} + P_3\,z^{-2}) / (1 - z^{-1})$$

or $G_c = y(z) / x(z) = (P_1\,z^2 + P_2\,z + P_3) / (z^2 - z)$ (6.61)

(iii). Algorithm PC (predictor corrector)

This ad-hoc derived algorithm is a one-step predictor corrector, i.e the corrective action aims to be effective on the (i+1)-th sample based on the error detected on the i-th sample and assumes that the error is proportional to the time between two successive intervals. A schematic representation is shown in the next figure 6.9

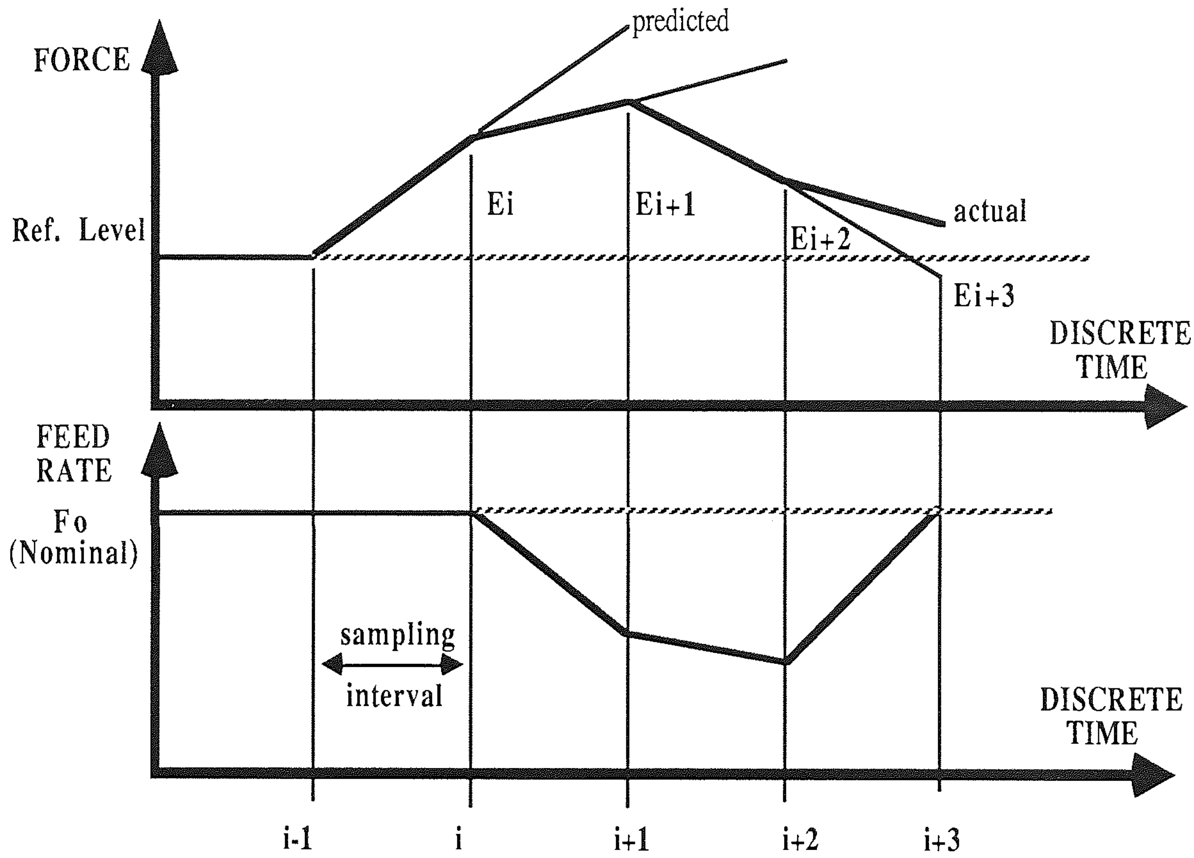


Fig. 6.9 : Algorithm Predictor Corrector

The predictor corrector algorithm was devised as an alternative to the PID algorithm that would require a smaller number of calculations on-line, would be able to cope with two input parameters (thrust and torque) and would take into account both the instantaneous as well as previous values of the error.

The PC algorithm comprises the following steps :

- Calculation of actual maximum error (Δ represents either thrust or torque).

$$E(i) = \Delta_i - \Delta_{ref} \tag{6.62}$$

- Calculation of predicted error.

$$E(i+1)_{pred} = E(i-1) + 2\{E(i) - E(i-1)\} = 2E(i) - E(i-1) \tag{6.63}$$

- Calculation of feed reduction to compensate for error.

$$E'(i) = E(i+1)_{pred} / K_\Delta = -(f_{i+1}{}^a - f_i{}^a) \tag{6.64}$$

- Calculation of new value of feed :

$$f_{i+1}{}^a = f_i{}^a - E'(i) \tag{6.65}$$

- Taking into account the initial condition $f_1 = F_0 / N$

$$f_{i+1} = \{f_i{}^a - E'(i)\}^{1/a} \tag{6.66}$$

New value of feed rate :

$$F_{i+1} = N f_{i+1} \tag{6.67}$$

The predictor corrector is implemented in the software according to the magnitude of the error (multilevel control strategy) described in detail in chapter 7.

6.6. Overall analysis of the thrust and torque feedback loop

From the above analysis it is seen that the open loop transfer function of the controlled process in the s-domain or z-domain depends on the control algorithm. The overall transfer function of the digital controller for each loop is given by :

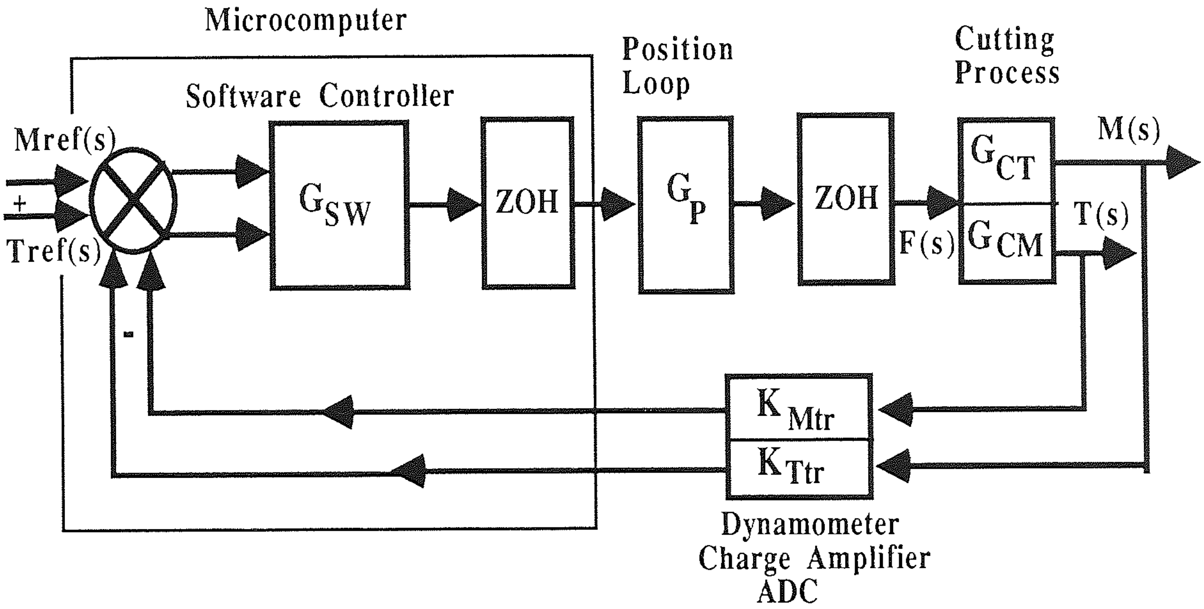


Fig. 6.10 : Simplified diagram of the thrust and torque loop

$$D_M(s) = KM_{tr}\, G_M(s)\,, \quad D_T(s) = KT_{tr}\, G_T(s) \qquad (6.68)$$

Therefore the simplified torque closed-loop has the following transfer function :

$$H_T(z) = G_{SW}\, G_P\, G_T \,/\, (1 + G_{SW}\, G_P\, G_T) \qquad (6.69)$$

And similarly the simplified thrust closed-loop has the following transfer function :

$$H_M(z) = G_{SW}\, G_P\, G_M \,/\, (1 + G_{SW}\, G_P\, G_M) \qquad (6.70)$$

Taking as an example expression 6.70, for the torque loop, it can be seen that the overall gain depends on the software controller gain G_{SW} and the process gain G_M where the latter is greately dependent on spindle speed **N** as shown by expression 6.36.

The overall gain can increase due to either an increase in controller gain or an increase in cutting process gain. Ideally the controller gain should be fixed so that it gives critical damping for a known cutting process gain, but this is not possible due to the unpredictable nature of the operation.

Hence some method of parameter adaptive control is necessary in order to achieve adequate performance over a range of cutting conditions. Changes in spindle speed **N** for instance, or workpiece material (constants C_4 and **b**) have an effect on G_M and this can be compensated by changing the software controller gain.

Another situation which needs to be catered for is when it is the drilling thrust as opposed to the drilling torque that imposes the greatest threat to the safety of the tool or the integrity of the process. For example, while there is no swarf clogging of the drill flutes which would cause alarming levels of torque to appear during a sampling cycle, a hard spot or inclusion in the workpiece would certainly affect the drilling thrust. In this case the controller should take corrective action according to the dynamics of the drilling thrust which is characterised by a different transfer function and steady state constants.

An approach which aims to eliminate the risk of catastrophic failure which would result from the inadequacy and poor design of a rigid, fixed gain controller, is attempted by using a multilevel control strategy which depends on the magnitude of the error between the reference and actual (sampled) value of drilling thrust or torque. Unique to the case of DHD amongst metal cutting processes is the addition of automatic tool withdrawal and reentry (pecking) as a one of the options for corrective action by the contoller. The approach is presented and documented in chapters 7 and 8.

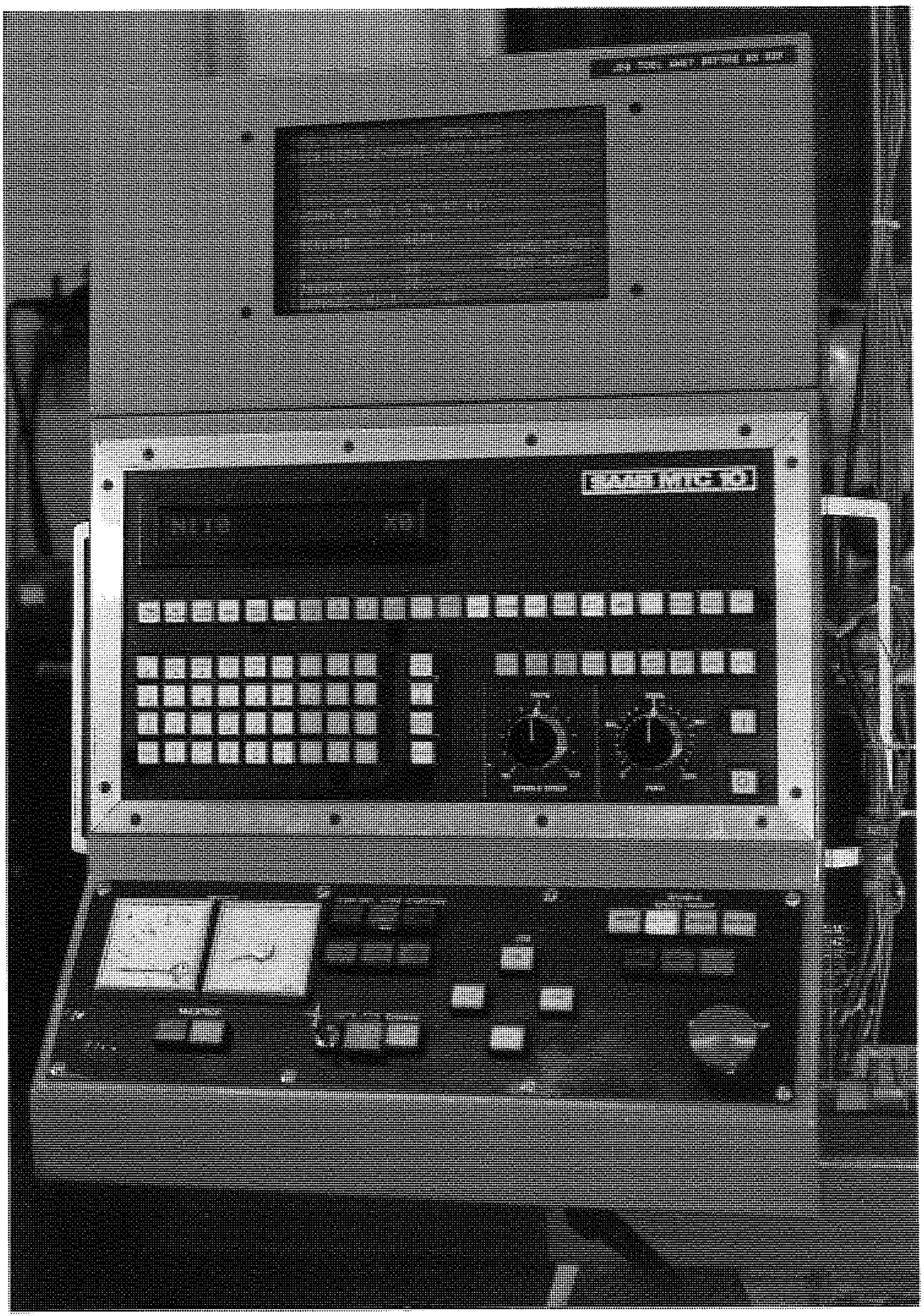


Fig. 6.11 The CNC panel of the Torshälla SAAB MTC-10 lathe
Control is performed by a PDP 11 microprocessor

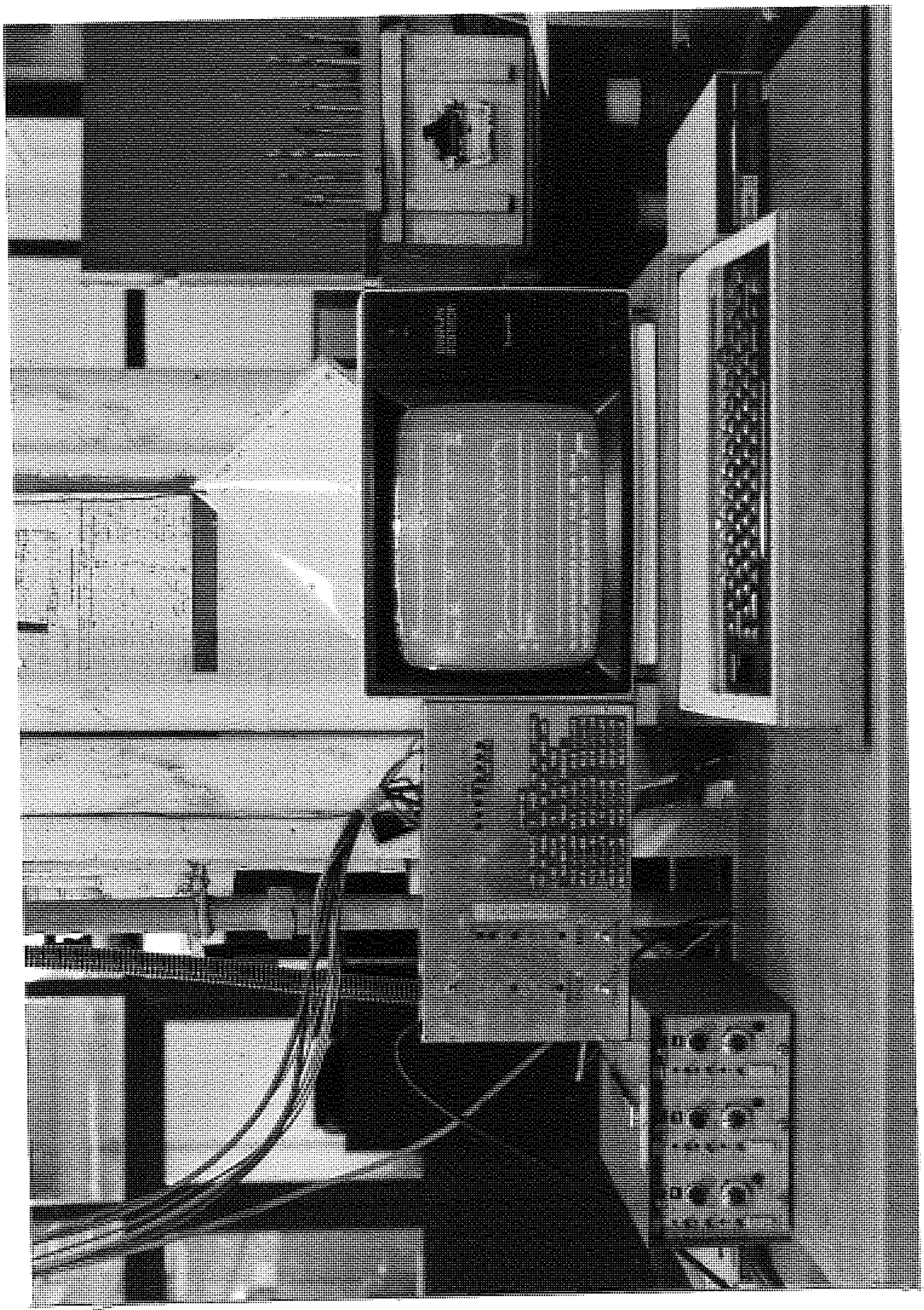


Fig. 6.12 Process Monitoring and Adaptive Control System :
Thrust and Torque transducer --> A/D --> computer (real time display, analysis) --> D/A (feed rate, spindle speed, Z-axis position) --> CNC

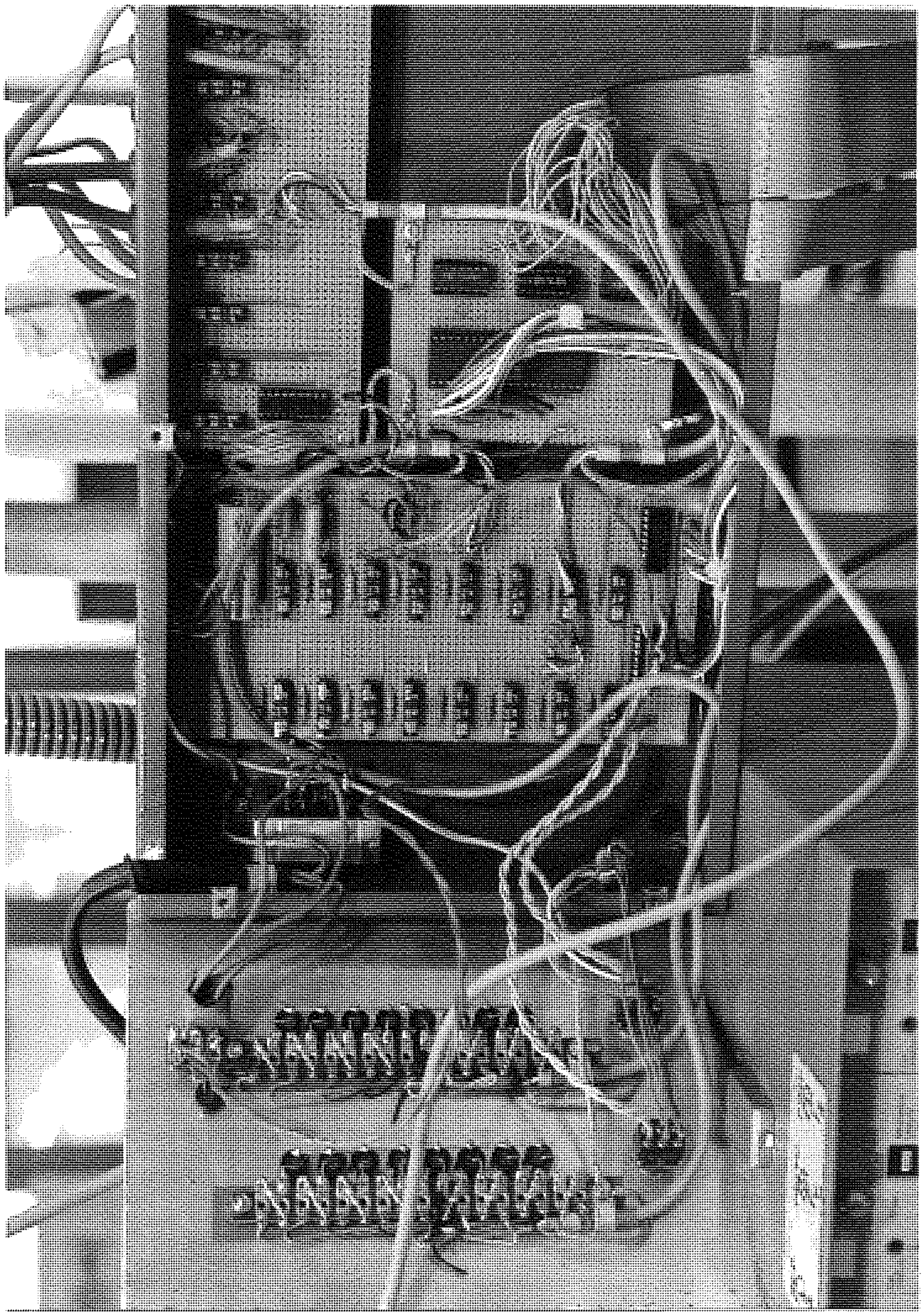


Fig. 6.13 Internal view of the in-house built DAC for control of the machine tool. Interface through switches and overrides on the CNC panel

CHAPTER 7

SYSTEM ANALYSIS AND FUNCTIONS

This chapter describes the flow of data in and out of the master control computer, its communication with the other elements of the system and the main functions of the latter, all implemented in the software. The computer serves a numbers of roles the most important of which are the data acquisition from the force transducer, the processing of the input signals and the manipulation of the three main parameters of the process, i.e the feed rate, spindle speed and tool position.

Secondary tasks include the updating of data files containing process data and tool life data and also the execution of graphics subroutines for real time or off-line display of the process parameters. These graphics subroutines would not be included in the system under actual production conditions but are extremely useful for a compact, quick and efficient analysis of the system performance.

7.1 General Description

The system software consists of two main modules, A and B. Module-A is the off-line processor and consists of 2 main programs:

Program **SET-UP** is an interactive, user friendly program written in basic which serves 3 purposes:

- Data acquisition from the operator regarding the metal cutting process, i.e feeds, speeds, tool geometry, workpiece material, etc.
- Creation of data files where the above data is stored and is accessible by the operator for updating, expansion, modification etc.
- Check by the computer of the two main parameters in machining, i.e the feed/rev and the tool surface speed against static calculations of tool strength limits (e.g fracture in buckling or torsion) and also against a range of feeds and speeds recommended form experience for each material ; the latter are held in a data base

Module-B is the main software code under the name **RLTME** : It comprises various subroutines written in BASIC and Assembly 6502 code and operates around a 2 MHz clock and the 16-bit 4-channel ADC of the BBC. At present only two of the input channels are used, one for the torque and the other for the feed force or thrust, while the conversion time is 10 msec per channel.

7.2 Off-line module

7.2.1 Program SET-UP

This program acquires from the operator the basic data concerning the next machining operation. A machining (DHD) operation is uniquely defined by an alphanumeric code which is the name of a data file.

If an operation has been previously defined and the data is already stored in the data-base then the operator is informed accordingly and has three basic options :

- Abort
- Open the file and inspect / modify the data (program INTERM)
- Open a new file (program SET-UP).

The data which the computer requires from the operator are the following :

1. **Name and type of the machine tool** or machining centre to perform the operation.
   (Each machine tool is identified by an alphanumeric code (variable MAC$) which is held in a data file by the name MACTL. In the present work MAC would take the default value MAC$ = "TORSHÄLLA S160".

2. **Work-piece material :** again a unique alphanumeric code (WMT$) identifies the material to be drilled. All the used materials are held in the data base in a file called WMATL ; other parameters regarding the material held in this data file are :
   Brinell hardness (BHN) which is used in the static calculations of strength for the tool and therefore the determination of the maximum initial feed rate.
   Work-piece code : alphanumeric code to identify components made of the same material (WP$).
   The recommended by experience machining conditions, i.e the working feed/ rev f_{max} , f_{min} (mm/rev) and cutting speed V_{max} , V_{min} (m/min)

3. **Tool data :** each tool is identified by a unique alphanumeric code which specifies the tool manufacturer, tool material and any special feature (e.g TiN coated). The following data is also held in the data file :
   Tool Diameter : D(mm) ;
   Tool overhang : L_0 (mm), necessary for maximum feed calculations ;

Tool working length : L_W (mm) i.e drill flute length;
Tool clearance : Z_0 distance in (mm) between tool tip and work-piece face ;

4. **Tool-life status :** three parameters describe the tool-life status :
Number of holes drilled HN
Cumulative cutting time LF_t (min)
Cumulative cutting distance LF_z (mm) these three parameters are automatically updated at the end of each operation performed by the tool and are used for off-line tool wear tracking.

5. **NC program depth** : Z_{NC} (mm)
Maximum penetration depth : Z_{max} (mm) , the computer automatically checks and ensures that the following obvious constraints are satisfied :
$L_W < L_0$ $\quad Z_{max} < L_W$ $\quad Z_{NC} = Z_0 + Z_{max}$

6. **Machining conditions** : the system relies on the operator to specify the cutting parameters which have also been typed in the part program :
Feed-rate F_0 (mm/min)
Spindle Speed N (RPM)
These parameters represent the optimal (according to the judgement of the part programmer) for performing a certain machining operation. These parameters represent the reference values when the system is operating under AC mode and the reference values for the cutting forces are calculated using these parameters. When the operator has specified F_0, N the computer calculates the values of working feed **f** (mm/rev) and cutting speed **v** (m/min) and ensures that the following constraints are satisfied :
$f_{min} < f < f_{br} < f_{max}$ and $v_{min} < v < v_{max}$
f_{br} (mm/rev) is the value of working feed for which the tool fails on impact when it contacts the work-piece face. The calculation of f_{br} is described in 7.7

7. **Slow approach feed rate** F_{sa} (% of F0) : in DHD a tool with great overhang is almost certain to be deflected as it is fed into the workpiece material. The operator can specify a slower entry feed (the software selects a default value of 25 %) which is kept until the tool is adequately supported after a certain depth.
Transition depth Z_{sa} (mm) : at this depth (default value 4xD) the computer increases the feed rate to its nominal value (100% F_0) which has been specified in the part program.

8. **Control limits of feed rate and spindle speed**: under AC conditions the feed rate and possibly the spindle RPM vary within a range for each one which the operator has an option to specify if not in agreement with the default (recommended) values.

F_{max} , F_{min} (default values 130% to 25%)

S_{max} , N_{min} (default values 125% to 75%)

F_{max} : cross-holes or soft spots in the work-piece material are traversed slightly faster but slow enough to avoid sudden impact or other emergencies.

F_{min} : lowest level of feed rate and therefore undeformed chip thickness beyond which drilling is no longer productive ; (determination of F_{min} is rather based on experience or alternatively on the basis of a minimum cycle time for completion of an operation).When this value of feed rate is attained the control system typically commands withdrawal of the tool from the cutting zone, described in section 7.4

9. **Rapid feed rate F_{rpd}** (mm/min) : auxiliary movements of the tool like rapid traverses or withdrawals from the hole take place at a rapid feed rate in order to minimise time. Although any value in the range 2000 - 10000 mm/min is possible (modern machining centres will do > 25 m/min) the default value in the software is at the low end, 2000 mm/min.

10. **Torque and Thrust absolute thresholds** : the operation of the whole system is based on the monitored values of thrust and torque for the tool. The thresholds are determined by the system and vary for different AC algorithms ; (detailed description in section 7.2.2).

Amplification factors T_{amp} (N/V) , M_{amp} (Ncm/V) for the charge amplifier required for conversion from pC into Volts and next into mechanical units. In the series of tests carried out in this work the default value 200 for both ensured that the operational voltage of 10 V would not be exceeded and damage the amplifier.

7.2.1 Program INTERM

This program is also interactive and user friendly and performs three main roles :

I. **Handling of data-files** ; the operator can access a data file and modify any data about a machining process previously defined in program SET-UP.

II. **Functions menu** ; enables the operator to select from a menu of options the fashion in which machining is to take place as far as monitoring and control is concerned there are four basic options which can be combined :

- **Monitoring only** with breakage prevention and rapid withdrawal active alone.
- **Monitoring and Adaptive Control** with feed rate and spindle RPM override control.
- **Real time graphics** VDU display of Thrust, Torque and Feedrate vs. hole depth or time.
- **Recording facility** (screen dumping) for off-line analysis of machineability data, cutting tool performance or control strategy assessment.

III. **Determination of AC loop characteristics** ; the program calculates and stores the main control parameters required in module-B (on-line program).

1. **Forces bandwidths** : as explained in chapter 7 (multi-level control) a proposed solution to the problem of Intelligent Machining, as far as AC is concerned was the introduction of a limited "decision" making capability into the system. Handling the forces error signal requires the limits T_a, T_b, T_c, T_d, T_e, for thrust and M_a, M_b, M_c, M_d, M_e for torque are displayed (default values) but the operator has an option to modify any of them.

2. **Sampling rates and timers** : the stability of the control loop which operates on discrete time and also the quality of the graphics picture in representation of the cutting forces and machining parameters depend to a large extent on various timers :

Forces sampling interval : DUR_f (multiples of 10 msec) ; the smallest discrete time interval that the system can operate in theory is 10 msec (100 Hz) per channel of the ADC. With two channels this is 20 msec (50 Hz) for acquisition and D/A conversion of the thrust and torque signals. The typical value for the system was 100 msec sufficient to create a "filtering" effect by means of averaging.

Graphics interval : DUR_g (multiples of 10 msec) ; the graphics interval determines the continuity of the forces and feed rate pattern appearing on the VDU. It is determined by the penetration rate and the ratio between actual depth and VDU graphics window length. Typically 1200 units on the VDU represent 60 sec of cutting time or distance equal to F_0 in mm. (see also section 7.3.2)

Control interval : DUR_c (multiples of 10 msec) ; typically a multiple of DUR_f to ensure stability and allow the cutting forces to settle to the new values.

3. **Feed rate and spindle RPM steps** : the variation of feed rate and spindle RPM takes place at discrete steps up or down expressed as percentages of their nominal values F_0, N_0 respectively. (see also DAC section).

4. **Control variables** : they specify action of the system in a number of events :
   Withdrawal WDR$ (ON-OFF) : determines whether the work-piece material allows interruption of cutting for pecking and reentry when the feed rate reaches its minimum value.
   Pecking counter : number of pecks the tool has performed.
   Emergency checks : interrupts to ensure that absolute limits of forces have not been exceeded.
   Real cut or software trial : informs the computer whether the next operation to take place is actually real in terms of metal cutting and therefore necessary to update the data files (tool life status etc.) or whether it is for controller tuning.

7.3 On-line module (real time)

7.3.1 Program RLTME

This part of the software performs in real time the tasks of data acquisition, processing and control of the machining parameters. A complete cycle, when machining under AC, lasts between 50 to 450 msec depending on the sampling interval and the functions selected by the operator and comprises the following steps :

(i). **Data acquisition** and DAC for channel one (torque) and channel two (thrust) ;
(ii). **Averaging** over the sampling period ;
(iii). **Calculation of errors** between the reference and current values ;

(iv). **Calculation of new** feed rate and spindle speed according to an algorithm ;
(v). **Graphics** display for thrust, torque, feed rate, spindle RPM, current hole depth ;
(vi). **Alarms** issuing (default value = 0) ;
(vii). **Storing of data** and repetition of the cycle ;

7.3.2 Stages of the DHD process under AC

With the set-up completed, the tool and work-piece in place the external computer starts execution of the NC part program (**AUTO** mode). With reference to the actual machining cutting there are three main stages of the process, the transition stage, the steady state and the adaptively controlled stage of the process.

STAGE I : Transition stage (slow approach and entry)

In stage I the tool is positioned rapidly in front of the work-piece at a clearance distance typically not exceeding 3 to 4 mm. At that point there is a feed-hold, the spindle stops and the option is given for a last inspection either by the operator or automatically if there is a touch probe available.

The program restarts and the tool advances slowly into the work-piece, Start of the cycle is triggered upon contact between tool and workpiece when a thrust threshold is exceeded (defined off-line)which during the drilling tests with drills of Ø 2.4 mm to Ø4.5 mm in diameter it was set to 1 N.

As soon as the above thrust threshold is exceeded it triggers a suitable flag set to logic one which informs the computer that machining has commenced and two timers are started :

- **Absolute time cycle timer** :
- **Machining cycle timer** :

The two times are normally identical unless the control system disengages the tool from cutting and the machining timer stops and restarts only if machining is resumed.

