MACHINING WITH TITANIUM NITRIDE-COATED METAL CUTTING TOOLS

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SUMMARY

The ability of cutting tool materials to perform efficiently when used under specific machining conditions, is an essential requirement if high production rates and low production costs are to be attained. There is a limit to improvements that can be made in bulk tool materials and so coatings have been used to achieve even better tool performance. These have shown great potential in improving the performance of all types of cutting tools when machining various engineering materials. However, the tools that may benefit most from surface coatings are those which would otherwise fail by progressive wear rather than by sudden fracture or breakage.

In this investigation, two grades of uncoated cemented carbide inserts were used for comparison with five different types of coated indexable, tungsten carbide turning inserts. The only feature in common between the coated tools was the top layer of TiN coating. Otherwise, they had different substrates, different geometries, different coating systems, or different coating thicknesses.

Preliminary cutting trials were undertaken on mild steel and En 8 steel before the main machining programmes which were performed on 316-austenitic stainless steel. Various machining conditions were employed and different cutting operations conducted on both a conventional centre lathe and a CNC lathe.

The main aim of this project was to undertake a joint study of the engineering and metallurgical behaviour of coated metal cutting tools subjected to fairly severe operating conditions such as the machining of difficult to machine materials at relatively high speed. The following techniques were employed.

1 Measurement of the cutting force using a Kistler cutting force dynamometer.

2 Measurement of the progressive flank wear width of the cutting tools using an optical microscopic universal measuring machine.

3 Determination of the work piece surface finish after machining, using a Talysurf surface analyser.

4 Examination of the experimental tools before and after machining by use of an optical microscope and a scanning electron microscope linked with an energy dispersive x-ray spectrometer for anlaysis.

Surface coatings brought about significant reductions in the cutting forces and tool wear, but the improvements in surface finish were not very significant, especially when machining mild steel and En 8 steel where the working conditions were less severe than those employed later for the machining of stainless steel. It was evident that surface coatings were advantageous when used to cut stainless steel, and the more severe the conditions, the more beneficial were the coatings. The use of expensive wear resistant coatings can be well justified when cutting difficult-to-machine materials with advanced machine tools such as a CNC lathe. However, when considering the performance of coated tools there was a wide variation in their behaviour. This indicates the necessity for precise selection of tooling for a particular application.

Keywords: Cutting tools, CVD coatings, tool performance, tool wear, machining of stainless steel.

DEDICATION

To all faithfuls

who have the will and never surrender to despair,

who keep their smiles during the times of agony,

and who are prepared to give without expecting rewards.

To my wife, and children who paid generously, from their comfort and welfare, and whose patience and endurance were flowing streams of inspiration.

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CONTENTS

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER ONE

INTRODUCTION

CHAPTER ONE

1 INTRODUCTION

1.1 Significance of Metal Cutting

In the manufacturing industries, despite the recent development and progress in important metal working processes such as forming and forging, metal cutting is still the main process for preparing engineering components and parts. Machined parts are needed by almost all branches of engineering and industrial establishments, for nearly every kind of machinery, devices and equipments. Metal cutting which is a basic part of mechanical engineering and carried out in all production workshops and repair sections, is the solution to practical problems of manufacture and control of product accuracy. As part of the whole modern industrial development, machine tools and tooling engineering is considered one of the important factors in the national and international economies[1-4].

Since the extensive work of Taylor[5] throughout the first quarter of this century, numerous investigators have carried out exhaustive research programmes involving metal cutting. However, they have had a very diverse approach to their studies, mainly due to the copious subjects involved in metal cutting and to the various interacting factors associated with machining operations. In modern technological life all streams of industry seem to flow into the trend of economic achievements. Accordingly, the main objectives of most metal cutting investigations have been shifted from studying the basic machining practice, towards the economics of machining and the optimisation of metal cutting[6-10]. However, this is only possible via intensive research programmes dealing with the various aspects of machining and tooling engineering. These include the work material, the tool material, the machining conditions and many other associated features.

1.2 Development of Tool Materials

It is well known by scientists and engineers that the failure of cutting tool material is one of the most important areas of study in the whole field of tooling engineering. It has been emphasised, by many authorities, that tool materials of poor performance are one of the most serious limitations on the productivity of manufacture, whether one looks at cutting, forging, cold working or at a wide range of other processes[11]. Tool wear, particularly in metal cutting, sets a limit to productivity of the machine tools, increases production costs[12], and consequently governs the economics of metal cutting processes. Moreover, tool wear has a decisive influence on the choice of the working conditions, along with the cutting forces, and the surface finish required[13].

There is a persistent need for tool materials of greater strength and toughness with high wear resistance so that tool life can be extended, and high accuracy and good surface finish achieved. Furthermore, it is necessary to reduce the costs resulting from the need to replace tools frequently. It is difficult to find the required properties in a single tool material, and the obvious choice in order to meet the needs of the complicated cutting situation, is to compromise between the production needs and the available properties. Under the pressure of the increasing demands of development, many tool materials have been tried for metal cutting, with some of them allocated for cutting certain work materials. The main types of tool materials include carbon steels, alloy steels, high speed steels (HSS), cemented carbides and oxides (ceramics). However, the most intensively used types are the HSS and the carbides with an exclusive use of the former for drills and the latter as turning inserts[3,14].

During the last decade and the present one development in metal surface engineering and coating techniques have had a great impact on metal cutting technology by the introduction of coated HSS and cemented carbide cutting tools. Although, the choice situation has been complicated to some extent by the availability of a large number of coating combinations, some significant benefits have been reported. However, it is believed that the full potentials of these coatings are yet to be discovered, and their exact effect on the interacting features of machining are awaiting thorough investigation and research efforts for more exploration and appropriate utilization.

1.3 Research Trends and Objectives

Few researchers have put great emphasis on the work material as a governing factor that dictates the tool wear characteristics in metal cutting. Originally, it was the need for engineering components and parts made from materials having certain properties that encouraged progress in metal cutting research, and led to further developments in cutting tool materials. Because of the prospect of achieving some significant reductions in the high production costs through machining optimisation, and because of the importance of stainless steel as a material of favourable properties for many applications, it was considered worthwhile to evaluate optimum conditions for machining stainless steel with a variety of surface coated tools.

Probably, the most frequent subjects that have received attention in metal machining research are; the machinability of work materials, the mechanics of chip formation, the tool geometry, the cutting temperature and the stresses involved[4,8,15-19]. Despite the great influence of these parameters on metal cutting practice, the strong link between the cutting tool behaviour, the workpiece material and the machining conditions that designate each operation, should not be overriden. However, tool wear which takes place during different cutting operations is the common important phenomenon that occurs as a result of complicated interactions of all factors involved in machining.

Although most production engineers would agree that tool wear is the major influencial factor in metal cutting, and all of them are aware of the poor machinability of stainless steel and its adverse effects on the cutting tools, very little work has been reported on studies involving this important work material.

Since the research work that took place recently on the performance of TiN-coated hot forging dies[20,21] in which titanium nitride coatings showed their superiority over other coatings and uncoated tools, it was suggested that the investigation needs to be extended to cover another type of metal working, namely metal cutting. However, the scope of the research work undertaken in the present investigation was intended to be wider and more comprehensive by handling more than one type of coating system, cutting more than one work material and using more than one method of assessment.

The main objectives of this research are three fold:

1 To study the performance of titanium nitride coatings, produced by chemical vapour deposition, on cemented tungsten carbide turning inserts when machining stainless steel.

2 To study the wear characteristics and mechanisms associated with the machining process employed.

3 To evaluate and assess the coated tools by comparison with uncoated ones and with each other.

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Introduction

Extensive information is available on almost every topic of interest in the field of machining. However, a wide diversity of research objectives and a variety of testing procedures with significant differences in analytical approaches and viewpoints have been experienced. Most of the wide fluctuations in research outcomes are atributed to the fact that metal cutting is a complex engineering activity which involves many interrelated variables operating at one time. Any metal cutting process was regarded by Shaw[22] as a production system containing a machine, a variety of inputs, internal items, and outputs. However, the ultimative objective of any machining system is to achieve high production rates and adequate product quality at the minimum production cost. It is widely accepted that the most influencial factor of the machining system inputs is the cutting tool which plays a leading role in metal cutting economics. The main subject of interest in this research is the tool coatings and their influence on performance when cutting a 'difficult-to-machine' material. However, it is essential to be aware of the influence of the machining system as a whole. The literature review is therefore in two parts. The first part concerned with the system mechanics and the second part with aspects of (workpiece/tool) material and wear.

PART 1: GENERAL ASPECTS OF MACHINING

2.2 The Basic Concepts of Machining Operations

The machining process is the most widely used metal working processes employed in industry. The term 'metal cutting' includes many machining operations which are essentially similar in that a cutting edge removes metal chips 'swarfs' to produce a required surface. However they differ largely in the ways by which these surfaces are produced. They employ differently designed tools operated with different motions relative to the work material to produce different shapes and surfaces. The main cutting operations include lathe turning, drilling, boring, shaping, planing, milling, hobbing, broaching, grinding, slotting and sawing[23,24].

Probably the most versatile of the known machine tools and the most widely-used one is the lathe, since it can be used for many cutting operations other than turning, such as boring and drilling. Consequently, it is the machine tool that is usually found in most production workshops and maintenance or repair departments. The most important function of the lathe is turning which is the basic cutting operation and the one commonly employed in experimental work of metal cutting research programmes. It consists mainly of a workholding device 'the chuck' where the workpiece is held firmly and rotated at a pre-selected speed, and a tool post on which the tool is fixed rigidly before the cutting action takes place by moving the tool post longitudinally along the surface of the rotating workpiece. A layer of metal 'chip' characterised by the chosen machining variables is cut away leaving the new required surface on the machined workpiece.

The fundamental mechanics of this process have been well established throughout this century. However, it is essential for every research worker taking part in the field of machining to start with the basic features of the cutting process and to understand the activities and changes that occur at the tool/work interface. A knowledge of the mechanics of the system tool-chip-workpiece is important for proper design and control of the tool, the workpiece, and the machine tool itself. It has been emphasised that this work-tool relationship ultimately determines the cutting-edge action, dimensional accuracy, the machined finish, and the economics of the operation. However, the basic tool-work relationship in cutting is adequately described by means of the tool geometry, cutting speed, feed and the depth of cut. These factors are involved in the mathematical consideration of metal cutting.

2.3 Turning Operations

Although the scope of 'metal cutting' is very wide as it covers various types of machining operations, the term, throughout the text of this research work, will be restricted to refer to the turning operations. For practical considerations only 'orthogonal turning' will be employed and this type of turning is the conventional configuration usually carried out for experimental work in metal cutting research.

2.3.1 Principles of Turning

According to Hatschek[25] one out of every five metal cutting machine tools in the United States is a turning machine.

Turning as defined by Berg[26] is essentially the machining of an external surface

- with the workpiece rotating
- with a single point cutting tool, and
- with the cutting tool feeding parallel to the axis of the workpiece and at a distance that will remove the outer surface of the work.

In fact several geometrically different surfaces, such as tapers or contours may be produced by turning after using special tool set-ups.

2.3.2 Machining Conditions

There are several conditions that characterise a certain machining operation. Among these conditions are the work material, the tool material, the tool geometry and the machine tool itself. However, these important factors in particular the tool material which is the main subject of interest in this investigation, will be discussed in the coming chapters.

The machining conditions that need to be clarified at this early stage of the research work, are the factors which specify each cutting operation by a special identity. These factors are: the speed, the feed and the depth of cut. According to their direct influence on the character of the cutting operation, these factors are commonly employed by production engineers to optimise any machining process, yet they represent the simplest factors in machining that are frequently adjusted and controlled by the machine operator.

The surface cutting speed: This is the rate at which a point on the circumference of the workpiece passes the cutting edge of the tool. It is expressed in surface metres per minute (m/min) or surface feet per minute (f/min). The surface cutting speed is calculated from the spindle speed (rotation speed) which is stated in revolutions per minute (RPM), and the workpiece circumference in (mms) or (inches), thus the cutting speed = spindle speed x circumference of workpiece.

However, the cutting speed magnitude depends on many factors such as the properties of the work material, the tool material, the shape and size of the tool, the tool life desired, the depth of cut, the feed, the coolant used, the rigidity of the work etc[27]. In general, the harder or tougher the work material, the slower the cutting speed[23].

The feed: This is the axial distance the tool moves in each revolution of the workpiece. In other words, it is the rate at which the cutting tool advances along its cutting path into the workpiece, and so it is measured in mm per revolution (mm/rev) or inches per revolution (in/rev). It may be used by some machinists and engineers to designate the undeformed chip thickness and it varies with the kind of cut taken and the surface finish required. A course feed is usually used for roughing cuts and a fine feed for finishing operations.

The depth of cut: The cutting depth is the distance the tool is set to penetrate the work, and it is stated in mms or inches. The depth of cut is equivalent to the width of the chip formed in turning operations, and its magnitude in roughing cuts is larger than in finishing operations.

Speed, feed and depth of cut are illustrated in Figure 2.1.

2.4 Theoretical Considerations

2.4.1 Tool Angles and Geometry

Probably the most important aspect in a cutting tool, after the tool material, is its geometry, particularly the angles. Variations in the angles of the cutting tool have a significant influence on the machined workpiece surface finish, the cutting forces and the tool life[23,28-30]. As far as turning is concerned the cutting tools are of a single-point type, where one tool face and one continuous cutting edge are involved. In various publications the tools are identified by the term 'tool signature', which is a sequence of numbers listing the magnitude of the angles in degrees, and the size of the nose radius. Although there is a design difference between a one solid unit tool and an indexable insert tool, there are many features in common between the former which is usually reground to be kept within specification after wear, and the latter which is a throw-away tip that is rotated periodically to present a fresh cutting edge or replaced by a new tip.

Usually, the tool angle identification system is the same in both types of tools but in the case of the indexable inserts the angles referred to relate to the situation when the insert is fixed to the toolholder which is originally designed to attain the working angles required. However, the indexable insert geometry will be considered later within the experimental arrangement, while the commonly important tool angles

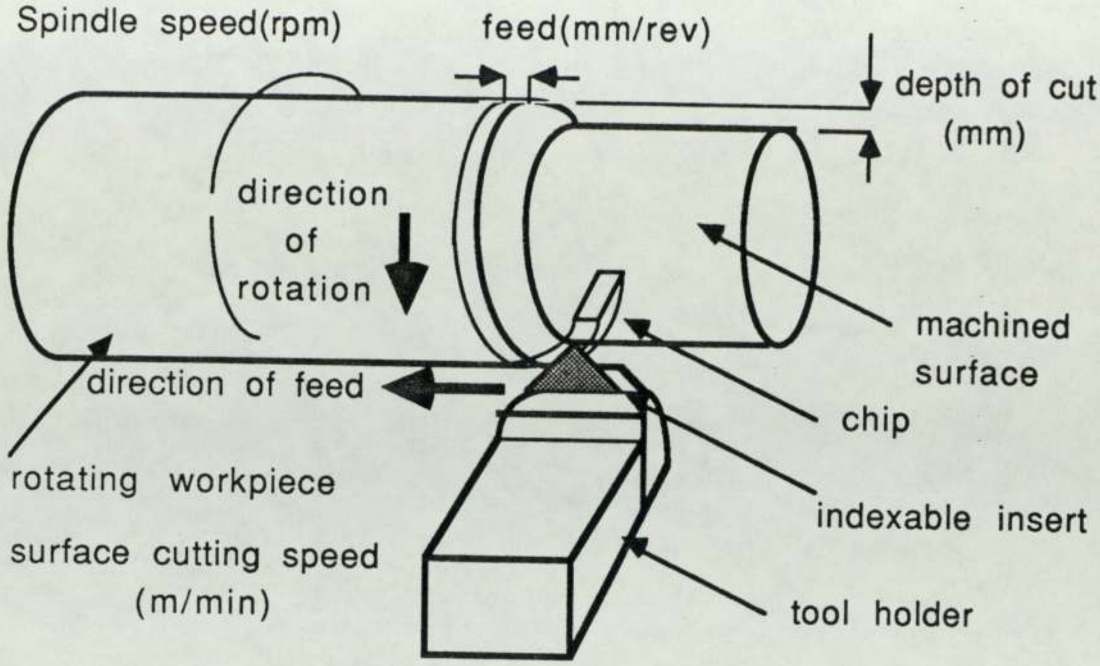


Figure 2.1: Basic variables in a turning operation

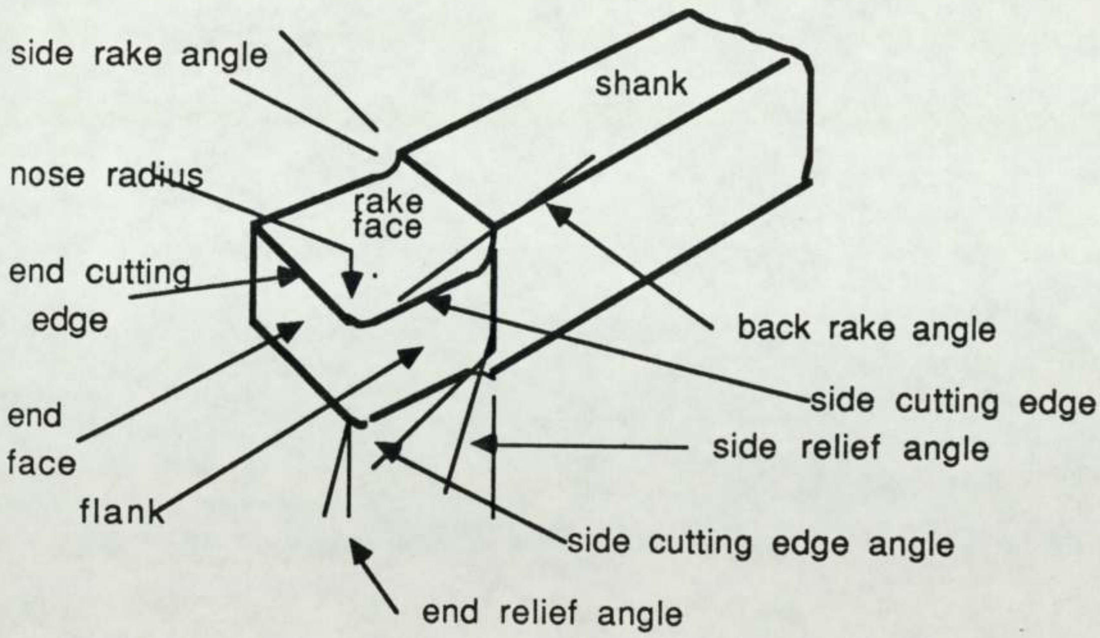


Figure 2.2: Angles of a single-point tool(24,29)

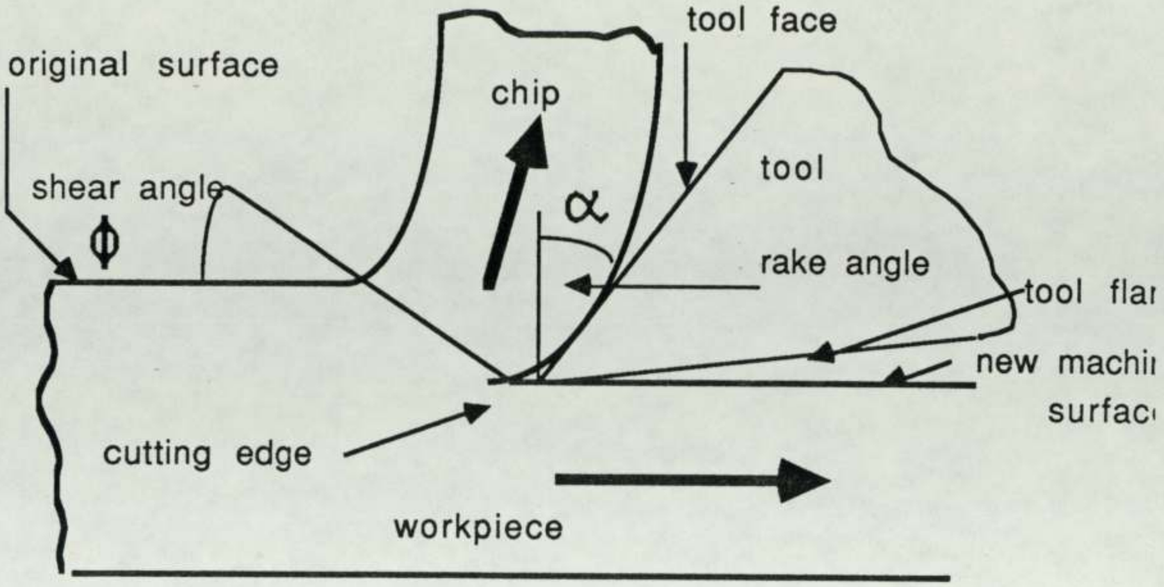


Figure 2.3: Orthogonal 'two-dimensional' cutting(24,28,31)

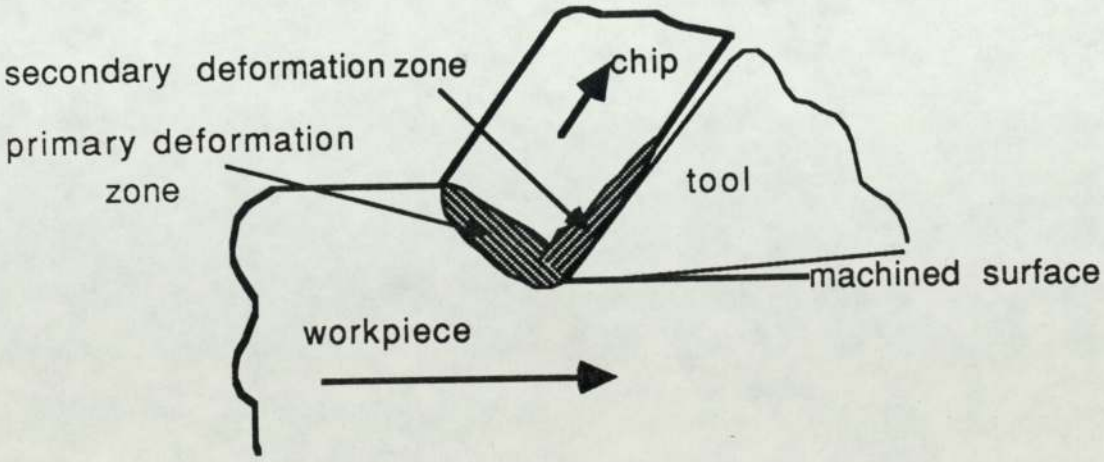


Figure 2.4: Zones of deformation in orthogonal-metal cutting(8)

are shown in Figure 2.2 which illustrates different views of a single-point tool to facilitate angle identification of a working tip, no matter whether this tip is an edge of a one-unit tool, a brazed tip, or an indexable insert 'throw-away tip'.

2.4.2 The Geometry of Orthogonal Cutting

There are two main methods of metal cutting, one is a two-dimensional process which is called "orthogonal cutting", and the other is a three-dimensional process called "oblique cutting". Since the former method is characterised by a relatively simple arrangement, it is widely used in theoretical and experimental work, and commonly employed for machining research. The term 'orthogonal cutting' which has been defined and explained by previous investigators(16-18, 32), according to Merchant(17,33), was coined to cover the case where the cutting tool generates a plane surface parallel to an original plane surface of the material being cut, and is set with its cutting edge perpendicular to the direction of relative motion of the tool and workpiece (Figure 2.3). This type of cutting has been used in the experimental tests carried out during this research work.

2.4.3 The Mechanism of Chip Formation

Despite the fact that chip formation is the principal element in the machining process, the detailed study of the mechanism of chip formation is not the objective of this research. However, some basic theoretical considerations and fundamental relationships should be regarded as a logical background for proper understanding of some experimental features in the research work.