The purpose of stage I is to give the tool an adequate support during the early penetration and ensure good hole straightness. Although an option for the operator it is most essential when any of the following situations is encountered :

- **Long drills** with no guide bush, pilot hole or other intermediate support.
- **Very tough materials** such as S.S or Titanium Alloys being drilled which can cause deflection of a non supported tool even with a small overhang.

The depth of tool penetration into the workpiece during stage I is typically 4 diameters and during this stage the feed rate is held constant at a value of 25% the maximum feed rate.

During stage I the main task of the system is to ensure that the absolute limits of thrust and torque for the particular tool are not exceeded. These limits are based on static calculations in program **SET-UP**, depend mainly on the tool material, diameter and tool overhang and in practice are reduced for safety reasons by a factor of 5.

In the event whereupon any of the two limits is exceeded, the control system stops machining immediately **(SHIFT-INIT)**, withdraws the tool to its initial position **(JOG, +Z)** and issues an alarm to the operator giving at the same time the maximum values of torque and thrust encountered.

The operator then has two options: either reset the absolute limits to new values, for example 20% or 25% higher than before and restart machining or return to program **INTERM** and specify a lower penetration feed rate for entry.

STAGE II : Transition to maximum (working) feed rate and steady state.

Beyond a certain depth specified by the operator the control system automatically brings the feed rate to 100% of its NC code value and therefore thrust and torque increase correspondingly to new values.

The pattern of increase of the drilling forces in such a step-input to the feed rate is very important for understanding the dynamics of the process, building a mathematical model and designing the control algorithm.

Whith the feed rate at 100% of its value the steady state has been reached, the new values of torque and thrust are automatically recorded and constitute the basis for the AC of the process ; at the end of stage I the feed rate and RPM override is active.

STAGE III : Adaptive Control of feed rate and spindle speed.

In stage III the main function of the system is to maximise the feed rate (hence the metal removal rate) maintaining at the same time the drilling forces constant by varying the feed/rev and when necessary to withdraw the tool in order to clear the swarf form the flutes and reenter the workpiece for a new peck.

The fundamental problem in the structure of any such system is how to avoid instability when taking corrective action. A considerable amount of research has already been done for turning and milling and various schemes have been proposed but although there are similarities with drilling and deep hole drilling, a different approach had to be taken in order to account for the particular aspects of the DHD process.

7.3.3 Feed rate and RPM override control

Various algorithms have been designed and implemented for controlling the machining parameters and one of these algorithms is presented in this work. Common to all algorithms are the two inputs, i.e the errors between the reference value (steady state value) and the current force value. These errors are due to external disturbances which arise from friction between the tool and the hole walls, variations of hardness in the workpiece material, tool wear propagating etc.

The algorithms differ in the way the error is manipulated in order to calculate the new value of the feed rate while they have in common the discrete feed rate steps-up or down. This means that the feed rate command actually sent out to the control panel corresponds to increments of +/- 5% of its NC code value. The calculated feed rate is rounded to the nearest percentage multiple of 5%. This is done so in order to save memory space in the program despite the fact that the resolution of the DAC allows steps of less than +/- 1 %.

Descrete feed rate control is achieved as following: In the control program **RLTME** two arrays are given, **PERF** (i) and **DIGFED** (i), each with 36 elements (i = 1 to 36).

PERF %	(DIGFED)	PERF %	(DIGFED)	PERF %	(DIGFED)	PERF %	(DIGFED)
5.3	(251)	**50.0**	**(191)**	95.5	(128)	**140.6**	**(62)**
10.2	**(244)**	55.3	(184)	**100.0**	**(116)**	145.3	(56)
15.5	(237)	**60.2**	**(178)**	105.6	(109)	**150.0**	**(49)**
20.3	**(231)**	65.5	(171)	**110.0**	**(103)**	155.5	(43)
25.6	(224)	**70.3**	**(164)**	115.2	(94)	**160.2**	**(36)**
30.5	**(216)**	75.2	(156)	**120.3**	**(87)**	165.2	(28)
35.2	(210)	**80.5**	**(149)**	125.3	(82)	**170.3**	**(21)**
40.6	**(203)**	85.3	(142)	**130.0**	**(75)**	175.5	(15)
45.3	(197)	**90.6**	**(135)**	135.5	(69)	**180.8**	**(8)**

The elements of array **PERF** correspond to the nearest percentage of feed rate in steps of 5% between 5% to 180% and were obtained through an experimental calibration procedure on the machine tool itself.

The elements of array **DIGFED** correspond to the digital value sent out from the computer to the DAC in order to achieve the corresponding percentage of the array **PERF** and the variable in the program which handles this task is **?FEED.**

A similar arrangement applies for the spindle speed in RPM but the resolution there is 10% and there are only 5 steps between 80% to 120% of the NC code value. The following example shows the procedure in order to send out a new feed rate command :

- Calculate the relative error for thrust and torque.
  Rel. Error = (Current value - Ref. Value) x 100 / Ref. Value
- Compare the two errors and take into account the greatest .
- The algorithm calculates the new value of feed rate F_i in mm/min according to the error.
- The first approximation percentage is obtained by $PF_1 = (100 \times F_i)/F_0$, say 73.7 %
- The nearest integer multiple of 5 % is then obtained: $PF_2 = PF_1/5 = 14.74$ %
- The decimal residual $PF_3 = PF_2 - \text{int}(PF_2) = 0.74$
- Comparison with 0.5 : if PF3 > = 0.5 then $PF_4 = 5 \times \text{int}(PF_2) + 5 = 75\%$
  else if PF3 < 0.5 then $PF_4 = 5 \times \text{int}(PF_2)$
  From the above procedure the value of a very important variable is determined :

VF = PF4 / 5 This variable is the argument which determines the order of the element of the array **DIGFED(VF)** to be sent out. In the above example **VF** = 15 which means that the value of the variable **?FEED = DIGFED(15) = 156**

The exact value of the feed rate percentage is found next using the same counter in the array **PERF(VF)**, with **VF=15 PERF(15)=75.2 %** hence $\mathbf{F_i=PERF(15) \times F_0 /100}$ is the new value of the feed rate in mm/min.

7.3.4 On-line identification of process parameters

The following procedure is performed in real time after machining has commenced during stages I and II ; it provides the computer with two pairs of necessary parameters for the control strategy taking into account the non linear relationship between feed and thrust/torque.

These parameters are the specific thrust K_{Tsp} and feed rate power index for thrust **a** and the specific torque K_{Msp} and the feed rate power index for torque **b** respectively.

It was shown that the steady values of thrust and torque are related to the cutting feed (mm/rev), cutting speed (m/min) and tool diameter with the following empirical relationships :

$$T_i = K_T f_i^a v_i^x d^p = K_1 F_i^a N_i^{x-a} = K_{Tsp} F_i^a \qquad \text{(N)}$$

$$M_i = K_M f_i^b v_i^y d^q = K_3 F_i^b N_i^{y-a} = K_{Msp} F_i^b \qquad \text{(Ncm)}$$

The purpose of this procedure is to identify these relationships automatically, without the intervention of the operator and therefore to enable the system to adapt to variations in work-piece material hardness, tool geometry between seemingly identical tools of the same batch or even tool wear (see section 7.3.6).

The on-line identification is based on a controlled variation of the feed rate between two known values (step input) and the recording and processing of the steady state values of thrust and torque corresponding to each feed rate. Averaging of the recorded signals over an adequate period of time (e.g time required for the tool to advance depth equal to two diameters)

This analysis is part of the self learning capability of the system, it need not take place time during each operation but only once and the data are held in the corresponding data file for the particular operation.

The following figure fig. 7.1 shows schematically the principle of the method ; the depth at which the values T_2 and M_2 are recorded is less than 5xd so that the phenomena related to chip breaking and flute clogging do not manifest themselves.

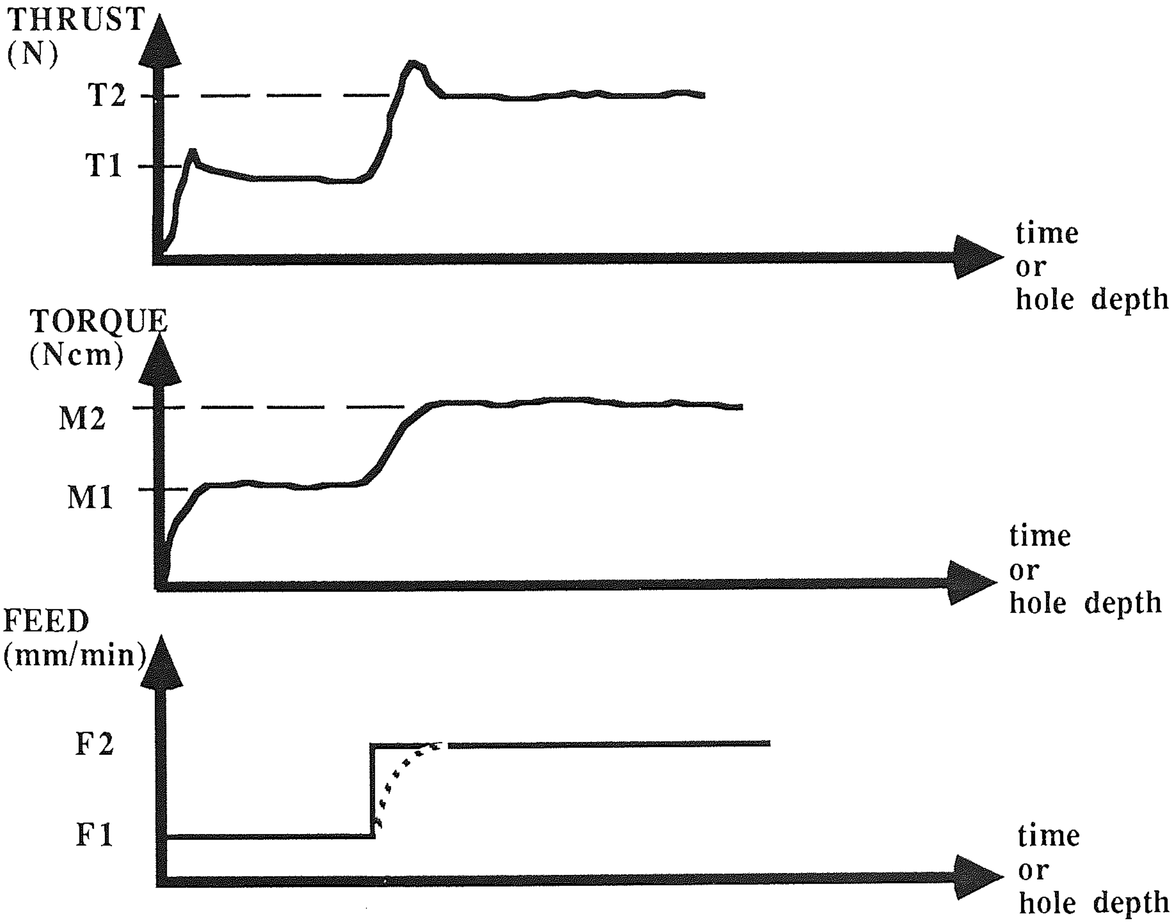


Fig. 7.1 : On-line identification of process parameters.

The algorithm which calculates the process parameters is the following :

$a=\{\ln T_2-\ln T_1\} \;/\; \{\ln F_2-\ln F1\}$;

$b=\{\ln M_2-\ln M_1\} \;/\; \{\ln F2-\ln F_1\}$;

$K_{Tsp} = 0.5\{\ln(T_1T_2)-a\ \ln(F_1F_2)\}$;

$K_{Msp} = 0.5\{\ln(M_1M_2)-b\ln(F_1F_2)\}$;

7.3.5 Maximum Error Calculation

The average force is reduced by an amount equal to the reference value and the current value of error is calculated :

Thrust error = $\{T_{dig}(i)-T_{SS}\}/KT_{tr}$ (N)

Torque error = $\{M_{dig}(i)-M_{SS}\}/KM_{tr}$ (Ncm)

Maximum error :

$E(i) = \max\left\{ (T_{dig}(i)-T_{SS})100/T_{SS}),\ (M_{dig}(i)-M_{SS})100/M_{SS} \right\}$

The variables $T_{dig}(i)$, $M_{dig}(i)$ correspond to the current digital values of thrust and torque at the i-th sampling interval while T_{SS} , M_{SS} are the corresponding digital values in the steady state at stage III after the feed rate has reached its 100 % value.

The thrust error results from either hard spots in the material or rapidly propagating wear of the cutting edges and resulting bluntness of the tool. The torque error is the resultt of excessive torsional loading of the drill due to swarf clogging the flutes and rubbing against the hole walls.

7.3.6 Error classification in bands and multilevel strategy

Justification

The main feature of the strategy adopted is the use of a multi-level control structure whose main objective is to eliminate the risk of catastrophic failure of the tool and workpiece by means of controlling the magnitude of the cutting forces. The deviation of the monitored values of torque and thrust from the reference values produces an error signal which generates the corrective response by the system.

The multi-level control structure is based on classification of the error in bands and the implementation of a different algorithm for each band. This layout emerged from the inability of a single algorithm to control the process efficiently in conjunction with the fact that the system has been designed to operate in a multi sensor environment with at least two inputs (thrust, torque) and three outputs (feed rate, spindle RPM, Z-axis control).

Although there has been excellent theoretical analysis by various researchers towards the investigation of performance and stability of various AC algorithms, it has been associated with the microscopic view of single input-single output systems.

In this work a different concept is presented, that of an overall intelligent machine tool in which AC is just one of the performed tasks. The up to date structure of ACC systems for machining processes has been dominated by a common characteristic the validity of which has been taken for granted among researchers.

This is the **reference value** of the control variable, in this case the cutting force or forces. All the control strategies in the literature aim to stabilise the process around this particular value. From a purely theoretical control engineering point of view this is correct in principle; three serious arguments emerge however when the concept is examined from an intelligent machining point of view :

First is the assumption by many researchers of a linearly proportional relationship between the cutting feed per rev. and the main cutting forces when it is known that a logarithmic relationship exists instead, with a slope well below unity in the range of 0.5 to 0.8 depending on the material, tool geometry etc. This assumption makes the elaborate efforts to design a stable, accurate, self tunning controller trivial.

Second is the arbitrarily selected value of the reference force which the controller attempts to maintain according to a strategy based on the first assumption.

Third is the fact that a cutting tool of any kind (drill, milling cutter, turning insert etc.) normally operates well below its fracture limits. The operating level of the cutting force depends on the machining parameters specified in the part program and the work piece material. Therefore it is safe to say that if a drill requires for example 10 kN of axial thrust or 5 Nm of torque in order to fail while it operates at 1 kN or 50 Ncm respectively, then the reference levels should be related to the actual machining process rather than tool strength and consequently if there is a safety factor of 10-fold or even higher, variations of up to 200% above the theoretical reference levels are tolerable.

Description

Based on the above concepts a multi level control structure has emerged shown in the next figure fig 7.2 where five distinct error bands can be identified:

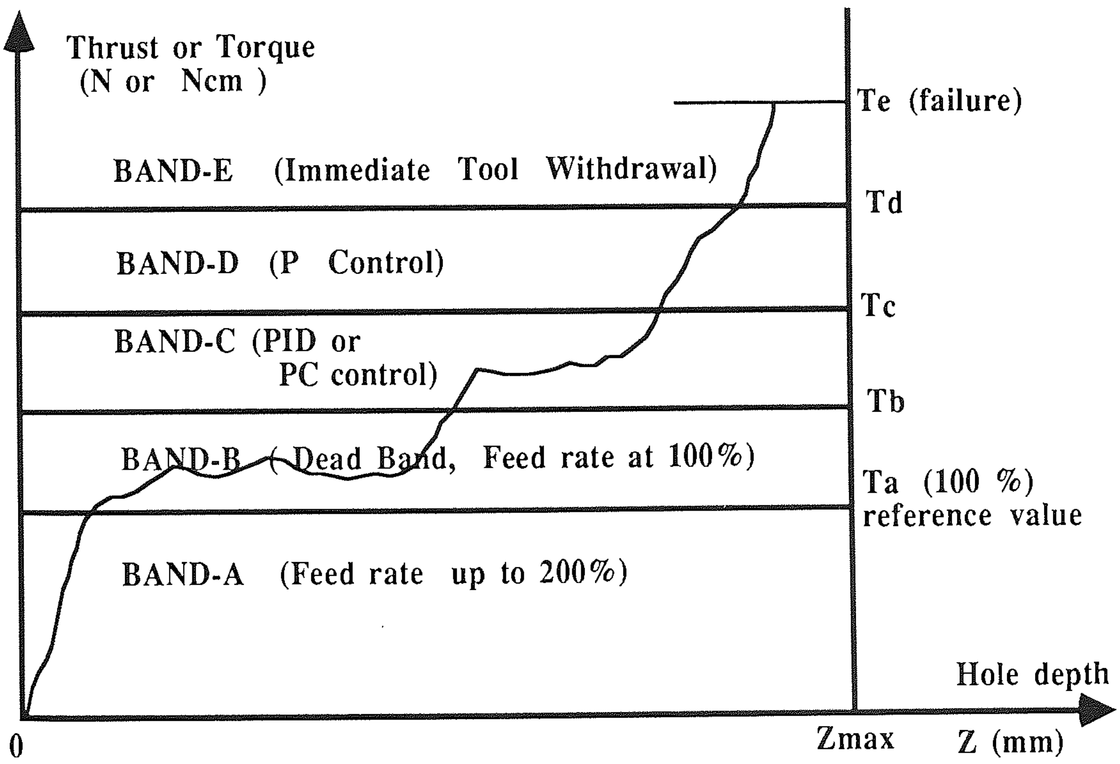


Fig. 7.2 Multilevel Control Strategy (Error bands)

band-A represents the region between nil to 100% of the force reference value (at steady state). The latter is **automatically identified** by the system on line (while cutting) and therefore is **self imposed** without the intervention of the operator.

band-B represents the region between 100% to 130% for torque and 100 % to 115 % for thrust and is the so called dead band. The purpose of the dead band is to provide the control system with flexibility and stability ; band-B accommodates the following cases: time lag between reduction in feed and subsequent response of thrust or torque, random disturbances such as variations in hardness of the workpiece, swarf clogging and breaking away etc.

band-C between 130 % to 160% for torque and 115% to 130% for thrust represents the region where the controller behaves like a PID controller, i.e the control action depends both upon the actual value as well as the rising or dropping pattern of the error or as a PC (predictor corrector) the relevant algorithm described in 7.3.2.

band-D between 160 % to 180% for the torque and 130% to 145% for the thrust where the controller takes into account only the integral of the error. In band-D the system automatically adjusts the two main control parameters, i.e the sampling rate which is doubled and the controller gains, the intergral gain is also doubled while the derivative gain is set to zero.

band-E is above 180% for the torque and 145% for the thrust and is the band where no control takes place except for immediate tool withdrawal.

The band widths (%) are determined off-line by the operator (program INTERM) and are by no means universal but depend on the workpiece material and the relevant experience of the operator. The flexible and user friendly structure of the software permits modification of any of the control parameters by the operator as knowledge and experience of the process increases.

7.3.7 Tool withdrawal from the cutting zone (pecking).

Tool withdrawal from the cutting zone and rentry is performed in principle in order to cool and lubricate the drill as well as to clear away the swarf from the flutes. The control system decides whether such action is permissible in the first place according to the material being machined.

It was found that when drilling Aluminum it is possible to interrupt cutting and start again while in the case of Titanium this is not the case. This was basically established from the performance of the controller which became unstable when attempting to reenter the Titanium workpiece when a series of successive alarms was initiated.

The most likely explanation for such a performance is that because of work hardening, a dominant characteristic of Titanium and its alloys, when reentering the workpiece the tool encounters extremely hard material and further penetration is impossible without triggering and alarm and also inflicting rapid wear to the tool.

The above is a typical example of the necessity for an intelligent controller based on knowledge of material characteristics held in a data base. It is clear that this knowledge is a fundamental element of the system and therefore the capability to increase, update and manage such knowledge should be built into the system if it is to be widely successful.

Refering to the problem of interrupted or non-interrupted cutting, which is obviously a critical decision in the control strategy of the described system, the following approach was adopted :

In the data file for each material an additional variable is held in the form of a software flag takes the value of either 1 or 0 and determines whether pecking action is permissible or not. with pecking permitted by the material in the first place there are two circumstances upon which the corresponding command for tool withdrawal is given :

- A minimum penetration rate has been achieved, typically less or equal to 25% of the NC programmed feed rate and held for more than 1xD penetration depth. Machining is no longer productive, even if the cutting forces lie inside band-B because the tool is simply rubbing against the hole walls.

- Alarming levels of torque or thrust have been encountered in band-E and it is too risky to attempt even a feed variation. This last case is a rather rare one and occurs either because of excessive rapidly propagating wear of the cutting edges or because of extremely hard spots in the material structure have been encountered.

Tool withdrawal and reentry into the workpiece occurs with the macine tool under **JOG** mode which enables a rapid feed rate of up to 10000 mm/min although in practice is restricted up to 2000 mm/min. A programmable delay of a few seconds with the tool clear off the workpiece enables lubrication, cooling and swarf washout and then the tool reenters and stops 2-3 mm clear from the previous depth when the rapid feed is reduced to 2% of its maximum value while **JOG** mode is still active.

Impact with the workpiece and triggering of a thrust threshold of 1-2% of the nominal force informs the computer that cutting has recommenced and an **AUTO-I** mode command is sent to the machine tool control panel.

Reentry takes place under 25% of the max feed rate and upon completion of one sampling cycle the control system starts increasing the feed rate by steps of 10% during every sampling period aiming at its maximum value under the torque and thrust constraints.

An integer counter is updated every time a withdrawal and reentry takes place and also a woodpecking frequency index is calculated as the depth increase between successive withdrawals. If it drops below a critical value, typically less than one diameter more than three times an alarm signal is issued, the tool is withdrawn and machining is aborted. This indicates excessive tool wear and regrinding or replacement of the tool.

7.3.8 Tool life monitoring

Tool life monitoring is an ambitious task and clearly highly desirable amongst engineers as the efforts to produce deterministic analytical models reveals (chapter 3). The basic philosophy in this work, with regards to tool life prediction, can be summised as follows :

It is possible to obtain some idea of expected tool life for a given combination of feeds, speeds, tool type and certainly workpiece material. This is not a practical method however for obvious reasons neither a totally reliable one as the practice in industry reveals ; tools are either changed on a conservative estimate of life basis or often fail for other reasons which the deterministic model cannot possibly incorporate.

Tool monitoring as performed by the proposed system occurs in two modes. One is the dynamic mode which runs during a machining cycle and aims to protect the tool and workpiece from random disturbances and catastrophic failure. The second mode operates in the background and its task is to identify signs of reduced ability to penetrate resulting from propagating wear.

Clearly in an unmanned or limited manpower environment or even during CNC machining it is practically impossible to measure tool wear itself on line and the problem is exacerbated even more in DHD. There has already been considerable research effort in modelling the correlation between the feed force and wear of the tool in metal cutting. During the useful life of a drill it has been shown that there is a constant increase in the level of the feed force against time or hole depth, **[115]** Subramanian and Cook, **[127]** Thangaraj and Wright, **[128]** Godforth and Kulkanni, **[146]** Li and Wu.

Such a criterion of constant gradient along with an absolute increase of the specific cutting force over a number of holes is used in this system for monitoring and alarms issuing. At fixed intervals the average feed force is measured and then normalised. Normalisation is achieved by means of dividing with the current values of initial feed per rev and surface speed raised at their specific powers. This is necessary under an AC regime where at least one machining parameter changes very often on-line.

The percentage increase of this normalised specific force is monitored at intervals defined by the operator expressed either in minutes or distance (mm) even between different machining cycles. The system simply keeps track of a life status of any tool held in the data base by means of an alphanumeric code which identifies each tool uniquely. This tool life status data is automatically updated at the end of each cutting cycle ready to be used for the next machining operation.

Although this function has been built into the system it has not been possible to assesss its reliability up to now because the relevant software has not been fully developed and also because long term testing is required in order to allow wear mechanisms to manifest themselves.

7.4 Calculation of maximum working feed rate

The calculation of the maximum feed rate is based on stability calculations for the most severe case of load on the tool. This is the case of initial impact between the unsupported tool and the workpiece in the beginning of the drilling cycle.

Drill buckling occurs when the thrust or feed force **T** on the drill exceeds a critical value T_{cr} . A number of researchers have performed analysis of the problem (Ivashin and Dechko, [35]), and have predicted this critical load ; the formula used here is :

$$T_{cr} = 2EI_{min}\, p^2/L^2(1+q) \tag{7.1}$$

$$q = I_{min} / I_{max} \tag{7.2}$$

where I_{max} , I_{min} = max. , min. moments of inertia of the drill cross section
E = Young's modulus of elasticity , L = total drill length (overhang)
Imax, Imin are given by the following expressions :

$$I_{max}=k^{0.45}d^4/27 \tag{7.3}$$

$$I_{min}=k^{1.60}d^4/25.6 \tag{7.4}$$

where **k = 0.3 to 0.5** (ratio of web thickness to diameter) ,
for example k = 0.35 for the GT 50 drills :

$$\frac{51.2}{25.6 + 27\,k^{1.15}} \quad \frac{E\,k^{1.6}\,\pi^2\, d^4}{25.6\ L^2} \tag{7.5}$$

Thrust **T** depends on the machining conditions, the geometry of the drill used and the workpiece material ; For example it was found that for the AMS 7075 alloy and drill GT50 Ø3.0 mm drilling thrust can be approximated by the following empirical expression :

$$T = 300\ f^{0.8}\ d^{0.8} \tag{7.6}$$

T(N) , f (mm/rev) , v (m/min)

Substituting **E = 213000 N/mm²** , **d=3 mm** , **L=150 mm** yields :

$$f_{max} = 0.098 \text{ mm/rev}$$

and for the smaller drills , **d = 2.4 mm , L=140 mm ,**

$$f_{max} = 0.048 \text{ mm/rev}$$

The above methodology is incorporated in the off-line part of the software and is executed automatically as soon as the operator has completed entering all the data concerning the process, the tool and the machining conditions.

7.5 Summary

The experimental study of the DHD process and the complex dynamics which result mainly from the need to monitor and control simultaneously two parameters, drilling thrust and torque, has resulted to the design of a non-conventional adaptive controller.

The controller is implemented almost entirely in the system software, which comprises two modules : An off-line module the aim of which is to determine as many as possible reference values for the various parameters for the process and consequently to reduce the effort required by the part programmer and process planner. Thus, the off-line module determines the general frame in which the controller is to operate and has been designed with sufficient built-in flexibility which enables the review or modification of the control strategy.

The on-line module features a multi-level control strategy based on distinguishing which one of the two parameters, drilling thrust or torque, imposes the greatest risk to the integrity of the process and safety of the tool and workpiece and also to which control action will require the least response time.

Finally, a recording capability of both the monitored parameters and the controller actions has been considered as a very useful diagnostic tool for post-process assessment of the system performance or study of the dynamics of the DHD process.

For this reason, a simple, automatically-updating-of-data-files facility has been included into the system while a screen dumping facility has also been added on the merits of graphics representation of the process ; results obtained with the above method are presented in chapter 8.

CHAPTER 8

IMPLEMENTATION AND PERFORMANCE OF MONITORING - ADAPTIVE CONTROL SYSTEM

This chapter presents the experimental results from the implementation of the system and its performance and discusses the difficulties and problems encounterd.

8.1 IMPLEMENTATION

As mentioned in the previous chapter all functions of the system are implemented in the software. Since the system was designed to allow an external computer to take master control of a real process and in particular to be able to interrupt an NC program and and govern auxiliary motions of the tool under rapid feedrate (pecking), care was taken to ensure safety and reliability.

A great deal of testing was performed in order to investigate whether the system is capable of coping with situations which had not been included or even conceived in the design and analysis stages.

Two main problems indeed manifested themselves and were dealt with appropriately ; one was the prevention of collision between the tool turret and the tailstock during tool withdrawal or between the tool turret and rotating spindle during reentry.

The problem was tackled by means of implementing both physical stops (contact actuated emergency switch actuation) and also soft stops, namely special subroutines which supervise the total duration of tool travel during pecking. The rapid feedrate was also restricted to 25% of its value during auxiliary motions.

The other closely related problem, although not as critical as the above (in terms of costs in case of accident) was the prevention of tool breakage during control. Although this appears to be erroneous and a rather unexpected performance from a system whose main task is to ensure tool and workpiece integrity, such a situation is possible and indeed did manifest itself durimg the early stages of the implementation of the system as it will be explained next.

The system is a basically a multi task system where upon the same computer performs a series of tasks during each cycle on a serial basis. The more sophisticated the on-line tasks become (graphics, complicated algorithms, data processing) the slower the response of the system to external disturbances. Since it takes fractions of a second for a small fragile tool to fail it is clear that it is quite possible for such an event to occur while the computer is involved elsewhere.

This problem was tackled by means of regular interrupts of the cycle in order to check that any of the two analogue voltages corresponding to the drilling thrust or torque is within absolute limits otherwise an emergency stop is activated.

Finally a problem which is classic and typical in control engineering is that of instability of the controller which can occur due to a number of reasons. For example instability arises if the control algorithm produces a negative value for a physical quantity such as feedrate, spindle speed, distance, force etc.

Another case is the one known as controller "wind-up" and "bursting" where the estimation of parameters is based on limited data or misleading data and the system starts oscillating between stable and unstable behaviour. The critical parameters on which this stability is dependent were found to be mainly the sampling rate and the process gain ; although these were varied in the software accordingly in order to achieve stability, a lot remains to be done in this direction in the context of future work (see also chapter 9).

8.2 RESULTS AND DISCUSSION

The performance of the system was investigated with the same combination of workpiece materials AMS 7075 T736 Aluminum alloy (68-72 BHN) and Titanium TA11-6% Al - 4% V (340 - 375 BHN) as reported in chapter 4. The same three diameters Ø 2.4 - 3.0 - 4.5 mm, depth to diameter ratios 33:1 and 40:1 and a wider range of feed rates and spindle speeds were employed for the above purpose.

After a number of initial difficulties and reliability problems the system was successfully used during deep hole drilling tests with small diameter long twist drills. The following improvements were observed when comparing the system performance with the typical method of canned (fixed) pecking cycles for drilling small diameter deep holes on the CNC machining centre of an aerospace industry :

- Total elimination of drill breakages and successful completion of machining

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- Total elimination of drill breakages and successful completion of machining cycles was achieved thanks to the system. The photographs in chapter 3, of drills which have suffered either partial or total damage of the cutting edges or excessive torsional loading because of swarf clogging, would have been impossible without the immediate action by the system (machining aborted).

- With the introduction of the system and the on-line manipulation of the feed and cutting speed, the problem of chip fragmentation and consequent instability of the process appears to have been alleviated. In figures 8.1 and 8.2, the photographs show the effect of variable feed which results to long, easily removed chips from the cutting zone and the drill flutes.

- Reduction in the number of tool withdrawals (pecks) was also achieved since the computer decides to withdraw the tool only when necessary (minimum feedrate or alarming levels of thrust or torque). For example from 18 down to 3 for the AMS 7075 alloy , Ø 2.4 x 90 mm, at 3200 RPM and 130 mm/min maximum feed rate).

- Subsequent reduction in the total cycle and machining times was also achieved by similar factors both because the system maintains a maximum possible feedrate and also auxiliary motions to a minimum.

- The above comparison however, is not entirely objective since the number of pecks used in industry for the particular application are dependent on the judgement and experience of the part programmer as explained in chapter 5.

- Reduction in the size of the NC part program from 80 lines required for a pecking cycle down to 10 lines was also made possible. This is an immediate result of the automatic cut distribution (pecking) performed by the system ; the latter requires knowledge of the entry and exit coordinates only (Appendix II).

- Drilling tests with Titanium alloy TA11 were performed with no pecking action at all because the work hardening characteristics of the material resulted into an oscillatory response of the system, namely successive withdrawals of the tool and attempts to reenter the workpiece with no increase in the actual drilled depth.

- The randomness and unpredictable nature of this type of metal cutting process, which has already been discussed in chapters 3 and 4, appeared also during the drilling tests under AC. There is clearly a lack of repeatability and consistency in machining conditions, controller strategy and above all between adjacent holes drilled in the same workpiece block.

- The response in reduction or increase of drilling thrust to variations of the feedrate is clearly more immediate when compared to that of the drilling torque. The reason is that thrust is associated only with the reaction at the drill point (cutting edges and chisel) while the torque incorporates the friction component because of swarf up the drill flutes.

- The performance of the system as far as the apparent stability of the cutting forces in the graphs is concerned cannot be compared to that of other systems reported in the literature for stabilisation and control of processes such as milling or turning. As mentioned in section 7.3.6 there is a fundamental difference in the approach to the problem of the force reference value between this work and those of other researchers.

- The use of different bandwidths in the control strategy explains why in some graphs the system does not appear to respond until the drilling forces have reached an alarming value while in other cases they fluctuations are clearly contained in a smaller band.

- An other point which is worth making is that the system performance in the above context seems to be also strongly dependent on the initial conditions, namely feedrate and spindle speed. Clearly the same hole can be drilled successfully both under 2000 RPM or 3000 RPM (Aluminium) and under a feedrate between 140 mm/min down to 60 mm/min or between 13 and 16 mm/min for the difficult to machine Titanium.

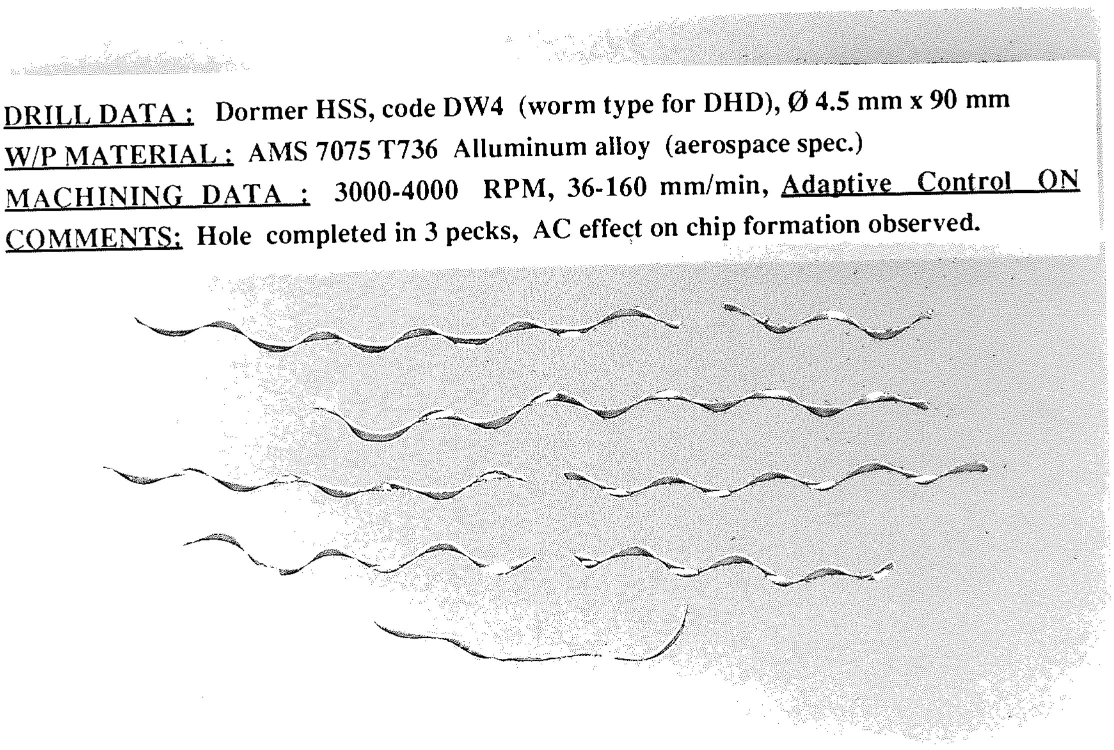


Fig. 8.1 Swarf of AMS7075 Aluminum Alloy drilled under Adaptive Control of feed rate, spindle speed and Z-axis position

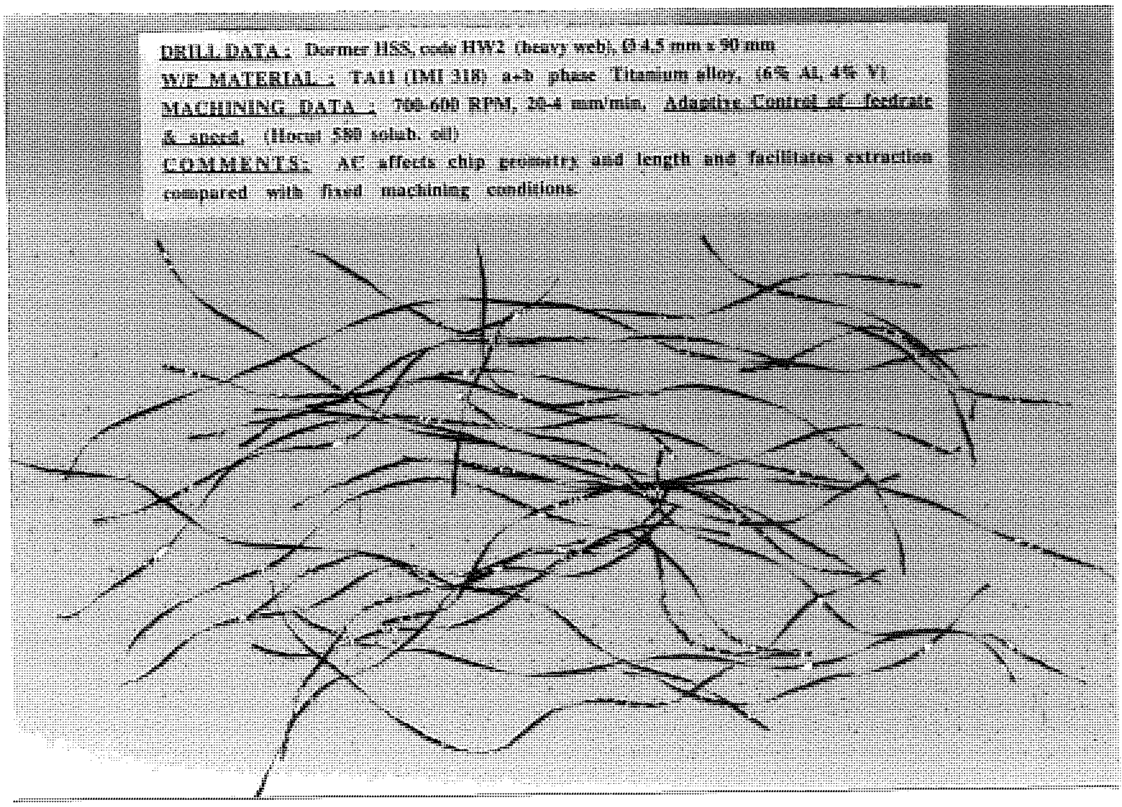


Fig. 8.2 Swarf of TA11 Titanium Alloy drilled under Adaptive Control of feed rate, spindle speed and Z-axis position

8.3 GRAPHS

The graphs which follow (fig. 8.4 to 8.39) were obtained by screen damping of the actual VDU patterns which appeared during drilling tests in real time. There are four main groups into which the tests results are classified according to the context of the test.

The first and second group comprise experimental results of drilling tests with Aluminium and Titanium alloys respectively, which were performed in Process Monitoring mode only. This means that no corrective action was taken other than rapid tool withdrawal and aborting the tests when the drilling thrust or torque exceeded a preset threshold of 200% of the steady state value.

The third and fourth groups comprise results of tests performed under Adaptive Control of feed rate, spindle speed and tool position (Z axis).Common to all four groups is the automatic identification of the process parameters in the beginning of the cycle and the determination of the steady state values of thrust and torque.

The basic display (fig. 8.3) comprises three displays : feedrate, torque and thrust variation with drilled depth as well as process parameters the general meaning of which is given next. At a later stage the graphs which were produced were accompanied by a detailed legend for various parameters.

With reference to fig. 8.3 the significance of the various symbols is given below :

1 : Absolute time (sec) (cycle time)
2 : Machining time (sec)
3 : Current drill depth Z(mm)
4 : Feed rate (mm/min)
5 : Spindle speed (RPM) (S-word)
6 : Peck number
7 : Alarm indicator (diagnostics)
8 : JOG - Z axis (tool <-- IN)
9 : JOG + Z axis (tool --> OUT)
10 : Jog Control (defines 8, 9)
12 : Maximum Torque (Ncm)
11 : Maximum Thrust (N)
13 : Work = Torque x Angular Speed (J) (This parameter, although not actually used by the software, has been included as a possible tool wear index if the system was to be used with larger tools and heavy cuts)

A : Material Code
B : Drill Code
C : Workpiece Block Code
a : Min. Feed rate (mm/min)
b : Work Feed rate (F-word)
c : Max. Feed rate (mm/min)
m : Steady State Torque (Ncm)
t : Steady State Thrust (N)

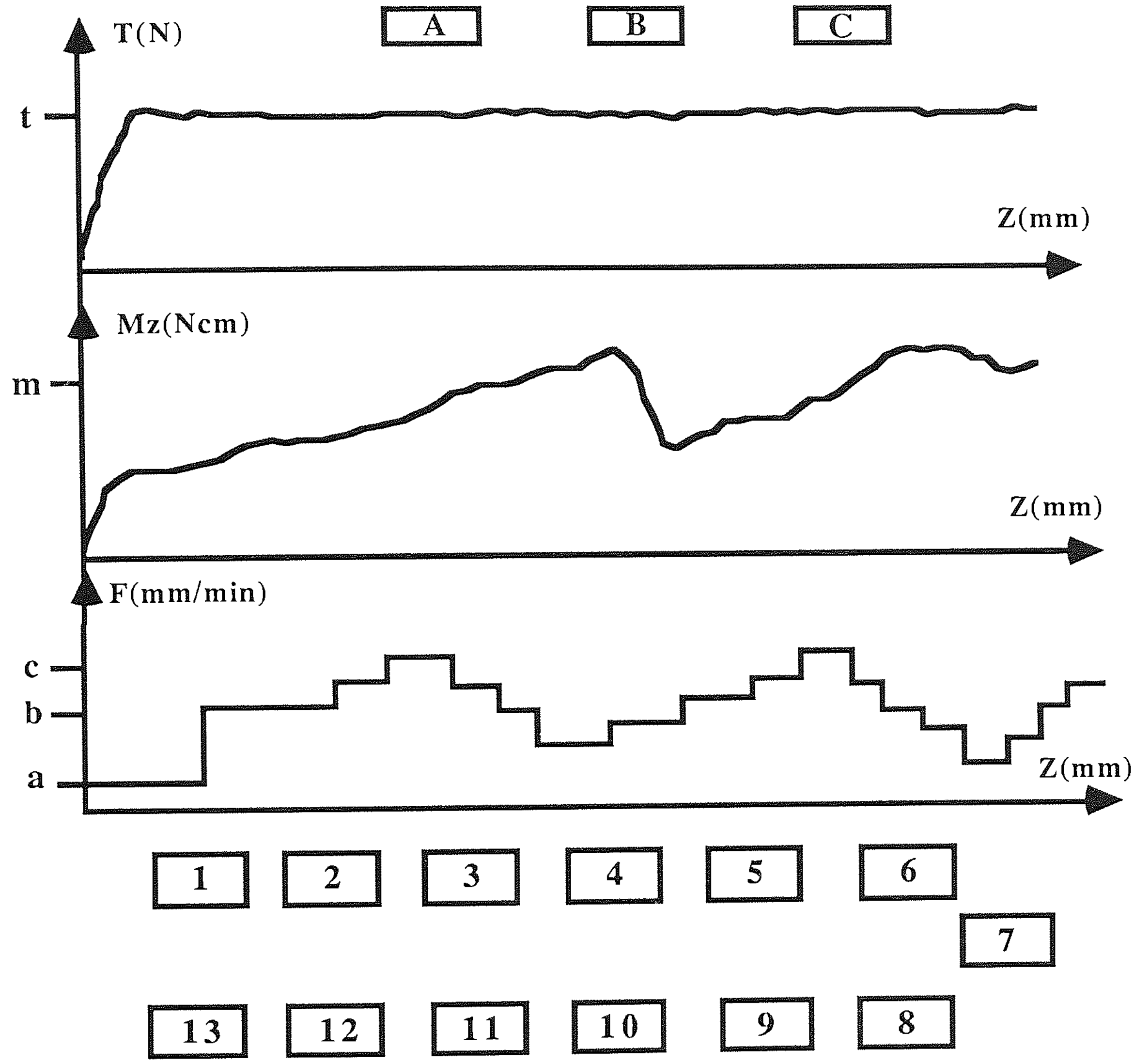


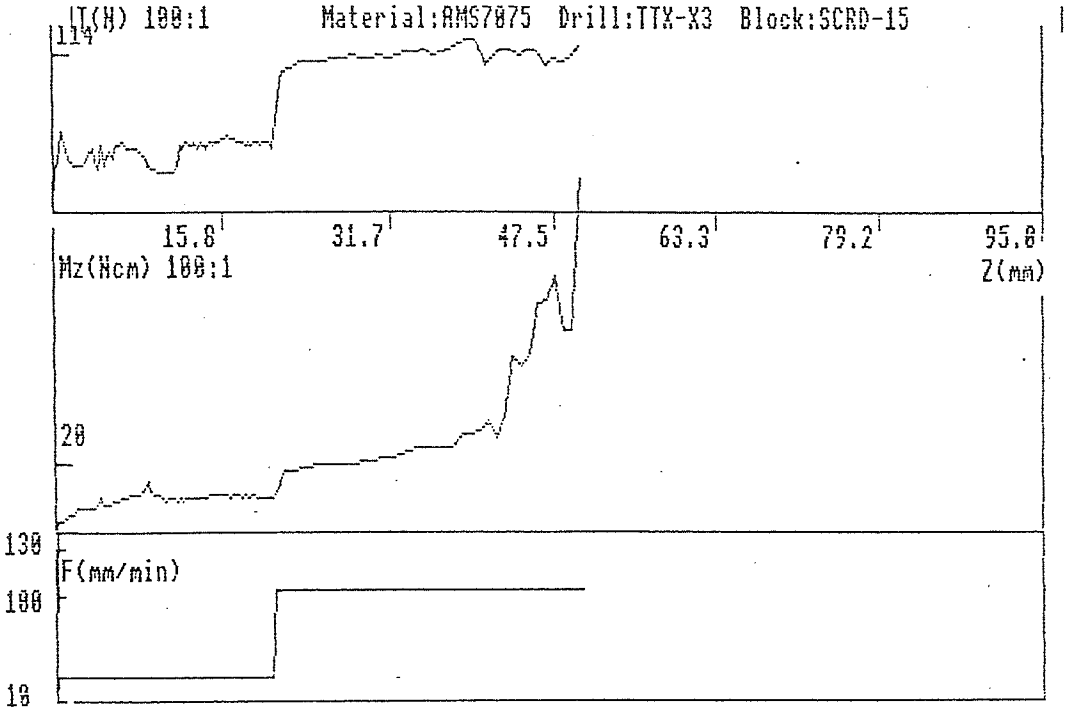
Fig. 8.3 : Graph appearing on VDU during drilling under AC

Selected Experimental Results of DHD AMS7075-T736 Aluminium Alloy under Process / Tool Monitoring : Emergency tool withdrawal active when alarming levels of thrust or torque are encountered while feed rate and spindle RPM are held constant.

Purpose of these drilling tests has been to illustrate the peculiarities of the deep hole drilling process and the problems associated with instability of the drilling forces and the high risk of tool and workpiece failure. In addition to the basic problem of instability the graphs indicate very strongly the unpredictable and non consistent nature of the process which excludes the use of any predictive open loop control technique with sufficient levels of reliability.

It is clear that the performance of the system under Monitoring mode alone is not sufficient because while the basic task of tool and workpiece safety has been accomplished the process has not been completed and the hole remains semifinished.

The level of permitted increase of the steady state forces in this case had been arbitrarily set to 300 % of their steady state value (programmable option) in which case machining is aborted. It is clear, by simple comparison of tests of adjacent holes with identical machining conditions, that whether machining can be completed within the above dead band of control intervention or not is beyond any safe prediction.



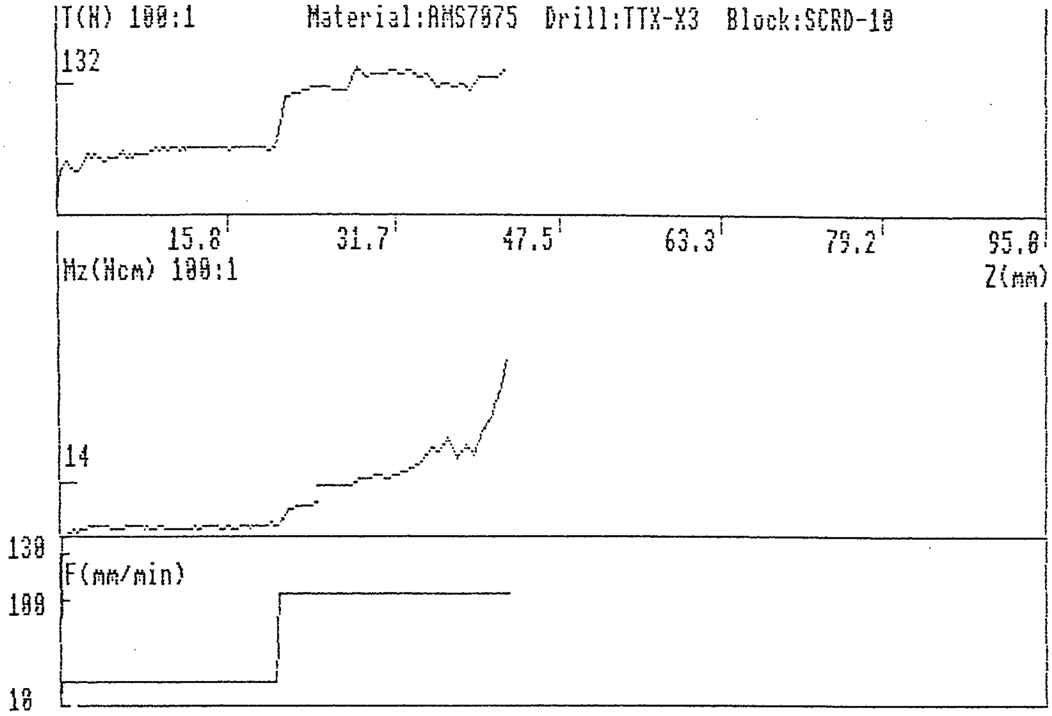
Abs.time=58.97 Mach.time=58.97 Z(mm)=50.14 F=2000.00 S=3750 Peck=0
ALARM=4
W(J)=3986.91 Mmax(Ncm)=103.79 Tmax(N)=126.92 Jog Cntrl. +Z=57.67 -Z=

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : DF

---

1. MATERIAL CODE=AMS7075
2. WORKPIECE CODE No.=SCRD
3. DRILL CODE=TTX-X3 DRILL DIAMETER (mm)=3.00
4. TOOL LIFE STATUS : No. OF HOLES=15.00
   CUMMULATIVE CUTTING TIME (min)=25.82
   CUMMULATIVE DEPTH (mm)=1047.60
5. NC PROGRAM FEEDRATE (mm/min)=100.00 CUTTING FEED (mic/rev)=26.6
6. NC PROGRAM SPINDLE RPM=3750.00 SURFACE SPEED (m/min)=35.34
7. NC PROGRAM DEPTH Zmax (mm)=90.00
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=5.00
10. ENTRY FEEDRATE (mm/min)=30.00 30.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=20.00 STEADY STATE DEPTH (mm)=25.00
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=100.00 THRUST (N/V)=100.00
13. MAXIMUM TOLERABLE THRUST (N)=229.23
    STEADY STATE THRUST(N)=114.61
14. MAXIMUM TOLERABLE TORQUE (Ncm)=82.38
    STEADY STATE TORQUE(Ncm)=20.59

Fig. 8.4 : Emergency stop of DHD cycle due to high levels of torque from swarf clogging (rise of up to 500 % steady state value)



Abs.time=54.35 Mach.time=54.35 Z(mm)=42.47 F=2000.00 S=3125 Peck=0

ALARM=4

W(J)=1383.17 Mmax(Ncm)=47.41 Tmax(N)=147.02 Jog Cntrl. +Z=50.67 -Z=

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : DA

1. MATERIAL CODE=AMS7075
2. WORKPIECE CODE No.=SCRD
3. DRILL CODE=TTX-X3 DRILL DIAMETER (mm)=3.00
4. TOOL LIFE STATUS : No. OF HOLES=10.00
   CUMMULATIVE CUTTING TIME (min)=16.61
   CUMMULATIVE DEPTH (mm)=686.33
5. NC PROGRAM FEEDRATE (mm/min)=100.00 CUTTING FEED (mic/rev)=32.0
6. NC PROGRAM SPINDLE RPM=3125.00 SURFACE SPEED (m/min)=29.45
7. NC PROGRAM DEPTH Zmax (mm)=90.00
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=5.00
10. ENTRY FEEDRATE (mm/min)=30.00 30.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=20.00 STEADY STATE DEPTH (mm)=25.00
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=100.00 THRUST (N/V)=100.00
13. MAXIMUM TOLERABLE THRUST (N)=264.35
    STEADY STATE THRUST(N)=132.17
14. MAXIMUM TOLERABLE TORQUE (Ncm)=43.66
    STEADY STATE TORQUE(Ncm)=14.55

Fig. 8.5 : Emergency stop of DHD cycle due to high levels of torque from swarf clogging (rise of up to 350 % steady state value) no significant variation of thrust is noticeable

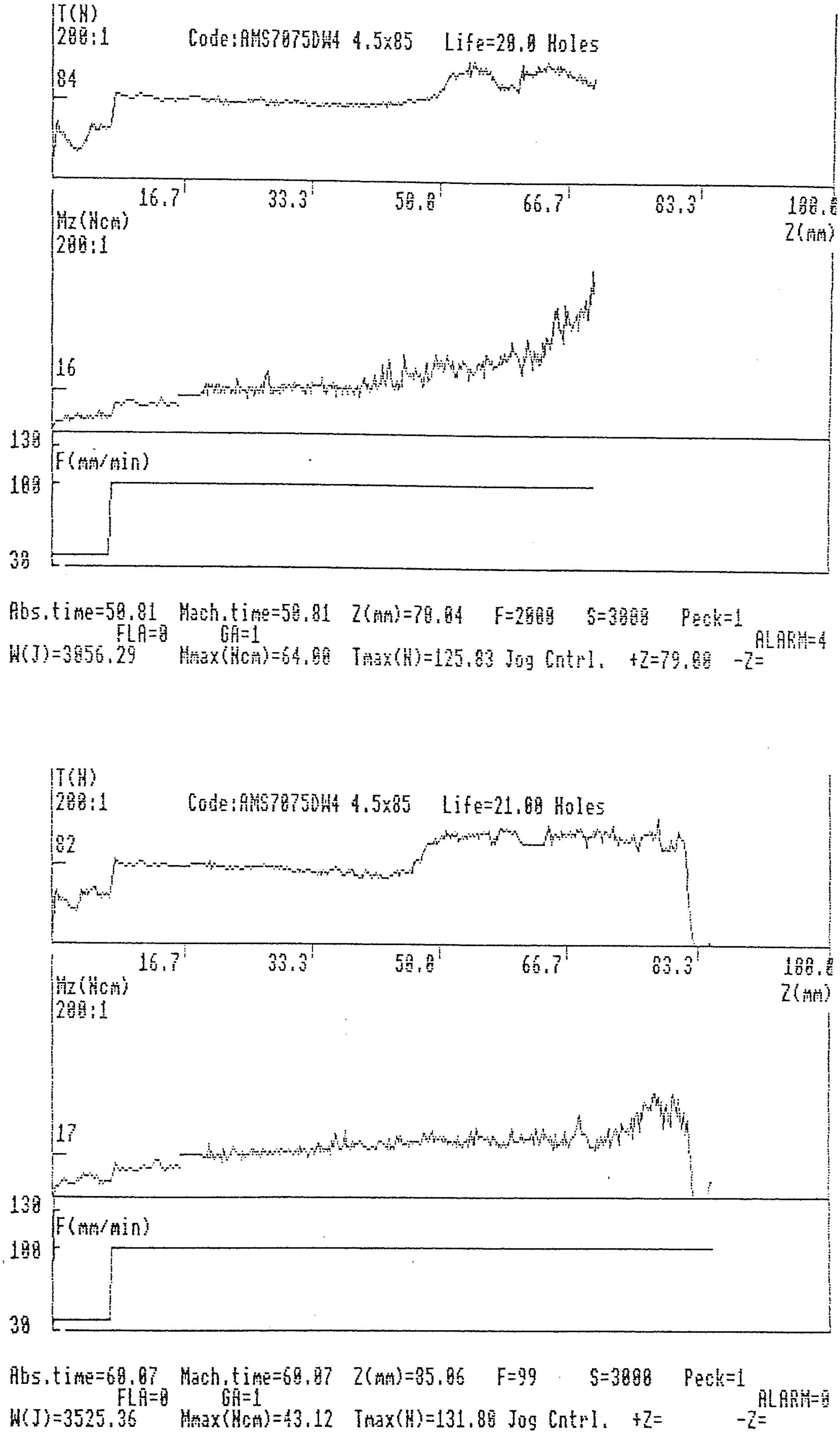
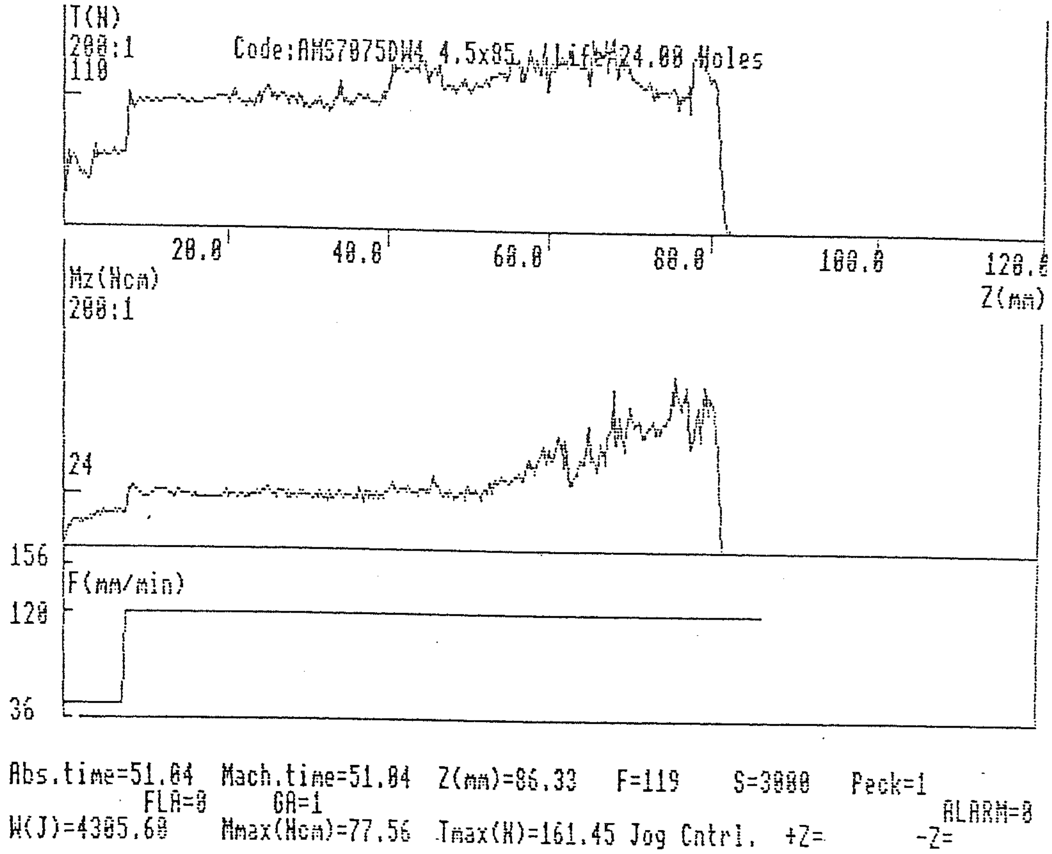


Fig. 8.6 : DHD of consequtive holes under the same machining conditions : 1st cycle (bottom) completed, 2nd cycle (top) aborted ;



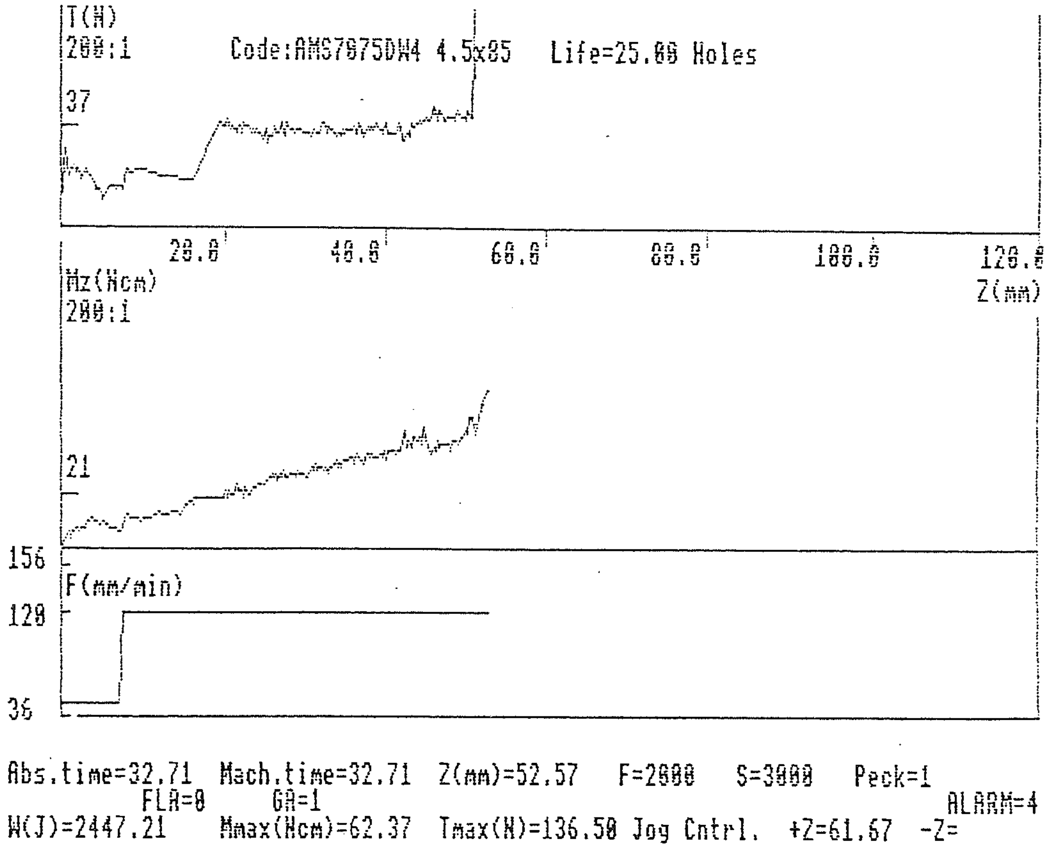


Fig. 8.7 : DHD of consequtive holes under the same machining conditions :
1st cycle (top) completed, 2nd cycle aborted : alarming levels of thrust