2.4.3.1 Deformation and Shearing of Work Material

When a process of orthogonal cutting takes place, the wedge-shaped tip of the cutting tool advances through the work material at a penetration rate equal to the feed. The metal which deforms at the tool cutting edge during its progress, is forced

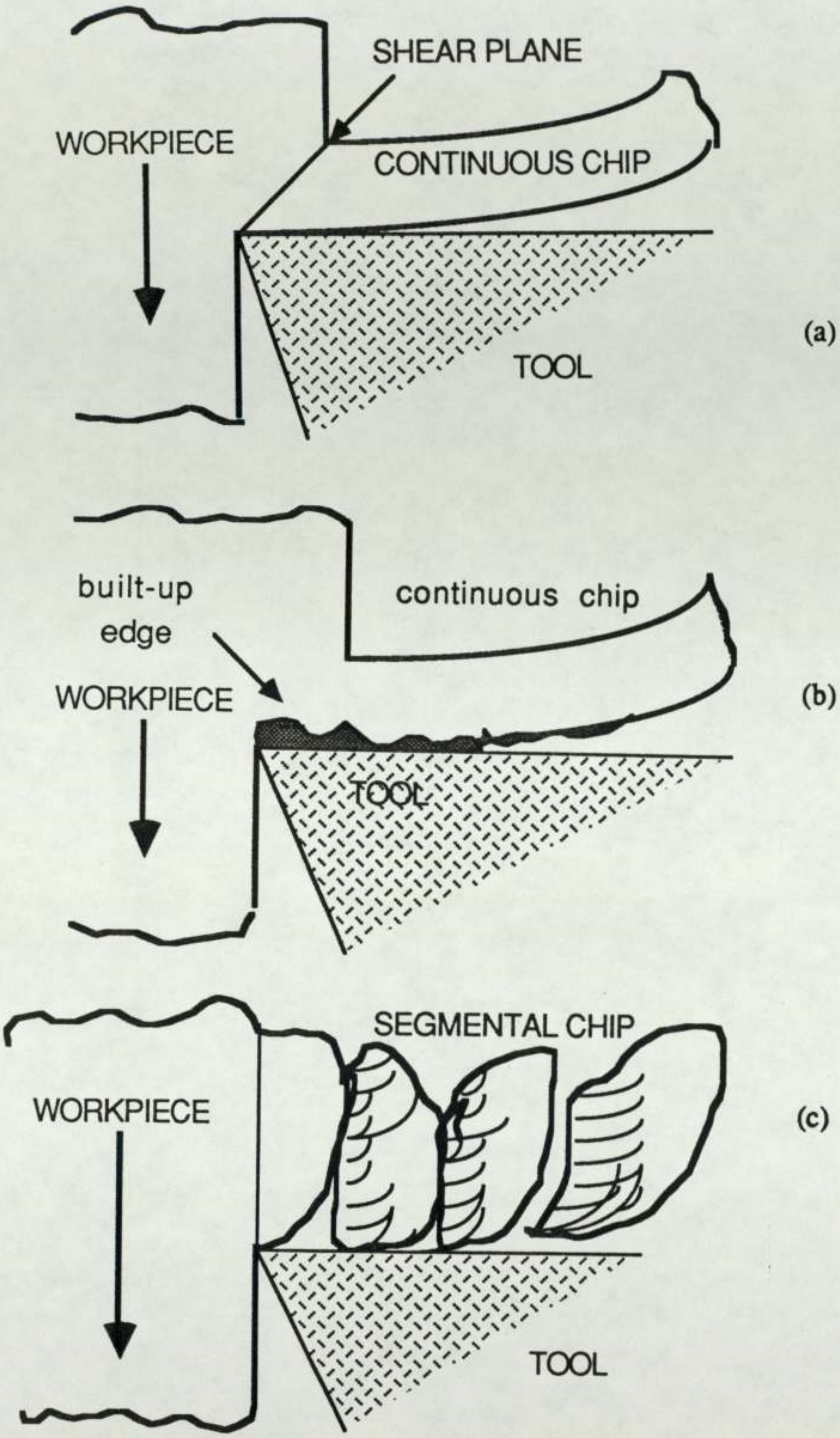


Figure 2.5: Basic chip forms(34,35)

(a) continuous type chip

(b) continuous type chip with build-up

(c) discontinuous type chip 'segmental'

to flow over the top 'rake face' of the tool to form the chip which is characterised by the properties of the workpiece material and the machining conditions employed in the process. The metal left under the wedge forms the machined surface. The formation of chips is accomplished after successive activities taking place at two main zones in the tool/work engagement vicinity; the primary deformation zone and the secondary deformation zone (Figure 2.4). In the former the work material just ahead of the tool-cutting edge is deformed and sheared continuously under high cutting and shearing forces, whilst in the latter the frictional force created between the sliding chip and the tool rake face at their area of contact, causes further deformation of the chip material.

2.4.3.2 Types of Chips

The type of chip produced during metal-cutting depends on the properties of the work material and the machining conditions used in the cutting operation. Amongst the different modes of chip formation the following are the most important:

(i) The continuous chip (Figure 2.5a)

This type is formed by continuous deformation of the metal without fracture ahead of the tool cutting edge, followed by steady flow of the chip on the tool rake face. This form is associated with low friction at the tool/chip interface, low power consumption, low wear, long tool life and good surface finish.

It is common when cutting ductile materials such as mild steel, copper and aluminium under factors favourable to the formation of this type of chip such as fine feed, high cutting speed, keen cutting edge, smooth tool face and an efficient lubricating system[34].

(ii) The continuous chip with built up edge (Figure 2.5b)

This type is formed in the same way as the previous one but in this situation the chip flow is confronted with excessive frictional resistance at the cutting edge and at the tool rake face where pressure welds occur and small fragments of the hot chip adhere to the tool face. As successive chips move along the face some of the pre-weld metal tears off and passes away with the moving swarf, while new fragmentation and welding takes place due to the increased friction. Chip material is gradually built up on the tool face. Some minute particles may adhere to the machined surface leading to a poor surface finish. The built-up-edge formation in metal cutting is one of the main factors affecting surface finish and tool wear.

(iii) The discontinuous chip (Figure 2.5c)

This type is formed when cutting brittle materials or ductile materials at very low cutting speeds and high feeds. Fracture occurs in the primary deformation zone when the chip is only partly formed. The metal ahead of the cutting edge undergoes a series of actual fracture where the chip is formed in individual segments which may be separate or in some cases loosely adhered to each other after formation. When this type of segmented chips is associated with brittle materials, the work surface finish is fair, the power consumtpion is low and tool life is reasonable. However, when it occurs with ductile materials, it may result in poor surface finish, excessive tool wear and short tool life[31].

2.4.4 Forces in Metal Cutting

A knowledge of the cutting forces involved in machining is needed by the machine tool manufacturers to evaluate the power requirements and to design sufficiently rigid and vibration-free structures. Nevertheless, scientific analysis of metal cutting also requires a knowledge of these forces along with their associated features.

When a cutting operation takes place, forces of different magnitudes and directions are created in the region of engagement between the tool and the work material. These forces are an important aspect in machining due to their connection with chip formation during the cutting process, and to their direct effect on power consumption and other features such as tool wear and job surface finish. When a cutting operation takes place there are three zones of significant importance. Zone one is the shear area where the chip is separated from the work material by plastic flow following the primary deformation of metal ahead of the tool cutting edge. This area experiences significant shearing stresses depending on the magnitude of the shearing angle[23]. Zone two is the area of contact between the moving chip and the tool face, where considerable friction and heat generation take place leading to distinctive characteristics at the chip/tool interface. Zone three is the machined surface whose quality is determined by the conditions existing at the other two zones.

The forces which act in zone one and zone two, have been investigated extensively and analysed by previous researchers[8,17,18,23,24,28,31,34,35]. However, the original research carried out by Merchant[17,33] provided the common background for all other workers. He based his analysis on the ideal orthogonal cutting operations performed under constant machining conditions that result in the formation of continuous chips without built-up-edges (BUE). The chip has been assumed to be a separate body which is kept in equilibrium under the action of two equal and opposite resultant forces, these are the force acting at the interface between the tool and the back surface of the chip in the secondary deformation zone, and the force which the workpiece exerts on the base of the chip in the primary deformation zone along the shear plane.

2.4.5 Stresses on Cutting Tools

A knowledge of the nature of the stresses acting on the cutting tools during machining may be needed for a thorough understanding of the properties and the behaviour of tool materials and tool design while cutting operations are taking place. However, very little information has been reported about the stresses acting on the tool during cutting. Trent[2] has highlighted two difficulties in determining stresses at the tool/workpiece interface. The first one is the ill-defined area of contact on the tool surface upon which the force acts. Secondly, the nonuniformity of the stress distribution over the contact area leads to a difficulty in determining the values of these stresses. Despite these difficulties, stresses acting on the rake face of a cutting tool have been analysed by a few workers. These stresses were classified into two types:

1 The compressive stress normal to the tool rake face, imposed by the cutting force and determined by dividing the cutting force, Fc, by the contact area. This stress can be of very high value when cutting materials of high strength.

2 The shearing stress imposed by the friction force, Ff (or tangential force, Ft) on the tool over the area of contact on the rake face. This stress is equal to the feed force per unit area, a value which is normally less than the compressive stress as Ff is less than Fc and both of them act on the same area of contact. The same types of stresses mentioned above can develop on the wear land of the flank face of a worn cutting tool, but it is difficult to determine the values of the forces acting in this area, and reliable estimates of stresses are unavailable[4].

Figure 2.6 shows a model adopted by Zorev[166] in which he assumed a cutting operation with no built-up edge and the chip able to slide beyond the sticking zone (region of seizure) which extends from the cutting edge for a short distance along the tool rake face. The distribution of stresses on the cutting tool is based on the simple theory that the compressive stress, σ_c, at any position on the tool face is represented by the expression[19B]:

$$\sigma_c = q\,X^y$$

where X = distance from the point where the chip departs from the tool face

q, y = constants

The maximum value of the compressive stress corresponds to the maximum value of X, ie. at the tool cutting edge, as illustrated in Figure 2.6. From this point 'A' the stress curve starts to drop tending to zero as it approaches point 'B' where the chip loses contact with the tool face. On the other hand the shear stress curve indicates a maximum value less than that of the compressive stress, and uniform near the cutting edge, remaining constant along the sticking zone where conditions of seizure prevail, then under sliding conditions it drops approaching zero in a steep path towards point 'B' as illustrated in Figure 2.10.

The existence of these features has been verified by many workers[8], and a detailed description of the conditions of seizure in the tool/workpiece interface has been presented by Trent[2,4]. Brown[19] has investigated the tool stresses caused by unsteady-chip formation and concluded that they were affected mostly by the tool geometry, and the most effective means of minimizing the variation in stress is [illegible] of a simple edge radius. However, earlier research [illegible] the dependence of tool stresses on the tool geometry such that an increase in the rake angle reduces the compressive stress. Nevertheless, the work material has a significant effect on the compressive stress when the geometry of different tools under test is kept constant. It was found that materials with high yield strength may exert very high stress that could cause tool failure by plastic deformation even at low cutting speeds where low cutting temperature is involved.

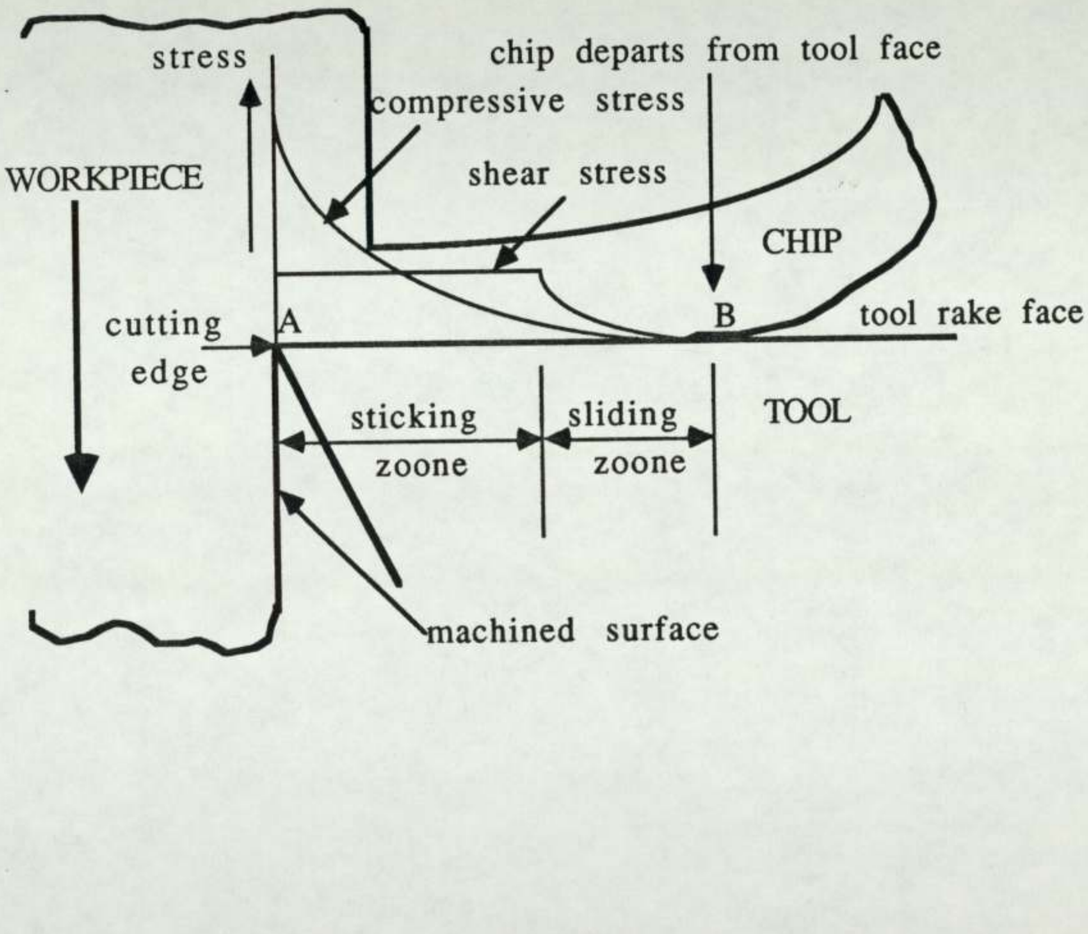


Figure 2.6: Model of stress distribution on cutting tool face "after Zorev"(36)

2.5 Temperature in Metal Cutting

2.5.1 Significance of Cutting Temperature

Temperature in metal cutting is one of the important factors that influence machining economics by accelerating tool wear, shortening tool life and limiting the cutting speed and the feed.

Trent(4) has pointed out that many of the economic and technical problems of machining are caused by the heat generated near the tool's cutting edge by the power consumed in metal cutting. The harder the work material, the greater the heat involved, hence the temperature of the tool surface increases significantly with the increase of metal removal rate when a highly alloyed steel is being cut. It has been emphasized that when conditions leading to high cutting temperature prevail, excessive tool wear occurs and the tool fails in a relatively short time resulting in a serious economic problem.

2.5.2 Heat Generation in Metal Cutting

It has been widely accepted by several researchers that more than 95 per cent of the input power of a cutting operation is transformed into thermal energy and the remaining small part is stored in the workpiece and the chip as residual stresses(37-40). Heat is generated by the work done in deforming the metal ahead of the tool's cutting edge, to form the chip, and by the work done in moving the chip along the tool face. Almost all of this heat goes into the workpiece, the tool and the chip. The main zones at which heat is generated are:

(i) The shear zone, where the primary deformation takes place.

(ii) The tool/chip interface, where heavy rubbing occurs under high friction conditions.

(iii) The flank face of the tool, where heat develops as a result of the rubbing action between the tool flank surface and the workpiece finished surface.

The large proportion of heat conducted by the tool and workpiece may cause serious cutting problems, whilst the relatively small part of heat carried away by the chip has a negligible effect on the process[23].

2.5.3 Factors Affecting the Cutting Temperature

Since almost all the work done in metal cutting is converted into heat, the factors which affect the power consumed per unit volume of metal removed during a cutting operation, will directly affect the cutting temperature. Of these factors the most influential one is the cutting speed which when increased results in the amount of heat transmitted to the workpiece being reduced as the short time of contact will permit only a limited amount of heat to pass into the work material. Consequently this will increase the temperature of the chip at the primary deformation zone. Nevertheless, the temperature in the secondary deformation zone will also increase as a result of a reduced size of this zone[4,8]. According to Mills and Redford[8] changes in parameters, other than the cutting speed and the rake angles, have little effect on the specific power consumed and consequently have little effect on the cutting temperature. This was based on the relationship used for calculating the specific cutting power in terms of the cutting speed and the tool rake angle.

2.5.4 Early and Recent Studies of Cutting Temperature

Due to the significant effect of the cutting temperature on machining economics the study of heat involved in metal cutting has been a focus of interest since the early days of machining research[5]. Several investigators have attempted to determine the cutting temperature and to analyse its distribution[41-47]. However, these studies have been shown to be difficult and uncertain due to the complexity of the process[4,23]. New techniques for analysing temperature have been used by Wright and Trent[48], Trent[4,49] and Mills et al[50]. However, the determination and distribution of temperature is still considered a technically difficult subject.

2.5.5 A Practical Feature of Cutting Temperature

In practical terms, the most clear indication of temperature changes is the change of the chip colour that takes place during cutting. The heated chip colours, experienced in machining of steel, are the brown and blue. Trent[4]has related these colours to the formation of a thin oxide layer on the steel surfaces to indicate a temperature of the order of 250-350°C. However, this change in colour takes place when high speeds are used, but at low speeds which are associated with low temperature and possible build-up-edges, the chip does not change its colour.

2.5.6 Cutting Temperature and Tool Wear

There is no doubt that the most important cost affecting factor in the economics of machining is tool wear and tool life. Several workers have related tool wear to temperature[8,28,40,51] by considering tool wear and life as a function of the tool/workpiece interface temperature. The tool wear/temperature relationships were based on widely varied assumptions reflecting the differences in interpretation and the disagreement in postulations[4,23]. However, it is widely recognized that even a small change in temperature will cause a significant effect on tool wear rate[8] and other features such as the built-up edges. Moreover, it is well known that certain mechanisms of wear are mainly temperature-affected in nature such as diffusion wear[28] and oxidational wear[52,53]. These types of wear will be considered in the next chapter together with the other tool wear mechanisms.

PART 2: MATERIAL/WEAR ASPECTS

2.6 Work Material

2.6.1 Significance of Work Material

Work material is the first item that is usually thought of when a metal cutting situation is considered. It has already been mentioned that at the time of Watt in the last century, his engine's need for components of special specifications represented the start of machine tool development. In fact, any engineering component, apart from its shape and dimensions, must possess certain material properties which are considered an essential aspect in its design. The work material's properties are usually needed for efficient performance and economical service life of the machined product. However, it has been emphasized by early and recent metal cutting researchers(54,55) that the desirable properties of work material may have a significant influence on the metal cutting process. For instance, when a component is needed for an application where high quality will not be sacrificed for any reduction in production cost, the work material properties give no room for compromise, and most likely the product quality is assured at the expense of the cutting tool service life, which is normally shortened by deterioration of the tool at its region of contact with the workpiece.

2.6.2 Development of Engineering Materials

The purpose of metal cutting processes is to generate cylindrical and flat surfaces, threads, grooves, slots and holes for production of metallic components of different geometrical shapes. Components of different sizes prepared from metals having different properties are used as parts of a wide range of machines such as trains, vehicles, aeroplanes, ships, weapons, domestic appliances and many other implements and equipment used in everyday life. Development in every field of application is accompanied by development in material. Cast iron, wrought iron and a few copper based alloys were the dominant work materials for many years after

Watt's steam engine invention[4]. The requirements of advancing technology necessitated the development of new alloys to withstand the severe service conditions of stress, temperature, wear and corrosive environments. Some of these alloys, such as aluminium and magnesium, are easy to cut but others which contain more alloying elements of certain types such as nickel-based alloys and high-alloy steels are difficult to machine. However, the much needed properties of these alloys led to further development in work materials directed towards the improvement of their machinability.

2.6.3 Machinability of Work Materials

Despite the frequent use of the term "machinability" in metal cutting research and publications, there is a considerable ambiguity about its precise definition. It is a property or quality of a material which can be used as an indication of the ease or difficulty with which the material can be machined using a cutting tool[4,8]. Several investigators attempted to arrive at an adequate definition of machinability in a conference jointly organised by professional institutions in the mid-sixties[15]. They all agreed on the fact, which was stated before then[54], that it was a complex situation. However, the authors covered a large number of variables associated with machinability in metal cutting. The different criteria used to evaluate machinability included the fundamental nature of the machining process, matters specifically related to the workpiece material properties, and others related to the cutting tool. Koenigsberger[56] posed three questions still to be answered:

(i) Is machinability, as the name would imply, the ability of the material to be machined at all?

(ii) Is it the degree of quality which can be obtained by machining?

(iii) Is it the degree of technical or economic efficiency with which it can be machined?

He concluded by emphasising that the term 'machinability' should cover the best value for money which can be obtained by selecting the process, the tools and the cutting conditions for machining a given material. Mills and Redford[8] summarised the attempts of previous workers who focussed their evaluation of machinability on specific characteristics of the cutting process such as the cutting tool life, the tool wear rate, the energy required for a standard rate of metal removal or the quality of the machined surface, and more recently the cutting forces. However, they suggested that 'machinability' should be understood to be some measure of the way in which a material wears away a cutting tool when it is being machined. This restricted meaning of machinability seems to be acceptable but only after specifying how this characteristic is to be measured. This is part of the complexity of metal cutting as a whole since there are many types of tool wear, different machining conditions and various types of tools. Based on these restrictions recent researchers appear to have considered machinability as a function of a specified test. However, an appreciable number of investigators have continued their efforts to establish the identity of 'machinability' by studying the behaviour of certain workpiece materials and their performance under specified cutting operations[16,57-63].

2.6.4 Surface Finish of Workpiece Material

Quality of the machined surface is one of the basic requirements of the production engineer, especially as it critically influences the service performance in many applications. The surface finish is often used as a criterion to assess machinability of work materials[4] and some investigators[12] have used the deterioration of workpiece surface finish as a criterion of termination of the tool's useful life. Early researchers in the field of machining related surface finish to the work material, the tool shape, and the cutting conditions[64]. Some of those workers[65] have shown that a relationship exists between surface finish, friction and the ratio of the feed to the chip thickness where larger cutting ratios (or less chip deformation) correlate directly with lower friction coefficients and better finishes. Trigger[66] put greater emphasis on the feed marks or ridges left by the tool on the workpiece, vibration displacements between tools and work, and the fragments of built-up edge shed on the work surface in the process of chip formation as the main causes of surface roughness. Consequently anything that could be done to reduce the height of the feed ridges, the size of the built-up edge or the amplitudeof the vibration, will improve the surface finish. However, there is a wide acceptance that the main factor which influences the workpiece surface finish is the presence or absence of a built-up edge. This built-up edge formation and its relation to the other characteristics of metal cutting has been the subject of study by many investigators[66-70].

2.7 Tool Material

2.7.1 Significance of Tool Material

It is widely accepted that the most important element of any machining system is the tool[71], which has the main influence on the production cost. The ultimate economic performance in metal cutting would be achieved with a cutting tool that takes the chips off the workpiece at high metal removal rate, produces a machined part of high quality, and stays in service efficiently for a long life time.

Hatschek[25] emphasized that many factors affect the profitability of a manufacturing situation, but it is unlikely that any factor offers a "leverage" of equal magnitude to that of the cutting tool. Every aspect that has a direct relation to the cutting tool, has received continuous attention from researchers in the field of metal cutting. Probably, the most important subject of all, is the tool's material. It must possess certain properties in order to fulfil the requirements and objectives of machining processes. It is important in solving the important questions of how to cut a certain work material and at what production cost. Certain workmaterials can only be cut with special tool materials. Nevertheless certain tool material cannot withstand the severe conditions experienced in metal cutting. Obviously, tool wear is the major burden in machining economics however different the types of wear. Consequently the properties required in a tool material are those which have a direct effect on tool wear, or an effect on other machining aspects strongly related to wear such as the forces and temperature in metal cutting.