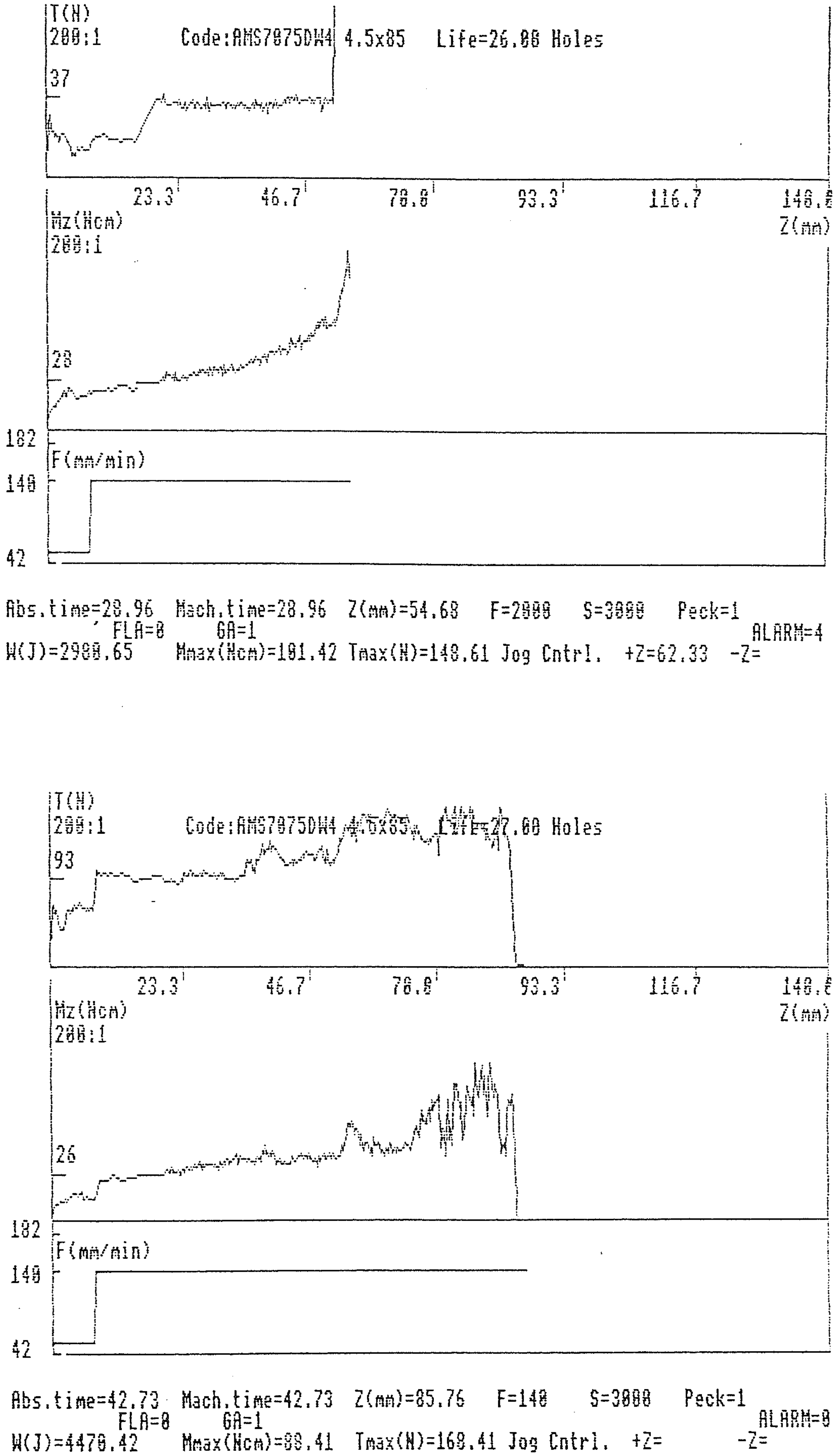
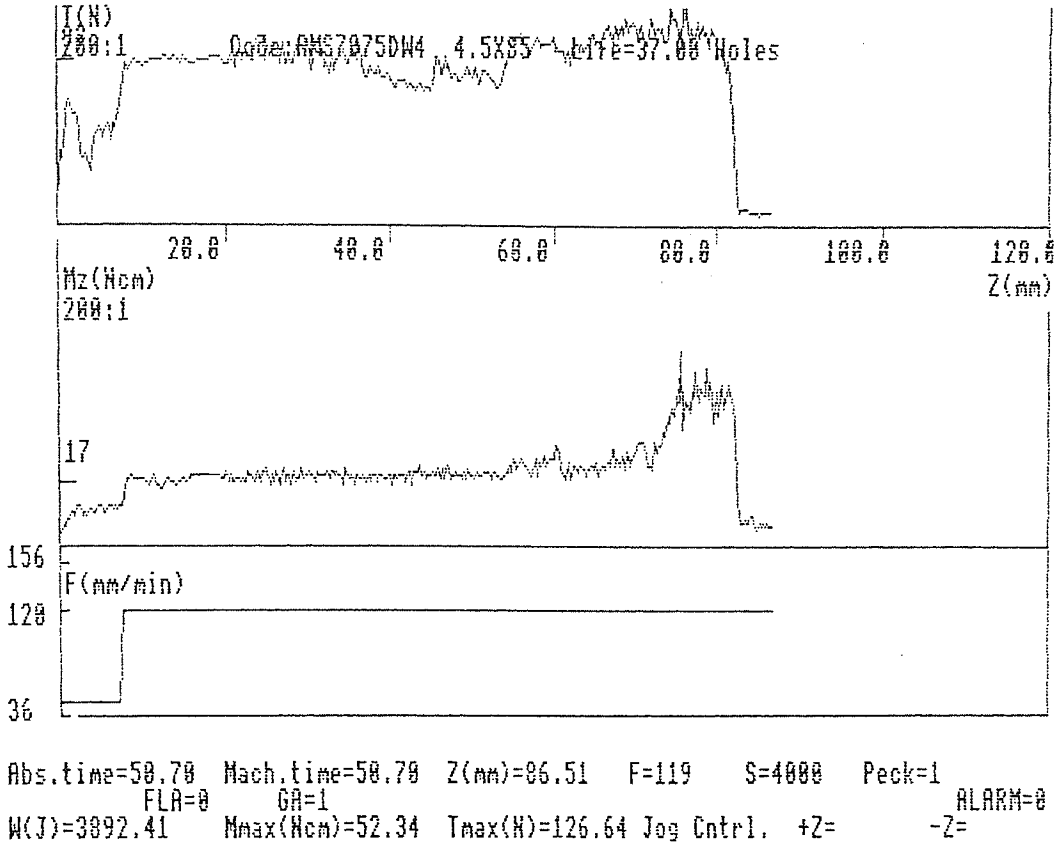


Fig. 8.8 : DHD of consequtive holes under the same machining conditions : 1st cycle (bottom) completed, 2nd cycle aborted : alarming levels of thrust and torque indicate high hardness area in workpiece



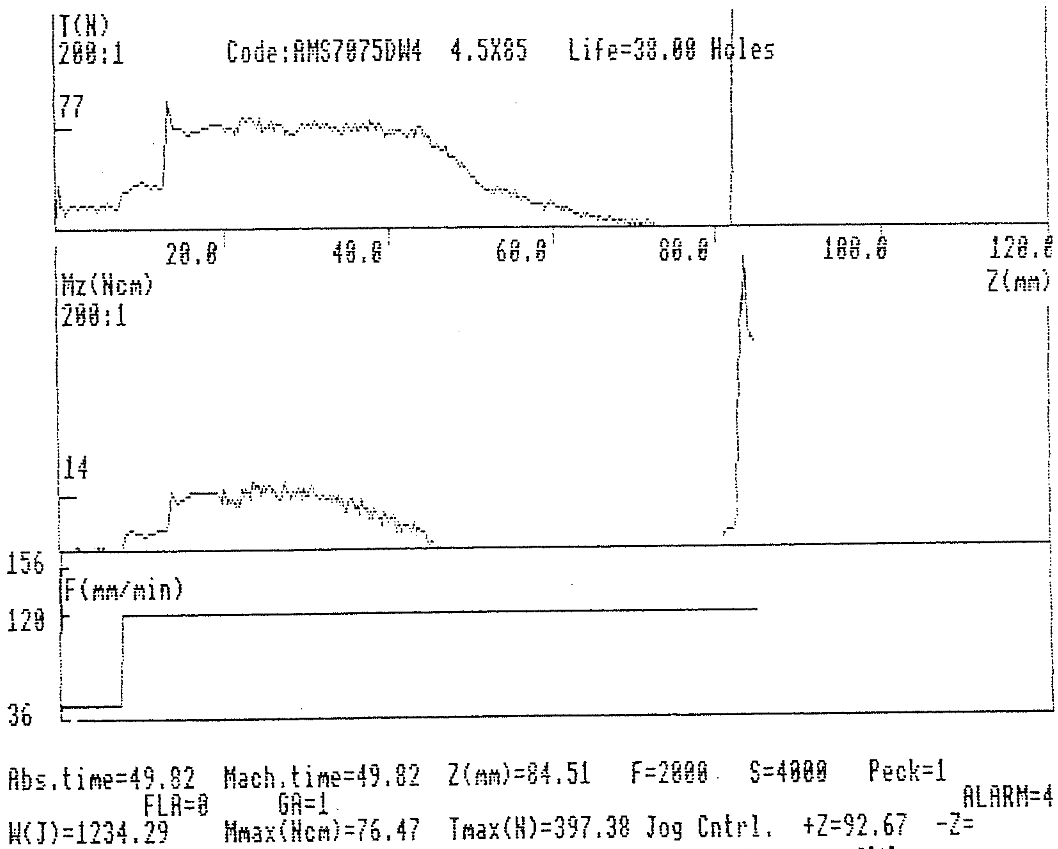


Fig. 8.9 : DHD of consequtive holes under the same machining conditions : 1st cycle (top) completed, 2nd cycle aborted : pattern of thrust and torque indicates unusual succession of low and high hardness zones in workpiece

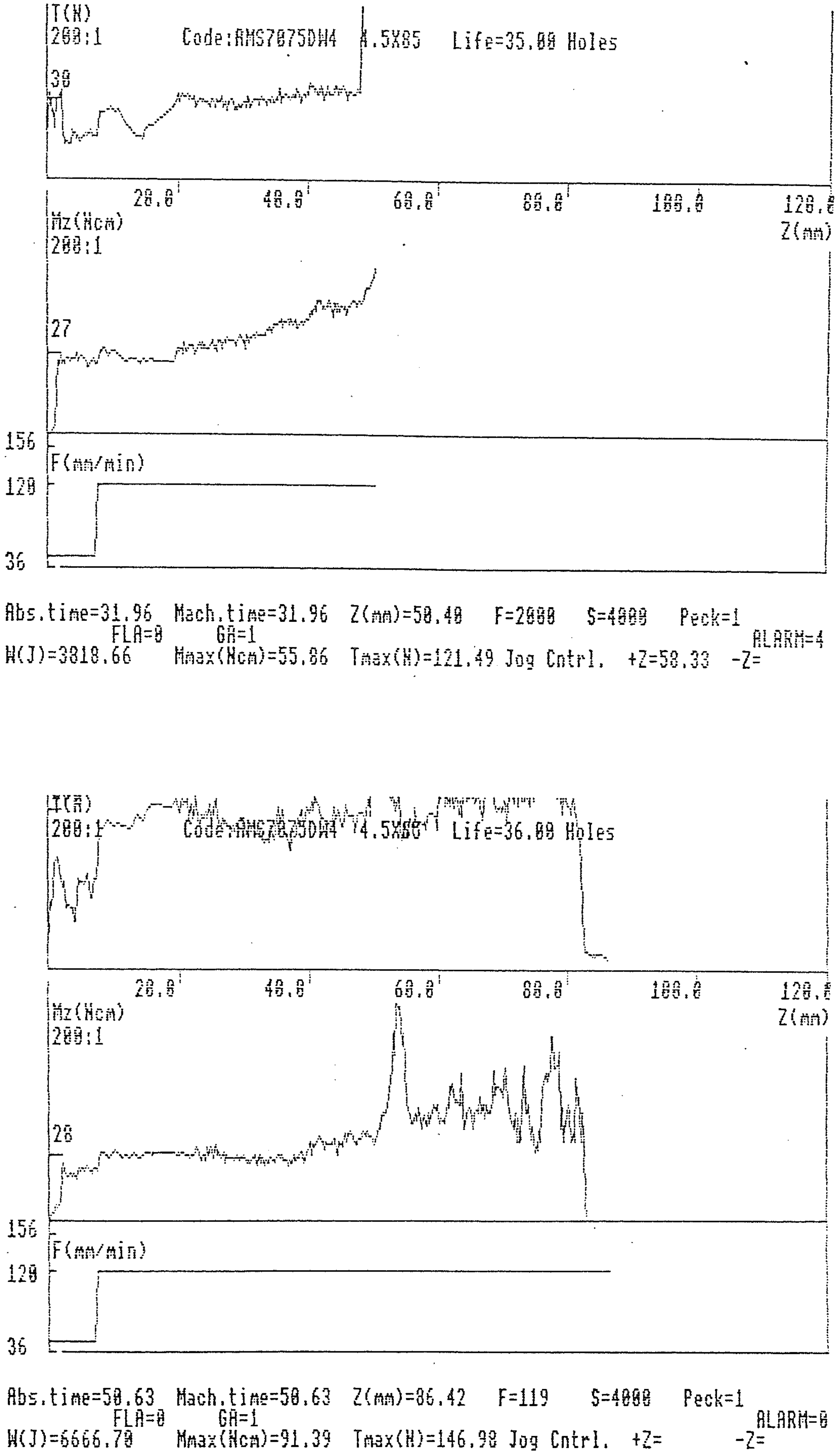
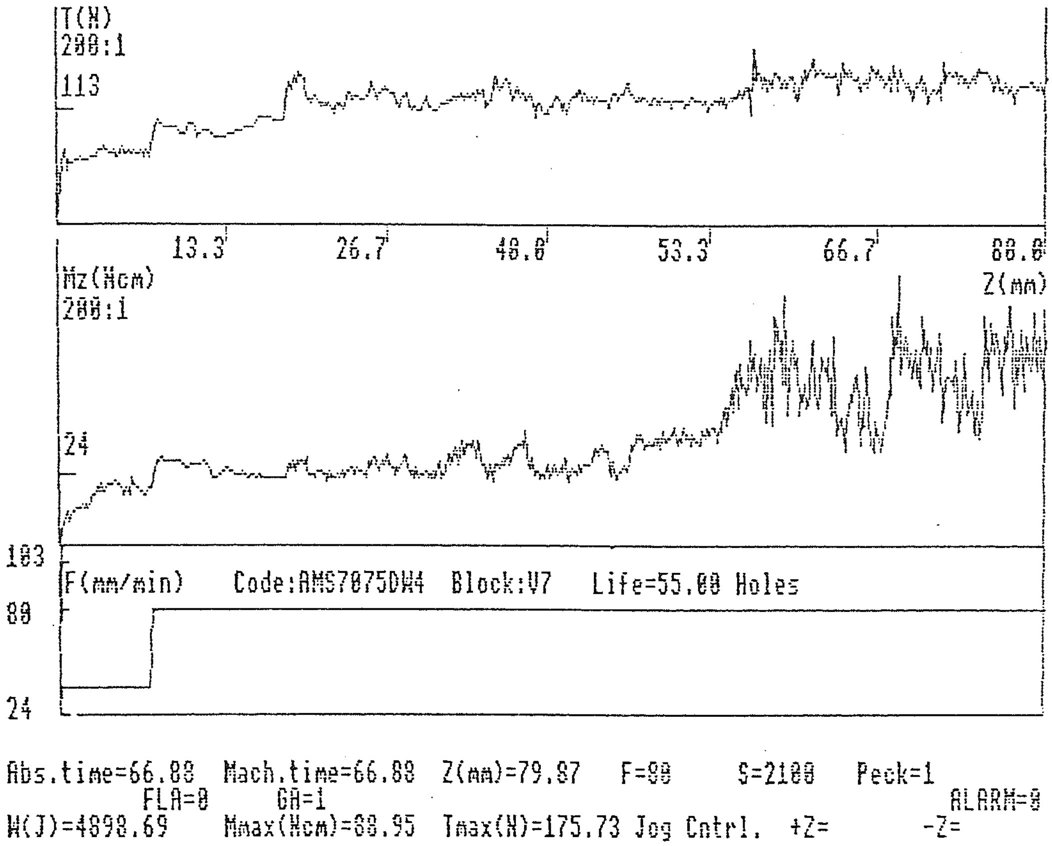


Fig.8.10 : DHD of consequtive holes under the same machining conditions: top cycle aborted, bottom cycle completed despite highly unstable torque



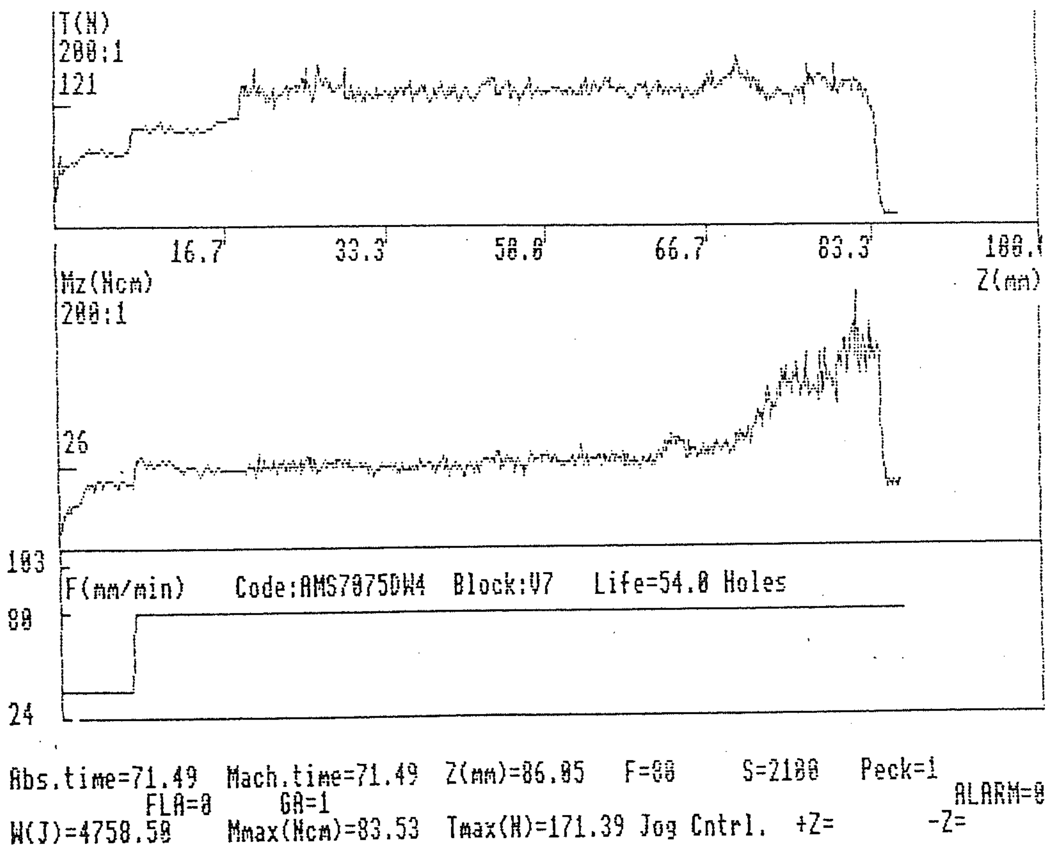
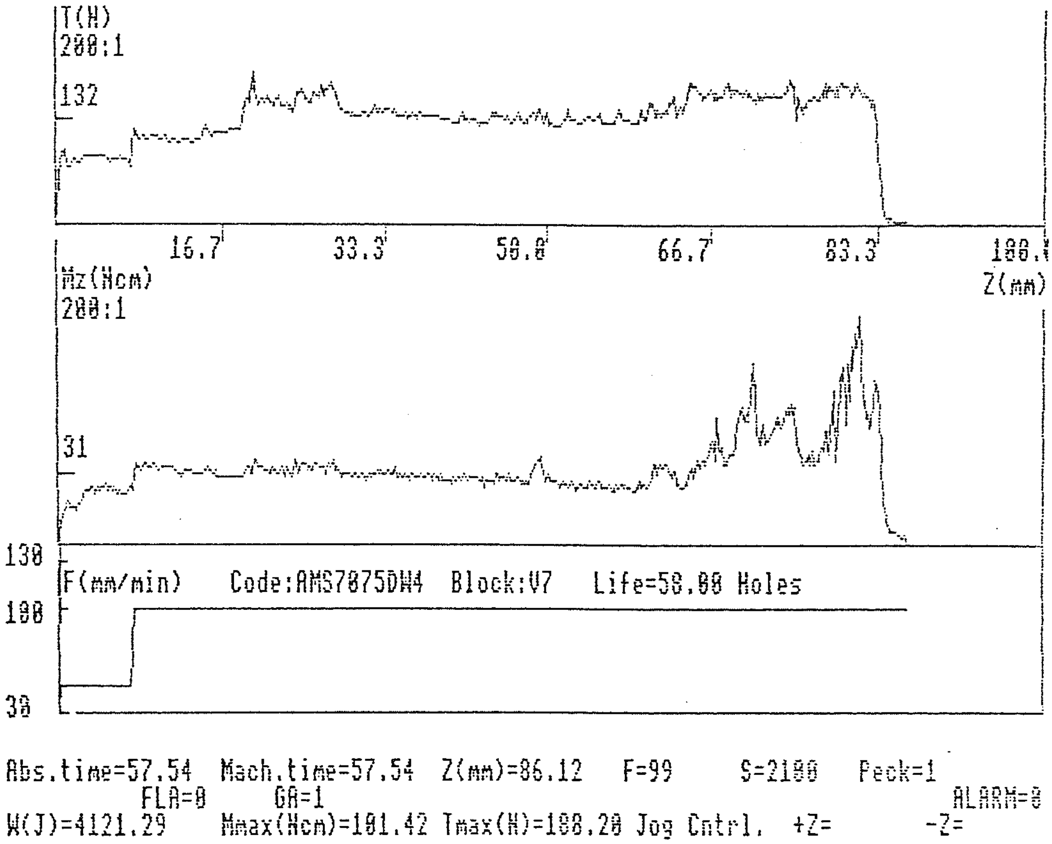


Fig. 8.11 : DHD of consequtive holes under same machining conditions : both cycles completed but instability patterns absolutely dissimilar



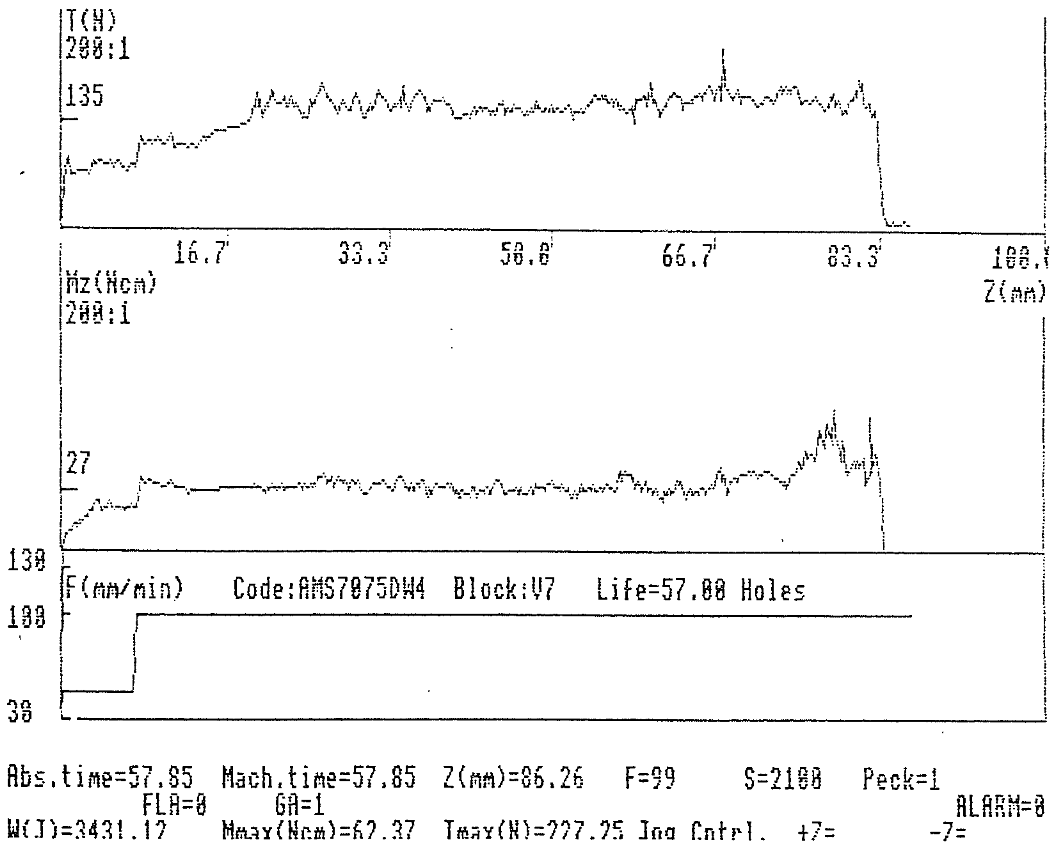
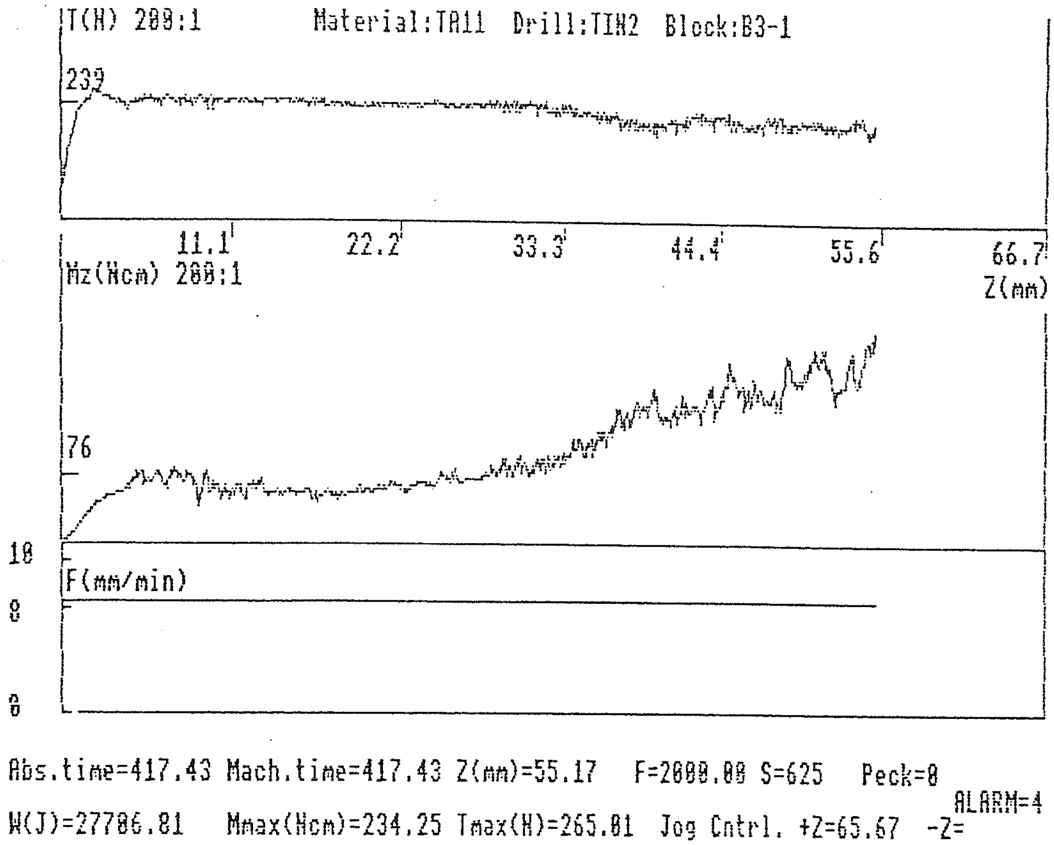


Fig. 8.12 : DHD of consequtive holes under same machining conditions : both cycles completed but instability patterns dissimilar

Selected Experimental Results of DHD TA11 IMI 318 Titanium Alloy under Process Monitoring :
Emergency tool withdrawal active when alarming levels of thrust or torque are encountered while feed rate and spindle RPM are held constant.

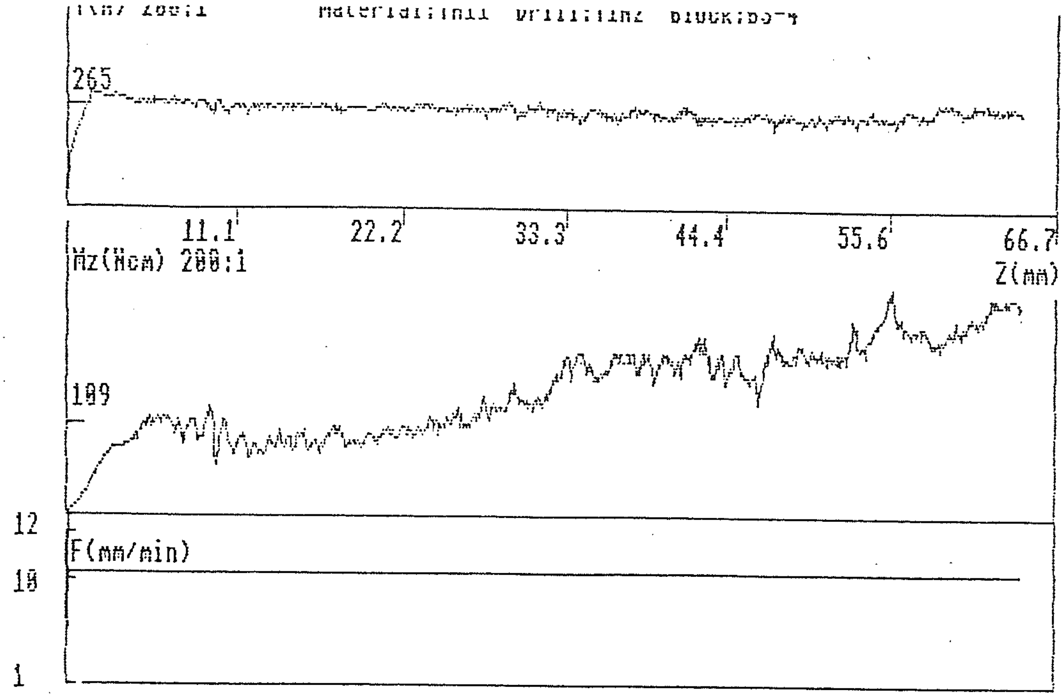
(The scope of tests has been described already in page 238 for tests with AMS7075 alloy)



INPUT, COMPUTED & RECORDED PROCESS DATA Source File : D

1. MATERIAL CODE=TA11
2. WORKPIECE CODE No.=B3
3. DRILL CODE=TIN2 DRILL DIAMETER (mm)=4.50
4. TOOL LIFE STATUS : No. OF HOLES=1.00
   CUMMULATIVE CUTTING TIME (min)=6.96
   CUMMULATIVE DEPTH (mm)=55.17
5. NC PROGRAM FEEDRATE (mm/min)=8.00 CUTTING FEED (mic/rev)=12.8
6. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.84
7. NC PROGRAM DEPTH Zmax (mm)=64.30
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
10. ENTRY FEEDRATE (mm/min)=8.00 100.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=3.70
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.0(
13. MAXIMUM TOLERABLE THRUST (N)=478.81
    STEADY STATE THRUST(N)=239.40
14. MAXIMUM TOLERABLE TORQUE (Ncm)=229.04
    STEADY STATE TORQUE(Ncm)=76.35

Fig. 8.13 : DHD in TA11 alloy, cycle aborted because of high levels of torque (350 % of the steady state value before feed halt and withdrawal)



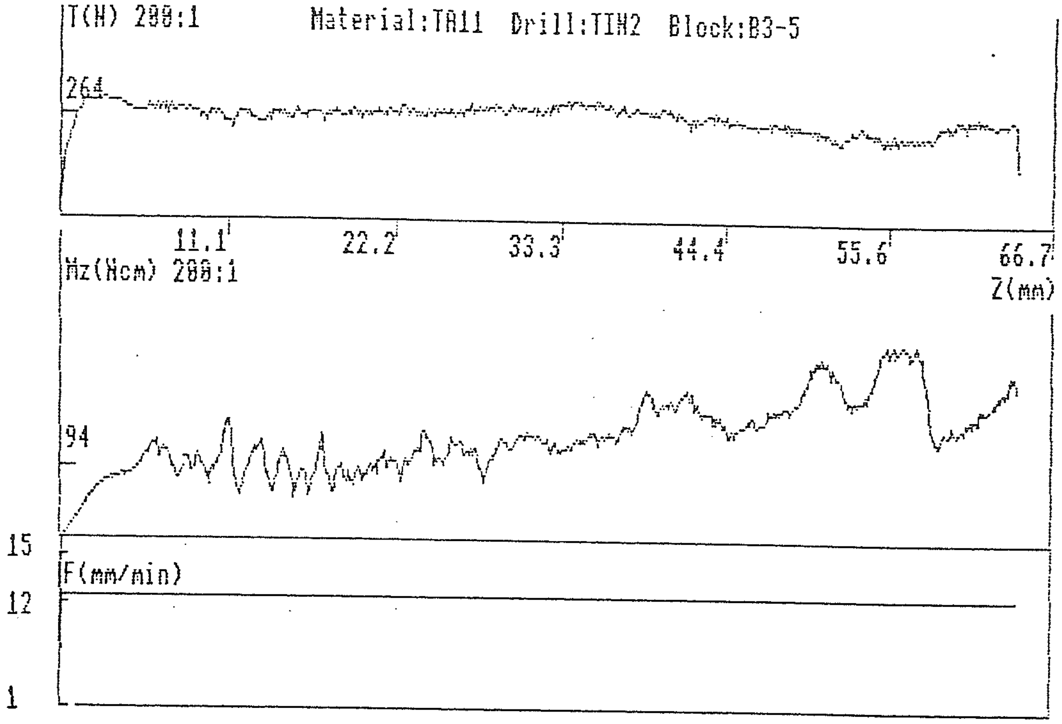
Abs.time=389.13 Mach.time=389.13 Z(mm)=64.36 F=10.00 S=625 Peck=0

W(J)=39060.75 Mmax(Ncm)=290.93 Tmax(N)=293.56 Jog Cntrl. +Z= -Z= ALARM=0

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : D.