2.7.2 Development of Tool Materials

The development of tool materials has been based on the properties required in the cutting tool which faces on extremely hostile operating environment. The properties required in the appropriate tool-material for a certain machining operation involve a degree of compromise as there is a considerable interaction between these properties with favourable and adverse effects on each other. There is general agreement on the main properties favoured in cutting tool materials. Smart[72] emphasised the variation of the relative importance of the properties according to the application. He summarized these properties as follows:

(i) adequate strength
(ii) strengh retention at high temperature
(iii) toughness
(iv) resistance to thermal shock
(v) resistance to wear
(vi) chemical stability

However, there are many other properties that could be added to the list. Most of the properties required in the tool material may be relative to the workpiece material, representing the conditions characterising the matching pair of metal surfaces working under specified machining conditions, such as the compatibility and the sliding and sticking friction between work/tool materials[73-76]. The cutting tool users usually specify their requirements in terms of function rather than of property. They need adequate tool life, avoidance of premature tool failure, reproducibility in cutting performance and applicability to a variety of machining operations[72]. Development of tool materials has been governed by these requirements and the extensive research that has taken place was intended to meet these 'users' requirements. This has led to the use of a wide variety of cutting tool materials, especially the surface coated ones, as will be discussed in the following sections.

The tool materials that dominated the metal cutting industry in its successive stages of development, were harder than the materials to be cut. This relative property of tool materials was the decisive factor in its early and recent development. The most widely used types of cutting tool materials are categorised in five groups as follows[4,8,23,24]:

1 Carbon steels
2 High speed steels
3 Cast alloys
4 Cemented carbides
5 Ceramics, cermets and 'ultra-hard materials'.

The usage of groups (1) and (3) diminished with the extensive advancement of the engineering materials. Tools of the last group are more recent than all other types and they have proven to be successful in machining special grades of engineering materials[62,63,71,77-78]. However, their application is limited for various reasons. Ceramics and cermets are outstanding cutting tools for very high speed machining, particularly of cast iron[79-81], but they are extremely brittle. Similarly, the 'ultra-hard tool materials' such as sialon, diamond, titanium carbide base materials and cubic boron nitrides, have restricted usage due to technical and economic reasons[59,82-84].

Despite their early appearance, HSS (1900) and cemented carbides (1923) are still the most prevalent cutting tool materials. The toughness and edge-retaining capability of HSS have tended to give them a wider range of applications than the carbides, which are preferred where very rapid metal removal is to be carried out on rigid and well controlled machines[72]. High speed steel tools have a near monopoly for such products as saw blades, and drills, and they also have a very large share of the market for turning, boring and milling where restricted cutting speeds are employed. Cemented carbides, on the other hand, are the tools of mass production in cutting cast irons and steels, and are used exclusively for turning operations[85]. However, the most significnat development which has occurred recently in the metal cutting industry is the introduction of a wide variety of coating systems applied to HSS and cemented carbides by various coating techniques. Before the introduction of coated tools the production engineers' choice of cutting tool materials was comparatively simple due to the availability of a few types of these tool materials. For instance, high speed steel was an obvious choice for drilling, and among the hard metals available the cemented carbides were the best tool materials for turning[86]. Extensive research efforts have been expended and concentrated on these two materials for a considerable time, at first as entire tool materials, and later as substrates for a wide variety of coating systems. Early researchers directed their efforts towards the study of tools' performance in relation to their bulk material grades where features such as the alloying elements and the structures were of prime importance[87-92]. Both high-speed steels and cemented carbides have been studied extensively by many investigators[93-95]. Consequently, copious useful information has been published and substantial knowledge established about the main aspects such as the chemical composition and structure, tool performance in cutting different types of metals, and guides for proper selection of cutting tools for different applications. This important information has simplified cutting tool material design and selection based on the availability of a number of different grades of both high-speed steels and cemented carbides[96-98].

Today the scope of metal cutting research has become wider than before and the subject of cutting tool material selection, and machining optimization has been made more complicated by the rapid development of wear resistant coatings and their application to the conventional cutting tool materials[99]. Researchers have continued to study these materials but mostly when used as substrates for new surface coatings, where the behaviour of the substrate/coating interface during machining has significant consequences on tool performance and tool life.

2.7.3 Protective Coatings for Cutting Tools

The introduction of surface coatings to cutting tools in the late sixties and the early seventies was regarded as one of the greatest impacts on the metal cutting industry. Coating development started with one layer of titanium carbide (TiC) applied to both high-speed steel and cemented carbide, but mainly to the latter in the form of indexable inserts for turning operations. Rapid development has taken place, and new layers of titanium nitride, (TiN), hafnium nitride (HfN), titanium carconitride (Ti C, N), aluminium oxide (Al_2O_3) and other carbides, nitrides or oxides have been produced in single and multilayer forms. The use of these coatings which has had a revolutionary influence on machining technology, has become an increasingly popular field of investigation for research establishments and universities.

The main factors that influence the coated cutting tool performance when machining a certain material are the substrate grade and the coating system type and quality. These factors have been studied extensively in relation to the processes by which the investigated coatings had been deposited.

Almost, all of the coatings applied to cutting tools, either single or multilayer systems, are deposited by chemical vapour deposition (CVD) or the physical vapour deposition (PVD) process. These produce coatings which offer outstanding performance advantages over conventinal uncoated tools. It has been claimed that vapour deposited coatings applied to cutting and forming tools could increase life by up to eight times, or permit a high increase in production speed, or both[10]. These coating techniques have been studied extensively in comparison with each other and with other surface-treatments. It is now well recognised by manufacturers of cutting tools and other professionals associated with the tooling industry that CVD coatings are best for tungsten carbide turning inserts, and PVD coatings are best for high-speed steel drills. However, both techniques have certain limitations, and the coatings have various advantages and disadvantages in their own areas of application.

2.7.3.1 Physical Vapour Deposited Coatings

This coating technique is relatively new and started to develop at the beginning of this decade[100,101]when it showed great promise as a successful process capable of producing almost any coating material, pure metal, metallic compound, or alloy in single or multiple layers on almost any metal or ceramic substrate[10]. Moreover the coating technique has many advantages which encouraged its rapid development and strong association with the metal cutting industry. Consequently, various investigators have promoted the technique and the potentiality of the coatings deposited by it on metal cutting tools, and engineering components of critical dimensions[10,102]. Early researchers have reported that titanium nitride coatings by PVD have 'revolutionized' both the appearance and the performance of high-speed steel metal cutting tools since their first commercial offering as coated drills in the US early in 1981. Within one year the list of coated tools included gear shaper cutters, milling cutters, reamers, taps, spade-drill blades, saw blades and even high-speed-steel inserts[100].

Boston[101] has reported that the significant overall results of cutting with PVD titanium nitride coated tools was not only the increase of tool life by up to 10 times, but less power was used at the same speed and feed, and heavier cuts at higher speeds were both practical and recommended. In drilling and tapping the greatest improvement appeared in tough and difficult materials where uncoated tools scarcely stood up at all. Whilst all the performance reports and conferences held recently have illustrated the growing acceptance of TiN-coatings by the physical vapour deposition process[102-105], some researchers have reviewed the techniques alongisde the already established process of chemical vapour deposition (CVD). Nicholls and Lawson[106] have discussed the PVD and CVD process in terms of their industrial applications where they have explained the terminology used, cited typical applications and discussed the future trends. The report is based on short courses run by the authors for the Cranfield Institute of Technology. This shows how far the importance of these processes has gone in the short period of their industrial recognition. Matthews[107] has outlined the background of the new technology of titanium nitride PVD coatings, and has provided information about the main commercial processes. The report is a surface engineering designer's guide based on information provided by various companies in the main countries where the techniques have developed.

The cutting performance of titanium nitride-coated twist drills has been the subject of recent research work in the Department of Mechanical and Production Engineering at Aston University[108-110]. A significant improvement has been illustrated by the use of coatings, eg. reduction in machining forces and tool wear, increase in tool life, and an improvement in hole quality.

Since the entire subject of the current research work is a comparative evaluation of the performance of different (CVD) coatings deposited on tungsten carbide turning inserts, the remaining part of this review will be confined to the indexable inserts of this material and to the TiN-coatings deposited by the chemical vapour deposition techniques.

2.7.3.2 Chemical Vapour Deposited Coatings

Chemical vapour deposition (CVD) is a coating technique by which a solid material is deposited onto the surface of a heated substrate as a result of chemical reactions. Any chemical reaction in which the primary products are gaseous and one of the resulting products is solid, is considered a CVD reaction(111). If the reaction between the primary gaseous products takes place in the gas phase, the resulting solid precipitates as a powder. Reactions which occur only at the solid/gas interface create a dense solid coating on the substrate surface. CVD is a well established coating technique which is capable of depositing coatings of a wide range of metals, carbides, nitrides, oxides and borides(112,113). Its real success and continuous development has been associated with metal cutting tools. CVD coated carbide cutting tools were introduced commercially in 1969/70 with a single layer of titanium carbide deposited on tungsten carbide indexable turning inserts(85,86,114). Since then a rapid development of the process, the coatings and the substrate materials has taken place, and now most of the tungsten carbide indexable inserts marketed for cutting applications are CVD coated(86,115,116). Nevertheless, the deposition of a large number of coating layers, as many as 13 on the same substrate has been reported(86,99,117,118). Moreover, a wide range of high speed steels and hot work tool-steels have been successfully coated by the CVD process and employed for different metal working processes to achieve a significant improvement in tool performance(20,21,119,120).

The detailed description of the CVD process and the chemical reactions that take place to form the various types of coatings are fully discussed elsewhere(9,112,113,115). However, of the wide range of different coatings available, the most widely used ones for metal cutting tools are titanium carbide

(TiC), titanium nitride (TiN), and aluminium oxide (Al_2O_3). The titanium carbide is formed by the reduction of gaseous titanium tetrachloride ($Ti\,Cl_4$) in the presence of methane (CH_4), using hydrogen as reducing agent and carrier gas as follows:

$$* \underset{(g)}{Ti\,Cl_4} + \underset{(g)}{CH_4} \xrightarrow{H_2(g)} \underset{(S)}{Ti\,C} + \underset{(g)}{4\,H\,Cl}$$

Titanium nitride coating is accomplished in a mixture of titanium tetrachloride, hydrogen and either nitrogen or ammonia as follows:

$$* \underset{(g)}{2\,Ti\,Cl_4} + \underset{(g)}{4\,H_2} + \underset{(g)}{N_2} \xrightarrow{H_2(g)} \underset{(S)}{2\,TiN} + \underset{(g)}{8\,H\,Cl}$$

Aluminium oxide is formed from a mixture of aluminium chloride ($Al\,Cl_3$), hydrogen and carbon dioxide as follows:

$$* \underset{(g)}{2\,Al\,Cl_3} + \underset{(g)}{3\,CO_2} + \underset{(g)}{3\,H_2} \xrightarrow{H_2(g)} \underset{(S)}{Al_2O_3} + \underset{(g)}{3\,CO} + \underset{(g)}{6\,H\,Cl}$$

where g = gas; S = solid

Important parameters influencing the deposition rate composition and structure of the coatings are the temperature, composition of the gas atmosphere, flow rate of the gas in the coating chamber, and the coating time[9]. Typical working temperatures are in the range of 850-1050˘, and the layer thickness which ranges between 5-10µm depends on the substrate and the processing conditions employed. Coatings of this order are usually preferred to thicker layers which may crack or even separate from the substrate under the variations in thermal expansion stresses of the substrate and the coating. Such extremely hard and thin coatings can take up these stresses and can even withstand some impact and shock. The hardness of these materials are as follows: TiC 3300-4000 HV, TiN 2500-3000 HV, and Al_2O_3 1900-2400 HV. Aluminium oxide is the newest of the three materials and is applied only to carbide tooling where the speeds and feeds of the inserts are increased substantially[115].

Because of their great hardness the CVD coatings offer good protection from abrasion, and due to their high melting point (> 2500^oC), their high chemical stability, their low solubility of metals in the coatings and their low coefficients of friction the coatings give excellent resistance to adhesive wear. However, TiC which is characterised by its high hardenss is a good abrasive wear resistance where this wear mechanism is dominant on the cutting tool flank[94]. $Al_2 O_3$ is chemically inert and this property might largely reduce built-up edges (BUE) on the rake face and the cutting edge of the tool[47]. TiN coatings are hard but most important have a low coefficient of friction; little tendency to galling, fretting and erosion, and they have a lubristic quality that resists metal pickup. Moreover TiN resists elevated temperature, retaining all of the above properties to an excellent degree at the high temperature encountered in metal cutting operations[100,115]. The whole coating system resists diffusion wear and reduces seizure[4,121]. These outstanding properties of CVD coatings, particularly the TiN layer which is common in most multi-layer coating systems, have therefore encouraged extensive metal cutting research.

Despite the success of the CVD process in coating cemented carbide inserts, the technique's success with high-speed steels and other tool steels has been limited due to its high operating temperature which is well above the tempering temperatures of these steels. Distortion, part-dimensional changes and softening of the tools to be coated are the problems which necessitate post-coating heat treatment to restore the original hardness, micro-structure and part-dimensions. This heat treatment must be done in a protective atmosphere since there is a danger of coated surface oxidation.

Another limitation of CVD is that the chemical systems used tend to be aggressive towards the substrate and generate an interfering layer which reduces adhesion. Halling, Matthews and Teer[122] have referred to this brittle transition layer as 'eta phase'. The layer is formed as a result of decarburization of the substrate surface, and it is often observed when TiC is deposited on steel substrates, where titanium tetrachloride (Ti Cl_4) has a tendency to combine with carbon from the substrate as well as from the gas phase. This decarburized brittle layer is formed directly beneath the TiC coating[123,124]. However, subsequent development has largely eliminated this decarburized zone effect by the use of multi-layer coatings[7,122].

These CVD process limitations have not affected the status of the technique and its further development especially with cemented carbide inserts, but have encouraged the development of the physical vapour deposition (PVD) process for coating high-speed steel cutting tools. The operating temperature for this process is about 500°C.

2.8 Tool Wear and Related Features

2.8.1 Significance of Tool Wear

Tool wear, in metal cutting, is extremely important since it has a significant effect on the production cost. Along with the cutting forces and the surface finish to be produced, tool wear has a decisive influence on the choice of the machining conditions. All variables in the machining system have a direct or an indirect effect on tool wear. The material to be machined, the material of the tool used, the tool geometry and the machining conditions employed, interact during the cutting operations and create a wear situation that limits tool life, affects accuracy and surface finish of the product, and implies rising costs due to the need to replace, regrind, or change tools[123,127].

Despite the intensive investigations that have dealt with tool wear in its various forms, the subject is increasingly attracting more research work, and it is quite evident that tool wear study publications occupy the largest share of metal cutting literature. However, it is likely that this situation will not change for a long time to come. Firstly due to the importance of wear in metal cutting and engineering economics, secondly because of the continuous development of tool materials.

2.8.2 Characteristics and Forms of Tool Wear

The literature on friction and wear is often not clear in explaining the fundamental mechanisms by which wear occurs. The causes of specific cases of wear are often misunderstood, the transition from one wear mechanism to another is not known, and even the scientific terminology varies from publication to publication(128,129). Peterson et al(130), in their comprehensive work, on the study of wear prevention, have listed many types of wear and included case studies showing the serious problems that exist due to different wear mechanisms and which lead to serious cost-affecting situations. They refer this lack of knowledge to the complexity of wear mechanisms when acting together. Wear in metal cutting, however, is part of these complicated interactions and uncertainties. According to Shaw(131), tool wear mechanisms are rarely of one type but generally consist of a combination of mechanisms, which act together at the same time or transform from one type to another at different periods in the same cutting operation.

However, the progressive wear of a cutting tool, takes place in two distinct areas of the working tip (Figure 3.1).

(1) Wear on the flank face where a 'wear-land' is formed from the rubbing action of the newly generated workpiece surface.

(2) Wear on the tool rake face, characterized by the formation of a wear scar known as 'crater wear' which results from the continuous sliding of the flowing chip against the tools' surface.

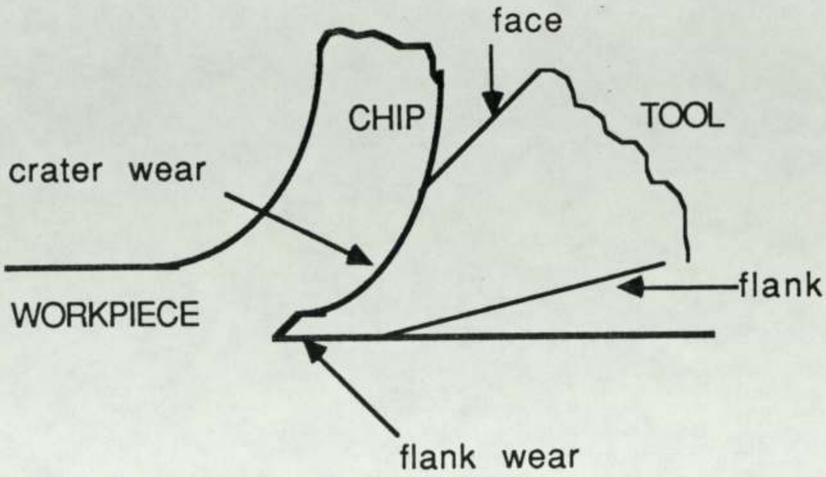


Figure 2.7: Regions of tool wear in metal cutting(31)

In fact several other characteristics of tool wear are experienced with the different tool materials, and the identity of most of them is quite different from the two common forms, flank and crater wear which have been categorized by Boothroyd(31) as the gradual or progressive wearing type. The other group are the failures which cause a premature end of a tool's life.

The characteristics of cutting tool wear, as cited in the extremely wide literature, are quite numerous and few are commonly named in the same way. However, the most frequent characteristics, as illustrated in Figure 3.2, include the following:

1 Flank wear
2 Crater wear
3 Nose wear

4 Notch wear or grooving wear

5 Built-up-edges (BUE)

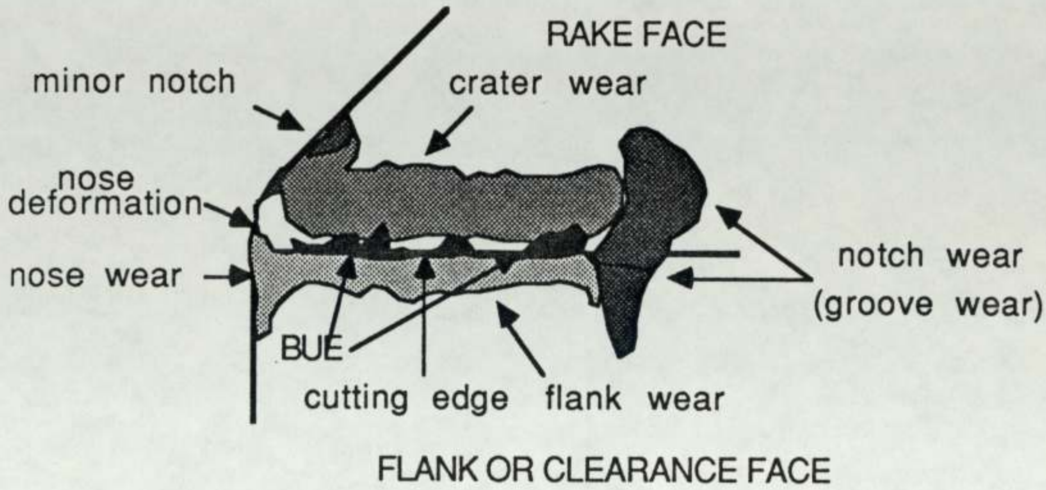


Figure 2.8: Wear features on a turning tool

2.8.2.1 Flank Wear

The type of wear which occurs on the flank of a cutting tool is usually called the flank wear, but some authors refer to it as the clearance face wear.

Flank wear is the most widely used criterion for evaluating tool life, and is often used in metal cutting research to assess different aspects of tool wear(132-134). It starts at the cutting edge and progresses downwards on the flank forming a band of worn area called the 'wear-land'. The length of this wear-land is associated with the depth of cut, and its progressive width is measured and used as a limiting criterion for tool life.

Flank wear is usually claimed to be the predominant factor during discontinuous chip formation, such as when machining cast iron, aluminium, brass or light alloys at high speeds(135). However, it has been reported that wear on the tool's flank occurs under all cutting conditions and with any tool or workpiece material[69]; this is one of the reasons of its frequent use as a limiting criterion.

Flank wear progresses with the cutting time, but the progress is not steady throughout the whole period of a cutting operation[31,35,69,75,89,132,136]. Figure 3.3 shows a typical flank wear width-cutting time relationship where three regions of different character are illustrated.

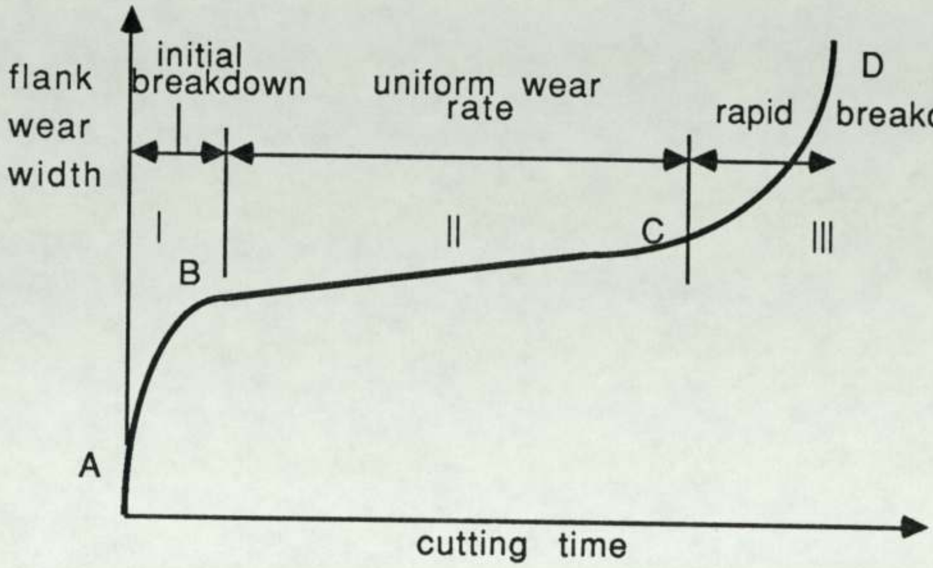


Figure 2.9: Typical wear vs time curve

I: region AB in which the sharp cutting edge is quickly broken down and orientates itself for the cutting operation. It is called break down wear, break-in wear or wear-in.

II: region BC in which flank wear width increases slowly and progressively at a uniform rate; 'linear-wear' or 'normal wear'.

III: region CD in which wear increases rapidly with time. It has been called by Colding[136] the period of catastrophic wear.

It has been thought that at this region where tool life approaches its end, the cutting tool becomes more sensitive to the increase in temperature as a result of the considerable increase of wear land. Boothroyd[31] has suggested that tool changing or regrinding should take place before the flank wear reaches this region where serious damage may occur. Mills and Redford[8] have indicated that the excessive flank wear which occurs on both the major and the minor cutting edges of the tools' working tip, results in increased cutting forces and higher temperature. It causes many other problems such as tool and workpiece vibration, that leads to oversize products or poor surface finish. Sarkar[75] has identified the increase of the cutting force as an indication of excessive wear resulting from the high temperature involved in the cutting process.

2.8.2.2 Crater Wear

The rake face wear or crater formation develops at the top face of the cutting tool covering an area representing the chip/tool contact zone.

The rake face region closer to the cutting edge where sticking friction or seizure takes place, experiences relatively mild wear, but heavier crater wear usually occurs at the region of heavy contact between the tool surface and the flowing chip underside. The side of the crater away from the cutting edge, where the chip breaks contact with the tool surface, is a region of light wear. According to Tourret[35] both the crater depth and width increase progressively, and when the crater approaches the cutting edge, the edge often breaks off resulting in sudden failure. However, for practical conditions, ie. when tools are used under economical conditions, crater wear is less severe than flank wear and consequently flank wear is the controlling factor which is often used as the failure criterion. On the other hand, at very high cutting speeds when temperatures are very high, crater wear increases more rapidly and the cutting tool life is determined by rake face wear rather than by flank wear[8,31,69]. Many researchers have related crater wear to the presence of built-up edges during continuous chip formation, but others emphasized that in some cases the built-up edges formed at the cutting edges, protect the region adjacent to it and stop the extension of the crater wear towards the cutting edge. However, there are many factors upon which the crater wear depends due to different wear mechanisms which are operative[69,134,137].