1. MATERIAL CODE=TA11
2. WORKPIECE CODE No.=B3
3. DRILL CODE=TIN2 DRILL DIAMETER (mm)=4.50
4. TOOL LIFE STATUS : No. OF HOLES=4.00
   CUMMULATIVE CUTTING TIME (min)=28.04
   CUMMULATIVE DEPTH (mm)=248.16
5. NC PROGRAM FEEDRATE (mm/min)=10.00 CUTTING FEED (mic/rev)=16.(
6. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.84
7. NC PROGRAM DEPTH Zmax (mm)=64.30
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
10. ENTRY FEEDRATE (mm/min)=10.00 100.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=3.70
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.0(
13. MAXIMUM TOLERABLE THRUST (N)=531.41
    STEADY STATE THRUST(N)=265.71
14. MAXIMUM TOLERABLE TORQUE (Ncm)=328.43
    STEADY STATE TORQUE(Ncm)=109.48

Fig. 8.14 : DHD in TA11 alloy, cycle completed successfully



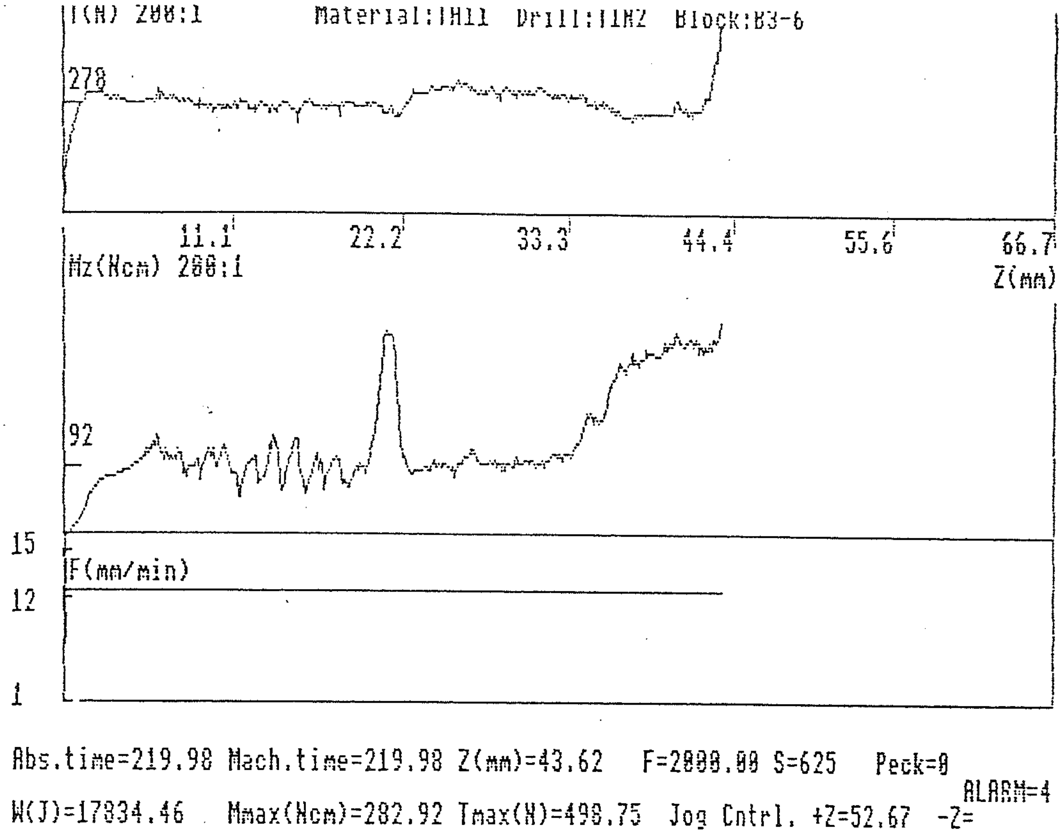
Abs.time=324.28 Mach.time=324.28 Z(mm)=64.32 F=12.00 S=625 Peck=0

W(J)=29258.61 Mmax(Ncm)=264.35 Tmax(N)=385.05 Jog Cntrl. +Z= -Z= ALARM=0

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : D:

1. MATERIAL CODE=TA11
2. WORKPIECE CODE No.=B3
3. DRILL CODE=TIN2 DRILL DIAMETER (mm)=4.50
4. TOOL LIFE STATUS : No. OF HOLES=5.00
   CUMMULATIVE CUTTING TIME (min)=33.44
   CUMMULATIVE DEPTH (mm)=312.48
5. NC PROGRAM FEEDRATE (mm/min)=12.00 CUTTING FEED (mic/rev)=19.2
6. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.84
7. NC PROGRAM DEPTH Zmax (mm)=64.30
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
10. ENTRY FEEDRATE (mm/min)=12.00 100.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=3.70
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.0C
13. MAXIMUM TOLERABLE THRUST (N)=529.61
    STEADY STATE THRUST(N)=264.80
14. MAXIMUM TOLERABLE TORQUE (Ncm)=282.88
    STEADY STATE TORQUE(Ncm)=94.29

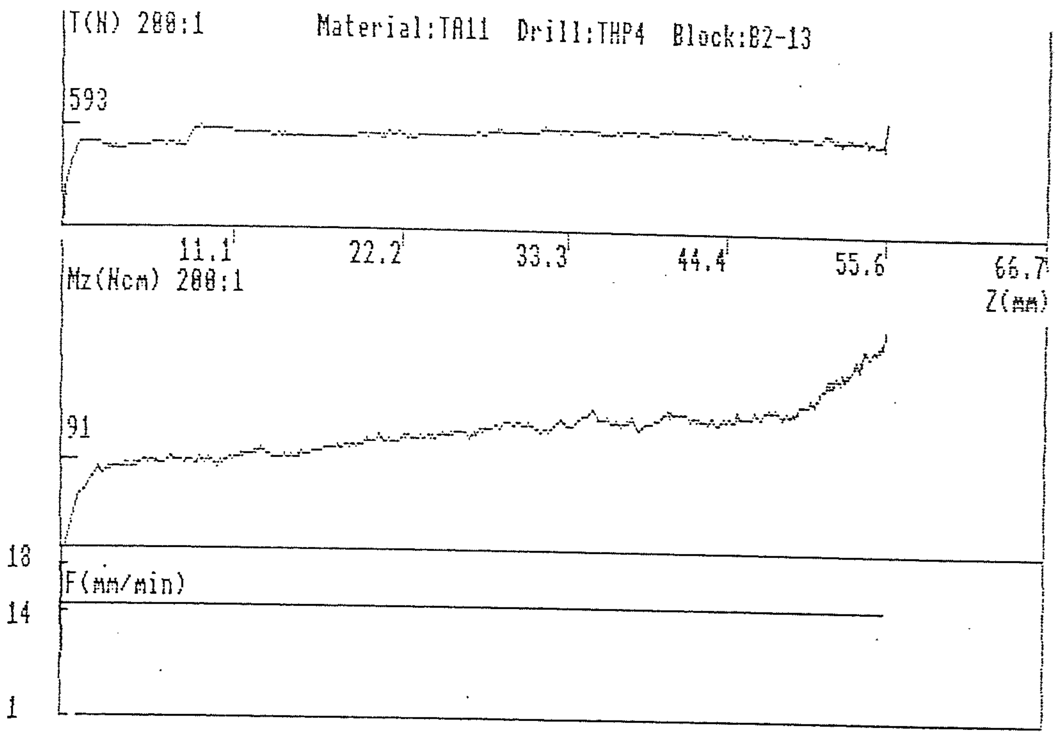
Fig. 8.15 : DHD in TA11 alloy, cycle completed successfully



INPUT, COMPUTED & RECORDED PROCESS DATA   Source File : DA

1. MATERIAL CODE=TA11
2. WORKPIECE CODE No.=B3
3. DRILL CODE=TIN2 DRILL DIAMETER (mm)=4.50
4. TOOL LIFE STATUS : No. OF HOLES=6.00
   CUMMULATIVE CUTTING TIME (min)=37.11
   CUMMULATIVE DEPTH (mm)=356.10
5. NC PROGRAM FEEDRATE (mm/min)=12.00 CUTTING FEED (mic/rev)=19.2
6. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.84
7. NC PROGRAM DEPTH Zmax (mm)=64.30
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
10. ENTRY FEEDRATE (mm/min)=12.00 100.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=3.70
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.00
13. MAXIMUM TOLERABLE THRUST (N)=556.15
    STEADY STATE THRUST(N)=278.07
14. MAXIMUM TOLERABLE TORQUE (Ncm)=278.43
    STEADY STATE TORQUE(Ncm)=92.81

Fig. 8.16 : DHD in TA11 alloy, cycle aborted due to high level of thrust and torque, end of drill life after 33.44 min of cumulative cutting time



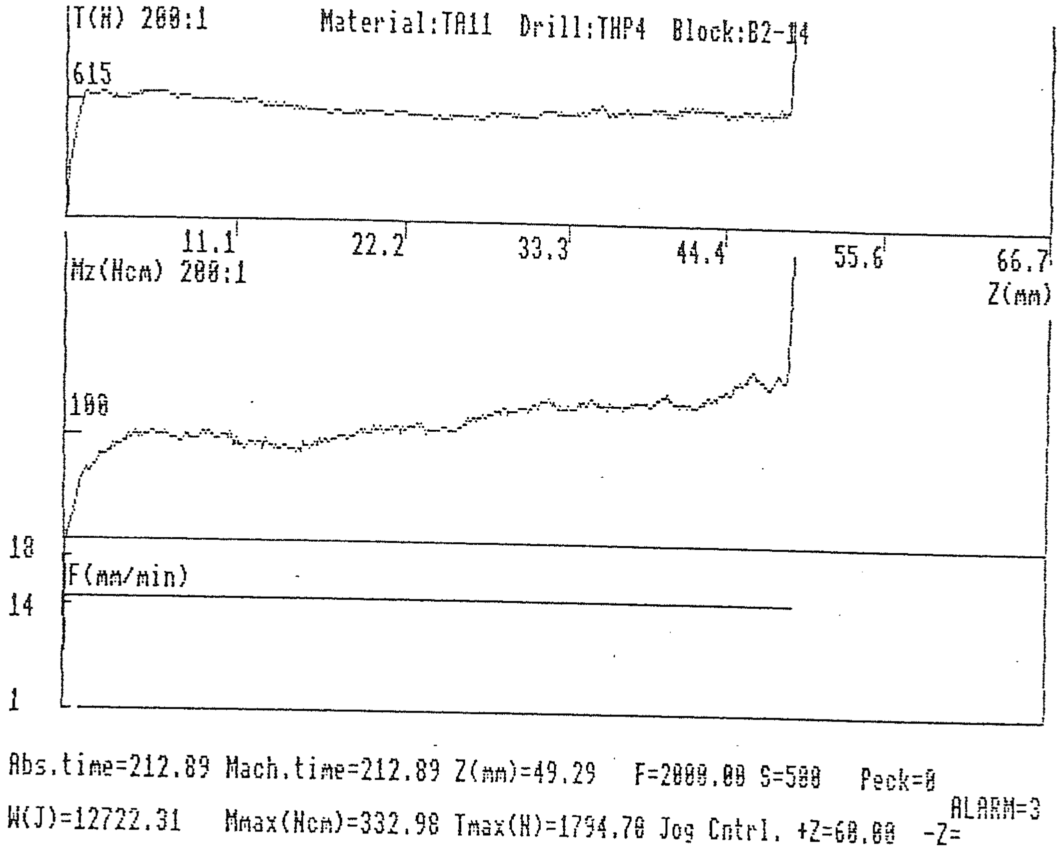
Abs.time=241.60 Mach.time=241.60 Z(mm)=55.69 F=2000.00 S=500 Peck=0

W(J)=15166.72 Mmax(Ncm)=313.04 Tmax(N)=1290.33 Jog Cntrl. +Z=67.00 -Z= ALARM=3

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : DA

1. MATERIAL CODE=TA11
2. WORKPIECE CODE No.=B2
3. DRILL CODE=THP4 DRILL DIAMETER (mm)=4.50
4. TOOL LIFE STATUS : No. OF HOLES=13.00
   CUMMULATIVE CUTTING TIME (min)=48.68
   CUMMULATIVE DEPTH (mm)=522.18
5. NC PROGRAM FEEDRATE (mm/min)=14.00 CUTTING FEED (mic/rev)=28.0
6. NC PROGRAM SPINDLE RPM=500.00 SURFACE SPEED (m/min)=7.07
7. NC PROGRAM DEPTH Zmax (mm)=65.50
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
10. ENTRY FEEDRATE (mm/min)=14.00 100.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=3.70
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.00
13. MAXIMUM TOLERABLE THRUST (N)=1186.34
    STEADY STATE THRUST(N)=593.17
14. MAXIMUM TOLERABLE TORQUE (Ncm)=274.54
    STEADY STATE TORQUE(Ncm)=91.51

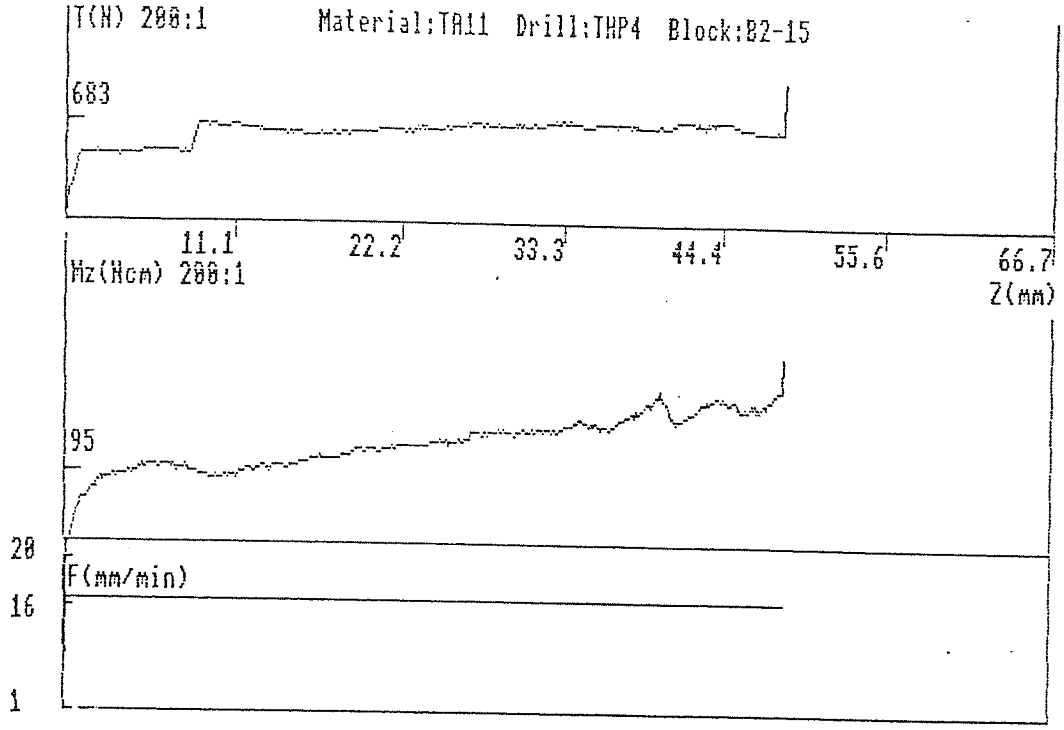
Fig. 8.17 : DHD in TA11 alloy, cycle aborted, high levels of torque



INPUT, COMPUTED & RECORDED PROCESS DATA   Source File : DA

1. MATERIAL CODE=TA11
2. WORKPIECE CODE No.=B2
3. DRILL CODE=THP4   DRILL DIAMETER (mm)=4.50
4. TOOL LIFE STATUS :   No. OF HOLES=14.00
   CUMMULATIVE CUTTING TIME (min)=52.24
   CUMMULATIVE DEPTH (mm)=571.47
5. NC PROGRAM FEEDRATE (mm/min)=14.00   CUTTING FEED (mic/rev)=28.0(
6. NC PROGRAM SPINDLE RPM=500.00   SURFACE SPEED (m/min)=7.07
7. NC PROGRAM DEPTH Zmax (mm)=65.50
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
10. ENTRY FEEDRATE (mm/min)=14.00   100.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=3.70
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00   THRUST (N/V)=200.00
13. MAXIMUM TOLERABLE THRUST (N)=1230.46
    STEADY STATE THRUST(N)=615.23
14. MAXIMUM TOLERABLE TORQUE (Ncm)=301.73
    STEADY STATE TORQUE(Ncm)=100.58

Fig. 8.18 : DHD in TA11 alloy, cycle aborted because of alarming levels of thrust and torque (over 300 % of steady state values), cause : zone of increased hardness at 50 mm depth (confirmed by fig. 8.19 also)



Abs.time=184.08 Mach.time=184.08 Z(mm)=48.78 F=2000.00 S=500 Peck=0

W(J)=12922.19 Mmax(Ncm)=300.05 Tmax(N)=1664.01 Jog Cntrl. +Z=60.33 -Z= ALARM=3

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : D:

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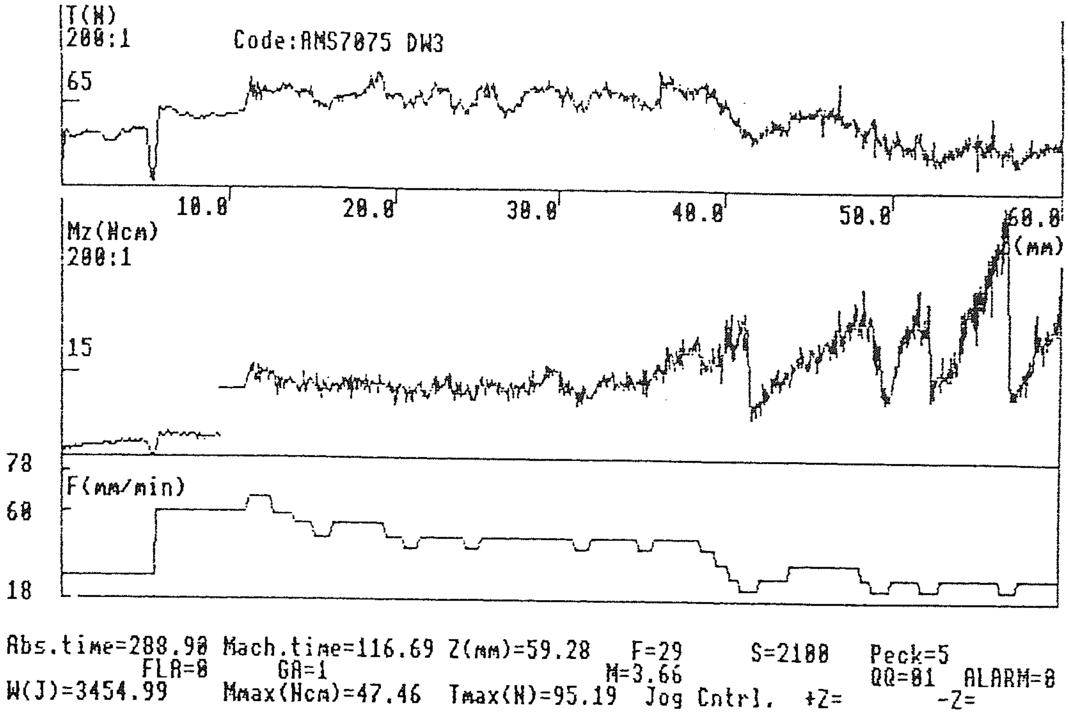
1. MATERIAL CODE=TA11
2. WORKPIECE CODE No.=B2
3. DRILL CODE=THP4 DRILL DIAMETER (mm)=4.50
4. TOOL LIFE STATUS : No. OF HOLES=15.00
   CUMMULATIVE CUTTING TIME (min)=55.32
   CUMMULATIVE DEPTH (mm)=620.25
5. NC PROGRAM FEEDRATE (mm/min)=16.00 CUTTING FEED (mic/rev)=32.0
6. NC PROGRAM SPINDLE RPM=500.00 SURFACE SPEED (m/min)=7.07
7. NC PROGRAM DEPTH Zmax (mm)=65.50
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
10. ENTRY FEEDRATE (mm/min)=16.00 100.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=3.70
12. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.00
13. MAXIMUM TOLERABLE THRUST (N)=1367.22
    STEADY STATE THRUST(N)=683.61
14. MAXIMUM TOLERABLE TORQUE (Ncm)=287.61
    STEADY STATE TORQUE(Ncm)=95.87

Fig. 8.19 : DHD in TA11 alloy, cycle aborted (as in fig. 8.18)

Selected Experimental Results of DHD AMS7075 T736 Alluminium Alloy Under Adaptive Control of feed rate, spindle speed and ± Z axis position.

These results are a few of the many tests performed after the system had been installed. Fundamental purpose of these tests was to ensure the two main functions of the system : that it can ensure the integrity of the process and the safety of the workpiece at any hole depth and that it can complete the machining of the hole to the depth specified in the NC part program.



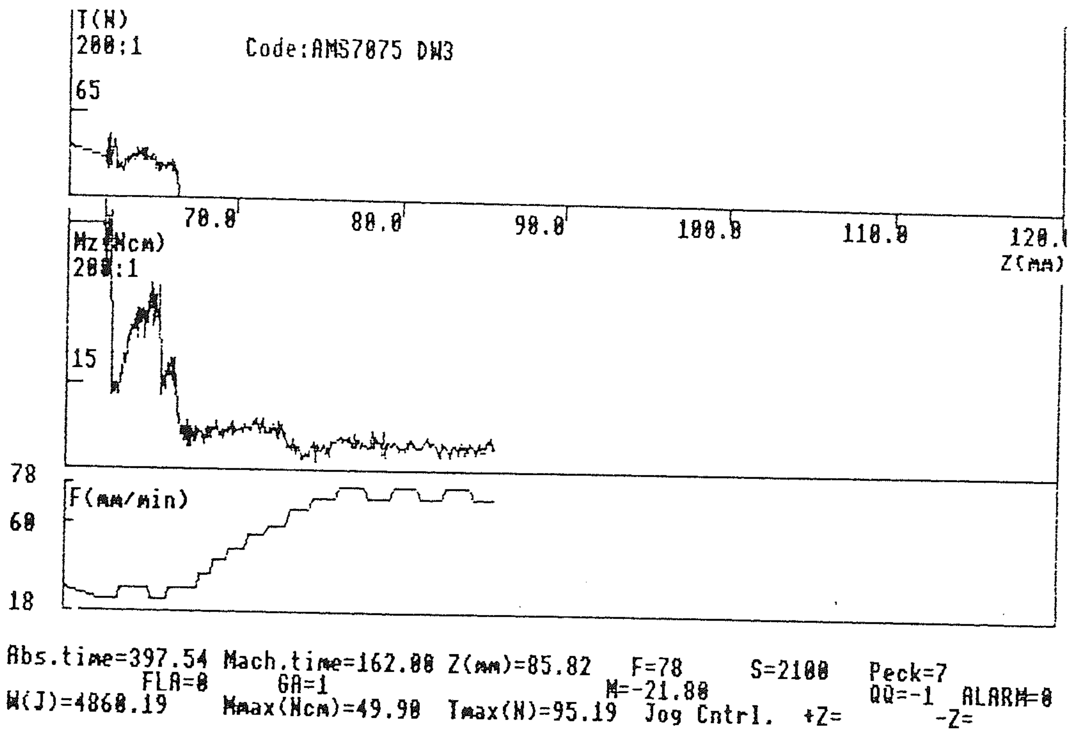


Fig. 8.20 : DHD in AMS7075 alloy, in 7 pecks : cycle completed successfully under Adaptive Control and automatic pecking. (cycle lasted 397 sec, thus recquired two VDU screens to be recorded)

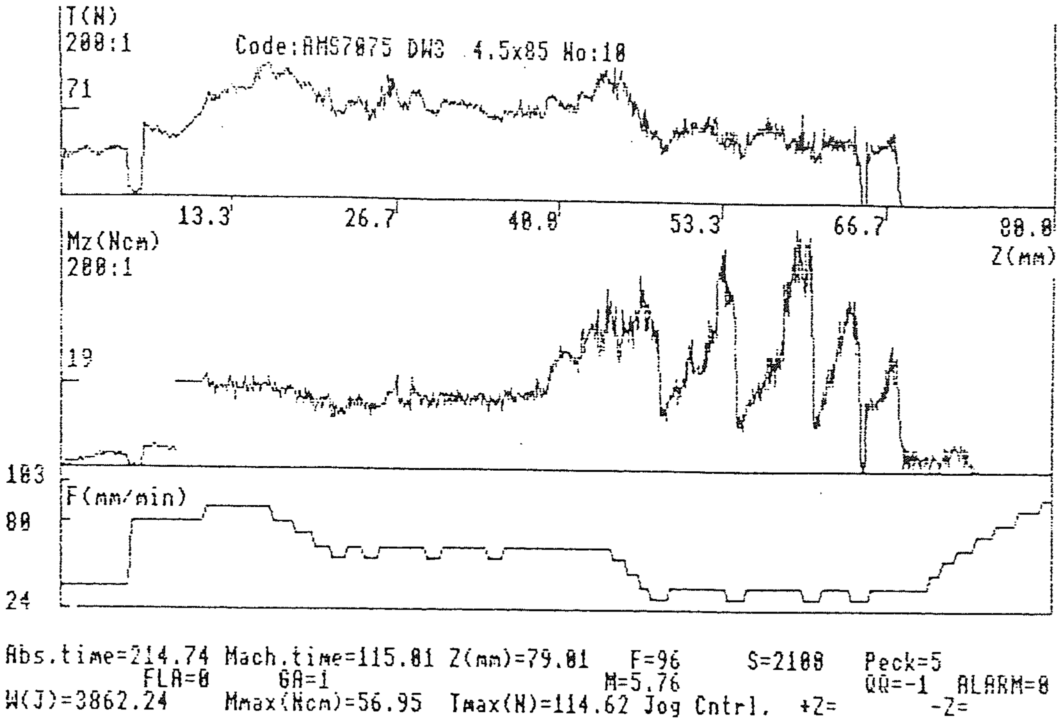
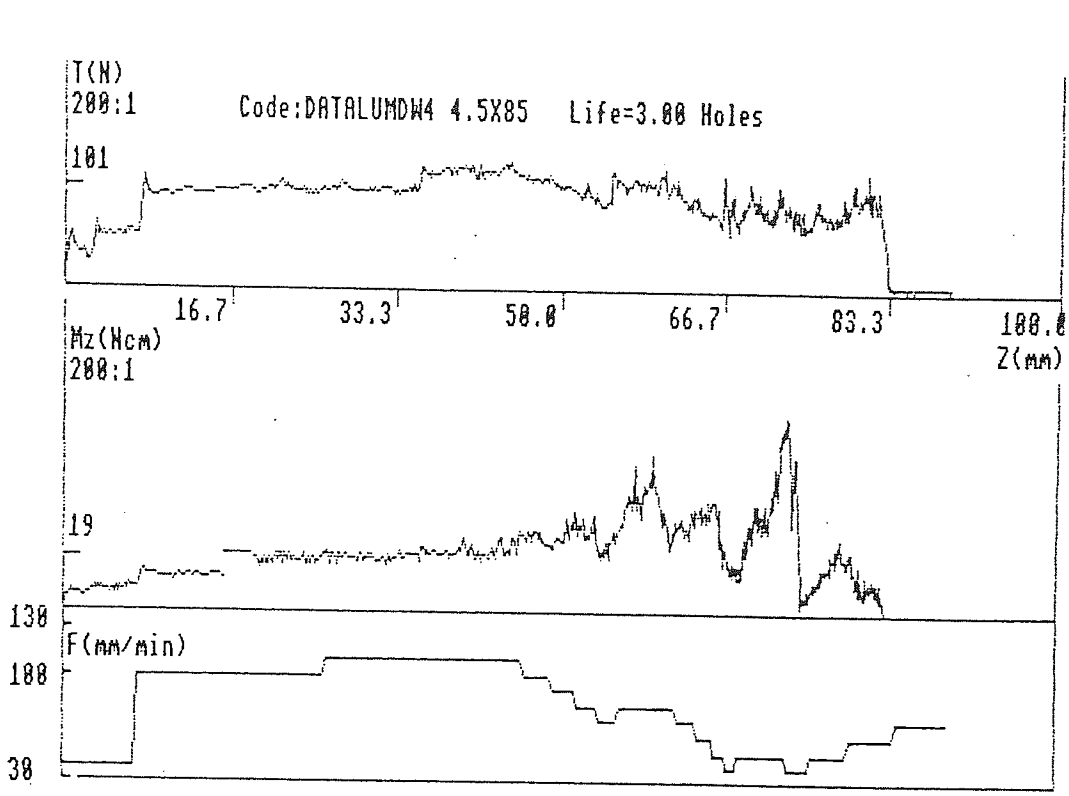
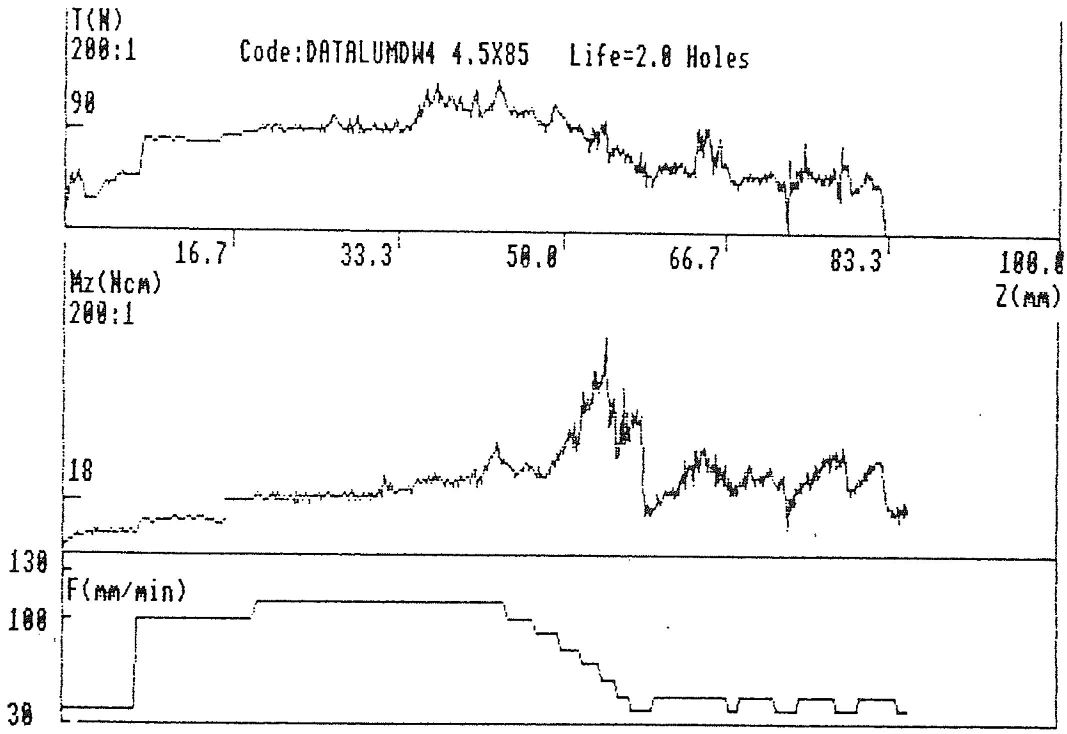


Fig. 8.21 : DHD in AMS7075 alloy, in 5 pecks : cycle completed successfully under Adaptive Control and automatic pecking.

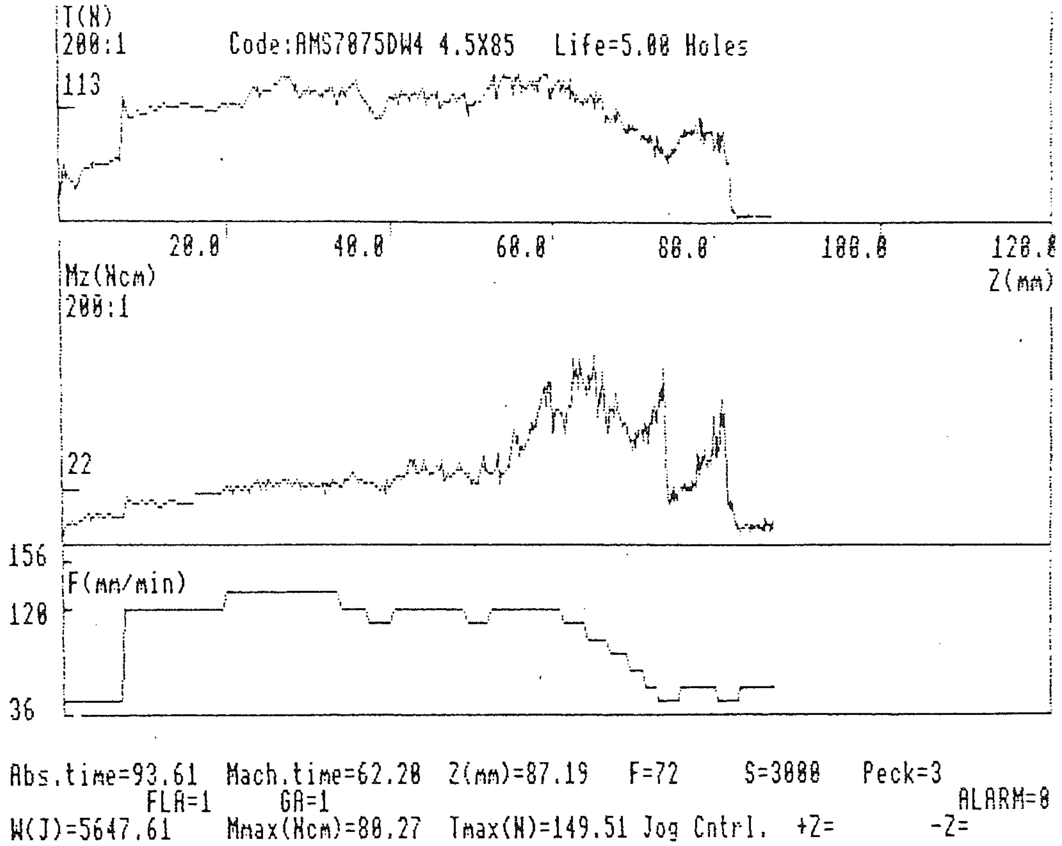


Abs.time=91.56 Mach.time=77.27 Z(mm)=89.52 F=80 S=3000 Peck=2
FLA=1 GA=1 ALARM=0
W(J)=4808.55 Mmax(Ncm)=70.24 Tmax(N)=127.10 Jog Cntrl. +Z= -Z=



Abs.time=131.72 Mach.time=81.17 Z(mm)=85.34 F=49 S=3000 Peck=4
FLA=0 GA=1 ALARM=0
W(J)=6066.40 Mmax(Ncm)=73.22 Tmax(N)=137.76 Jog Cntrl. +Z= -Z=

Fig. 8.22 : DHD in AMS7075 alloy, in 2 and 4 pecks : cycles completed successfully under Adaptive Control and automatic pecking.



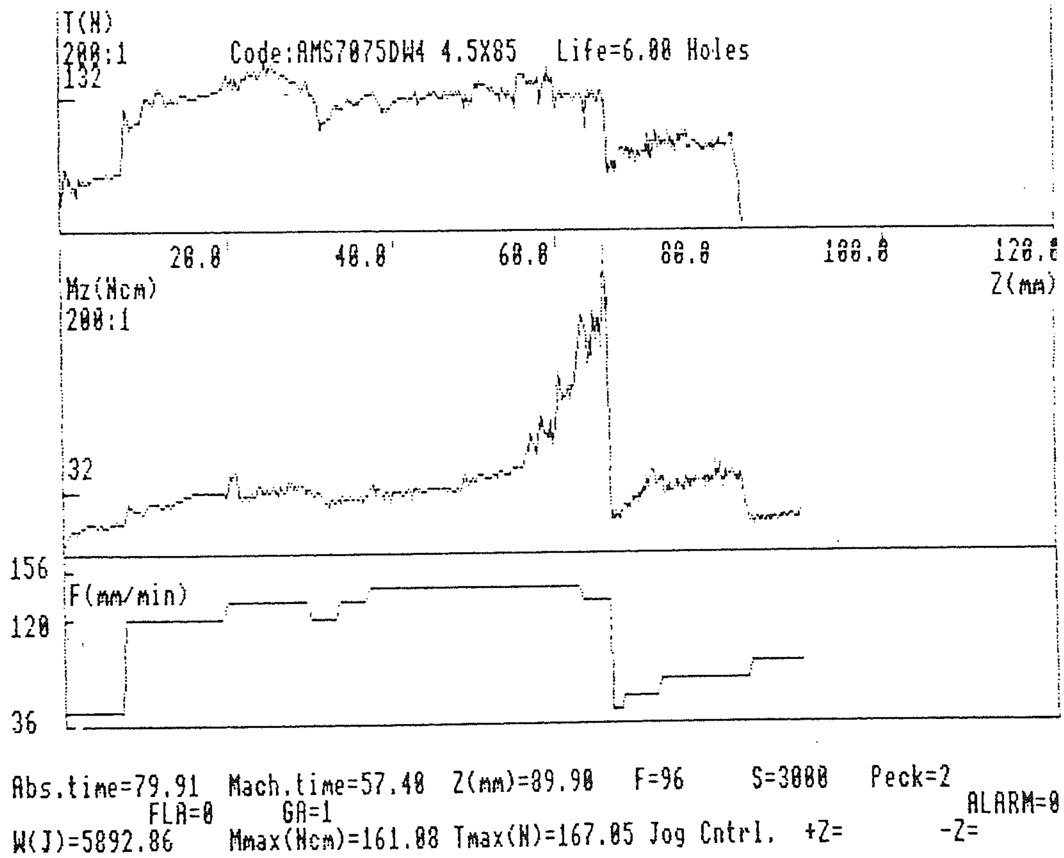
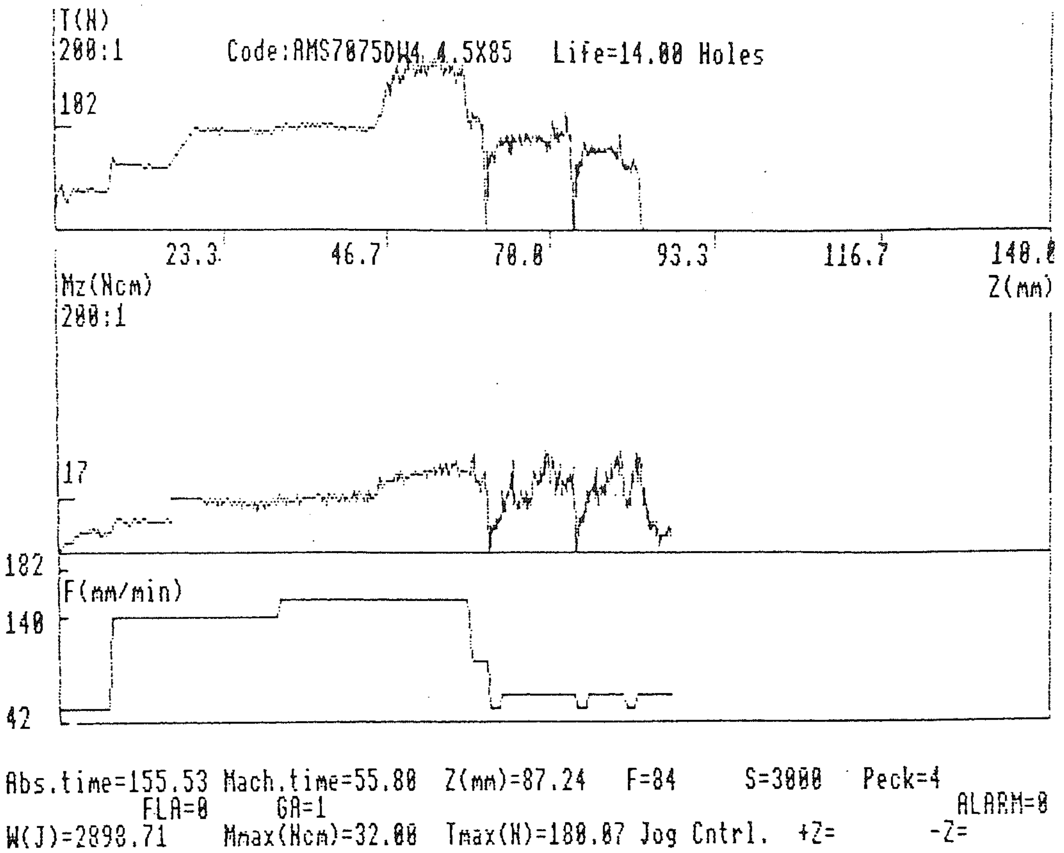


Fig. 8.23 : DHD in AMS7075 alloy, in 2 and 3 pecks : cycle completed successfully under Adaptive Control and automatic pecking.



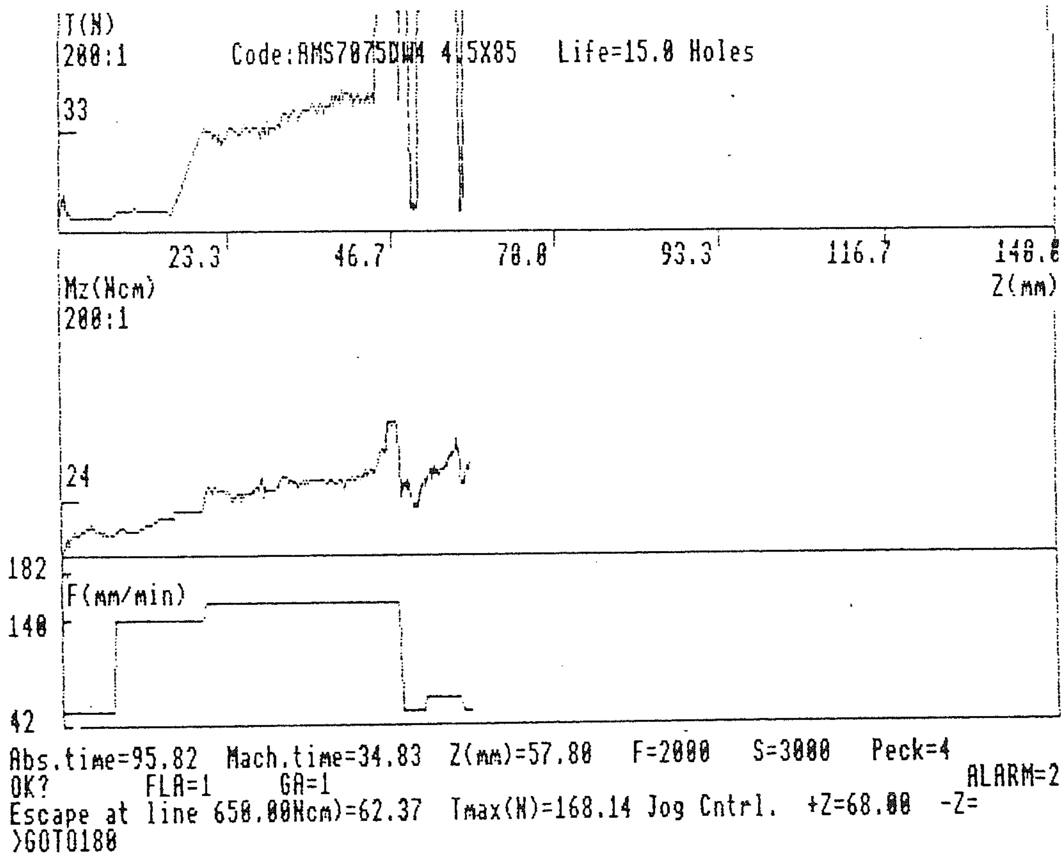


Fig. 8.24 : DHD in AMS7075 alloy, in 4 pecks : cycles completed successfully under Adaptive Control and automatic pecking.

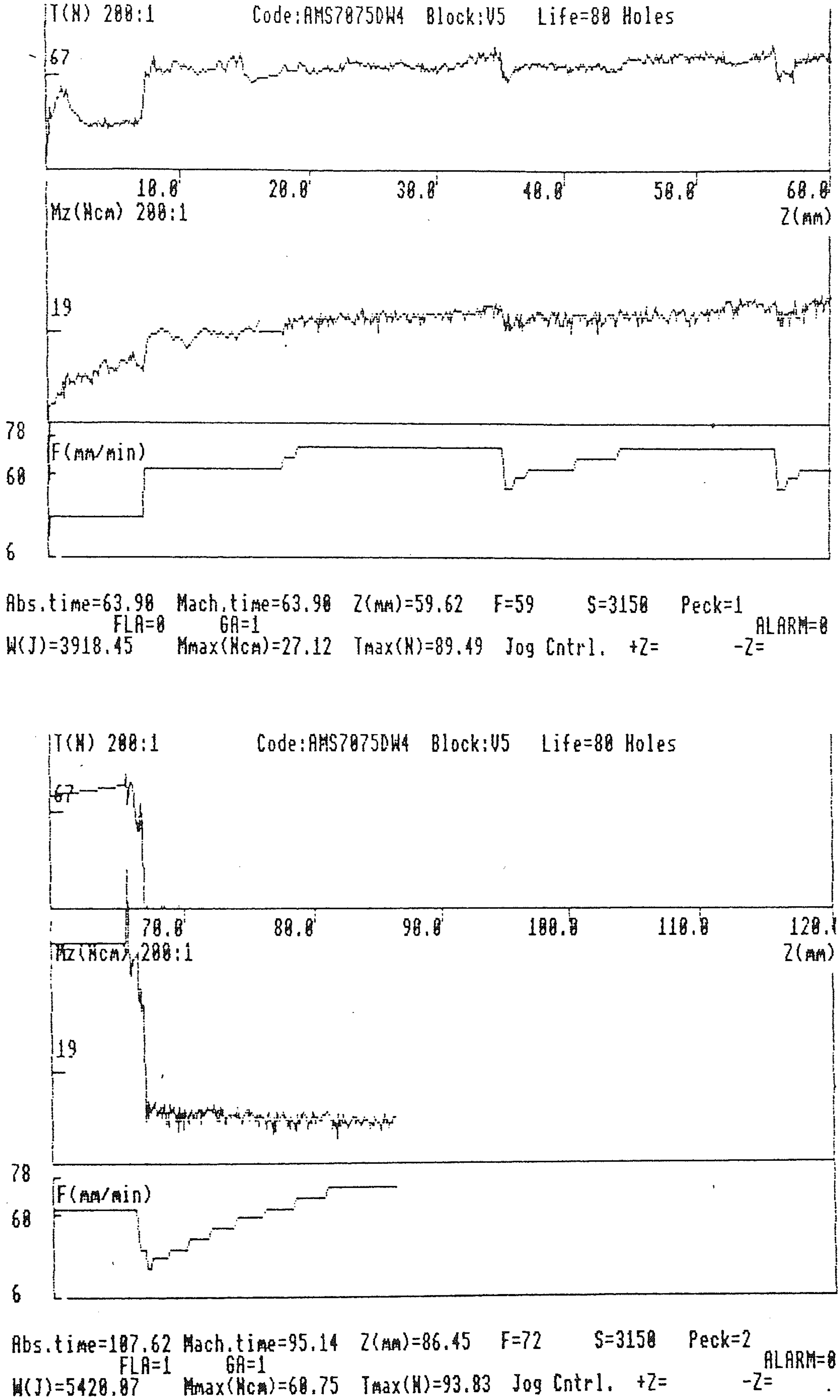


Fig. 8.25 : DHD in AMS7075 alloy, in 1 and 2 pecks : cycle completed successfully under Adaptive Control and automatic pecking.
(low initial feed rate ensures stability and fewer pecks)

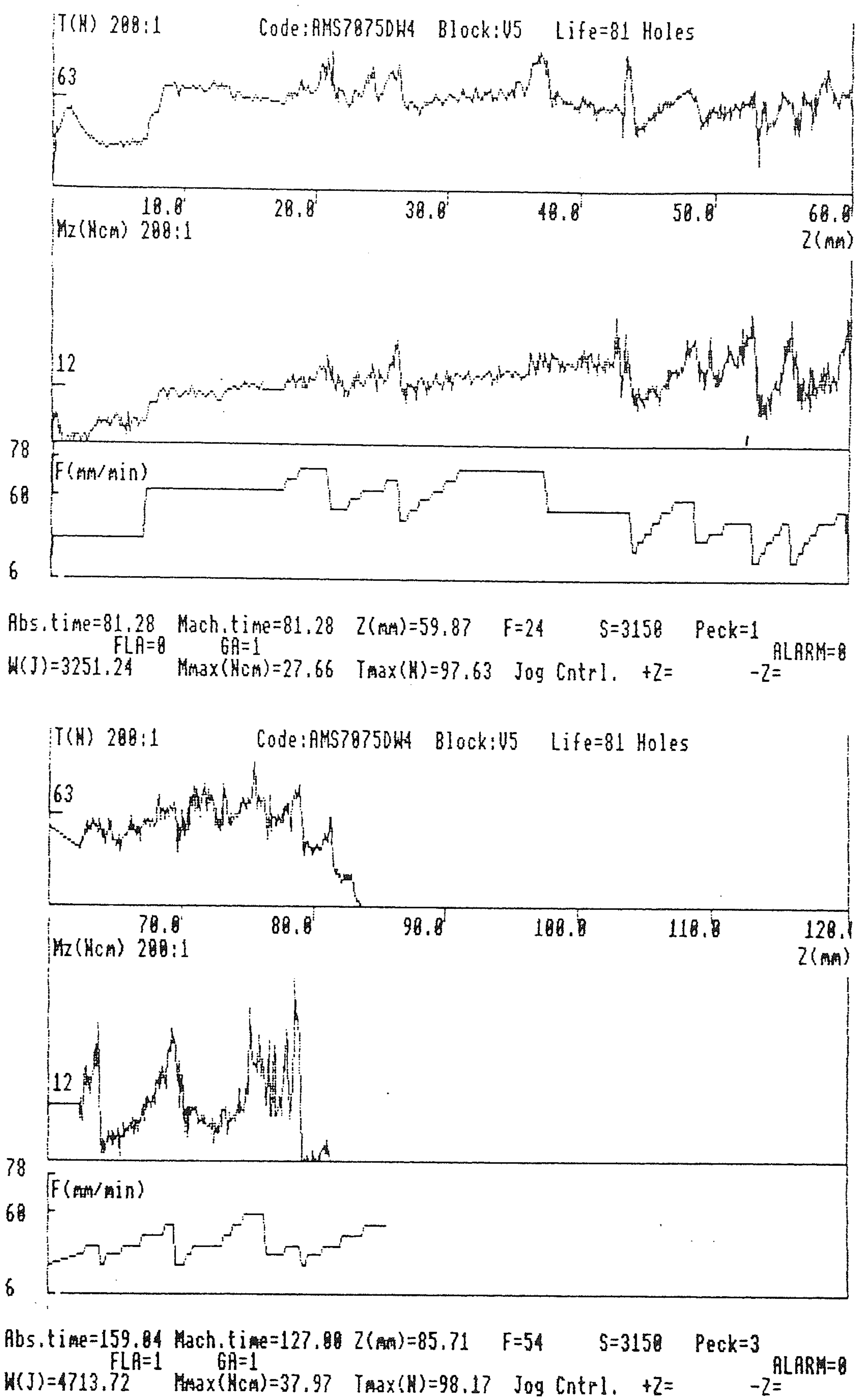
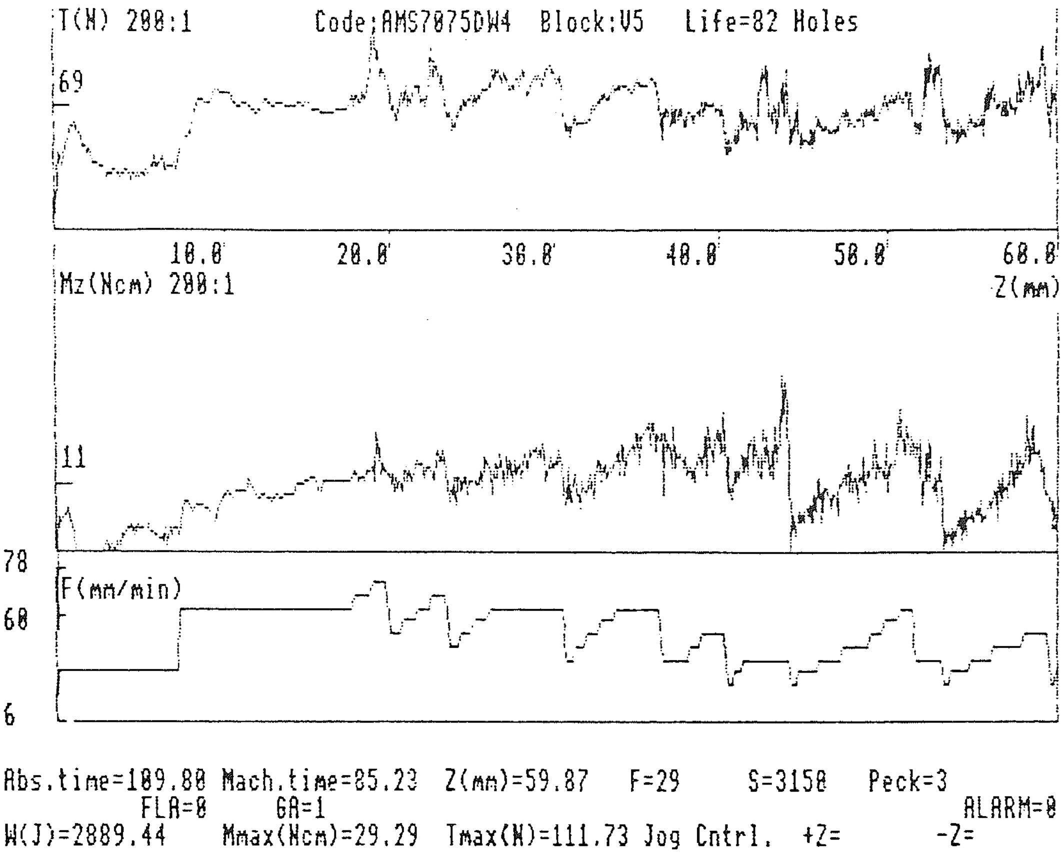


Fig. 8.26 : DHD in AMS7075 alloy, in 3 pecks : cycle completed successfully under Adaptive Control and automatic pecking.



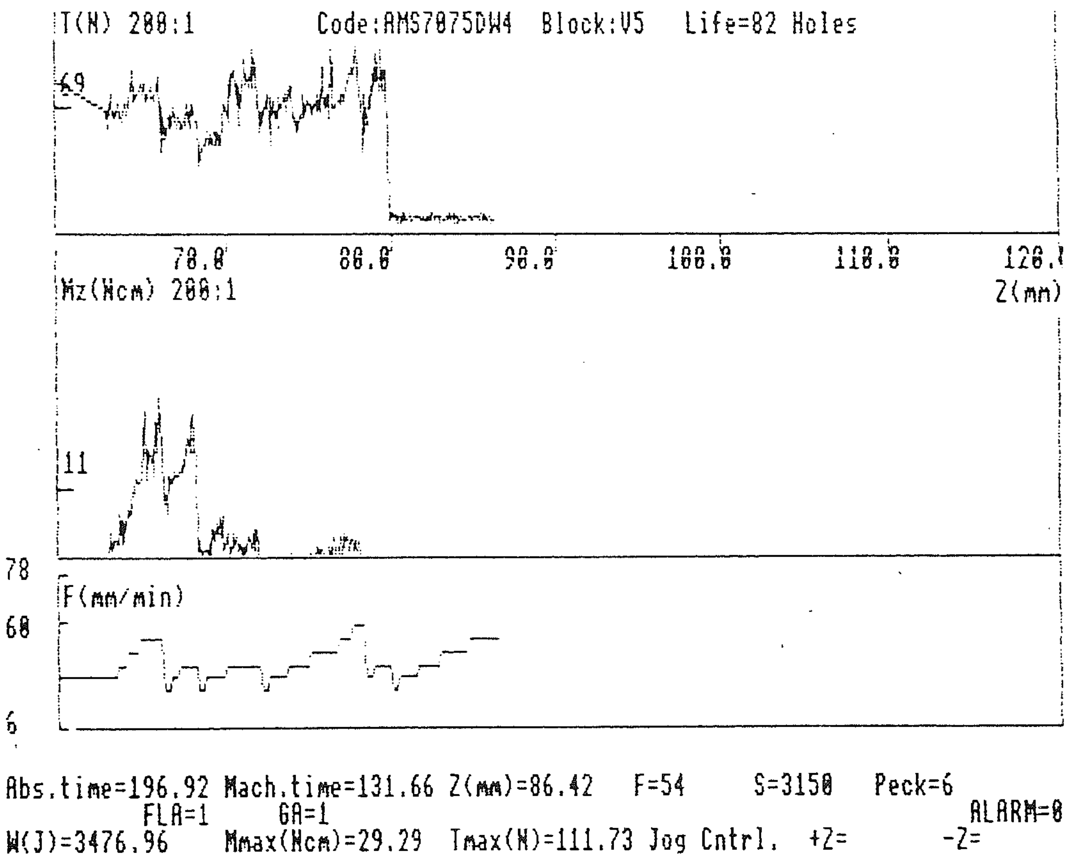
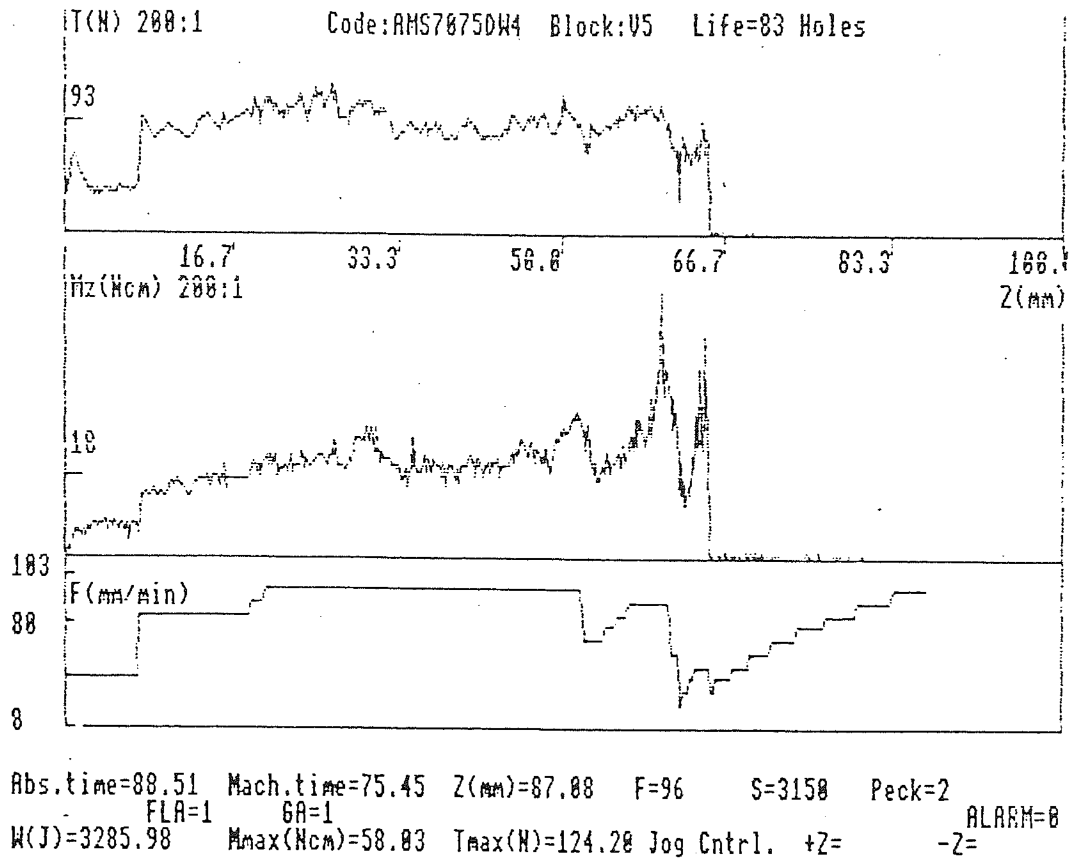


Fig. 8.27 : DHD in AMS7075 alloy, in 6 pecks : cycle completed successfully under Adaptive Control and automatic pecking. (same conditions as in fig. 8.26 but more pecks required)



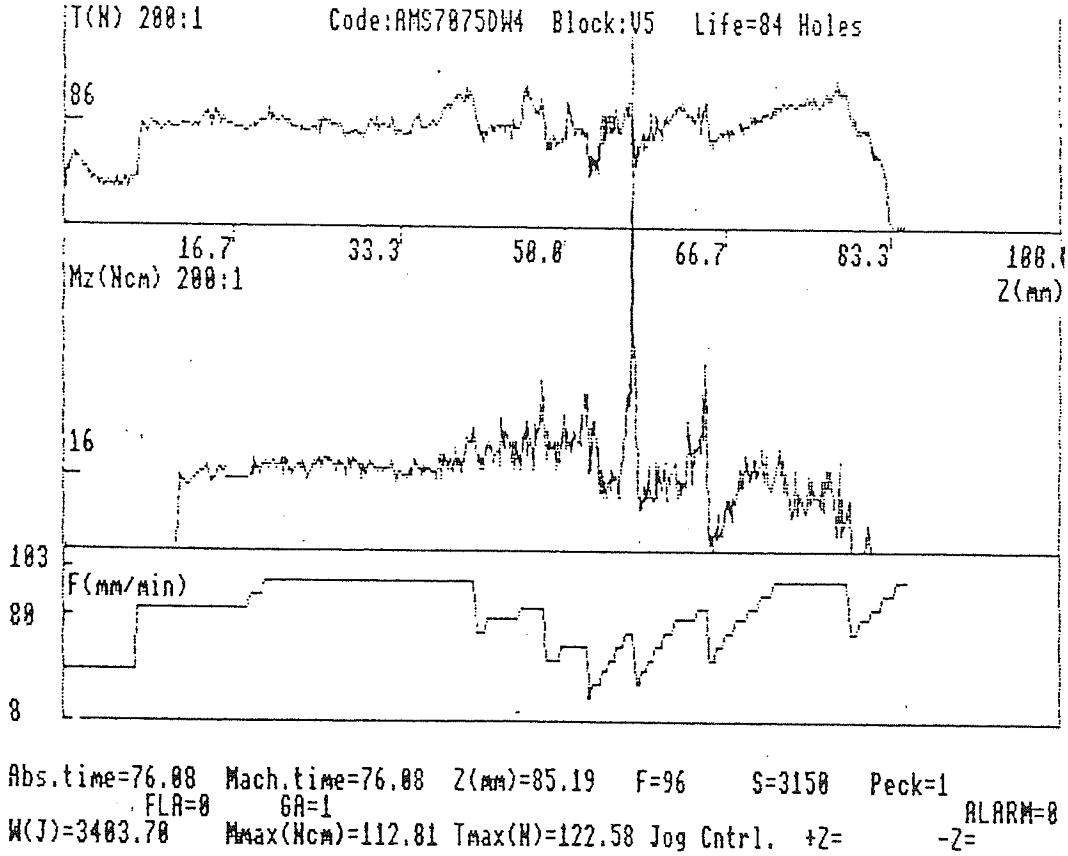


Fig. 8.28 : DHD in AMS7075 alloy, in 1 peck : cycle completed successfully under Adaptive Control and automatic pecking.

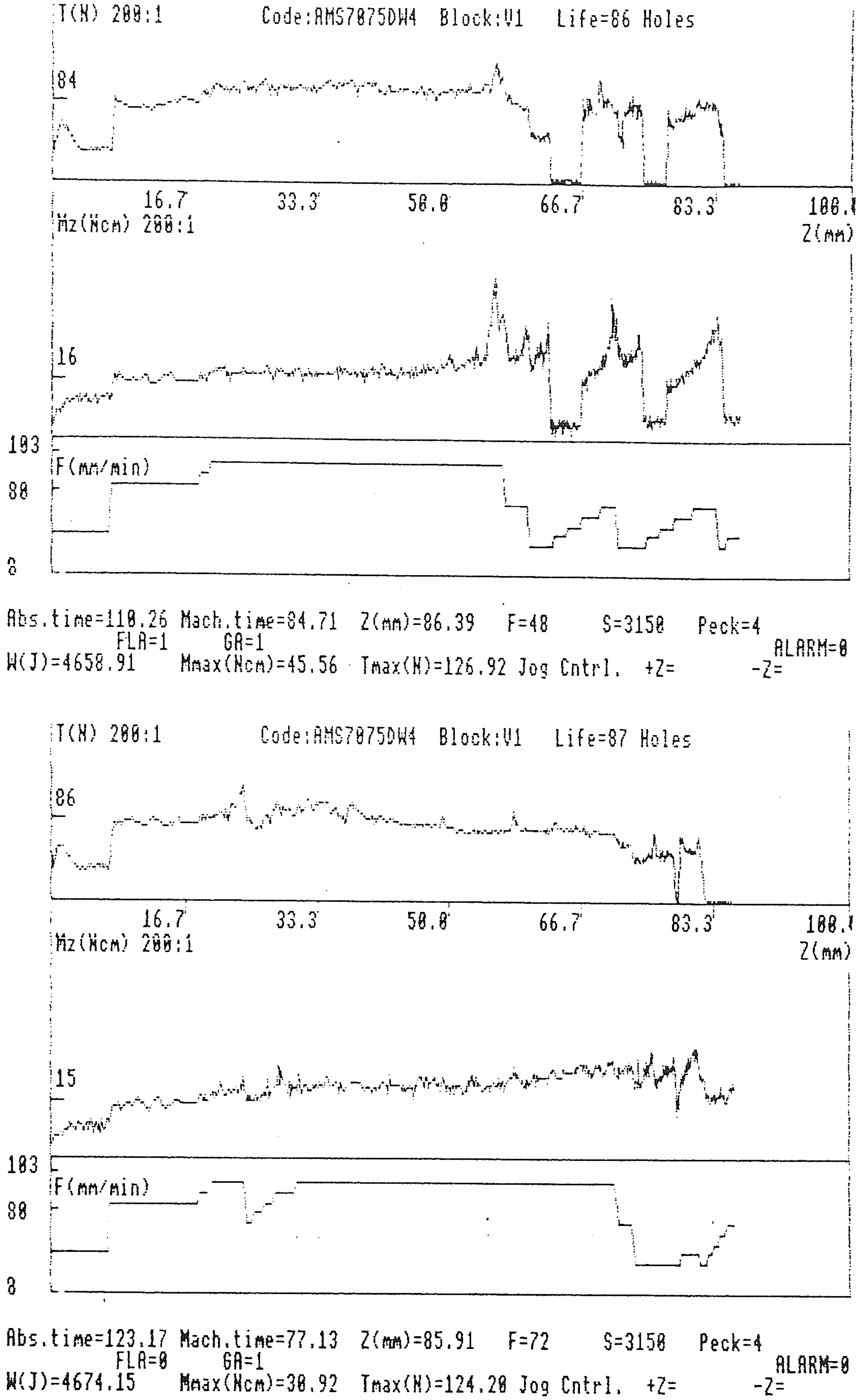


Fig. 8.29 : DHD in AMS7075 alloy, in 4 pecks : cycle completed successfully under Adaptive Control and automatic pecking.