During a cutting operation at high cutting speeds, the highest temperatures occur on the rake face of the tool at a distance from the cutting edge. These temperatures may reach 1000°C[31,35,138,139] and cause thermal softening and rapid cratering of the tool. This usually happens to high-speed steel tools[31]. Carbide-tools, however, retain their hardness at this temperature but suffer rapid crater wear as a consequence of solid-state diffusion (dissolution-diffusion)[4,62,63,140-142].

2.8.2.3 Nose Wear

Nose wear is the cutting tool's damage that occurs at the nose radius. It is localized wear which develops at the corner radius where the tool's cutting edge is in intimate contact with the workpiece during the cutting operation. It has most influence on the quality of the machined surface (surface finish).

A number of researchers have considered nose wear as a separate type of wear[77,143] although it is often regarded as a continuation or part of flank wear[62,63]. Moreover it can be very difficult to distinguish between wear and the plastic deformation which often occurs in the nose vicinity. Consequently it is quite possible for a mixed feature to be dealt with either as nose wear or nose deformation. It is preferable to consider wear at the nose as part of the flank wear since in both cases wear is caused by the same source, which is the rubbing action between the revolving workpiece and the engaged parts of the cutting tool. In situations where the depth of cut is small such as in finish turning, flank wear does not extend far from the nose radius area and, consequently, there is no point in considering nose wear and flank wear separately.

2.8.2.4 Notch Wear Groove Wear)

Probably, the third most common tool-wear feature, after flank and crater wear, is notch formation on the cutting edge of the tool at the two extremities of the cutting depth (Figure 3.2). This form of wear is called 'notch wear', and it usually occurs when cutting hard workpiece material such as titanium, alloy steel, carbon steels and stainless steels[62,63,140]. Although a few investigators have discussed notch wear as a mode separate from flank and crater wear, its effect which initiated as grooves and appears on both flank and rake faces of the tool has led some researchers to consider it as a localized form of one of the two main types of tool wear.

Mills and Redford[8] have emphasized that the presence of the notch will not seriously affect the tool's performance, but may lead to tool fracture if the notching is of significant depth and the cutting operation continues for longer times.

Trent[2,4,144-147] in his extensive work on metal cutting has referred to notch or groove wear as accelerated wear in a region of sliding. He has indicated that wear under sliding conditions may depend upon mechanisms different from those which cause flank or crater wear. However, it is a type of wear that may lead to a sudden end of tool life.

2.8.2.5 BuiltUup Edge 'BUE'

The small fragments of workpiece material that break off the chips and weld to the tools' cutting edge and rake face are called the built-up edges. The 'BUE' is not a type of tool wear but is characteristic of a certain type of chip formation during machining under specific cutting conditions as mentioned earlier. However, 'BUE' is an extremely important feature which plays a leading role in the performance of the cutting tool such as the product surface finish. Moreover, it has a significant influence on the mechanisms of wear, particularly those which act on the tool's rake face. Consequently, the study of the cutting conditions under which the 'BUE' is formed; and the effects of its presence in metal cutting, has been a subject of interest for many investigators[68,69,148,149].

The built-up edge is dependent in the first place on the type of work material which in turn dictates the type of chips formed during cutting at low speeds[27]. More recently Trent[4] has indicated that the BUE can occur with continuous or discontinuous chip formation, and most commonly it occurs at intermediate cutting speeds. However, the BUE is a dynamic structure which occurs in many shapes and size, and in some situations, it is not easy to ascertain its presence as changes occur rapidly.

Some authors refer to it as a built-up layer 'BUL'[8,150] when it is very thin, or as built-up cap 'BUC'[150,151] when it forms a small cap wrapped around the cutting edge.

Kuznetsov[68], in his critical study of the BUE, has put great emphasis on seizure as the main factor in the occurrence of the build-up which keeps the same properties of the workpiece material for a short time. He assumed that the BUE formed from pure metals looses its purity during machining and that its chemical composition changes as the temperature rises to form hard oxides that give the BUE good cutting properties. Consequently, the cutting operating at some periods is done by the BUE and not by the original cutting edge of the tool, leading to a significant change in performance. These assumptions have been supported by recent authors who have studied the different conditions under which BUE's are formed when machining various materials with different tools[4,58,69,148].

2.8.3 Mechanisms of Tool Wear

The types and features of tool wear discussed above are modes of damage that lead to poor performance and a short sevice life of the cutting tool. The mechanisms by which these types of wear take place have been an important field of research for a long time. Consequently, many modes of failure have been proposed to occur by one or more mechanisms acting at the same time, and some, at the same region of the tool face.

Despite the complex nature of wear in its wide scope, and the possibility of unlimited interaction between various variables involved in any wear situation, certain mechanisms of wear seem to be associated with metal cutting tools more than any other application. This is due to the presence of special factors such as high temperature, materials of certain properties, and tool geometries. The mechanisms of wear and tool failure encountered in metal cutting have been identified and classified by many authors(128,131,146,152-158), where the following are the most frequently discussed processes:

1 Abrasive wear
2 Adhesive wear
3 Attrition wear
4 Diffusive wear
5 Oxidative wear
6 Erosive wear
7 Grooving wear
8 Delamination wear
9 Plastic deformation
10 Thermal fatigue and microcracking
11 Edge chipping.

However, in each specific cutting process, it is common to find that one or two of these wear mechanisms are more dominant than the others(143). The workpiece material, the tool geometry and the machining conditions are the factors which dictate the dominant wear mechanism, whilst the extent of wear is determined by the properties of the cutting tool material.

Recent developments have led to a commercially available wide range of tool coating systems and deposition techniques which have intensified researchers interest in studying tool failure and wear mechanisms.

Obviously, the main requirement of the coatings is to enhance the wear resistance of the cutting tool surface so that the wear mechanisms prevailing during the use of uncoated tools, are eliminated or delayed when using the coated ones. However, the study of coated tools has illustrated that the wear mechanisms and tool performance can be quite different from those encountered with uncoated ones.

CHAPTER THREE

EXPERIMENTAL PROCEDURE

CHAPTER THREE

3 EXPERIMENTAL PROCEDURE

3.1 Introduction

Selection between a large number of commercially available indexable inserts, is rarely done on a scientifically correct basis. Assessment of the widely different grades of uncoated and coated cutting tools is a difficult task. However, the wide choice provides an excellent subject for research to optimise all metal cutting operations.

Although there are several large manufacturers of uncoated and coated tungsten carbide indexable inserts, and a wide variation in their grades, machining optimization is unlikely to be attainable by selection between products from different manufacturing companies. This is due to the fact that, even a single manufacturer produces a range of insert grades which can be utilized for a certain cutting operation. Consequently it seems more logical to concentrate on a number of options offered by one producer.

Machining optimization cannot be reached via one route. The different machining conditions are one of the important factors in optimizing the cutting of a certain work material, and this in itself is a big research field. However as far as this research programme is concerned, the coating performance is the main subject. Accordingly the purpose of these experimental tests is to perform a series of turning operations using a number of uncoated and coated tungsten carbide indexable inserts, mainly, to cut a 'difficult-to-machine' material. The performance of the coated tools in comparison to the uncoated ones and to each other will then be evaluated.

It is widely accepted, now, that multi-layer coatings offer the best prospects for economical production in metal cutting. However, few researchers have attempted a comprehensive assessment of tool performance. The types of coatings, the machining conditions, and the evaluation techniques are rarely similar. Hence, the choice of tests carried out in this investigation was designed to offer new and realistic information in order to rationalize machining with coated cutting tools.

3.2 Tool Material

All the experimental tools were obtained from Sandvik Ltd, one of the major international producers of cutting tools. Seven grades of indexable turning inserts were selected. Two of them were different types of uncoated tungsten carbide inserts, and the other five were tungsten carbide substrates coated with double and triple layers of different coatings deposited by chemical vapour deposition (CVD) processes.

The uncoated tools and the substrates of the coated tools were fabricated from cemented tungsten carbide as the main constitutent, and a small amount of cobalt as binder, with variable small additives of titanium carbide, tantalum carbide and niobium carbide which characterize this category of inserts as 'steel-cutting grades'.

The coating systems consisted of layers of titanium carbide (TiC), titanium nitride (TiN), and aluminium oxide (Al_2O_3), deposited by CVD techniques. They covered the whole surface of the tungsten carbide inserts as triple or double layers. The configuration of these coatings and designations of the experimental tools are given in Table 3.1.

Table 3.1: Experimental Tool Conditions (as received)

Exp tool No	Insert-classification (ISO)	Producer's No	ISO No	Surface condition	Coating system (Inner / Outer)	Total coating thickness
T1	TNMG 160404	SIP	P10	Uncoated	- -	-
T2	TNMG 160404	S6	P40	Uncoated	- -	-
T3	TNMG 160404	GC415	P-K15	Coated	$TiC+Al_2O_3+TiN$	5-8μm
T4	TNMG 160404	GC435	P35	Coated	$TiC+Al_2O_3+TiN$	5-8μm
T5	TNMG160408QM	GC435	P35	Coated	$TiC+Al_2O_3+TiN$	5-8μm
T6	TNMG 160408QM	GC425	P25	Coated	TiC+TiN	5-8μm
T7	TNMG160408QM	GC235	P45	Coated	TiN+TiC+TiN	2-3μm

3.3 Tool Designation and Geometry

All the turning inserts supplied by Sandvik Coromant UK and used for the cutting tests in this research were triangular in shape, each with six usable cutting edges, for turning in a right-hand or left-hand direction. Some of the inserts and a tool holder are shown in Figure 3.1.

The inserts were classified according to the International Standards Organization (ISO) system and designated by the producer's own numbering system in conjunction with the ISO grading number (Table 3.1).

All the tools were steel cutting grades, where this application category is indicated by the letter 'P', followed by a number such as P01, P05, P10 and so on up to P50. Higher numbers signify greater toughness but reduced hardness and wear resistance, whilst lower numbers indicate high hardness and wear resistance, but low toughness. ISO category 'P' tools are appropriate for machining steels, steel castings, stainless steels and long chipping malleable iron; roughing,

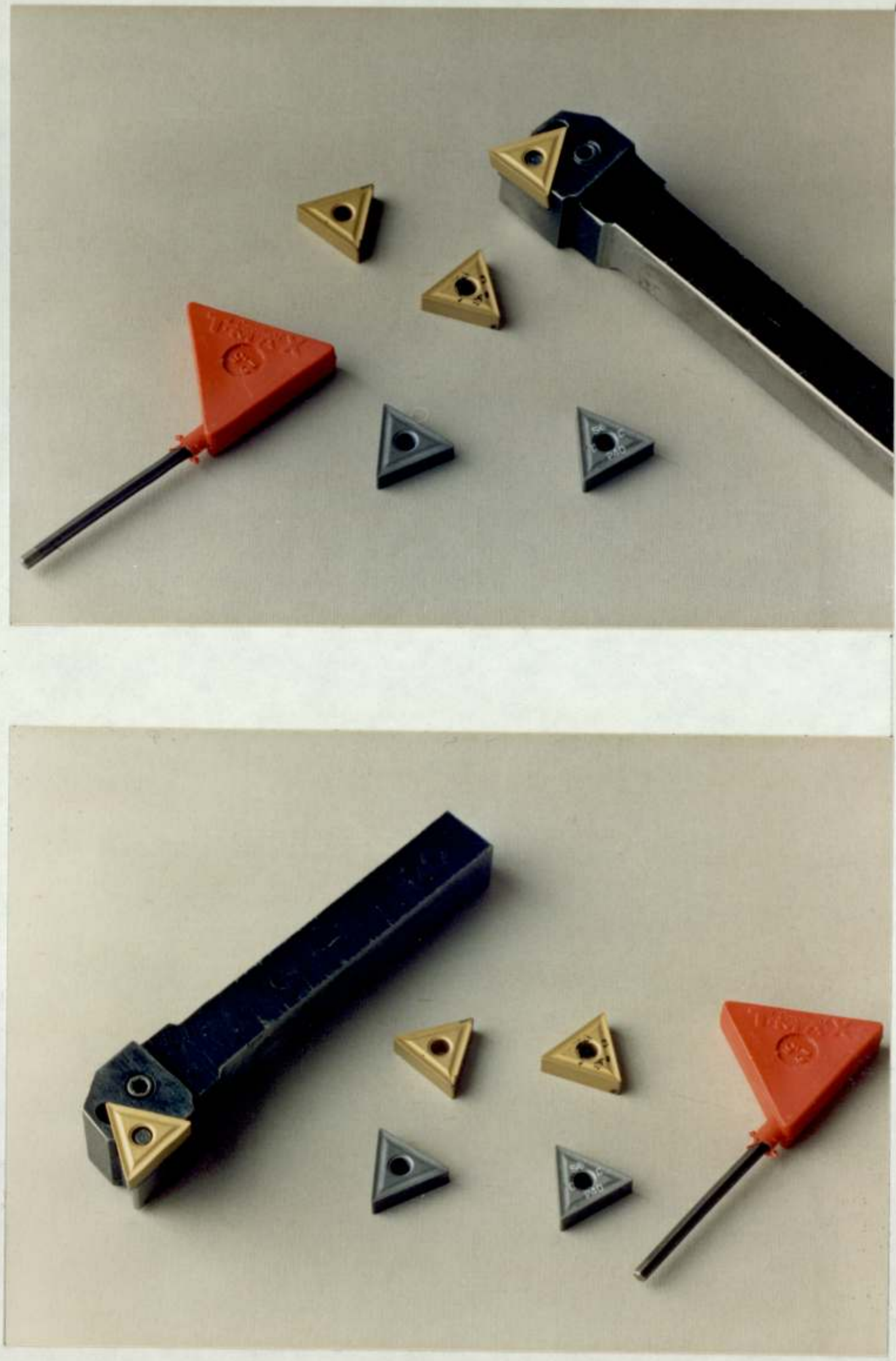


Figure 3.1: Samples of the indexable inserts and a tool holder

medium and general purpose, light finishing, and precision finishing[118, 159].

Roughing	P30-P50
General purpose	P20
Light finishing	P10
Precision finishing	P01

The inserts used in this investigation ranged between P10 and P45. Their detailed specifications were indicated by the ISO classifications:

(i) TNMG 16 04 04, and

(ii) TNMG 16 04 08-QM

where

T, (insert shape): Triangular

N (major cutting edge clearance angle): 0^{o}

M (tolerances), d (9.525mm): ±0.05mm

m (13.856mm): ±0.08mm

s (4.76mm): ±0.13mm

G, (chip breaker and fixing style): grooves on both sides
with centre hole for fixing

16, insert size (equilateral) t: 16mm

04, insert thickness S: 4.76 mm

04 or 08 nose radius r: 4mm, or 8mm

QM, Sandvik designation of one of the latest range of cutting tool geometries for medium cuts, light roughing and semi-finishing. This grade plus QF and QR grades represent a 'new generation' of turning tool insert geometries which were the latest products of Sandvik Ltd[160].

All the inserts had the same geometry with effective rake and clearance angles 18^{o} and 7^{o} respectively, in the cutting position when mounted on the standard tool holder of ISO code PTGN R 16 16 H 16 when using the conventional centre lathe, or the holder PTGN L 16 16 H 16 when using the CNC lathe.

The letters and numbers denote the following:

P   clamping system (hole and lever)

T   insert shape (triangular)

G   holder style (lead angle 90^{o})

N   insert clearance angle (0^{o})

R/L hand of tool (right or left)

16   shank height (16 mm)

16   shank width (16 mm)

H   tool length (100 mm)

16   cutting edge length (16 mm)

The system by which the inserts were clamped to the tool holder was the hole and lever system T-MAX P lever (P)[159].

This system permits the use of all negative basic shapes T-MAX P inserts with the following advantages:

(i) The effective rake angle can be varied from -6^{o} to $+18^{o}$ by selecting from the range of modern P+ geometries.

(ii) Rigid clamping by the lever gives unobstructed chip flow over the top face of the insert.

(iii) The threaded hole and lever pin are not affected by the critical heat zone.

(iv) The pocket design gives maximum support to inserts, as well as improved indexing accuracy.

(v) The lever locking screw is accessible from the top and bottom of the tool.

3.4 Workpiece Materials

Three types of work material were employed for the machining operations carried out in the experimental programme. The first two of these types were mild steel and En 8 carbon steel, which were both considered as general purpose engineering steels. Mild steel is a low carbon, readily-machinable steel, which is suitable for welding, while En 8 is a steel of higher carbon content which is widely used for applications where properties superior to those of mild steel are required without going to the expense of alloy steels(161,162).

Typical chemical compositions of both mild steel and En 8 carbon steel are given in Table 3.2(163):

Table 3.2: Typical Composition of Workpiece Material 1&2

Steels	% Elements				
	C	Si	Mn	S	P
Mild steel	0.25 max	0.05-0.35	1.00 max	0.06 max	0.06 max
En 8 steel	0.35-0.45	0.05-0.35	0.60-1.00	0.06 max	0.06 max

The third type and the main work material used in this investigation was 316S austenitic stainless steel. Different grades of this type of steel are used for extremely wide applications due to their favourable properties, particularly corrosion and heat resistance.

Austenitic stainless steel is a chromium-nickel alloy which contains different alloy additions to improve its properties. The molybdenum-bearing grade (BS 316S-AISI 316) has superior corrosion resistance to other grades of stainless steels(164). The addition of molybdenum and silicon improves the corrosion resistance, while sulphur improves machinability(165,166). It is well known that the machinability of stainless steels is very low and they are considered among the most difficult materials to machine. Their machinability rating is lower than carbon and alloy steels since they have higher strength, a higher strain hardening rate and lower thermal conductivity. The high work-hardening rate of austenitic stainless steel causes higher energy consumption during a machining process. Colombier and Hochmann(165) have indicated that the energy consumed in removing a given volume of chips from an austenitic stainless steel is roughly 50% greater than that consumed in removing the same volume of mild steel chips.

During machining of austenitic stainless steel, its low thermal conductivity causes higher temperature gradients within the chips, and the heat generation that increases the interfacial temperature of the sliding chip on the tool's rake face increases diffusion wear rates(16).

However, when machining stainless steel, carefully selected machining conditions have to be used, and powerful machines with rigid setups are important, to avoid common problems such as chatter and catastrophic failures(165-167).

Austenitic stainless steel was chosen as the main work material in this investigation, since it is generally agreed by manufacturers and users of cutting tools(63) that tool life is severely limited and many problems arise during cutting of stainless steels.

The rapid development of new coatings for cutting tools, provides a good chance of achieving solutions to the inherent problems associated with machining the difficult-to-machine materials. Consequently, it was felt that austenitic stainless steel would represent a real challenge to the new coating systems, particularly those with TiN as a top layer, in order to prove their creditability by facing these hostile conditions.

The 316S stainless steel used in this work was obtained from RGB stainless Ltd, West Midlands.

A bar of S/S round BS 970 316 peeled, 3" diameter, was received accompanied with an inspection test certificate from the manufacturers, Krupp Steel Company Ltd, according to DIN 50049 (BS 970: Part 1: 1983). Its tensile strength was 571 N/mm^2 and hardness 145 HB. The chemical compositions are given in Table 3.3.

Table 3.3: Chemical Composition of 316 S Stainless Steel

% Element								
C	Si	Mn	P	S	Cr	Mo	Ni	Cu
0.015	0.25	1.14	0.027	0.02	16.86	2.06	11.09	0.08

3.5 Machine Tools and Instrumentation

3.5.1 Conventional Centre Lathe

All the cutting tests conducted at the early stages of the research work were carried out on a conventional centre lathe which had a wide range of feeds with variable spindle speeds up to 900 rpm. The lathe was in good condition and the operations were undertaken efficiently. The only limitation was the low maximum possible numbers of revolutions per minute (900). The lathe was used for cutting mild steel and En 8 steel, where there was no danger from fragments of chips, as the materials were not very hard and the chips formed were continuous types in most cases.

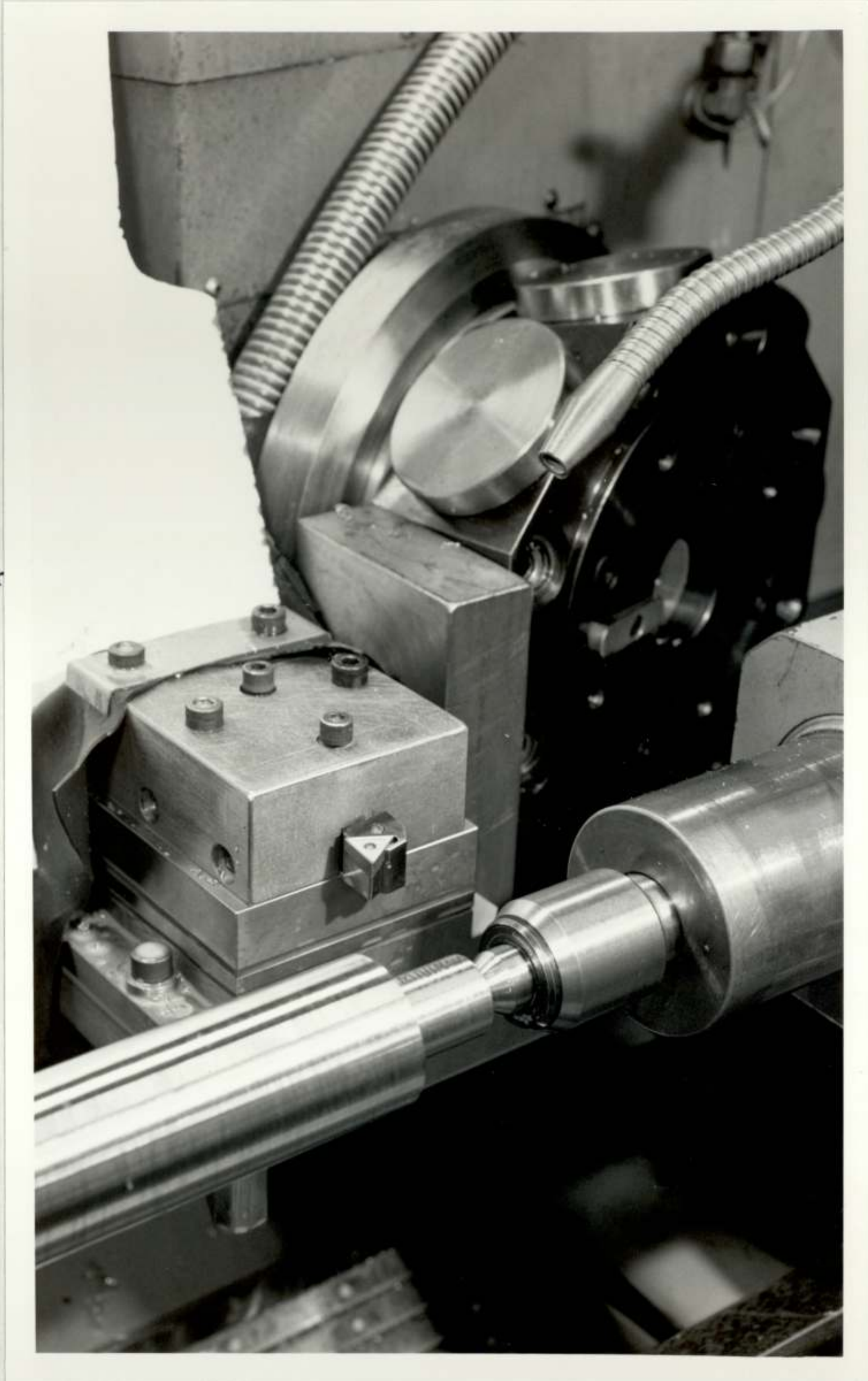
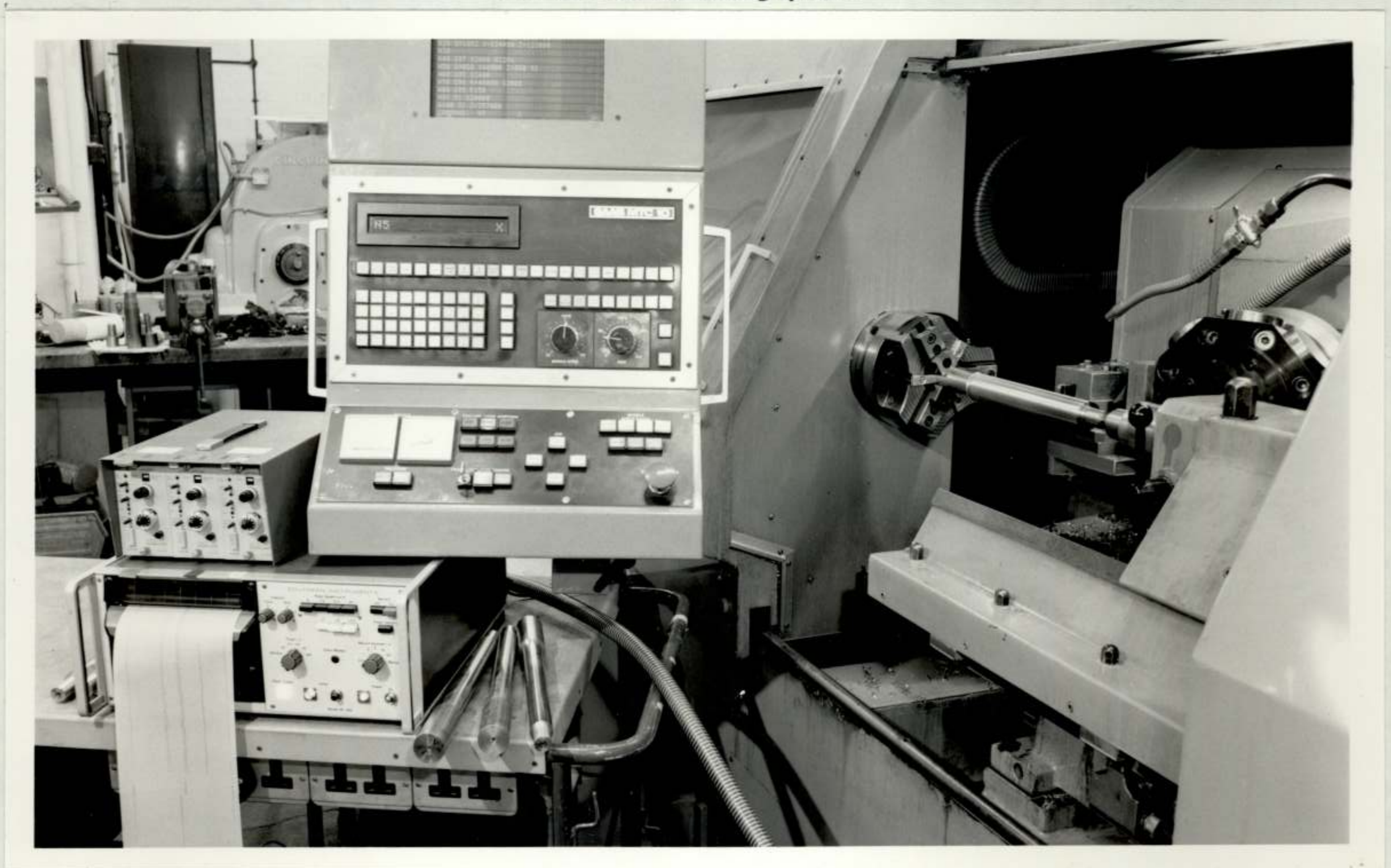


Figure 3.2: The experimental machining arrangement before commencement of cutting

Figure 3.3: General view of the CNC lathe showing the machining arrangement, the control panel, and the force-measuring system



It was not possible to carry out the cutting tests on stainless steel on this type of lathe as more precautions were needed and much higher spindle speeds were required.

3.5.2 Computer Numerically Controlled Lathe (CNC)

This was the main machine tool used for the major part of the experimental turning work. The essential features of the lathe, together with the tool set-up, the computer programme control board, and the force measuring equipments, are shown in Figures 3.2 and 3.3.

The machine itself was a Torshalla numerically controlled production lathe type S-160 CNC which was operated by a d.c motor (16 kW) via a separate gearbox to the spindle. It featured four speed ranges of 20-600, 40-1200, 80-2400 and 160-4800 rpm. The carriage and cross-slide were located behind the spindle, with the carriage above the cross-slide. The lathe was equipped with a hydraulically-indexing tool post with double tool holding fixtures each unit accommodating eight tools. The lathe was provided with a fully enclosing plate guard offering scope for extractor connection: Carriage and cross-slide control, starting off spindle clockwise and counter-clockwise rotation, spindle stopping, coolant engagement and disengagement, hydraulic unit starting and stopping, chip-conveyer starting and stopping, and $1/8^{th}$ revolution tool indexing were manageable from the machine's control panel. Spindle speed was displayed on a speed indicator. The control panel was mounted on a flexible external attachment where the computer programme was displayed and controlled according to the operator's instruction and the whole attachment orientated to his convenience.

3.5.3 Force-Measuring and Recording System

The accurate measurement of the forces acting on a cutting tool was one of the difficulties experienced in metal cutting research that remained unsolved for a long period. The development of force and torque dynamometers has led to a more quantitative understanding of cutting tool performance. The dynamometers were designed to meet certain requirements in order to measure the force components to high accuracy. The primary requirements are high sensitivity, sufficient relative rigidity and good stability. Cutting forces should not be influenced by external deflections, and no interference between different force components should occur during a machining operation.

The forces involved in the cutting operations performed on the centre lathe, were measured by a Kistler Turning Dynamometer type 9259A-SN 40505. It was clamped to the tool holder and attached firmly to the lathe saddle. The dynamometer used for measuring the forces when machining stainless steel on the CNC lathe was a Kistler type 9257A-SN271074. A special bracket with rigidly assembled parts was designed to facilitate the requirements of machining on the CNC lathe (Figure 3.3).

Both dynamometers had a high natural frequency of vibration enabling any slight force exerted on the tool to be transmitted to a recording system by three cables allocated for the three force-components. The force deflections produced as physical displacements were transformed to electrical signals by a transducer, amplified by a Kistler amplifier type 5006 and recorded by a UV recorder as deflection traces on graph paper.

3.5.4 The Taylor-Hobson Talysurf

The surface measuring instrument employed to assess the quality after finish turning operation was a Model 3 Taylor-Hobson Talysurf. It had a pick-up unit with a stylus of small radius of curvature that traversed across the surface by means of a motorised driving unit (the Gear Box). The vertical movements of the stylus were converted into corresponding changes in an electric current which was amplified by means of a valve amplifier and then used to control the following:

(i) a Recorder which provided a graphical representation of the surface irregularities.

(ii) an Average Meter which shows the Centre Line Average (CLA) index of all irregularities coming within a standard length of surface.

The main part of the instrument is shown in Figure 3.4

3.5.5 Optical Microscopy

Two types of optical microscopes were used to detect and measure tool wear and related features observed on the surfaces of the cutting tools during and after machining.

(a) The Universal Measuring Apparatus S1P Type MU-214B (Figure 3.5) is a high accuracy instrument that can be used in a variety of ways. During the cutting tests, this microscope was employed to follow the development of tool wear and to measure the flank wear width.

(b) The optical Polyvar microscope which can produce highly magnified images and which is equipped with a high quality camera was used for wear surface studies and for producing photomicrographs of the turning inserts before and after the cutting tests. The instrument is shown in Figure 3.6 in which the tool is situated in the inspection position.

3.5.6 The Scanning Electron Microscope (SEM)

This instrument which is shown in Figure 3.7 is a Cambridge Stereoscan model, 180-60 KV. The SEM was extremely important for studying the tool wear characteristics and the coating behaviour. Detailed examination was possible and

Figure3.4: The Taylor-Hobson Talysurf

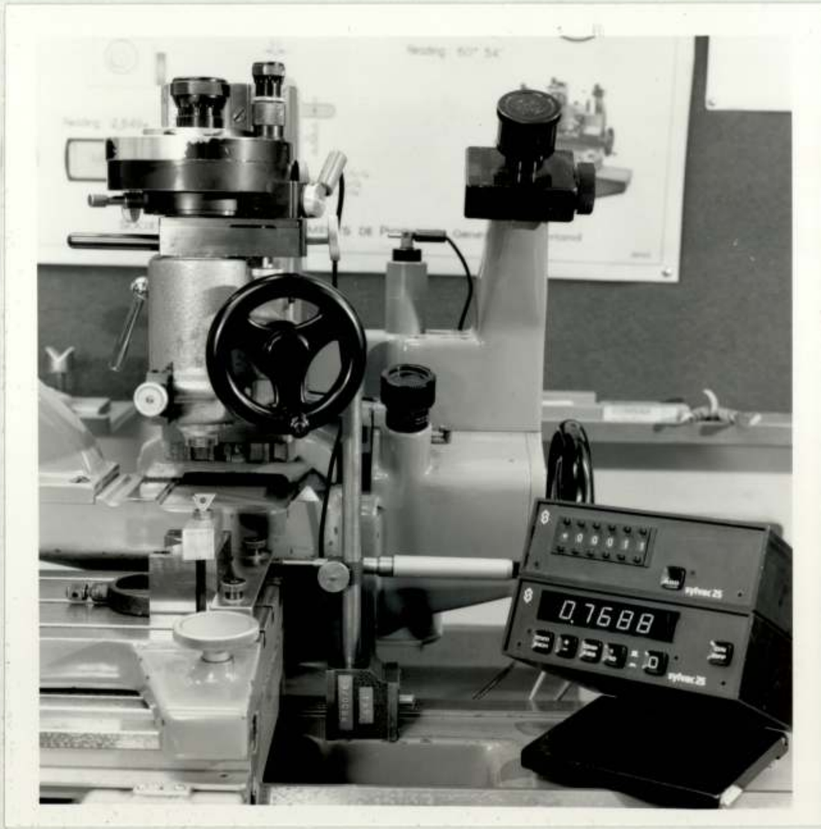


Figure 3.5: S1P Universal Measuring Machine

all types of tool failure could be studied by using a wide range of low and high magnifications. A high quality camera is attached to the microscope for production of photomicrographs. An X-ray analysing equipment was connected to the microscope, enabling metallurgical analysis to be done when required.

This microscope was used extensively for studying the tool's pre-machining conditions and for investigating the details of wear characteristics after machining.

3.6 Pre-Machining Examination of Tools

In order to carry out a proper metallurgical diagnosis of the failure mechanisms and to investigate the wear characteristics of the cutting tools after machining, it was of prime importance to ascertain the tool's conditions prior to machining.

The use of the SEM to study the tools in their 'as-received' conditions was aimed at establishing an understanding of those tools. To judge the quality of the tool, many factors related to both the substrate and the coating should be considered.

3.6.1 Surface Examination of Tools

The seven different types of turning inserts were inspected under the SEM, and photomicrographs which revealed the general topography, inclusions, and defects of the surface were produced. The linked X-ray analysis equipment was used, in the same time, to carry out Energy-Dispersive X-ray analysis (EDXA) which revealed the chemical composition of the tool's surfaces and their inclusions.

3.6.2 Substrate and Coating Inspection

Metallographic sectioning of the uncoated and coated inserts was carried out very carefully due to the brittle nature of the tool materials. The cross-sections were studied by the SEM and photomicrographs were produced.

Figure 3.6: The Optical Microscope

Figure 3.7: The Scanning Electron Microscope (SEM)

The substrate inspection covered the microstructure, the carbide size, the carbide distribution and uniformity, size of the binder area and distribution, plus the analysis of the chemical composition.

The coating system inspection involved thickness measurement, the continuity, and relative defects. The subsurface and interface inspection covered the carbide and cobalt distributions, the coating adhesion and defects, and the (EDX) analysis.

3.7 Turning Test Design

All the machining operations involved in the different stages of this investigation were carried out using a standard soluble oil as cutting fluid. This was a Hocut 580 grade, produced by "Edgar Vaughan UK". The dilution of the fluid was 1:10 oil-water. The cutting fluid's functions were to cool the cutting tool and workpiece, reduce friction, provide anti-weld properties, wash away the chips, and protect work against rusting.

Other machining conditions used in the cutting operations, were different for each of the three types of work-material used.

3.7.1 Mild Steel Cutting Operations

A series of turning operations were conducted on a number of readily prepared stock of cylinderical mild steel blank's of 38.1 mm lengt and 63.5 mm diameter. Two sets of machining conditions were used:

(a) Constant surface cutting speed 129 m/min, constant depth of cut 2.5mm, and variable feed rate ranging from 0.1 mm/rev to 0.5 mm/rev with successive increments of 0.05 mm/rev.

(b) Constant surface cutting speed 141 m/min, constant depth of cut 0.5 mm, and variable feed rate ranging from 0.1 mm/rev to 0.3 mm/rev with successive increments of 0.5 mm/rev.

As mild steel was a readily machinable material, no significant differences in performance between coated and uncoated tools were expected to be revealed. The tests were aimed mainly at evaluating the workability of the instrumentation, and establishing preliminary ideas about the effect of feed rate on the cutting forces and surface finish, related to the coated inserts in comparison with the uncoated ones. The machining conditions (a) were employed when cutting with the uncoated tool type T_2 and the coated tool type T_4. The machining conditions (b) were used with the uncoated tool type T_1 and the coated tool type T_3.

3.7.2 En 8 Steel Cutting Operations

The cutting trials employed to evaluate the tool performance when using En 8 steel as workpiece material, were carried out on bars of 254 mm length and 82.55 mm diameter. These sizes were selected to allow for many successive cuts and longer cutting time for tool-workpiece engagement in each cut.

The cutting operations conducted on En 8 steel were designed to be performed with an approach different from that of cutting mild steel. Light roughing was carried out with a constant feed rate of 0.15 mm/rev, a constant cutting speed of 100 m/min, and a depth of cut of 2.5 mm. Finishing operations were also carried out with a constant feed rate of 0.15 mm/rev, but an increased speed of 150 m/min, and a reduced depth of cut of 0.5 mm. Nine successive roughing operations were performed with the uncoated tool type T_2 and the coated tool type T_4 taking a cumulative cutting time of 27 minutes with each tool. On the other hand thirty one successive finishing operations wre performed with the uncoated tool type T_1 and similar cuts with the coated tool type T_3, each one taking 67 minutes cumulative cutting time.

During the cutting tests visual observations of the chip formation were made to follow the changes that took place under the conditions used. The cutting forces were measured to investigate their development with the cutting time, and metallurgical examination of the worn tool surfaces was carried out.

3.7.3 Machining of Stainless Steel

Stainless steel was the main work material employed in this project and so several programmes were employed. The first and second programmes employed the same types of uncoated and coated tools, as those used in machining mild steel and En 8 steel. Accordingly, a comparison was made between the performance of coated and uncoated tools. However, a new approach was attempted on cutting stainless steel. Part one of the programme was fulfilled by cutting the entire length of the workpiece without interrupting the programme for measurement or any other reason. Part two was similar to part one, but the programme was interrupted 5 times to take wear and surface finish measurements. Part three of the stainless steel machining was a comprehensive programme where the severity of the test was increased by removing more material and using higher speeds. Moreover, three new grades of coated tools were added to the former four and they were all subjected to the experimental tests and the performance assessment.

3.7.3.1 Continuous Cutting Tests

3.7.3.1.1 Rough turning operations

The uncoated tool type T_2 and the coated tool type T_4 were employed to cut a bar of 254 mm length and 77 mm diameter. Each cut was carried out through to the end of the bar at one cutting speed, then a fresh tip of the same tool was used for the second cut in the same way but with a different speed. The third cut was also carried out at a third speed with a new tip of the same tool. The tips were marked carefully before commencing the cutting to avoid mix up of the working tips. The machining was performed without interruption of the single cuts. The tools were then examined under the optical microscope and tool wear was measured using the universal measuring machine.

Both the feed rate (0.4 mm/rev) and the depth of cut (2.5 mm) were kept constant throughout the three speeds 62, 78 and 94 m/min.

This test enabled comparison between wear of the uncoated and coated tools, but only within one speed as economy of workpiece material necessitated the successive cuts to be undertaken on the same bar, and the volume of metal removed, consequently, was not the same.

3.7.3.1.2 Finish turning operations

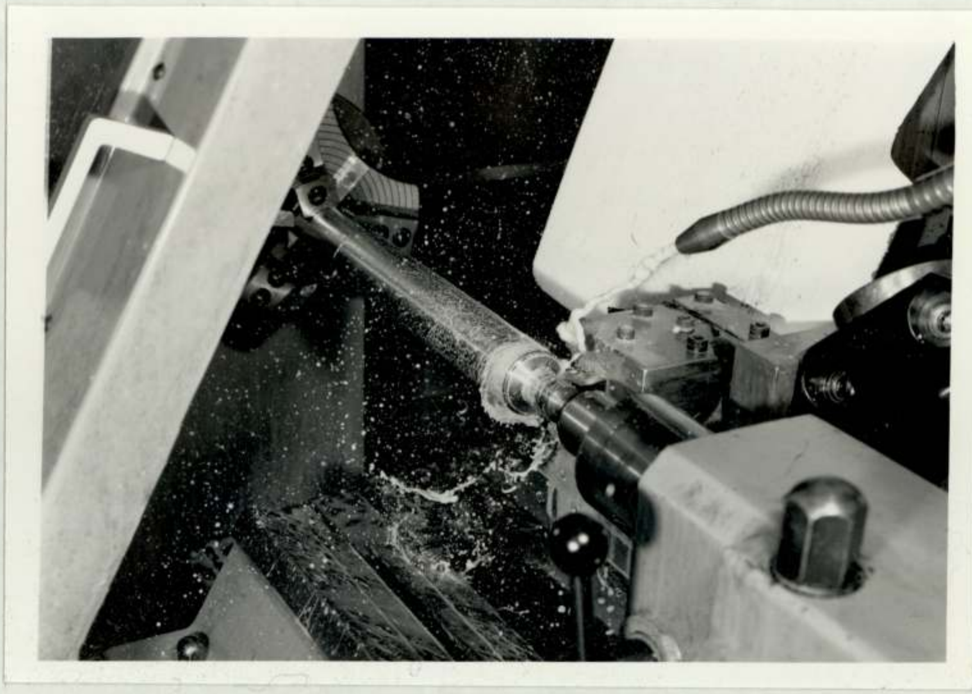
The same procedure followed in the rough turning test was carried out on similar workpieces during finish turning tests with the uncoated tool type T_1 and the coated tool type T_3. The machining conditions employed were as follows:

Cutting speeds:	125, 141, 157 m/min
Feed rate:	0.15 mm/rev
Depth of cut:	1.0 mm

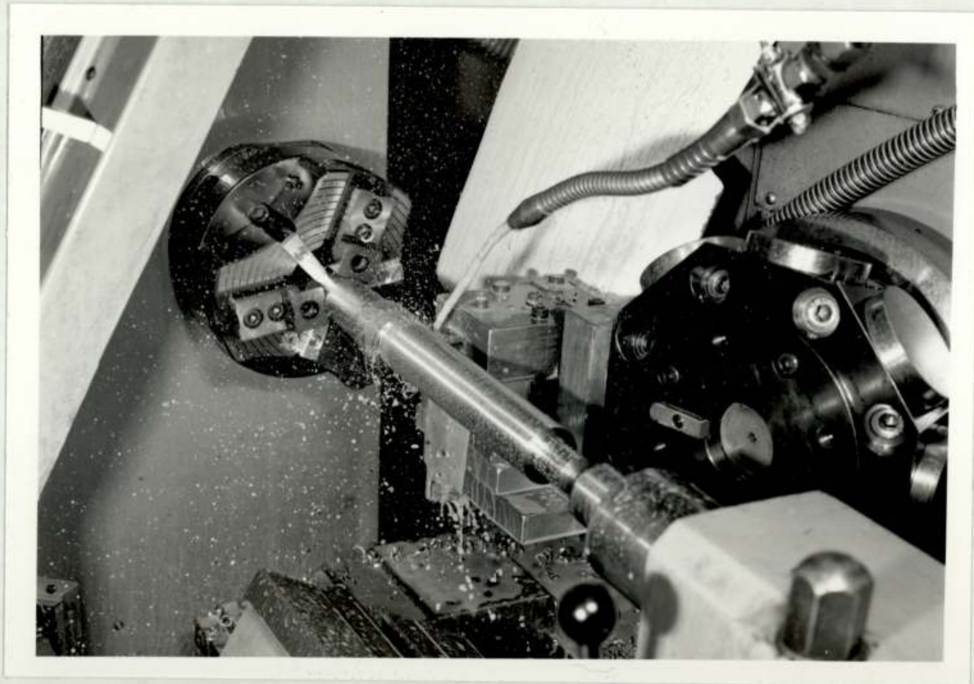
After the continuous finish turning, both flank wear and surface finish were measured. Figure 3.8 illustrates a continuous cutting operation on the CNC lathe.

3.7.3.2 Interrupted Cutting Tests

It is widely known that intermittent cutting is most damaging to the cutting tool, even when short-time machining is involved. Consequently the short-time interrupted test carried out was devised to compare the performance of the uncoated



(a) Start of the operation



(b) End of the operation

Figure 3.8: Continuous cutting operating on the CNC lathe

tools and the coated ones and the progress of wear during this type of machining. The surface finish of the workpiece was expected to fluctuate due to the changing conditions and the extent of wear at the end of each complete cut was anticipated to differ from that after continuous cutting.

The workpiece dimensions and the machining conditions used were the same as those employed for the continuous cutting tests. Both roughing and finishing operations were undertaken with the same set of tools T_2, T_4 and T_1, T_3 respectively. The only difference was that the lathe was programmed to make four stoppages before the fifth and last one at the end of the 254 mm long bar. The tools were examined for wear at each stoppage during rough turning and both the tools and workpieces were examined at the stoppages during finish turning. The short-length cuts of 51 mms took place in succession after short periods of about two minutes maximum duration of a single stoppage.

This approach enabled detection of progressive wear at early stages, and the effect of coating on the development of flank wear, nose deformation, and surface finish.

3.7.3.3 Comprehensive Cutting Tests

All the speeds at which the previous tests were carried out, were relatively low or medium cutting speeds. The severity of the cutting tests were, consequently, intended to be increased in order to carry out a comprehensive assessment of the coated tool performance in cutting stainless steel. It was decided that both rough and finish turning should be undertaken, and that the number of coated tools should be increased by including three of the newest grades of Sandvik's indexable turning inserts. The seven types of tools were used to carry out 4 successive cuts of a 254 mm long bar of diameter, 56 mm at the start of roughing and of 36 mm at the start of finishing. The rough operations were conducted at a cutting speed of 100 m/min; feed rate of 0.4 mm/rev, and depth of cut of 2.5mm. The finish operations were conducted at a cutting speed of 200 m/min; feed rate of 0.15 mm/rev; and depth of cut of 1.0 mm. These machining conditions were decided after a series of unsuccessful trials with more severe machining conditions. Premature tool failure occurred despite the use of the toughest tool type T_2.

The performance of the different coatings was assessed by measuring the forces involved during cutting, measuring the flank wear width, measuring the workpiece surface finish, and by carring out a comprehensive metallurgical study of the worn tools.

3.8 Force measurement

The main force components involved in the turning tests were:

(i) the tangential or vertical force which is often called the cutting force;

(ii) the axial force of the feed force;

(iii) the radial force which was the lowest of the three.

These were measured and their values were represented graphically against cutting time.

The measurement was carried out directly from the force deflections produced as traces against cutting time. The deflections were measured in centimeters and multiplied by the sensitivity indices which were pre-set in Newtons per Centimeter. The sensitivity adjustments were made according to the magnitude of each force component, ie. increased sensitivity for low force and reduced sensitivity for high force. After measurement the force values were given as Newtons.