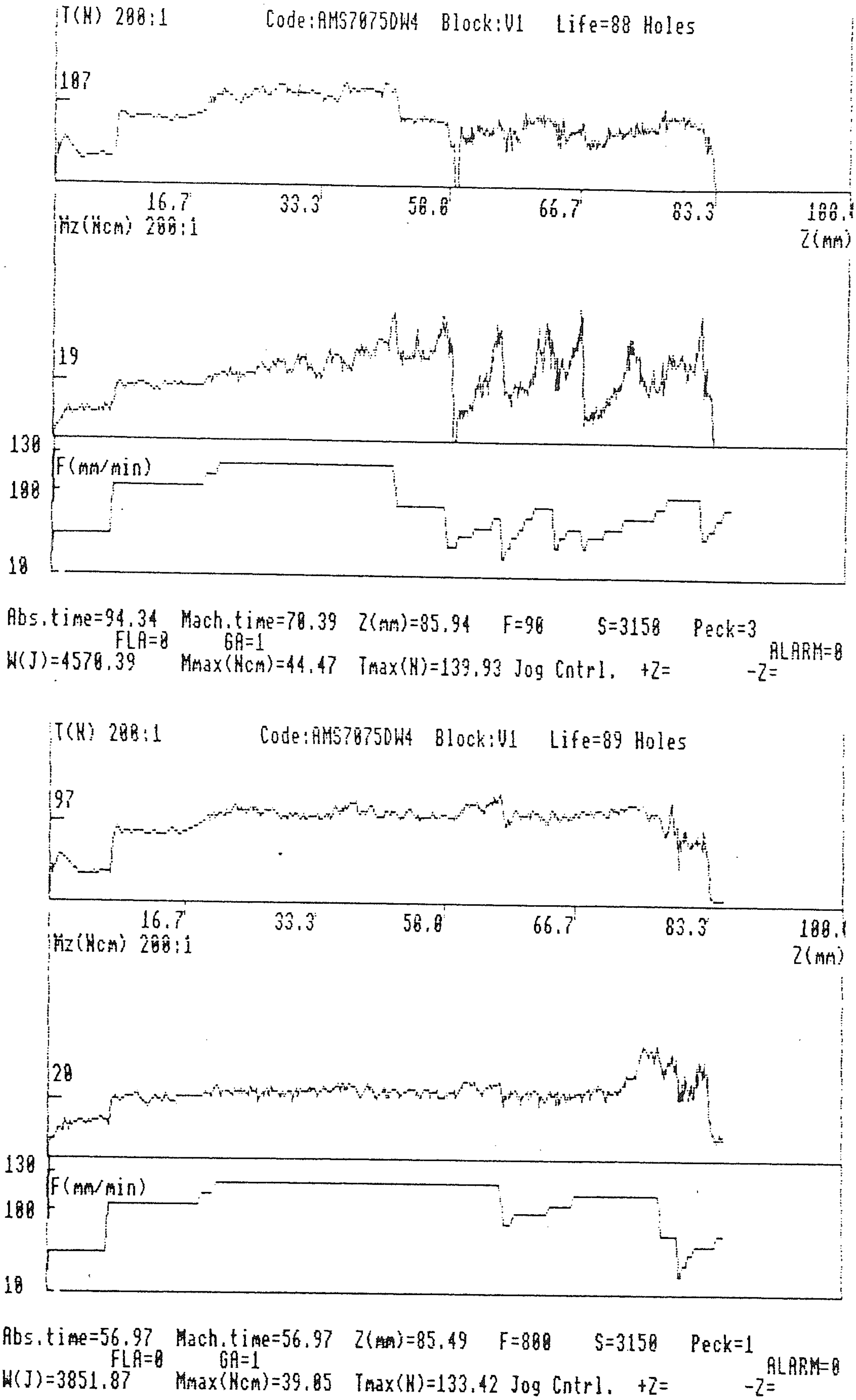
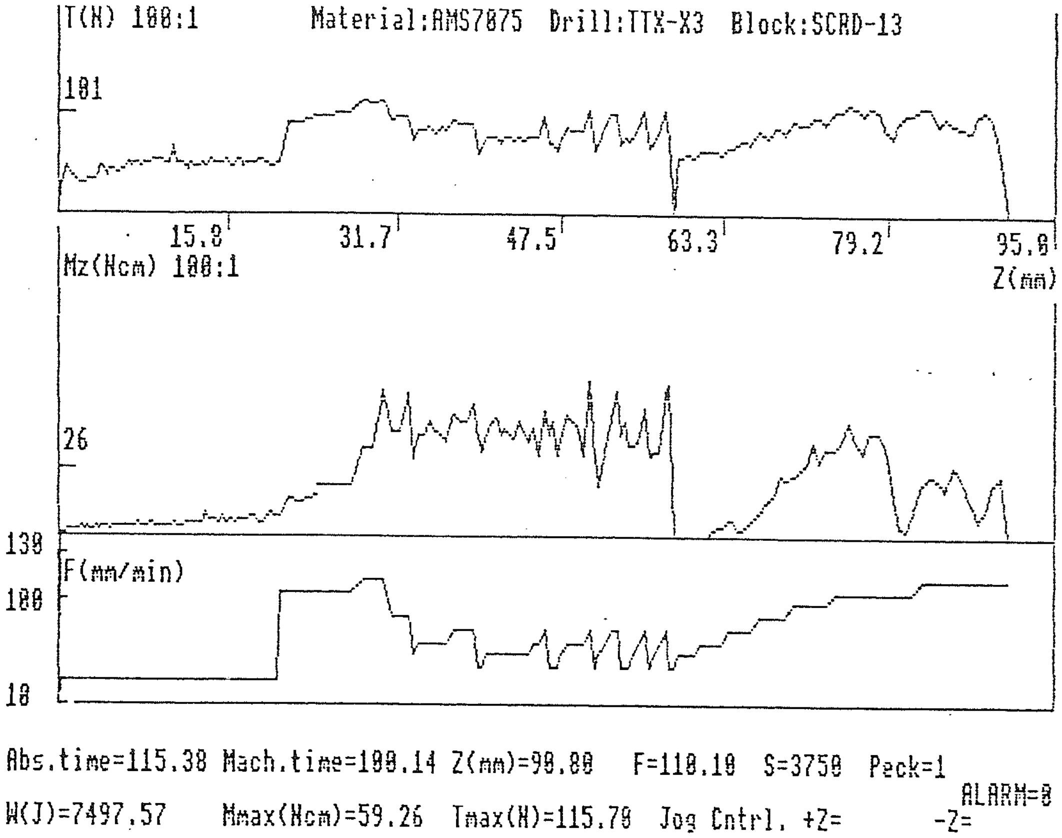


Fig. 8.30 : DHD in AMS7075 alloy, in 1 peck : cycle completed successfully under Adaptive Control and automatic pecking.



INPUT, COMPUTED & RECORDED PROCESS DATA   Source File : DA'

1. MATERIAL CODE=AMS7075
2. WORKPIECE CODE No.=SCRD
3. DRILL CODE=TTX-X3   DRILL DIAMETER (mm)=3.00
4. TOOL LIFE STATUS :   No. OF HOLES=13.00
   CUMMULATIVE CUTTING TIME (min)=22.31
   CUMMULATIVE DEPTH (mm)=905.15
5. NC PROGRAM FEEDRATE (mm/min)=100.00   CUTTING FEED (mic/rev)=26.6'
6. NC PROGRAM SPINDLE RPM=3750.00   SURFACE SPEED (m/min)=35.34
7. NC PROGRAM DEPTH Zmax (mm)=90.00
8. PILOT HOLE DEPTH (mm)=0.00
9. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=5.00
10. ENTRY FEEDRATE (mm/min)=30.00   30.00 % of MAX. FEEDRATE
11. FEED TRANSITION DEPTH (mm)=20.00   STEADY STATE DEPTH (mm)=25.00
12. AMPLIFICATION SCALES:- TORQUE (Ncm/V)=100.00   THRUST (N/V)=100.00
13. MAXIMUM TOLERABLE THRUST (N)=203.48
    STEADY STATE THRUST(N)=101.74
14. MAXIMUM TOLERABLE TORQUE (Ncm)=78.44
    STEADY STATE TORQUE(Ncm)=26.15

Fig. 8.31 : DHD in AMS7075 alloy, in 1 peck : cycle completed successfully under Adaptive Control and automatic pecking. (multilevel control strategy and tool-workpiece data base introduced)

Selected Experimental Results of DHD TA11 IMI 318 Titanium Alloy under Adaptive Control of feed rate, spindle speed and ± Z axis position.

These results are a few of the many tests performed after the system had been installed. Fundamental purpose of these tests was to ensure the two main functions of the system : that it can ensure the integrity of the process and the safety of the workpiece at any hole depth and that it can complete the machining of the hole to the depth specified in the NC part program. The nominal machining conditions throughout these drilling tests of Titanium TA11 alloy (specified in the part program) were 625 RPM and 16 mm/min.

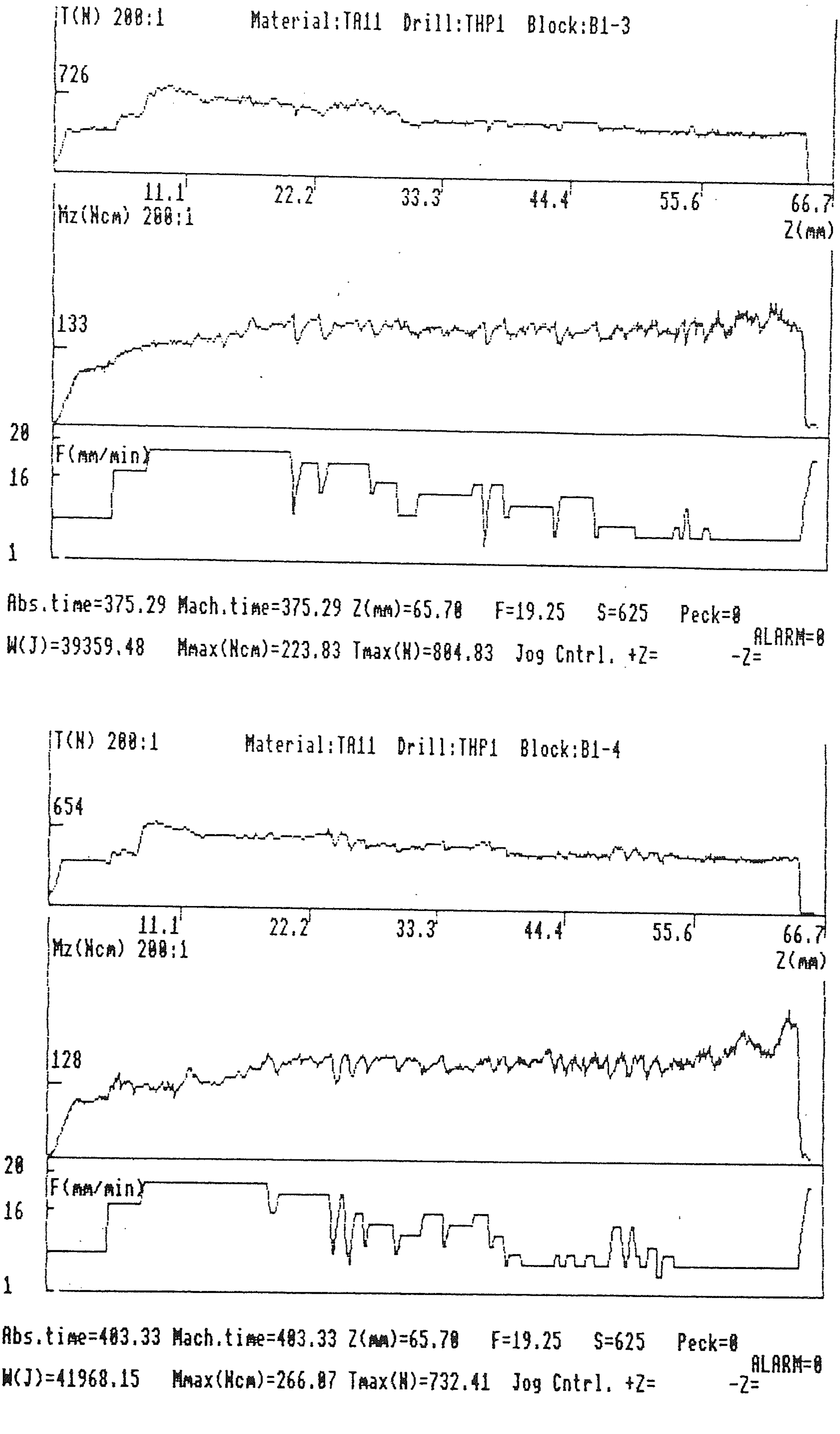


Fig. 8.32 : DHD in TA11 alloy, no pecking : cycles completed successfully under Adaptive Control

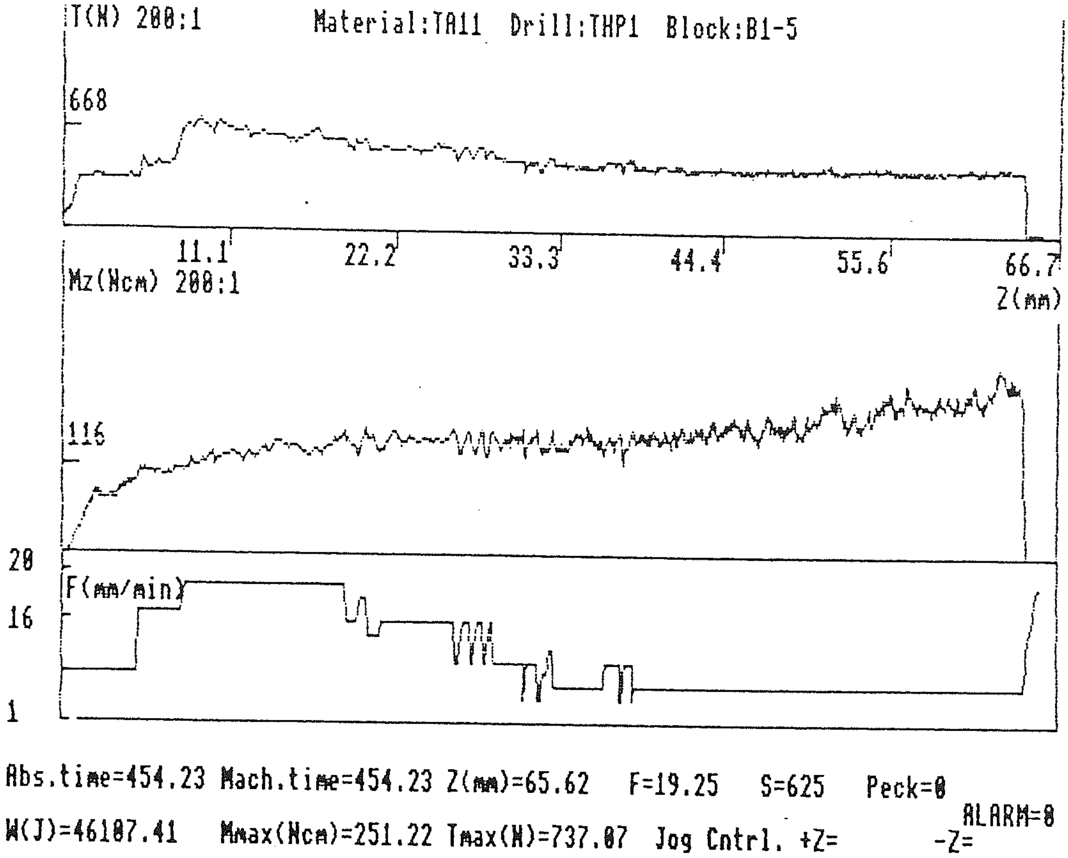
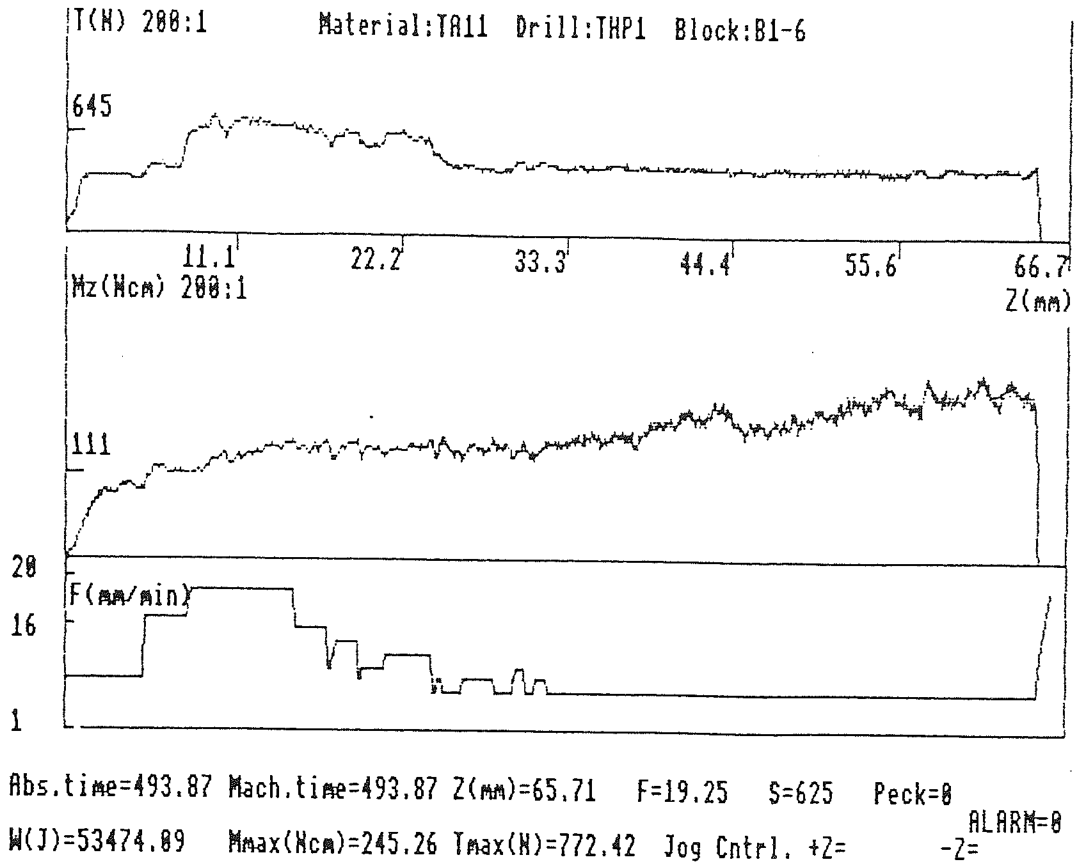


Fig. 8.33 : DHD in TA11 alloy, no pecking : cycle completed successfully under Adaptive Control



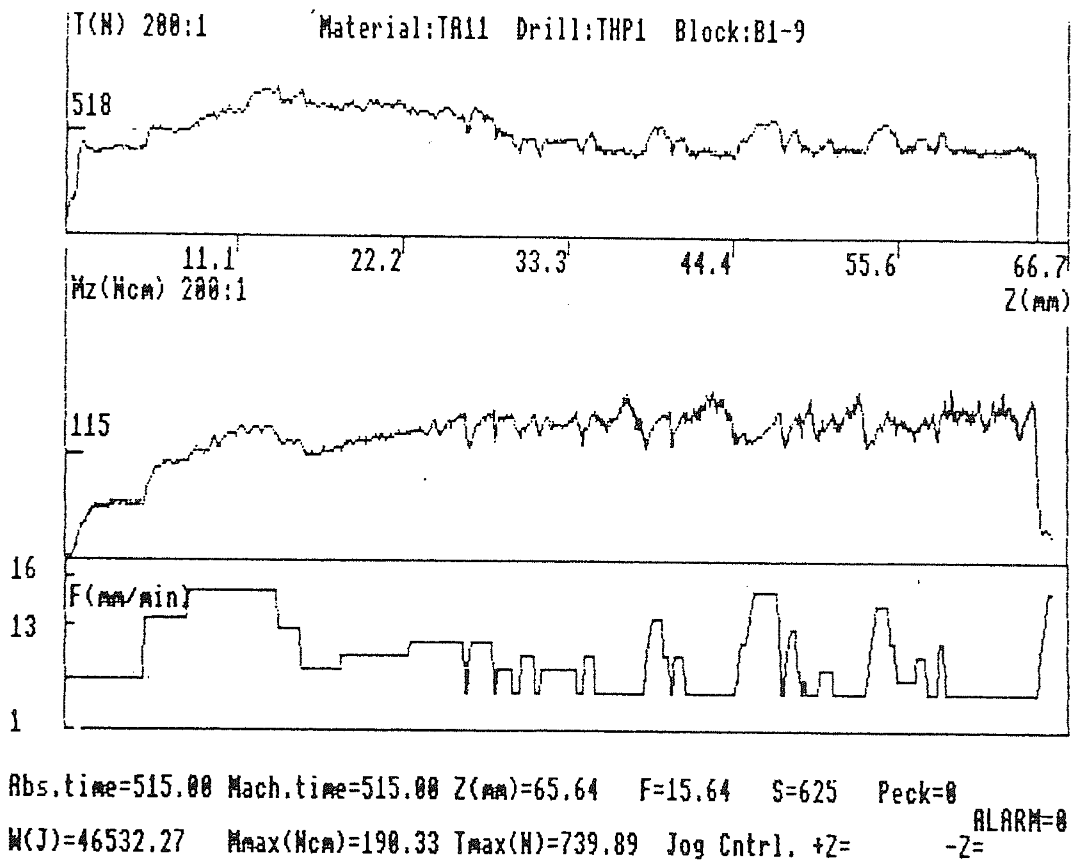
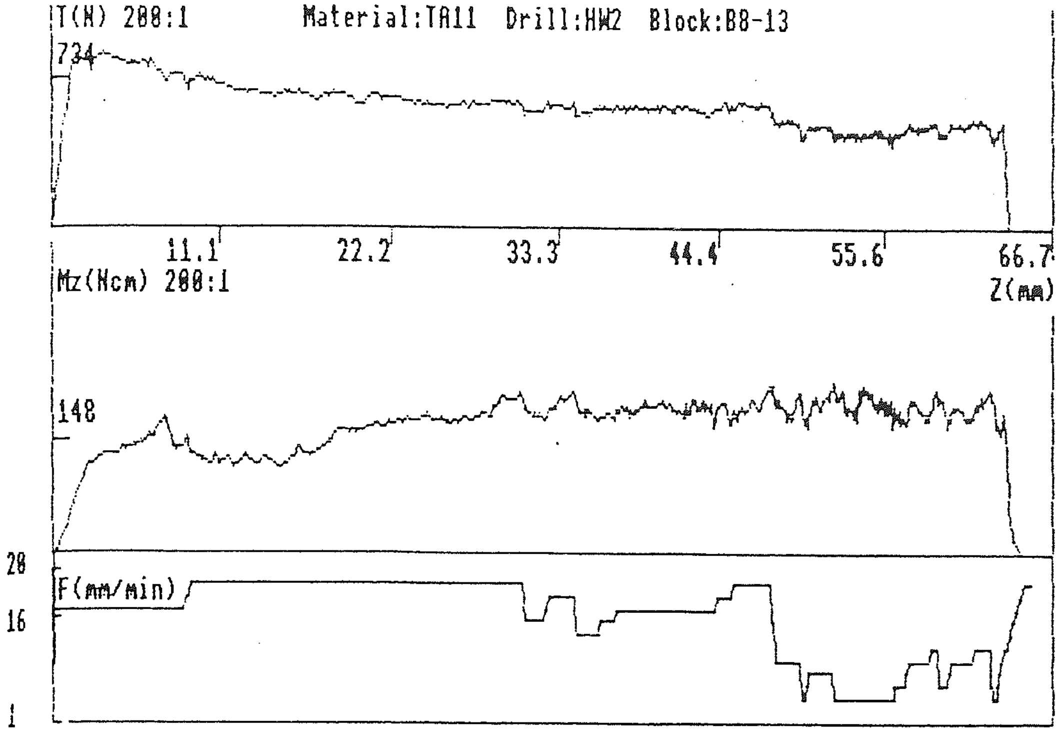


Fig. 8.34 : DHD in TA11 alloy, no pecking : cycles completed successfully under Adaptive Control



Abs.time=306.85 Mach.time=306.85 Z(mm)=65.22 F=19.25 S=625 Peck=0 ALARM=0

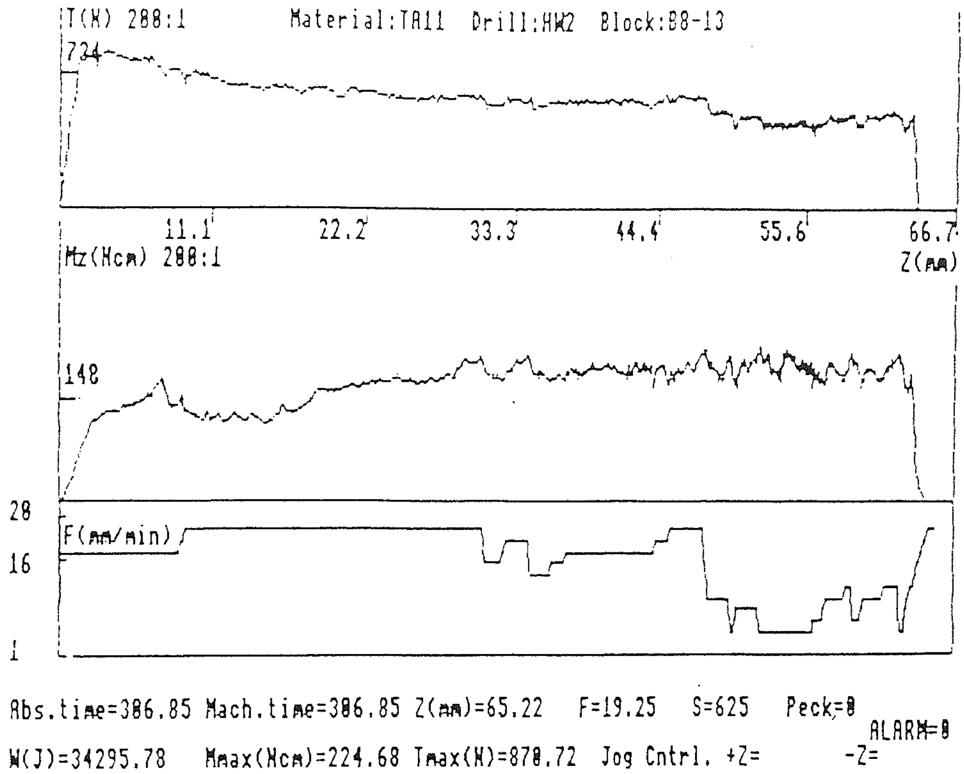
W(J)=34295.78 Mmax(Ncm)=224.68 Tmax(N)=870.72 Jog Cntrl. +Z= -Z=

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : DAT2

---

1. MATERIAL CODE=TA11 BLOCK No.=B5
2. DRILL CODE=HW2 DRILL DIAMETER (mm)=4.50
3. TOOL LIFE STATUS : No. OF HOLES=13.00
   CUMMULATIVE CUTTING TIME (min)=65.32
   CUMMULATIVE DEPTH (mm)=745.42
4. NC PROGRAM FEEDRATE (mm/min)=16.00 CUTTING FEED (mic/rev)=25.60
5. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.84
6. NC PROGRAM DEPTH Zmax (mm)=65.00
7. PILOT HOLE DEPTH (mm)=0.00
8. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
9. ENTRY FEEDRATE (mm/min)=16.00 100.00 % of MAX. FEEDRATE
10. FEED TRANSITION DEPTH (mm)=3.70
11. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.00
12. MAXIMUM TOLERABLE THRUST (N)=1469.95
    STEADY STATE THRUST(N)=734.98
13. MAXIMUM TOLERABLE TORQUE (Ncm)=444.66
    STEADY STATE TORQUE(Ncm)=148.22

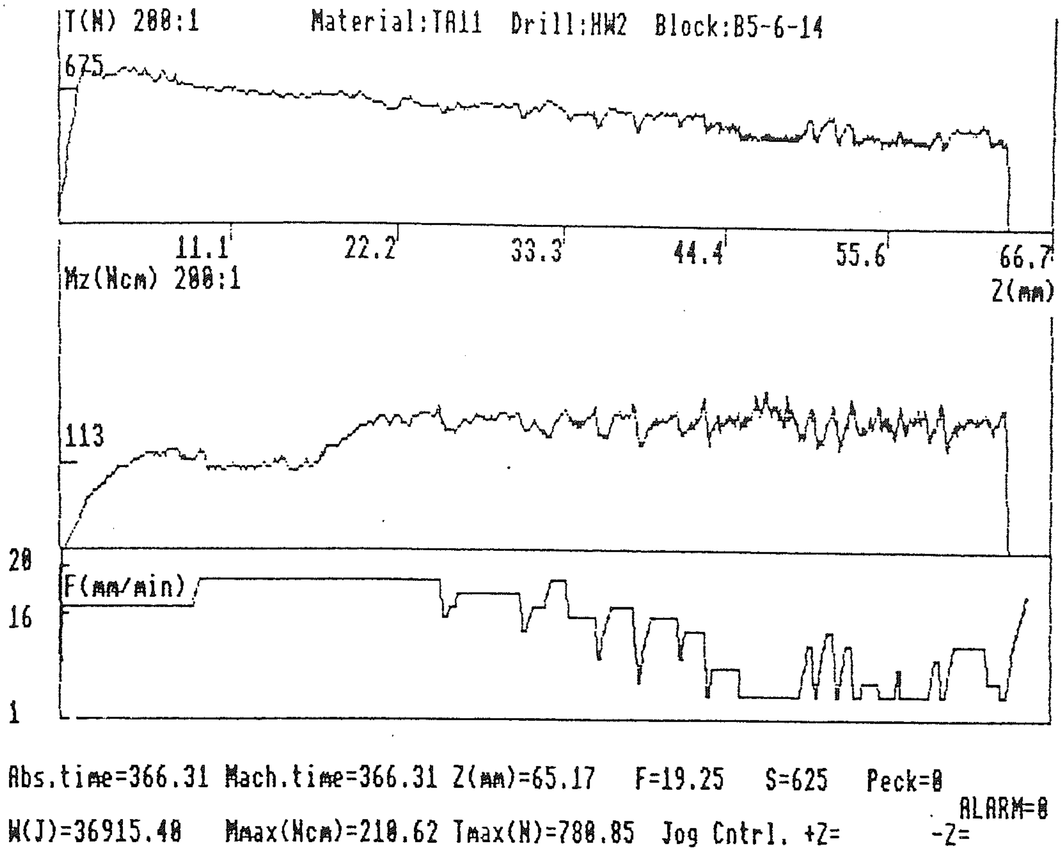
Fig. 8.35 : DHD in TA11 alloy, no pecking : cycle completed successfully under Adaptive Control (Tool data base has been introduced)



INPUT, COMPUTED & RECORDED PROCESS DATA Source File : DAT2

1. MATERIAL CODE=TA11 BLOCK No.=B5
2. DRILL CODE=HW2 DRILL DIAMETER (mm)=4.50
3. TOOL LIFE STATUS : No. OF HOLES=13.00
   CUMMULATIVE CUTTING TIME (min)=65.32
   CUMMULATIVE DEPTH (mm)=745.42
4. NC PROGRAM FEEDRATE (mm/min)=16.00 CUTTING FEED (mic/rev)=25.60
5. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.84
6. NC PROGRAM DEPTH Zmax (mm)=65.00
7. PILOT HOLE DEPTH (mm)=0.00
8. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
9. ENTRY FEEDRATE (mm/min)=16.00 100.00 % of MAX. FEEDRATE
10. FEED TRANSITION DEPTH (mm)=3.70
11. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.00
12. MAXIMUM TOLERABLE THRUST (N)=1469.95
    STEADY STATE THRUST(N)=734.98
13. MAXIMUM TOLERABLE TORQUE (Ncm)=444.66
    STEADY STATE TORQUE(Ncm)=148.22