3.9 Flank Wear Measurements

Measurements of flank wear width and nose deformation were made by the use of the S1P Universal Measuring Maching and the digital electronic measuring probe SYLVAC 25 (Figure 3.5). The wear land width was measured by placing the turning insert on the device table with the flank's wear pattern facing upwards under the microscope's eyepiece. A datum line which could be seen through the eyepiece was aligned with the tool's cutting edge which represented one extremity of the flank wear land. Then the probe which was coupled to the measuring device table by a sensitive pointer was zeroed. By appropriate use of the table controls, it was possible to realign the datum line with the other edge of the flank wear pattern. The distance across which the datum line travelled, ie. the wear land width, was shown on the digital reading of the probe which had an accuracy P$\pm$0.1μm. As the flank wear width was not uniform in some tools, the measurement was made at different widths and the average value was recorded as flank wear width.

This procedure was followed after each cutting operation carried out in most of the experimental test programmes. The relationships between flank wear width and the cutting time were established.

3.10 Surface Finish Measurement

The surface qualify of the machined workpieces was tested after every finishing operation using the Talysurf. Due to the unsteady conditions of the surface quality of the workpieces, that were observed visually during most of the cutting operations, a careful method of measuring the surface finish was adopted. Readings were taken at three different distances along the workpiece, and at each distance three readings were taken circumferentially by rotating the workpiece at each area. The average readings at each of the three areas were added together and the ovrall average was considered to represent the surface finish.

3.11 Metallurgical Examination

Metallurgical examination of the worn tools was carried out after machining En 8 steel, and more extensively after the comprehensive programme of machining stainless steel. The tools involved in cutting En 8 steel were examined directly after the cutting operations without chemical cleaning or sectioning. Both the optical microscope and the scanning electron microscope were used to produce a limited number of micrographs to compare wear of the coated tools with that of the uncoated ones.

Metallurgical examination after machining stainless steel, involved the seven different types of turning inserts.

3.11.1 Tool Surface Cleaning

After cutting stainless steel, some of the worn tools were examined under the SEM, but it was very clear that the wear features were masked by adherent iron and other machining impurities. Consequently, it was decided to carry out light chemical cleaning of the tool surfaces. Before cleaning all the tools, a trial was undertaken to ensure the stability of the structures. All the tools were then cleaned in a 50% diluted HCl in an ultrasonic bath for 5 minutes and then they were prepared for examination.

3.11.2 Tool Surface Examination

The worn tool surfaces were first examined under the optical microscope to give a general idea about the comparative wear features on the rake face surfaces.

As closer examination was required to identify the wear characteristics, extensive studies were carried out using the scanning electron microscope.

3.11.3 Coating/Substrate Interface Examination

In order to study the subsurface of the worn tools and the coating/substrate interface behaviour during machining, it was intended to undertake metallographic preparation for some of these tools. Due to the brittle nature of the insert materials, careful sectioning and polishing were carried out. The tools utilised for this purpose were those employed in rough cutting of stainless steel since they showed the most significant results revealed by other examination techniques. Detailed examination of the cross-sections was carried out using the scanning electron microscope.

CHAPTER FOUR

EXPERIMENTAL RESULTS

CHAPTER FOUR

4 EXPERIMENTAL RESULTS

4.1 Pre-Machining Studies

Some preliminary studies were undertaken for the experimental tools in their 'as-received' condition. These were based on microscopic examination and analysis. They were intended to identify the nature of each tool, and the main differences between the substrates, the coating systems, the tool-surfaces and the coating/substrate interface. Furthermore, the tool examination prior to machining was essential to enable easy detection of any changes resulting from the cutting operations. Consequently, the pre-machining condition of the tools represents a datum for realistic comparison to enable a constructive assessment of tool performance and a comprehensive study of the wear situation after machining.

4.1.1 Tool Substrate Inspection

Figures 4.1 to 4.6 are scanning electron micrographs of cross-sections of the uncoated and coated tools in the 'as received' condition. Figure 4.1 illustrates the microstructure of the uncoated tool S1P-P10 (T_1), where the concentration of the fine grains of tungsten carbide is very low and the proportion of the cobalt binder to carbide is relatively small. However, both the tungsten carbides and the cobalt areas are evenly distributed through the dense round shapes of the complex carbides of tungsten mixed with other additives, mainly titanium whose presence was evident after the composition analysis that was carried out using SEM and EDXA. Figure 4.2 shows the microstructure of the uncoated tool S6-P40 (T_2). The tungsten carbides in this tool are of mixed fine and coarse sizes highly concentrated on the closely connected net of the cobalt-matrix. A notable feature of this structure is the numerous voids and pores along the carbide grain boundaries. Figure 4.3 shows the coarse grained tungsten carbide of the substrate of the coated tool GC415-P/K15 (T_3). The binder phase is formed of unevenly-distributed and disconnected islands of cobalt,

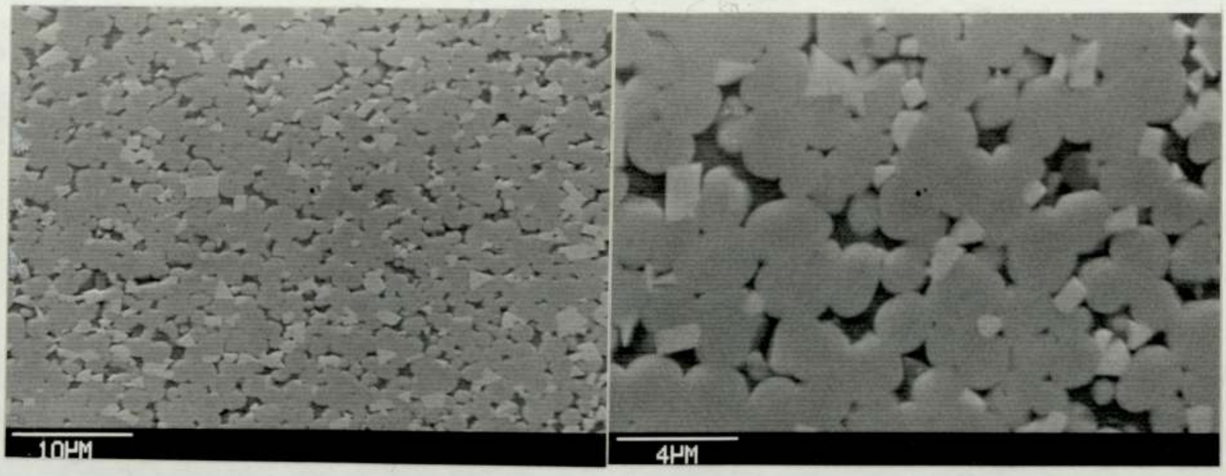


Figure 4.1: Scanning electron micrographs of a cross-section of the uncoated tool T_1 showing the even distribution of the fine grains of pure WC (angular) and mixed carbides (rounded).

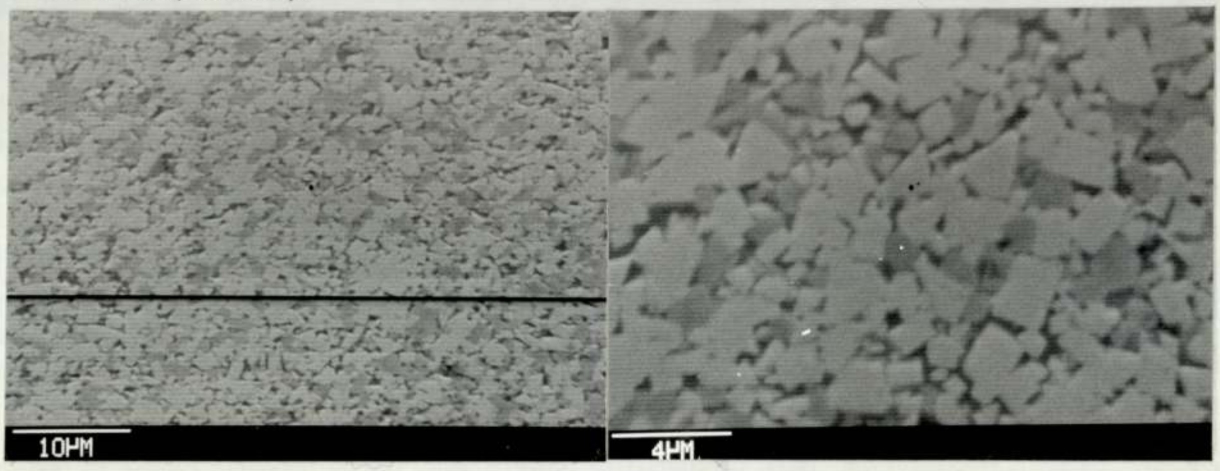


Figure 4.2: Scanning electron micrographs of a cross-section of the uncoated tool T_2 showing the closely connected cobalt-matrix (dark) and a considerable number of voids.

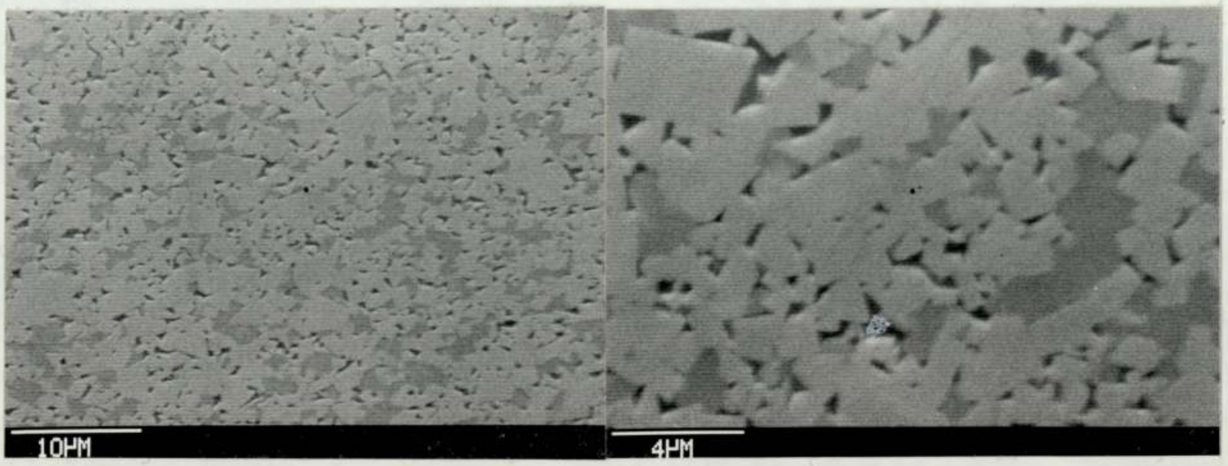


Figure 4.3: Scanning electron micrographs of a cross section of the coated tool T_3 showing the microstructure of the substrate with its coarse grains of WC, disconnected islands of cobalt (dark) and considerable micropores.

surrounded by the tungsten carbide grains. However, there is considerable porosity forming longitudinal patterns at the grain boundaries.

Figure 4.4 shows a section through the substrate of the coated tool GC435-P35 (T_4 & T_5). It illustrates a mixed structure of small and large grains of tungsten carbide which are distributed uniformly in a binder matrix of small islands of cobalt. The structure is almost pore-free and homogeneous. Figure 4.5 shows the microstructure of the substrate of the coated tool GC425 (T_6) where the coarse tungsten carbide grains have a uniform distribution in the cobalt. There is an indication of a fine-grained titanium carbide; this was supported by the information obtained from the x-ray analysis. The photographs show some porosity on the carbide grain boundaries. Figure 4.6 shows the microsctructure of the substrate of the coated tool GC235 (T_7). The carbide grain size is quite large (about 5 x 3 μm) with a very homogeneous and pore-free structure. However, it is notable that the cobalt areas are very small in size.

4.1.2 Tool Surface Inspection

The tool surface at the working tip is the region in direct contact with the workpiece material and the first area to experience deterioration during metal cutting. Accordingly, the study of tool wear phenomena requires a detailed examination of the surface condition prior to the cutting operations. Table 4.1 shows the chemical composition of the tool surface obtained by the EDX analysis. The data reveal the percentages of the main constituents of the uncoated and the coated tool surfaces, while Figures 4.7 to 4.13 illustrate topographical details of these surfaces.

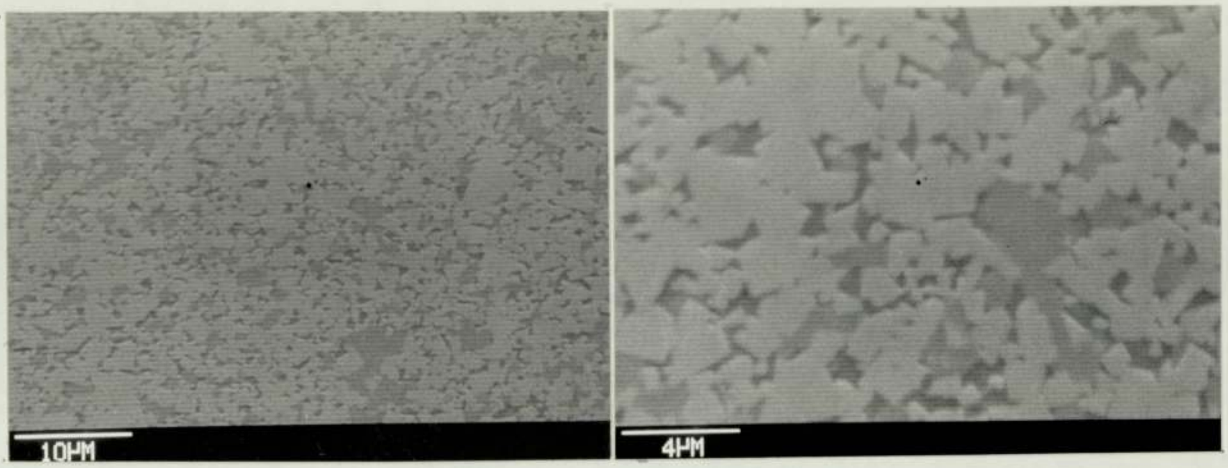


Figure 4.4: Scanning electron micrographs of a section through the substrate of the coated tool T_4 (the same grade as T_5) illustrating a mixed fine and coarse carbide grains. Unhomogeneous size and distribution of Co.

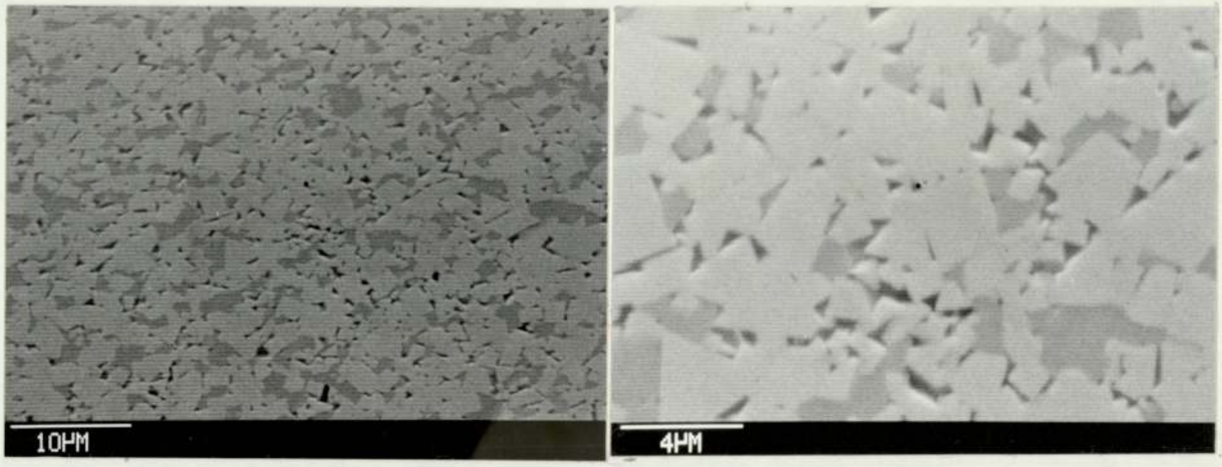


Figure 4.5: Scanning electron micrographs of a cross section through the substrate of the coated tool, T_6 showing the coarse angular WC grains, uniformly distributed with localised pattern of micro pores.

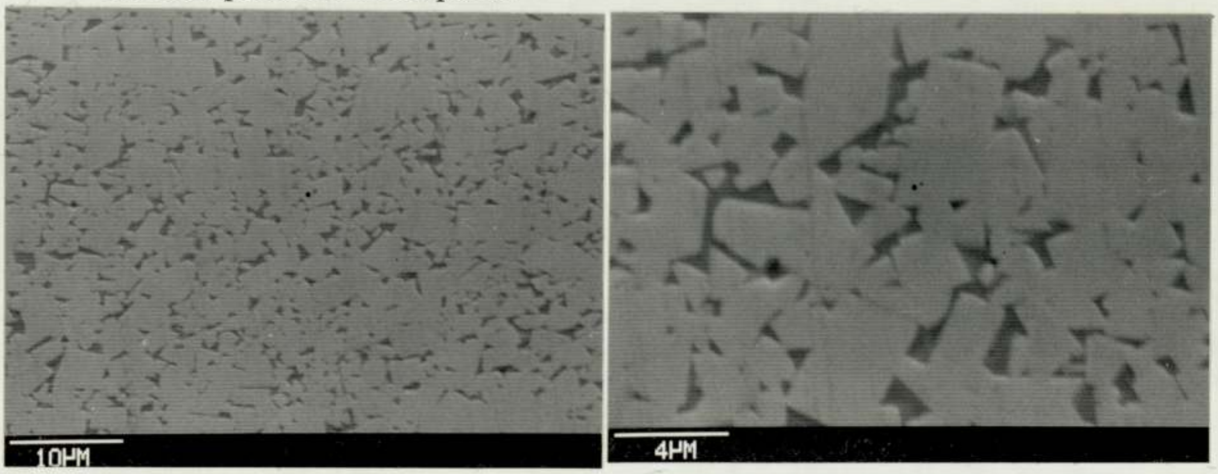


Figure 4.6: Scanning electron micrographs of a cross section through the substrate of the coated tool T_7 illustrating the large carbides (about 5 x 3 μm) with a pore-free structure

Table 4.1: Chemical composition of the tool surfaces, examined prior to machining operations

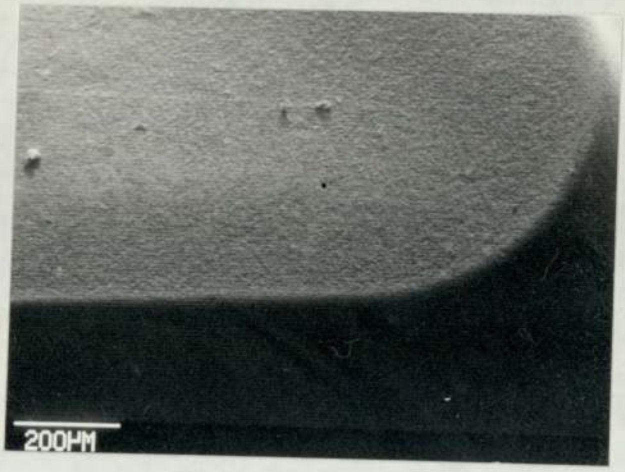
Tool No	Area of analysis	% age of element			
		W	Ti	Al	Co
T_1	Rake face	92.54	2.33	0.00	4.54
T_2	Rake face	90.26	1.23	0.00	8.11
T_3	Rake face	1.88	24.54	71.98	0.42
T_3	Surface inclusion	1.75	30.82	64.29	0.92
T_4	Rake face	2.53	32.02	63.47	1.11
T_4	Surface inclusion	1.09	18.73	78.75	0.24
T_5	Rake face	1.29	30.07	66.89	0.41
T_5	Surface inclusion	2.09	22.63	75.52	0.37
T_6	Rake face (smooth area)	16.60	79.22	0.00	2.08
T_6	Rake face (nodular area)	15.75	79.72	0.00	2.59
T_7	Rake face	1.87	94.81	0.22	0.67

C&N were not included in the analysis due to an instrument limitation.

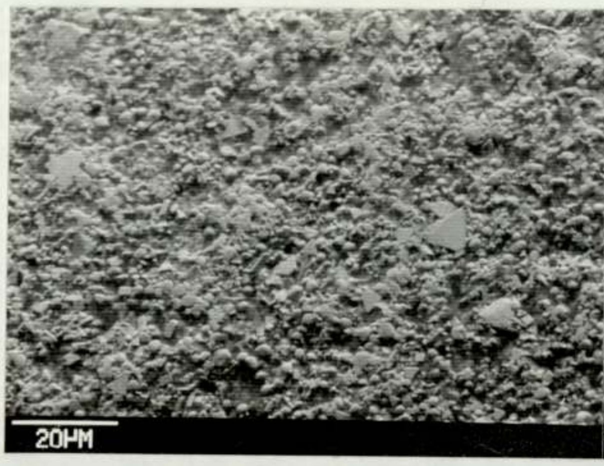
Note: the balance in each tool composition is small percentages of one or more constitutes such as Ta, Mo, V, Cr, Ni, Cu, Fe.

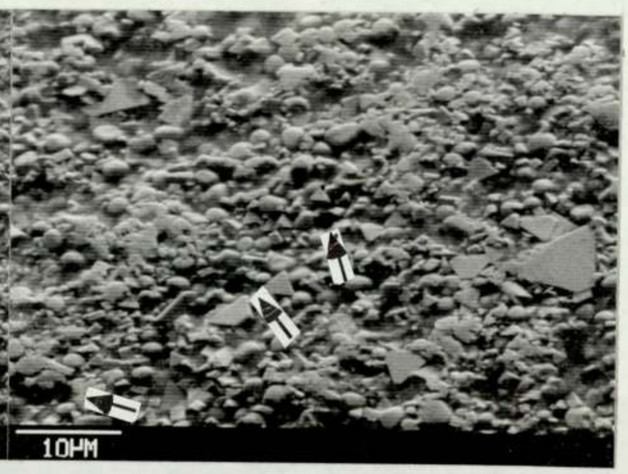
4.1.2.1 Uncoated Tool Surfaces

The surface topography of the uncoated tools T_1 and T_2 are shown in Figures 4.7 and 4.8 respectively. Figure 4.7a shows a smooth cutting edge and nose, while Figures 4.7b&c reveal the fine carbide grains of the tool 'T_1' with a few micro-cracks and small pores. On the other hand, Figure 4.8a shows a slightly rougher surface and



(a) smooth cutting edge and nose

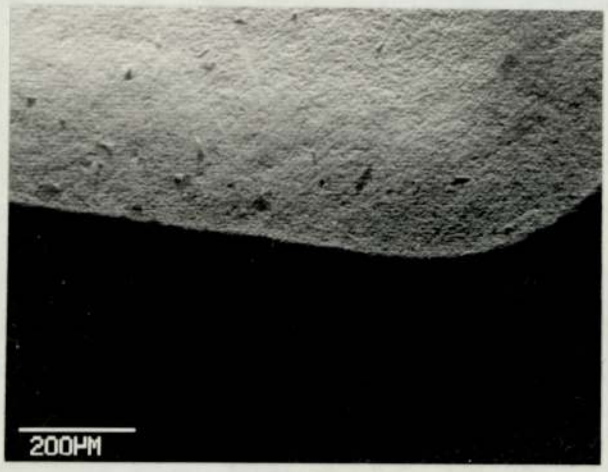




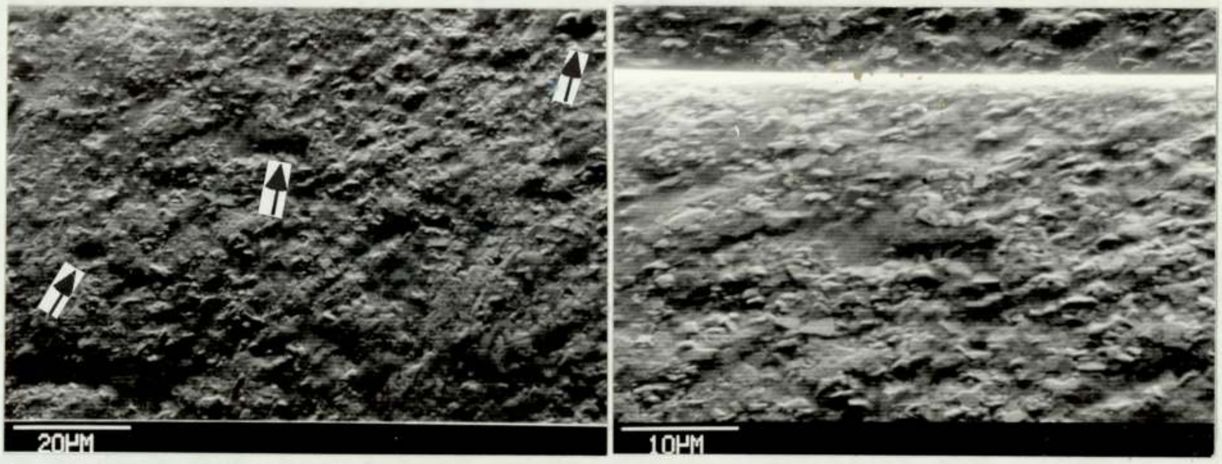
b c

(b&c) angular WC grains and rounded micrograins of mixed carbides. Few microcracks and pores "arrowed".

Figure 4.7: Scanning electron micrographs of the surface of the uncoated tool type T_1



(a) relatively rough cutting edge, nose and rake face



(b&c) matt nature of the surface with few voids "arrowed"

Figure 4.8: Scanning electron micrographs of the surface of the uncoated tool type T_2

cutting edge, while the Figures 4.8b&c illustrate the matt nature of tool 'T_2' surface and the presence of a few voids of relatively large size.

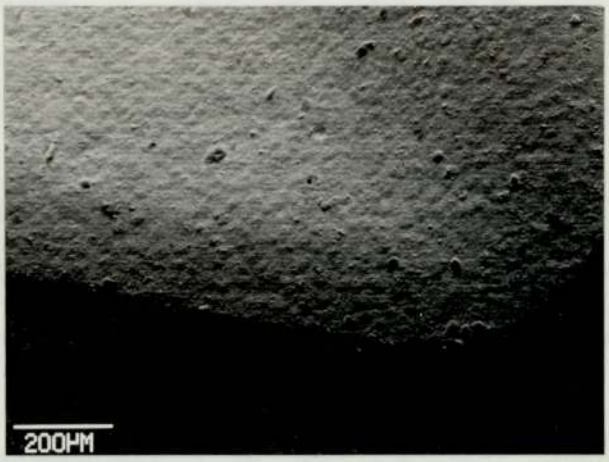
4.1.2.2 Coated Tool Surface

There is one feature in common between the five types of coated tools used in this investigation, that is the top layer of titanium nitride. Consequently, it might be expected that the surface conditions of all these tools would be the same, or at least very similar. In fact the scanning electron micrographs of the coated tool surfaces revealed noteworthy dissimilarities between them, especially at higher magnifications.

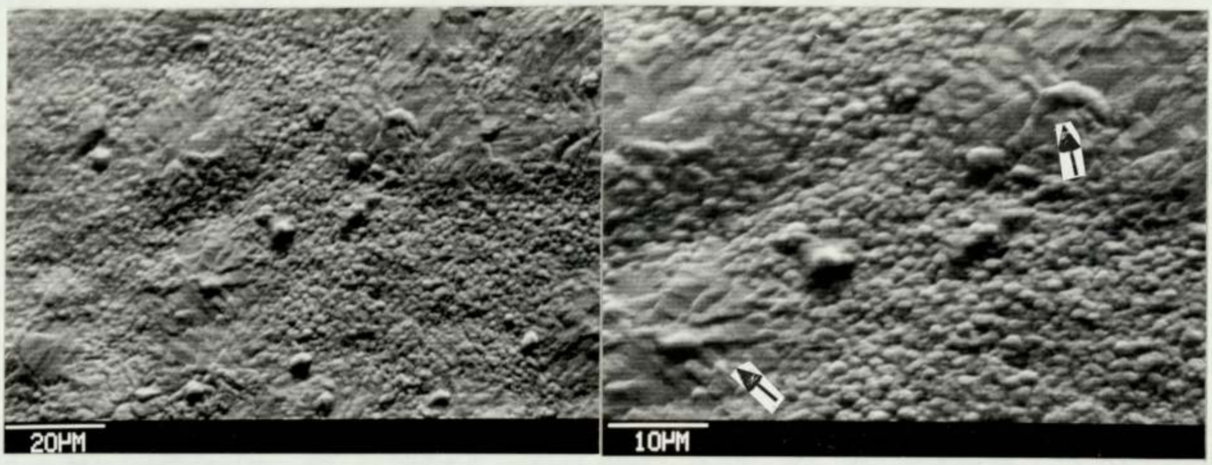
The surface features of tool 'T_3' are shown in Figure 4.9 where (a) shows the working tip and 'b' and 'c' show the rake face at a higher modification. The cutting edge, and the nose radius of the tip are fairly smooth, while the rake face is slightly rough with a few inclusions and microcracks. These surface defects are of more significance in tool 'T_4'.

Figure 4.10 illustrates the different types of defects, where 'a' and 'b' show the rough cutting edge and nose radius, 'c' and 'd' show star-shaped microcracks around large nodules and voids, and 'e', 'f', 'g' and 'h' show the detailed features of these nodular inclusions.

Figure 4.11 shows a relatively smooth cutting edge and nose, but a rake face containing a few inclusions and micropores in the surface of tool 'T_5'. Figure 4.12 shows the feature of 'T_6' surface, where 'a' illustrates a smooth cutting edge and tool nose, and 'b', 'c' and 'd' demonstrate that the rake face is characterized by patches of fine nodules surrounded by larger smooth areas. However, no other surface defects are detectable. The surface of tool T_7 is featured in Figure 4.13, where 'a' shows a sharp cutting edge and a smooth nose radius, while 'b', 'c' and 'd' display rake face free of inclusion, but containing significant irregularities and voids.

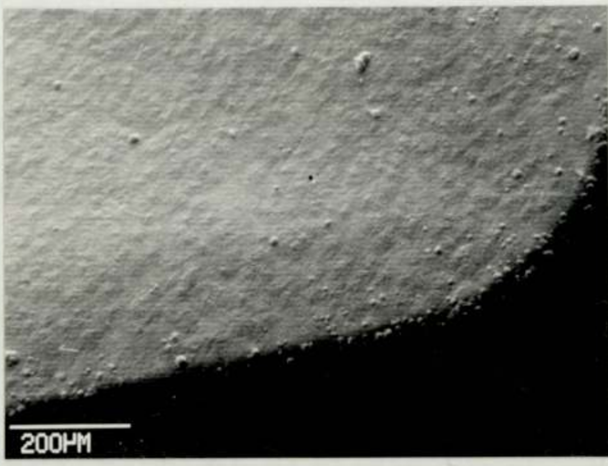


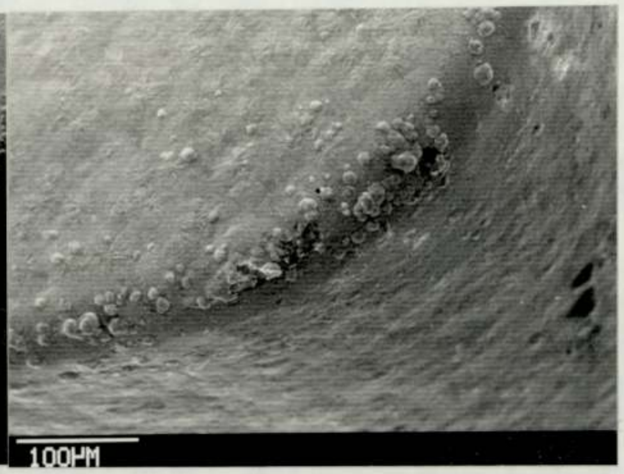
(a) fairly smooth cutting edge and nose



(b&c) rough rake face surface with few inclusions (arrowed)

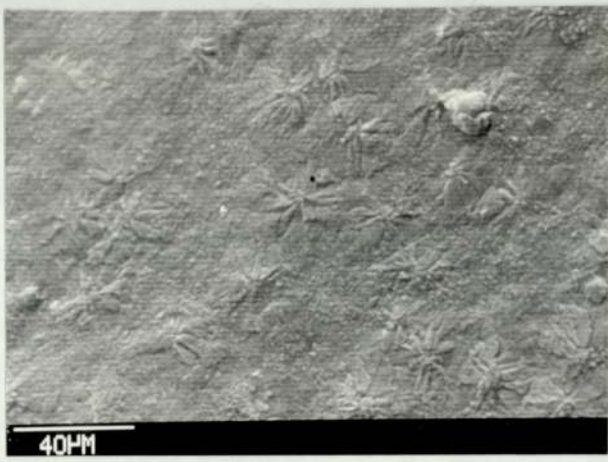
Figure 4.9: Scanning electron micrographs showing the topography of the rake surface of the coated tool type T_3.

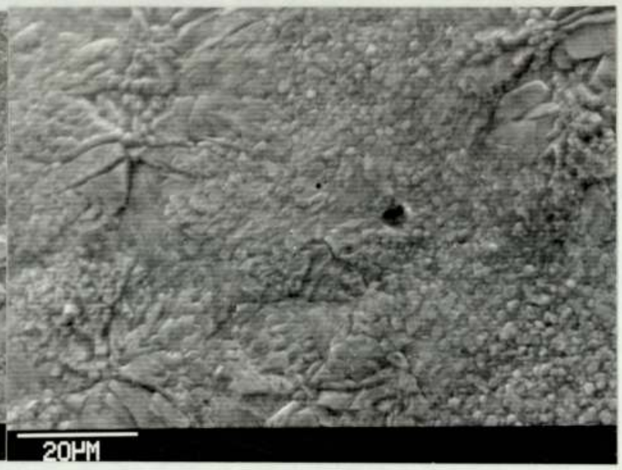




a

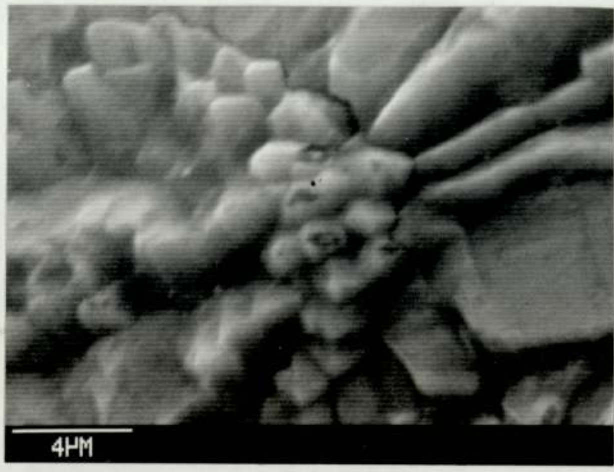
b

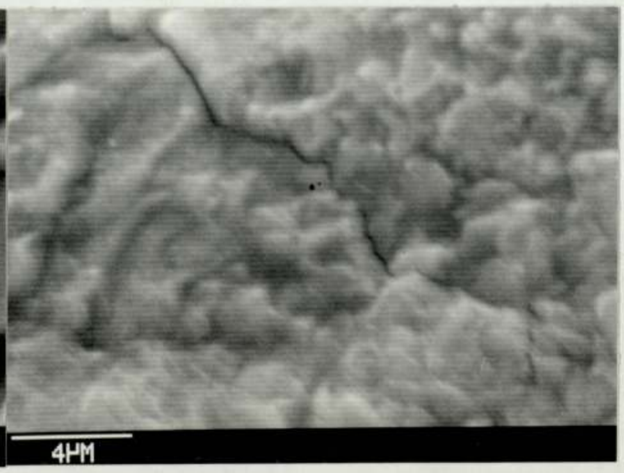




c

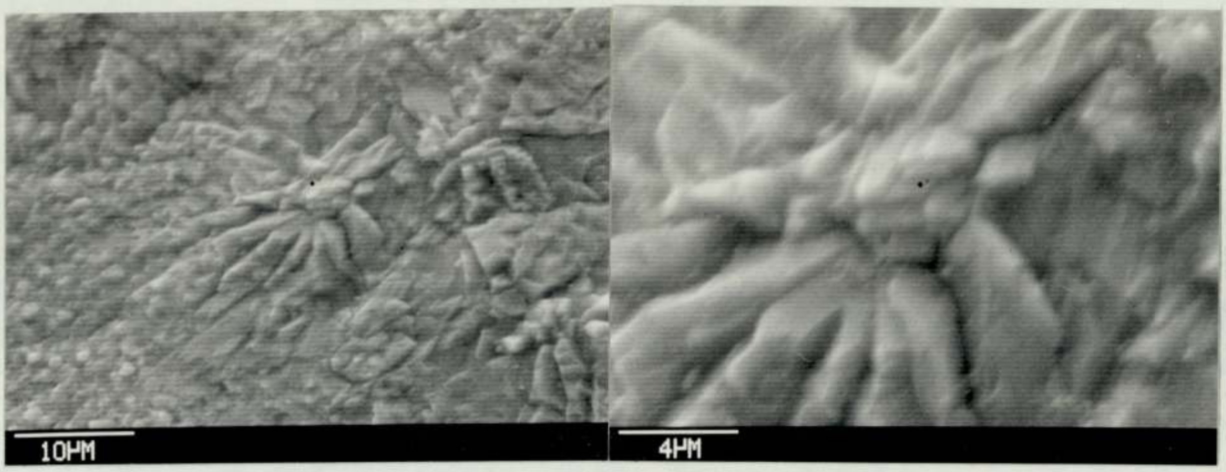
d





e

f



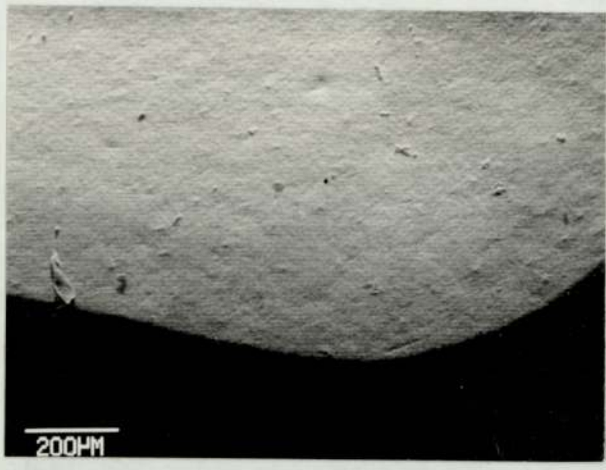
g h

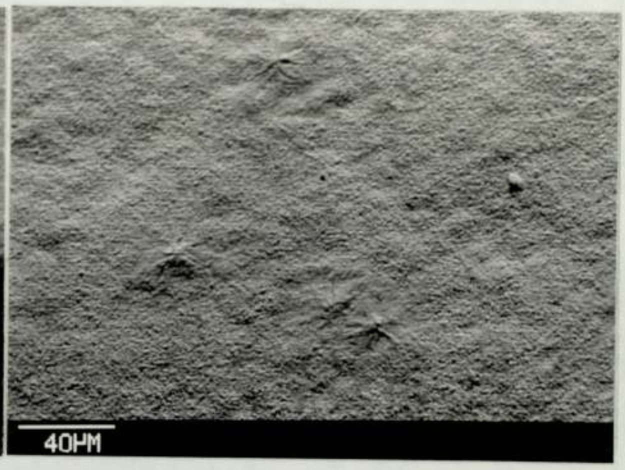
Figure 4.10: Scanning electron micrographs showing details of the surface of the coated tool type T_4.

(a&b) illustrate the rough nature of the cutting edge and nose

(c&d) show star-shaped microcracks, surface inclusions and voids

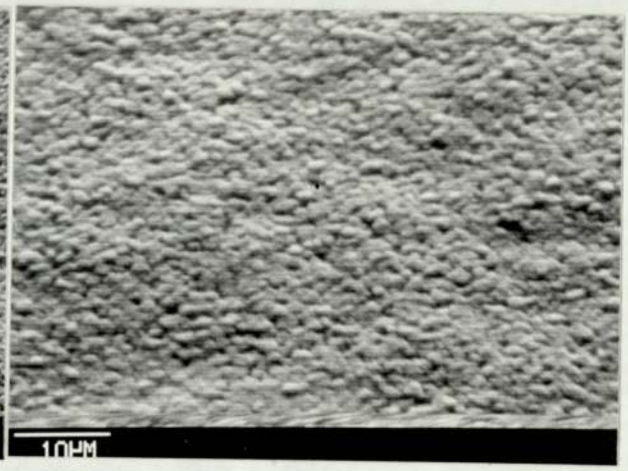
(e-h) illustrate the detailed features of nodular inclusions associated with different shapes of cracks





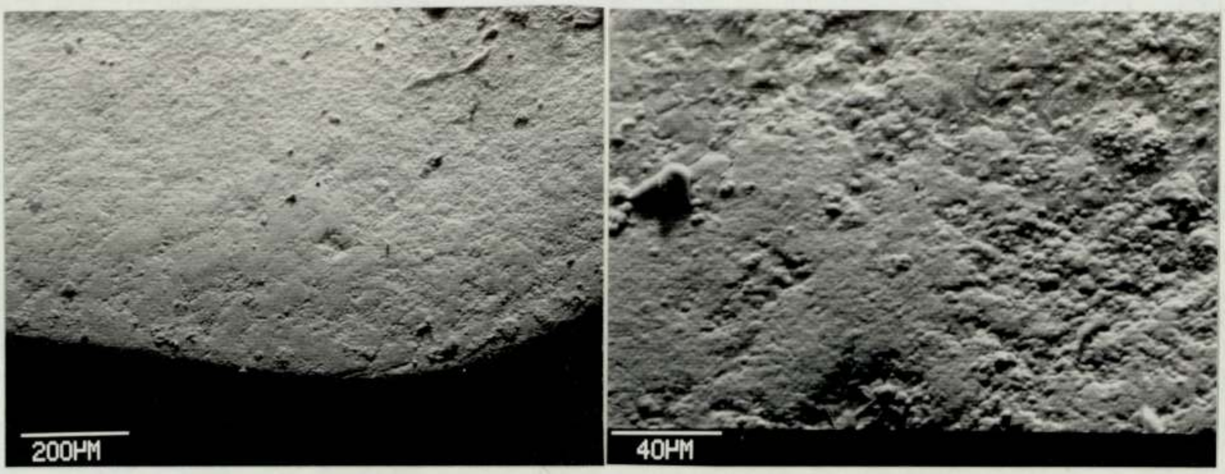
(a) Smooth cutting edge and nose

(b) Fine nodules with few inclusions of the rake face



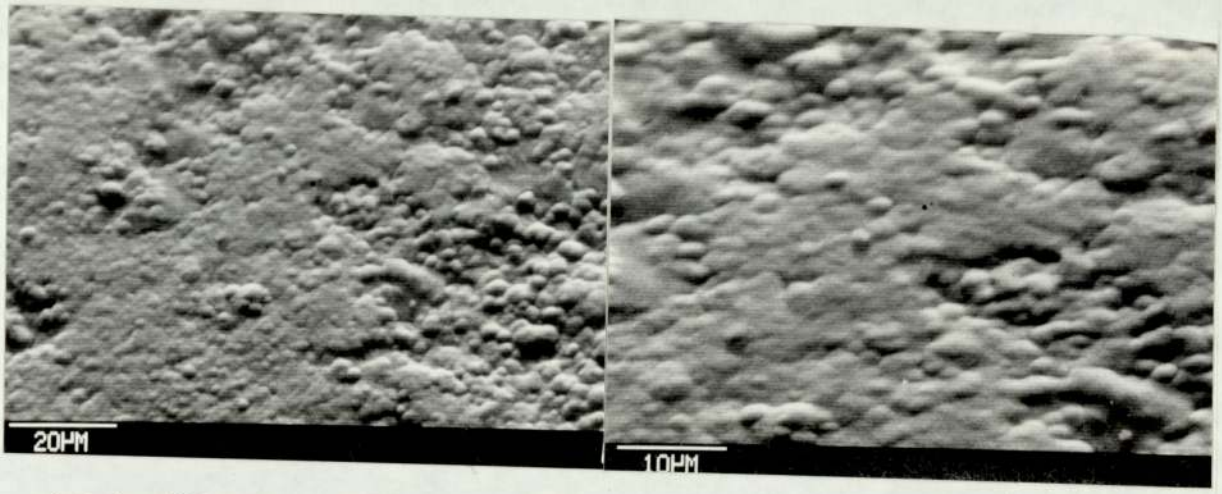
(c&d) smooth surface with very fine pores in the surface of the rake face

Figure 4.11: Scanning electron micrographs of the surface of the coated tool type T_5



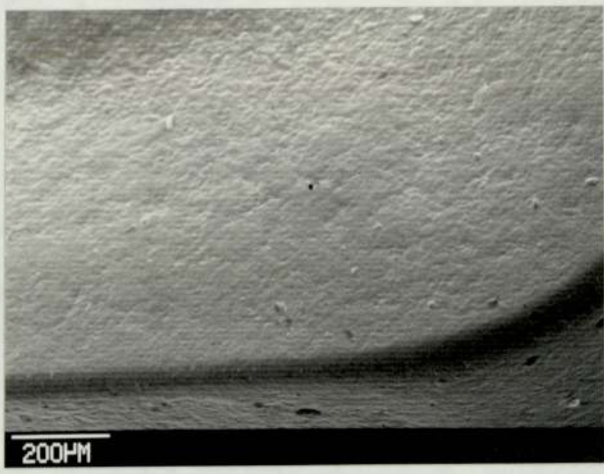
(a) fairly smooth cutting edge and nose

(b) smooth and nodular areas in the rake face



(c&d) different magnifications of the nodular surface in (b)

Figure 4.12: Scanning electron micrographs showing the surface features of the coated tool type T_6

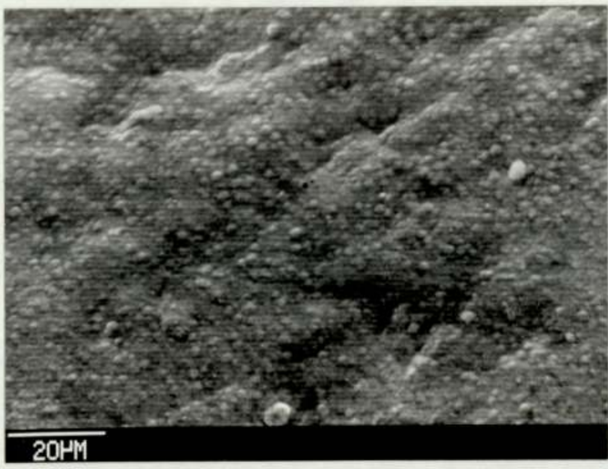


(a)

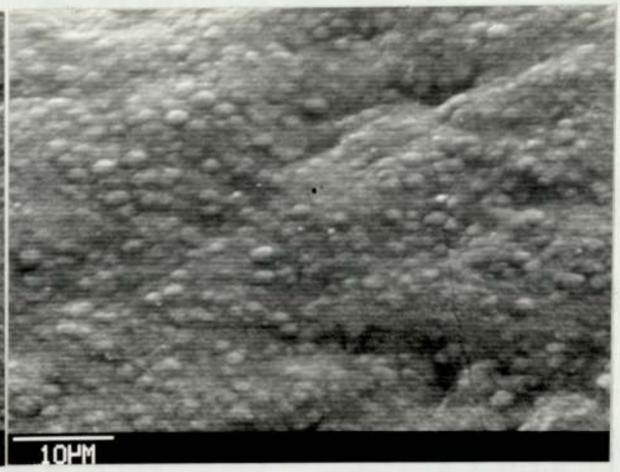
(b)

(a) Sharp cutting edge and smooth nose

(b) Inclusion-free rake face



(c)



(d)

(c&d) Irregularities and voids of the rake face

Figure 4.13: Scanning electron micrographs showing the general features of the surface of the coated tool type T_7.