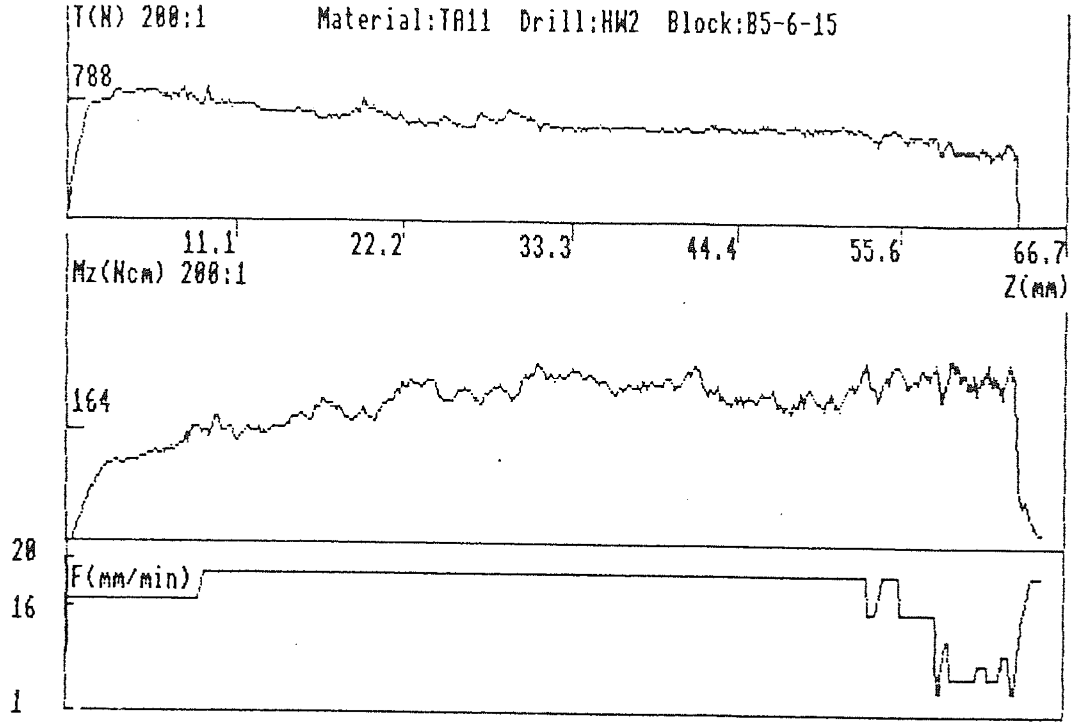
Fig. 8.35 : DHD in TA11 alloy, no pecking : cycle completed successfully under Adaptive Control (Tool data base has been introduced)



INPUT, COMPUTED & RECORDED PROCESS DATA Source File : DA

1. MATERIAL CODE=TA11 BLOCK No.=B5-6
2. DRILL CODE=HW2 DRILL DIAMETER (mm)=4.50
3. TOOL LIFE STATUS : No. OF HOLES=14.00
   CUMMULATIVE CUTTING TIME (min)=71.43
   CUMMULATIVE DEPTH (mm)=810.59
4. NC PROGRAM FEEDRATE (mm/min)=16.00 CUTTING FEED (mic/rev)=25.6
5. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.84
6. NC PROGRAM DEPTH Zmax (mm)=65.00
7. PILOT HOLE DEPTH (mm)=0.00
8. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
9. ENTRY FEEDRATE (mm/min)=16.00 100.00 % of MAX. FEEDRATE
10. FEED TRANSITION DEPTH (mm)=3.70
11. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.00
12. MAXIMUM TOLERABLE THRUST (N)=1351.24
    STEADY STATE THRUST(N)=675.62
13. MAXIMUM TOLERABLE TORQUE (Ncm)=339.22
    STEADY STATE TORQUE(Ncm)=113.07

Fig. 8.36 : DHD in TA11 alloy, no pecking : cycles completed successfully under Adaptive Control



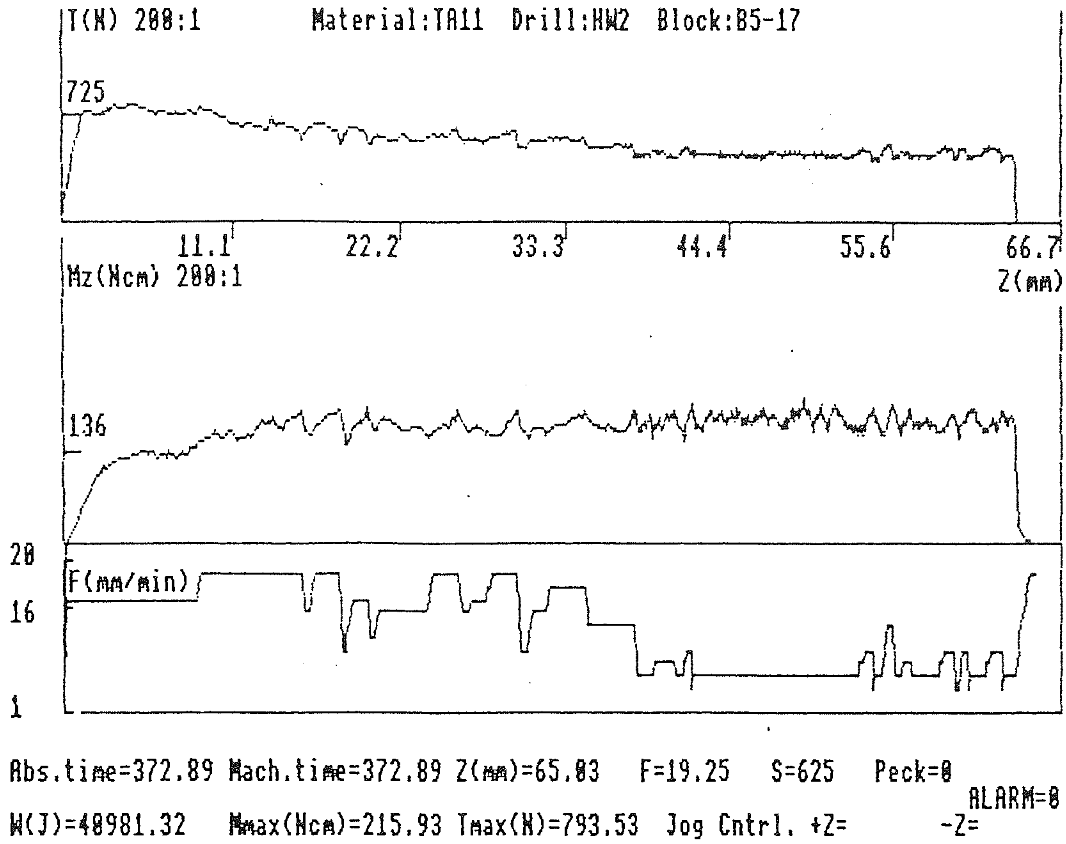
Abs.time=247.17 Mach.time=247.17 Z(mm)=65.14 F=19.25 S=500 Peck=0

W(J)=26162.04 Mmax(Ncm)=274.98 Tmax(N)=879.80 Jog Cntrl. +Z= -Z= ALARM=0

INPUT, COMPUTED & RECORDED PROCESS DATA Source File : D

1. MATERIAL CODE=TA11 BLOCK No.=B5-8th
2. DRILL CODE=HW2 DRILL DIAMETER (mm)=4.50
3. TOOL LIFE STATUS : No. OF HOLES=15.00
CUMMULATIVE CUTTING TIME (min)=75.55
CUMMULATIVE DEPTH (mm)=875.73
4. NC PROGRAM FEEDRATE (mm/min)=16.00 CUTTING FEED (mic/rev)=32.0
5. NC PROGRAM SPINDLE RPM=500.00 SURFACE SPEED (m/min)=7.07
6. NC PROGRAM DEPTH Zmax (mm)=65.00
7. PILOT HOLE DEPTH (mm)=0.00
8. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
9. ENTRY FEEDRATE (mm/min)=16.00 100.00 % of MAX. FEEDRATE
10. FEED TRANSITION DEPTH (mm)=3.70
11. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.00
12. MAXIMUM TOLERABLE THRUST (N)=1576.62
STEADY STATE THRUST(N)=788.31
13. MAXIMUM TOLERABLE TORQUE (Ncm)=493.23
STEADY STATE TORQUE(Ncm)=164.41

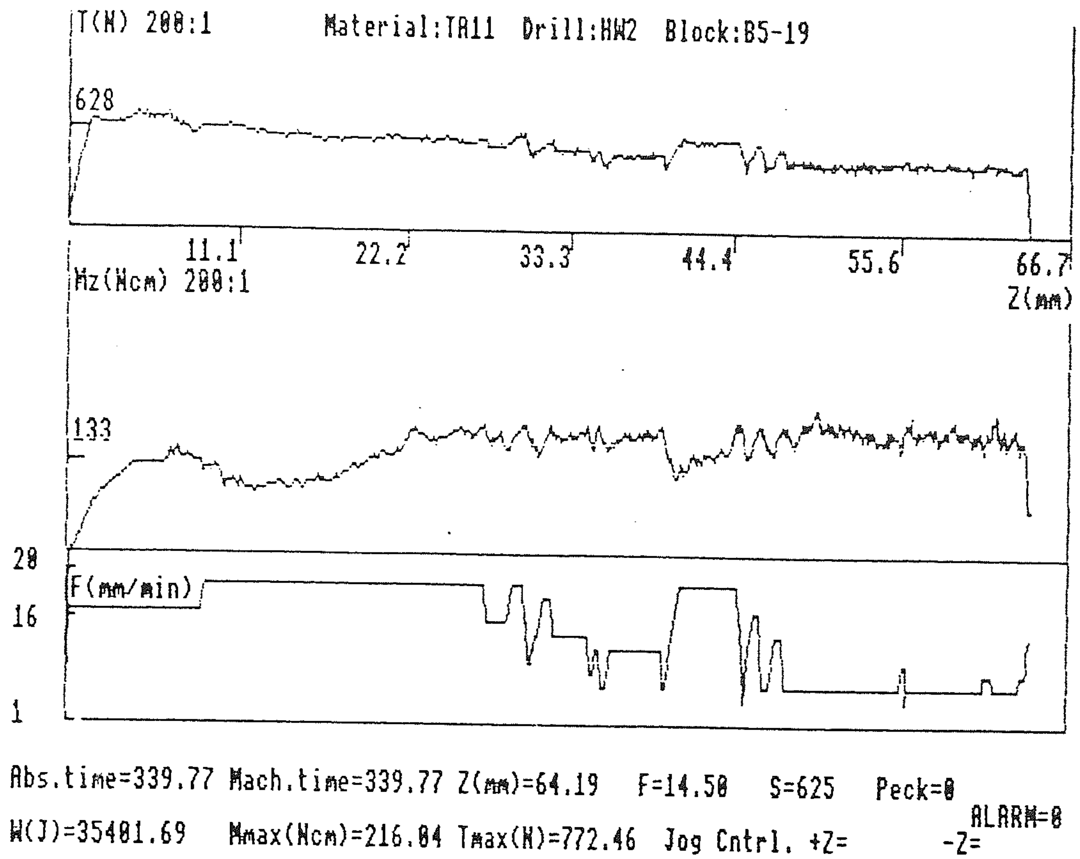
Fig. 8.37 : DHD in TA11 alloy, no pecking : cycle completed successfully under Adaptive Control



INPUT, COMPUTED & RECORDED PROCESS DATA Source File :

1. MATERIAL CODE=TA11 BLOCK No.=B5
2. DRILL CODE=HW2 DRILL DIAMETER (mm)=4.50
3. TOOL LIFE STATUS : No. OF HOLES=17.00
   CUMMULATIVE CUTTING TIME (min)=89.91
   CUMMULATIVE DEPTH (mm)=1005.86
4. NC PROGRAM FEEDRATE (mm/min)=16.00 CUTTING FEED (mic/rev)=25
5. NC PROGRAM SPINDLE RPM=625.00 SURFACE SPEED (m/min)=8.8
6. NC PROGRAM DEPTH Zmax (mm)=65.00
7. PILOT HOLE DEPTH (mm)=0.00
8. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
9. ENTRY FEEDRATE (mm/min)=16.00 100.00 % of MAX. FEEDRATE
10. FEED TRANSITION DEPTH (mm)=3.70
11. AMPLIFICATION SCALES: TORQUE (Ncm/V)=200.00 THRUST (N/V)=200.
12. MAXIMUM TOLERABLE THRUST (N)=1451.88
    STEADY STATE THRUST(N)=725.94
13. MAXIMUM TOLERABLE TORQUE (Ncm)=410.41
    STEADY STATE TORQUE(Ncm)=136.80

Fig. 8.38 : DHD in TA11 alloy, no pecking : cycle completed successfully under Adaptive Control



INPUT, COMPUTED & RECORDED PROCESS DATA　　　　Source File :

1. MATERIAL CODE=TA11
2. BLOCK No.=B5
2. DRILL CODE=HW2　　　DRILL DIAMETER (mm)=4.50
3. TOOL LIFE STATUS :　　No. OF HOLES=19.00
　　CUMMULATIVE CUTTING TIME (min)=101.11
　　CUMMULATIVE DEPTH (mm)=1134.17
4. NC PROGRAM FEEDRATE (mm/min)=16.00　　CUTTING FEED (mic/rev)=2
5. NC PROGRAM SPINDLE RPM=625.00　　SURFACE SPEED (m/min)=8.
6. NC PROGRAM DEPTH Zmax (mm)=64.10
7. PILOT HOLE DEPTH (mm)=0.00
8. CLEARANCE BETWEEN TOOL & W/PIECE (mm)=6.30
9. ENTRY FEEDRATE (mm/min)=16.00　　100.00 % of MAX. FEEDRATE
10. FEED TRANSITION DEPTH (mm)=3.70
11. AMPLIFICATION SCALES:　TORQUE (Ncm/V)=200.00　　THRUST (N/V)=200
12. MAXIMUM TOLERABLE THRUST (N)=1257.27
　　STEADY STATE THRUST(N)=628.64
13. MAXIMUM TOLERABLE TORQUE (Ncm)=400.60
　　STEADY STATE TORQUE(Ncm)=133.53

Fig. 8.39 : DHD in TA11 alloy, no pecking : cycle completed successfully under Adaptive Control

CHAPTER 9

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

9.1 CONCLUSIONS

A theoretical and experimental study of the deep hole drilling process, using small diameter non coolant-fed twist drills on a CNC machine tool, has been carried out. An extended literature survey has shown that very little knowledge about this particular process exists or has been published. The work is divided into two major areas which are presented in sections A and B of the thesis :

Section A : DHD as a metal cutting process

1. The fundamental problem in drilling small diameter deep holes is that catastrophic failure of the tool is highly probable because of its inherent low strength in conjunction with increased loading of the tool. Catastrophic failure can occur either under torsion or under axial loading.

2. Torsional failure is the result of inefficient swarf extraction from the drilled hole, a problem very acute in DHD where the tool has a dual role of producing and conveying chips. Failure under axial loading (buckling) is caused by either a very high penetration rate (feed rate) or normal wear of the cutting edges of the tool or hard inclusions in the workpiece.

3. Drilling thrust and torque have been shown to convey the best picture regarding the dynamics of the process and the status of loading of the tool. Other parameters, such as cutting power or tool vibrations have proven to be innaccurate, unreliable or extremely complicated to analyse in real time (on-line).

4. Drilling thrust and torque in DHD are functions of the workpiece material, drill diameter, feed and speed but unlike conventional drilling they also strongly depend on the drilled depth. The effect of drilled depth is mainly identified in two areas : Increase in the magnitude of torque and thrust and variation to the shape and size of produced swarf.

5. The drilling torque in deep hole drilling, consists of two components : a cutting component and a friction component. The cutting torque represents the plastic deformation of the workpiece material performed by the cutting edges at the tool point ; the magnitude of this component (steady state value) is generally predictable, using empirical expressions of feed, diameter, workpiece hardness and cutting speed ; a similar expression applies for the steady state thrust.

6. The friction component is superimposed to the cutting component after some depth has been reached which is defined as the depth of instability. The latter is a function of feed and speed since these parameters determine the size and shape of the chips produced.

7. Drilling thrust (feed force) is not directly affected by the increase in drilled depth since it is generated purely by the action of the cutting edges and in particular the extrusion by the chisel edge due to lack of clearance. For this reason, thrust remains fairly constant during the early stages of the process.

8. In the early stages of instability the increase in drilling torque can be approximated by a linear function of drilled depth or in certain cases a quadratic one. Beyond a sufficiently large depth however (typically greater than 12 to 15 diameters), the instability pattern changes to a much more random pattern. The reason for this transition is that the tool is subjected to torsional vibrations, the frequency of which is a function of cutting speed and tool stifness.

9. As a result of the torsional vibrations of the tool the drilling thrust is also affected. The torsional loading of the tool under extremely high torque values causes instantaneous variations in the tool length and this in turn changes the undeformed chip thickness, thus giving rise to a dynamic thrust component which experimental evidence suggests that can cause tool failiure.

10. The depth where the pattern of instability becomes random has been plotted against a range of different machining parameters (feed ans speed). This investigation has revealed that it is not possible to predict accurately the exact pattern of instability even if

the same conditions and same tool are employed, during successive tests and with the same workpiece. From this point of view the deep hole drilling process is characterised as a stochastic process.

11. In the early stages of instability (up to 8 diameters), when the drilling torque rises linearly with depth, it has been shown that if the feed is reduced according to a logarithmic law, a constant level of torque is achieved. In practice it is easier to approximate this variation by a linear algorithm which is achieved by parametric part-programming.

12. Drilling tests with variable feed rate or spindle speed according to the above method have shown that it is possible to control the magnitude and duration of fluctuations of drilling torque and to complete succesfully a deep hole drilling cycle.

13. Although drilling with a variable feed is an improvement over the execution of a rigid part program (canned pecking cycle), it remains a predictive form of control because it requires a-priori knowledge of the linear rise pattern of torque and certainly knowledge of the steady state value for each combination of drill geometry and machining conditions.

14. In order to eliminate the need for extensive off-line analysis and to eliminate the risk of catastrophic failure of the tool and workpiece, it is necessary to employ a methodology of real time monitoring and control of the process.

Section B : DHD as a Monitored and Adaptively Controlled Process

1. When a DHD operation is executed under part program control (CNC), the integrity of the process, namely the successful completion of the drilling cycle and consequently the safety of the tool and the workpiece cannot be ensured due to the high risk of catastrophic failure of the tool as the drilled depth increases.

2. Process Monitoring and Adaptive Control are two technologies which can replace to a large extent the skills and experience of a machine operator and therefore are necessary requirements in CNC deep hole drilling.

3. Process Monitoring alone is not sufficient in deep hole drilling because unlike other machining operations where machining of a component can be normally resumed

after detection of tool breakage and replacement, in the case of deep hole drilling this is accompanied by failure and scrapping of the workpiece.

4. Adaptive Control in deep hole drilling is the on-line manipulation of feed rate, spindle speed and pecking (tool withdrawal and reentry) in order to maintain the magnitudes of drilling thrust and drilling torque within safe limits.

5. The simplest way to achieve feed rate and spindle speed control during CNC deep hole drilling is through the override controls for the above functions of the machine tool. These are standard elements of any CNC system, while pecking is achieved by using the also standard JOG and AUTO functions of the CNC system.

6. The response of the cutting process to variations of feed and speed can be approximated by a first order system the open loop gain of which depends on the workpiece material, the tool diameter (depth of cut) and the spindle speed. The time constant is equal to half the time of a spindle revolution.

7. The dependence of the open loop gain on the above parameters implies that the stability of a fixed gain controller cannot be ensured unless predetermined parameters are used. This in turn necessitates the use of a non-conventional controller with self-adjusted gain and on-line identification of the process parameters.

8. The use of a multilevel control strategy based on classification of the error between the reference and current values of drilling thrust and torque, ensures that the controller is stable under a wide range of conditions. It also ensures that the controller can cope with random disturbances, such as variations in material hardness (e.g hard spots or work hardening) or drills with dissimilar characteristics (e.g unequally ground points or amount of wear present), by automatically selecting the most suitable control strategy.

9. In order that a Process Monitoring and Adaptive Control system is viable in a production environment, its dependence on data supplied by an operator should be kept minimal. It is important therefore, that there is a limited built-in learning capability. This is realised basically in two areas : The ability to identify on-line the process parameters which determine the magnitudes of thrust and torque and hence to enable automatic setting of the process thresholds ; also the ability to take into account the effect of cumulative cutting time for a specific tool, i.e the effect of wear between successive cuts. This is achieved by automatic identification of a tool from using a special code and updating of a database where data concerning the past performance of any tool are held.

9.2 FUTURE WORK

9.2.1 Analysis of the deep hole drilling process

Investigation of the torsional vibrations of the drill during instability : An experimental set-up using accelerometers and vibration analysis equipment is necessary in order to confirm the existence of torsional vibrations. In this work this mechanism has been proposed as a hypothesis and the only evidence in support which was presented have been the variations in shape and size of the swarf and fluctuations of the drilling forces.

An other area which certainly ought to be investigated is the behaviour of other workpiece materials in which deep hole drilling operations are applicable. For example : nitriding steel (steel shells), 13 Cr Mo 4 (crank shafts - oil holes), 42 Mn V 7 (gear shafts), special cast iron. Objective of the investigation will be to confirm that the characteristics of the process described in this work do indeed manifest themselves with other materials. The following characteristics in particular : Swarf fragmentation, ever increasing drilling torque and thrust (during instability), modes of catastrophic failure.

9.2.2 Drill design

In the work presented in the thesis it was stated that under identical machining conditions (feed, speed, diameter) during deep hole drilling tests, certain drills exhibited superior performance compared with others. Such performance is clearly attributed to differences in point geometry and flute characteristics of these drills.

The prototype system for Process Monitoring and Adaptive Control, described in this work, can play a major role in this context as a test bed of drill performance. Clearly with process integrity and tool safety ensured the records of each test can be used as criteria for assesement of various drills in addition to the quality of holes they produce.

Specific parameters such as level of forces, number of pecks, total cycle and machining times, number of holes etc. can provide valuable information and be used to enhance drill geometrical characteristics or other design attributes such as tool materials, use of coatings, etc.

9.2.3 Sensors

The data required for the investigation of the dynamics of the deep hole drilling process and the functioning of the Process Monitoring and Adaptive Control system has been obtained by thrust and torque measurements using a dynamometer. Although the rationale and the advantages for this choice were presented in the thesis, it would be beneficial to investigate the use of other transducers and corresponding signals for analysis.

In particular, Acoustic Emission and Vibration signals could possibly convey significant amounts of information regarding the state of the process even if only off-line analysis is possible because of the complexity of the signals and the amount of processing required. In this case it is clear that a much more powerful microprocessor should be considered and perhaps one of the commercially available software packages for this type of analysis.

9.2.4 Control Strategies

The strategies for Process Monitoring and Adaptive Control implemented in the software of the described system have been successful in the context of successfully stabilising the drilling thrust and torque and thus ensuring the integrity of the process and safety of the tool and workpiece.

These strategies examined from purely a control engineering point of view however, are somewhat ad hoc and are open to criticism while there is scope for further tuning of the controller. There has been excellent theoretical work in the area of parameter adaptive control with results obtained at present mainly from simulations of sytems and it is possible that some of the proposed schemes mainly derived for the adaptive control of mechanical manipulators would be quite applicable in the case of metal cutting processes.

9.2.5 Higher level languages and Expert Systems

In the presentation of the Process Monitoring and Adaptive Control system in this work, it became clear that the system performance is greatly dependent on knowledge of data regarding the geometrical attributes and wear state of the tool and the machining characteristics of the workpiece material.

The use of Basic and Assembly language, although it has fulfilled its task in coding the system software, clearly restricts the capabilities of the system if the support of a large database was required (off-line processing) or if more complex monitoring and control strategies were to be implemented (on-line functions).

As a first step for future improvement, a higher level language could be used such as "C" or even a commercially available expert system software package. This is an already existing trend in condition monitoring and diagnostic engineering management receiving world wide attention by various research and commercial organisations.

An other strongly emerging trend which justifies the above comments is the appearance and increasing application of a new generation of CNC systems embracing powerful, multitasking, 32-bit microprocessors with advanced graphics capabilities, high level language programming and potential for interfacing to a central host computer for DNC purposes.

It was argued in the thesis (chapter 6), that the functions of Process Monitoring and Adaptive Control should really be incorporated into the CNC unit rather than be externally imposed. An area where further work is required therefore, is to investigate the market demand for the above technologies and also whether manufacturers of machine tools and CNC systems would consider as technically feasible and economically viable the use, in their range of products, of special sensors and control systems for Process Monitoring and Adaptive Control.

APPENDIX I

SPECIFICATIONS OF WORKPIECE MATERIALS

(a) Titanium TA11 IMI 318

The titanium alloy used in the tests program is coded IMI 318 by the pertinent supplier while the full specification is given by the British Standard BS 2TA 11 of May 1974. The chemical composition of the alloy is the following :

Constituent	Proportion
Al (Aluminimum)	5.5 - 6.75 %
V (Vanadium)	3.5 - 4.5 %
Fe (Iron)	0.3 % (max)
H_2 (hydrogen molecules)	0.0125 % (max)
Ti (Titanium)	remainder

The mechanical properties were obtained from a test piece selected, prepared and tested according to BS TA 100 :

Property	Value
0.2 % Proof Stress	830 MN/m^2 (min)
Tensile Strength	900 - 1160 MN/m^2
Elongation	8 % (min)
Reduction of area	25 % (min)
Hardness	360-380 BHN

The specification states that the material is to be supplied in the annealed condition as follows :

(i) Heat to a temperature between 700 ^0C and 800 ^0C
(ii) Hold at temperature (+ / - 10 %) for a time dependant on the cross section (60' min)
(iii) Cool in air or furnace.

The TA11 in addition to the problem of swarf fragmentation which results to catastrophic failure of the drill under torsion, also exhibits work hardening characteristics which make the use of the woodpecking technique in DHD impossible to implement.

Its machineability window (see chapter 3) is also extremely small, especially in the range of permissible cutting speeds, and finally, as a result of its high hardness, it inflicts very rapid wear to the cutting edges of the drill resulting to a rather poor tool life.

(b) Aluminium AMS 7075 T736

The Aluminium used during the test program is a special alloy used in the aerospace industry for the manufacture of actuation components and aircraft hydraulics, manifolds, etc. The exact composition of the alloy is classified ; it is known however that there is a Silicon component and that the coding T736 is referred to as "final condition" and is associated with the thermal treatment of the alloy.

The AMS 7075 alloy is soft, its Brinell hardness was found to be consistently between 69 to 71 BHN and it does not represent a particular problem to the cutting tool in the context of tool wear. It demonstrates however the tendency to compact the flutes with fragmented swaf and therefore extra torque is required by the spindle in order to overcome the frictional resistance between the drill lands and hole bore and maintain the required rotational speed in RPM, specified in the part program. As a result of that a very high rate of catastrophic failure is encountered from as early as the first hole.

APPENDIX II

NC PART PROGRAMS
FOR DEEP HOLE DRILLING

(Variable Feedrate and Spindle Speed techniques)

```
%
&N10SP1M3M23
&N20Z-5400F100
&N30G4I2000
&N40Z+54000F800
&N50M0M5
N70G71
N80G97S1600M3M23
N90G90G0X240000Z312000
N100X0
N110G91G1Z-10000F1500M0M5
C120 F100 MTI VS2 DEPTH 100 MM
P130P1=4762
N140G27I10K50
P150P1=4348
N160G27I10K50
P170P1=4000
N180G27I10K50
P190P1=3703
N200G27I10K50
P210P1=3571
N220G27I10K50
P230P1=3448
N240G27I10K50
P250P1=3333
N260G27I10K50
P270P1=3226
N280G27I10K50
P290P1=3125
N300G27I10K50
P310P1=3030
N320G27I10K50
P330P1=2941
N340G27I10K50
P350P1=2857
N360G27I10K50
P370P1=2777
N380G27I10K50
P390P1=2703
N400G27I10K50
```

NC program for variation of spindle RPM while drilling a through hole Ø3 mm x 100 mm in Aluminum AMS 7075 T736

```
P410P1=2631
N420G27I10K50
P430P1=2564
N440G27I10K50
P450P1=2500
N460G27I10K50
P470Z+100000
N480G90G0X240000Z312000D0
N490G25X2Z2M2
```

```
%
&N10G4I500
&N20Z-P1FP3
&N30G4I500
&N35Z+P2F500
&N40G4I1000
&N45Z-P5F500
&N50Z-1000FP3
N70G71
N80G97S1000M3M21
N90G90G0X240000Z312000
N100X0
N110G91G1Z-54000F1500M0M5
N115Z-80000F70
C120  SERIES  TA11  PECK VS3  PECKS   2X5  +  10X3  MM
C125  P1=PECK DEPTH  P2=WITHDRAWAL DEPTH
C130  P3=WORK FEED  P4=RAPID FEED
C135  P5=P2-1000 RAPID REENTRY DEPTH
P140P3=10
P145P1=5000
P150P2=2000P5=19000
P165P1=5000
P170P2=25000P5=24000
N180G27I10K60
P185P1=3000
P190P2=28000P5=27000
N200G27I10K50
P210P2=31000P5=30000
N225G27I10K50
P250P2=34000P5=33000
N270G27I10K50
P290P2=37000P5=36000
N300G27I10K50
P310P2=40000P5=39000
N320G27I10K50
P330P2=43000P5=42000
N340G27I10K50
P350P2=46000P5=45000
N360G27I10K50
P370P2=49000P5=48000
```

NC program for drilling with fixed pecking depths and feedrate.

```
N380G27I10K50
P390P2=52000P5=51000
N400G27I10K50
P410P2=55000P5=54000
N420G27I10K50
P430P2=58000P5=0
N440G27I10K50
N480G90G0X240000Z312000D0
N490G25X2Z2M2
```

```
%
N70G71
N80G97S1800M3M23
N90G90G0X240000Z312000
N100X0
C120 CNC DELTA VS 3 Ø2.4 MM
C122 PARAMETER P8(MM)
C123STEPS IN DROP OF FEEDRATE
P125P8=1000
P130P2=3600
P135P3=23
P140P5=1500
P145P6=5000
N150G91G1Z-P6FP5SP2MP3M3
N155M0M5
C160 MACHINING STARTS
C165 CONSTANT FEED
C166UP TO 10 MM DEPTH
N170Z-10000F120
C175 FEEDRATE DROPS
C1772MM/MIN PER MM FOR 42 MM
N180Z-P8F118
N185Z-P8F116
N190Z-P8F114
N195Z-P8F112
N200Z-P8F110
M205Z-P8F108
N210Z-P8F106
N215Z-P8F104
N220Z-P8F102
N225Z-P8F100
N230Z-P8F98
N255Z-P8F88
N260Z-P8F86
N265Z-P8F84
N270Z-P8F82
N275Z-P8F80
N280Z-P8F78
N285Z-P8F76
N290Z-P8F74
N295Z-P8F72
N300Z-P8F70
N305Z-P8F68
N310Z-P8F66
N315Z-P8F64
N320Z-P8F62
N325Z-P8F60
N330Z+69000F2000
N335Z-68000F2000
N340Z-2000F80
C500 FEED RATE DROPS
C540 1 MM/MIN FOR 15 MM
P580P8=1000
N585Z-P8F78
N590Z-P8F76
N595Z-P8F74
N600Z-P8F72
N650Z-P8F70
N655Z-P8F68
N660Z-P8F66
N665Z-P8F64
N670Z-P8F62
N675Z-P8F60
```

```
N235Z-P8F96
N240Z-P8F94
N245Z-P8F92
N250Z-P8F90
```

NC program for drilling under variable feed rate and depth increments.

```
N680Z-P8F58
N685Z-P8F56
N690Z-P8F54
N695Z-P8F52
N700Z-P8F50
C702  END OF VARIABLE
C704  FEED RATE
C706  BREAK THROUGH
N800Z-2000F30
N805G4I500
N810Z+105000FP5
N820G90G0X240000Z312000
N900G25X2Z2M2
```

APPENDIX III

SPECIFICATIONS OF *KISTLER* DRILLING DYNAMOMETER AND CHARGE AMPLIFIER

APPENDIX IV

FRICTION COEFFICIENTS
(Marks Std. Handbook for Mechanical Engineers)
(Macmillan Press 1984)

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APPENDIX V

Listings of various programs
(in BBC Basic and 6502 assembly)

SET-UP : Interactive process definition
INTERM : File handling and post-processing
INTELMACH : Real time monitoring and control
PANEL : 2-D graphics simulation of CNC panel
INDEX : Performance data display
CALIBS : Calibration of spindle speed and
feed rate values for D/A converter

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