4.1.3 Coating System Inspection

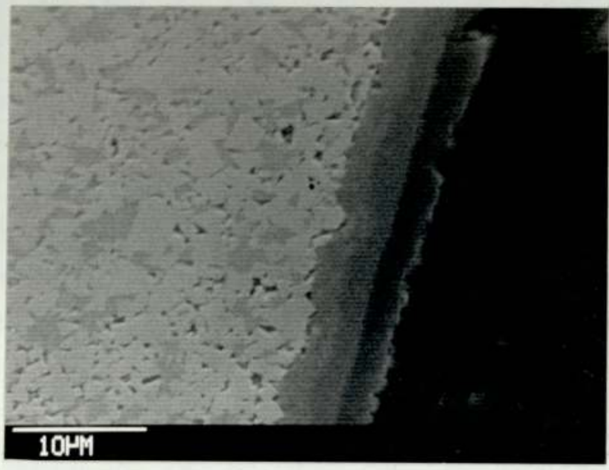
By using the scanning electron microscope with an EDXA attachment for chemical analysis, it has been made possible to identify the coating systems applied to the commercially available tools employed in this investigation. Figures 4.14 to 4.18 show 'SEM' microgaphs of sections cut from these tools. They reveal the number of layers, the thickness of these layers and the condition of the coating/substrate interface. Figures 4.14 to 4.16 illustrate tools T_3, T_4 and T_5 respectively. These tools were coated with the same triple layer system. Starting from the substrate, the carbide grain concentration may vary from one zone to another. For instance, Figure 4.15 (c&d) shows areas of low carbide and high cobalt concentration close to the coating/substrate interface of tool 'T_4'. In most of the tools, especially those coated with the three-layer system, the substrate zone nearer to the interface shows scattered voids associated with the low carbide concentration (Figures 4.14a, 4.15c, 4.16b). When these voids are adjacent to each other in a certain region under the coating, they create a weak area above which the coating layers may crack or collapse when they come under stress in service. The coatings are titanium carbide TiC, aluminium oxide, Al_2O_3 and titanium nitride TiN. In all cases there appears to be an additional layer at the interface, representing almost half the thickness of the TiC coating. Figure 4.17 shows the type of coating applied to tool 'T_6'. It consists of a layer of TiC with a second layer of TiN on top. However, there is no clear boundary separating the two layers from each other, but there is a gradual change in composition from the interface to the outer surface. Both triple layer coatings as mentioned previously and this double layer coating have approximately the same overall coating thickness, ranging from 5 μm to 8 μm. Figure 4.18 shows the coating system on tool T_7. It reveals a very thin coating of total thickness between 2 and 3 μm. Although the manufacturers' specification for this tool indicates a three layer coating system of TiN-TiC-TiN, the micrographs show two thin layers. However there is a possible indication of a very thin strike layer of TiN.

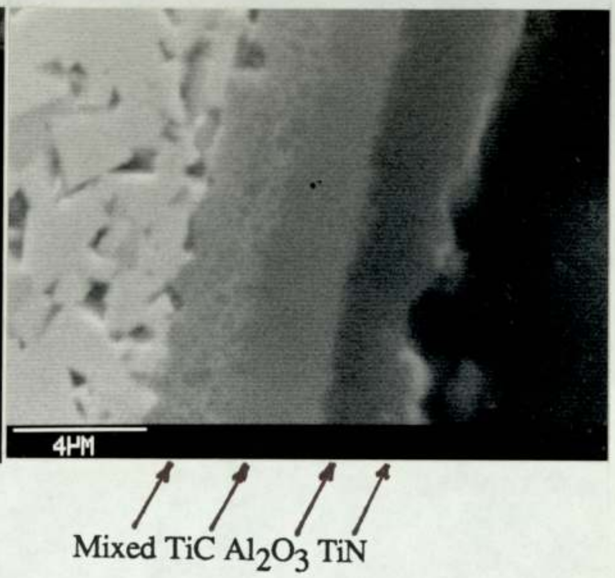
4.1.4 Subsurface and Interface Inspection

It has already been shown that the substrates of the coated tools have different concentrations of carbides. However, even within one coated tool some zones could be weaker than others. Figures 4.15b&e and 4.18c show examples of such weak zones.

In many cases the interface defects may appear as an interconnected chain of longitudinal voids extending along the interface, just under the coating. They represent sites of crack initiation prior to machining (Figures 4.15a, 4.16a and 4.18c. These voids indicate the weakness of the coating/substrate interface. Moreover, it seems that the weak part of the coating system is the intermetallic phase developed under the TiC layer. This layer of intermetallic phase which is formed during the coating process is subject to serious cracking at sites adjacent to the weak, void-enriched areas beneath the coating. Figure 4.15b&e illustrates the types of cracks formed across the inner coating which propagate along the coating interface with the layer above. Figure 4.14a&b demonstrates an example of good coating/substrate adhesion in the case of tool 'T_3'. Figure 4.15 illustrates the interface condition of tool 'T_4', whilst tool 'T_5' which is only different from T_4 in its geometry, has a slightly better interface condition as shown in Figure 4.16a&b. Tool 'T_6' has significant porosity in the 'body' of the substrate although the interface between coating and substrate is reasonably sound (Figure 4.17).

Despite the fact that the coating of tool 'T_7' is very thin, it is clear that the adhesion of this thin coating is excellent in comparison to the other thicker coatings of the remaining tools. Figure 4.18a&b shows the well bonded coating which might be one of the significant advantages of thin coating layers.



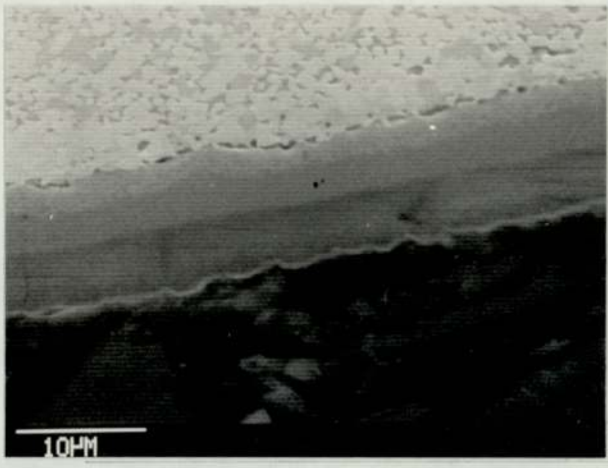


(a) (b)

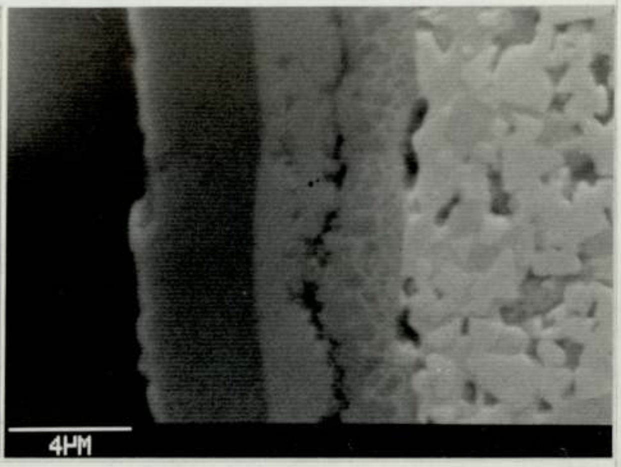
Figure 4.14: Scanning electron micrographs of a cross-section through the coated tool type T_3 showing the coating system and the interface condition.

(a) voids in the substrate close to the coating system of four layers of overall thickness (5-8µm). A mixed carbide inner layer, then TiC, Al_2O_3 and a very thin layer of TiN of about 1µm

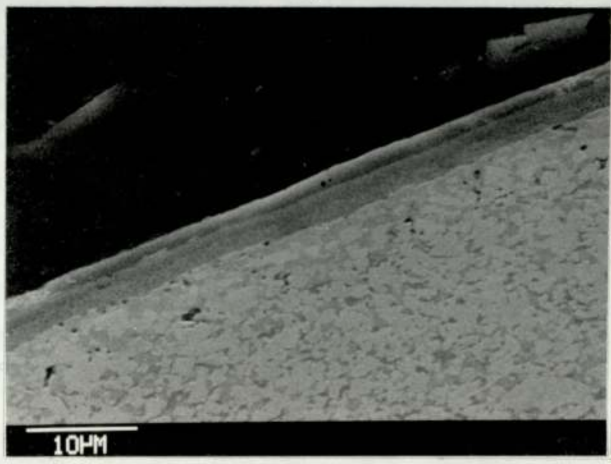
(b) cluster of the angular tungsten carbides in a region exhibiting voids beneath the coating



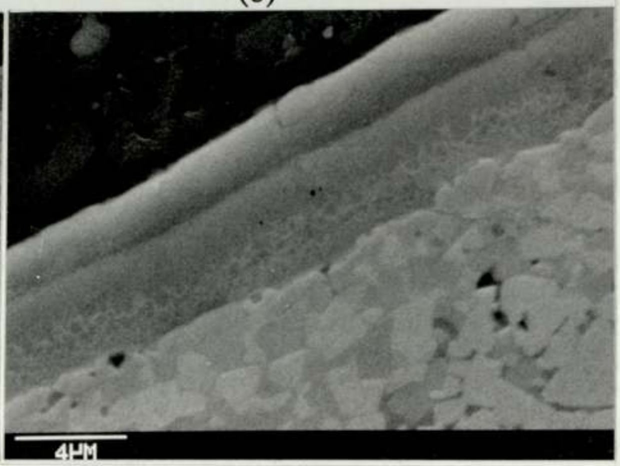
(a)



(b)



(c)



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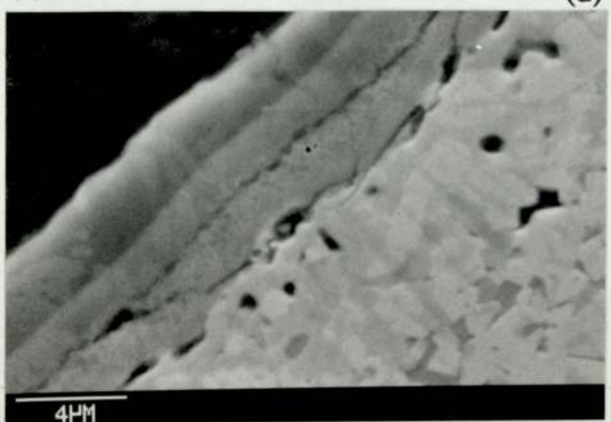
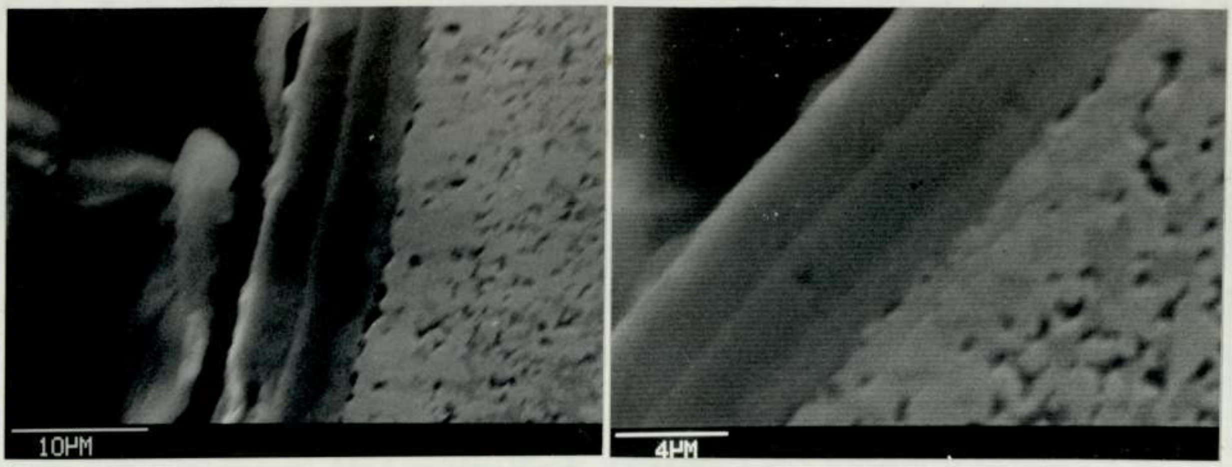


(e)

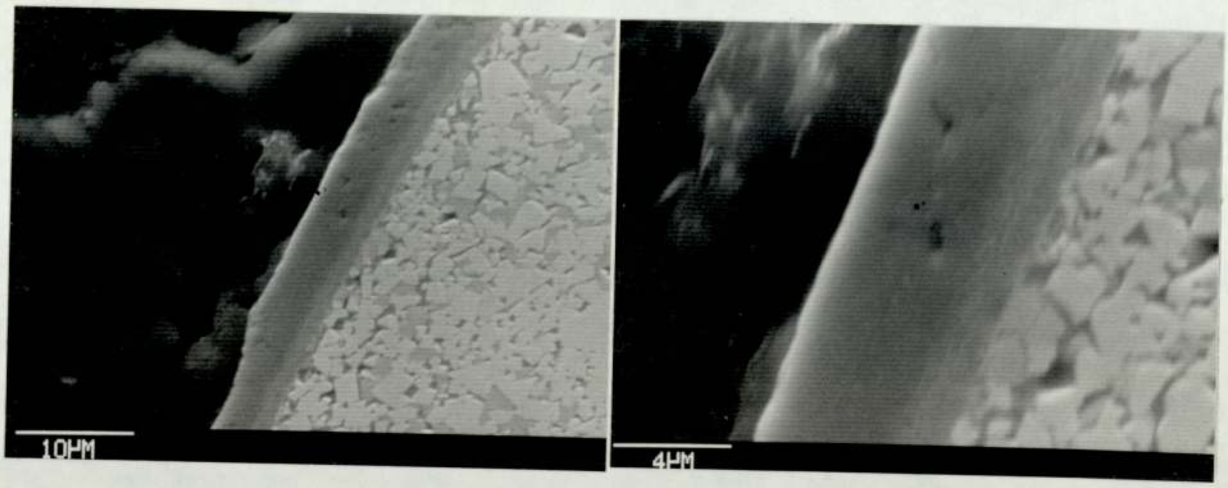
Figure 4.15: Scanning electron micrographs of a cross section through the coated tool type T_4 showing the same coating system as T_3 (Figure 4.14) but with more extensive interface defects. Note the voids and cracks (a, b, e) and the good adhesion in a region of low carbides and high cobalt (c,d).



(a) (b)

Figure 4.16: Scanning electron micrographs of a cross section through the tool type T_5 showing the same coating system as tools T_3 and T_4:

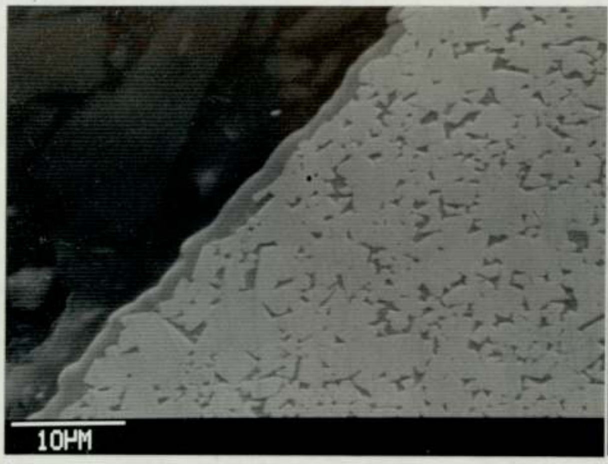
(a) voids at the interface
(b) voids in the substrate away from the interface



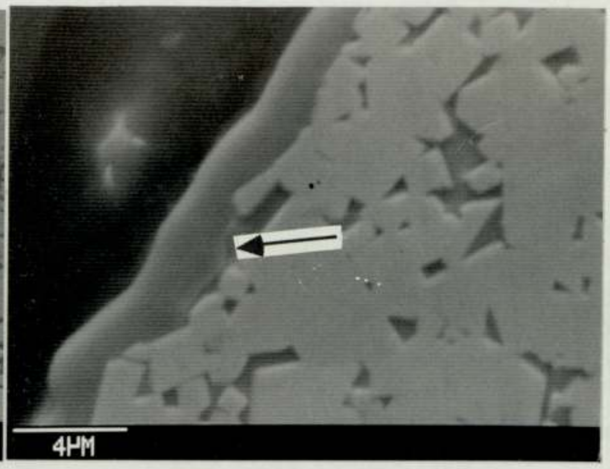
(a) (b)

Figure 4.17: Scanning electron micrographs of a cross section through the tool type T_6 showing the double layered coating of a thin top layer of TiN and a bottom layer of TiC with a thin layer of mixed carbides at the interface;

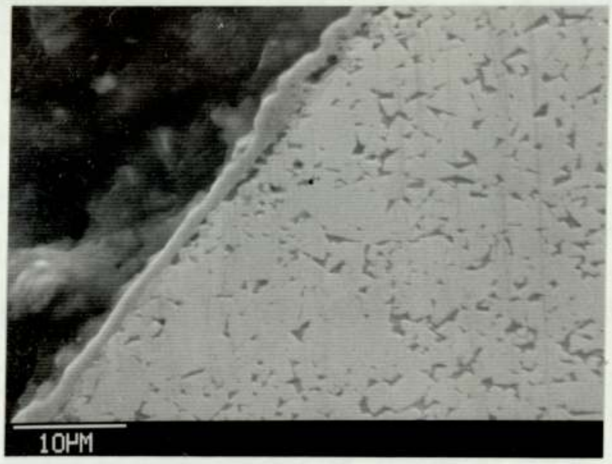
(a) relatively good coating/substrate bonding
(b) localized voids in the substrate and within the coating



(a)



(b)



(c)

Figure 4.18: Scanning electron micrograph of a cross section through the tool type T_7 showing the thin coating of TiN-TiC-TiN of total thickness about 2-3µm

(a) homogeneous, structure of defect-free substrate and excellently adhered thin coating

(b) extremely thin inner coating layer (arrowed) joining the protruding edges of the coarse tungsten carbides

(c) localized voids at the coating/substrate interface

4.2 Cutting Tests when Machining Mild Steel

Mild steel is regarded as a readily-machinable material and was not expected to bring about significant changes to the cutting tool surfaces during short time machining. Moreover the turning inserts used in this investigation were made of extremely hard and tough materials designed deliberately to withstand the tool more severe conditions experienced when cutting steels of relatively low machinability. However, the operations carried out were used as trials to test the workability of the machines, the force measuring system and the test arrangement. Accordingly, tool wear measurement and metallurgical studies have not been carried out, but the results obtained after measuring the forces and workpiece surface finish (CLA) did show some difference between the coated and uncoated tool performance with respect to the machining conditions used. The experimental data and results have been summarised in Tables 4.2.1 and 4.2.2, whilst these results are shown graphically in Figures 4.19 to 4.22. Figure 4.19 illustrates the influence of feed rate on the cutting force F_z, feed force F_x, and radial force F_y, when machining with the uncoated tool T_2 and the coated tool T_4. There is a slight improvement in the performance of the coated tool in comparison with that of the uncoated one especially in the two most important forces, the cutting and the feed force. The trend of the curves shows that the coated tools performed better at higher feeds when the forces involved became very high, especially the cutting force Fz. Figure 4.20 shows the influence of feed on the job surface finish in the same cutting operations as illustrated in Figure 4.19. The surface finish is very rough at values of feed over 0.2 mm/rev, and the best finish corresponds to low feeds where both the uncoated and coated tools produced the same quality of finish. However, the coated tool job-surface finish at the upper limit of feed shows an improvement of 26% compared with that achieved with the uncoated tool.

Table 4.2: Data obtained during cutting of mild steel at cutting speed 129 m/min; depth of cut 2.5mm, and variable feed rate

Cut Operations	Feed mm/rev	Forces on tools (N)						Workpiece S finish CLA (µm)	
		Tangential Fz		Axial Fx		Radial Fy			
		T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4
1	0.05	300	320	225	280	50	70	0.6	0.6
2	0.10	530	510	420	380	108	105	0.9	0.8
3	0.15	720	680	480	450	138	140	1.7	2.0
4	0.20	900	850	550	475	175	163	4.3	3.2
5	0.25	0150	1075	600	575	200	200	-	-
6	0.30	1250	1250	650	625	245	255	-	-
7	0.35	1400	1350	750	650	275	280	-	-
8	0.40	1575	1525	800	700	310	315	-	-
9	0.45	1750	1650	850	750	350	350	-	-
10	0.50	1950	1925	925	850	400	410	-	-

T_2: Uncoated tool
T_4: Coated tool

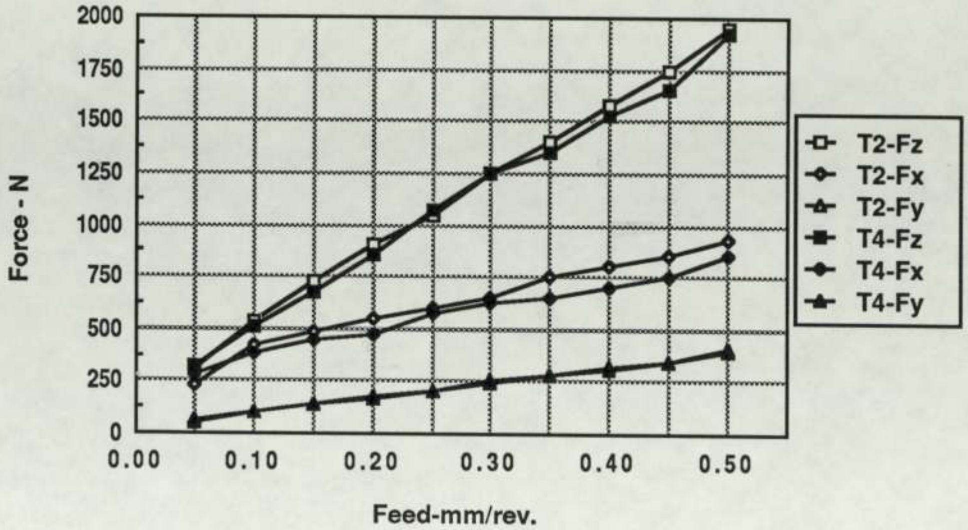


Fig. 4.19 : Influence of Feed on Forces when Machining Mild Steel with Uncoated"T2" and Coated"T4" Turning Inserts-Light Roughing
(Cut. Speed: 129 m/min; Cut. Depth: 2.5 mm)

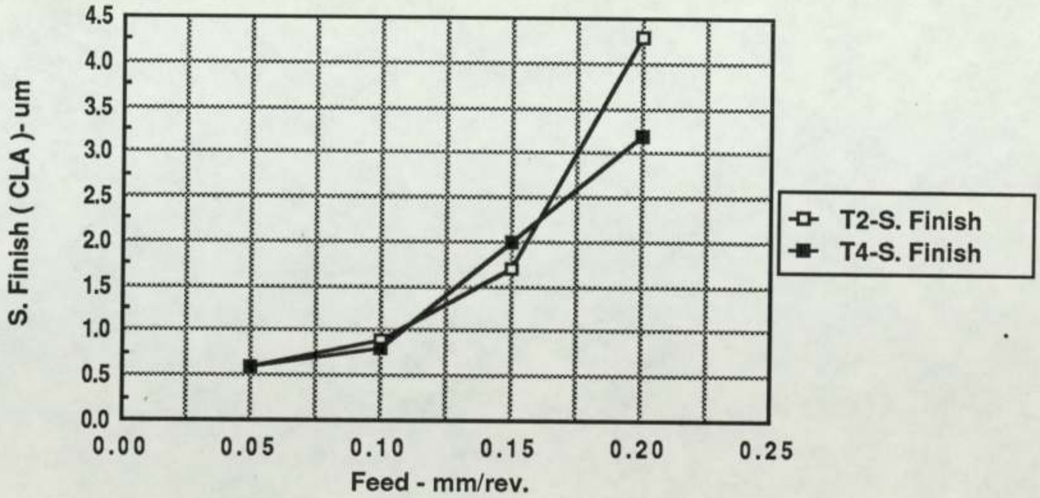


Fig.4-20: Influence of Feed on Surface Finish when Machining Mild Steel with Uncoated"T2" and Coated"T4" Turning Inserts-Light Roughing
(Cut. Speed: 129 m/min; Cut. Depth: 2.5 mm.)

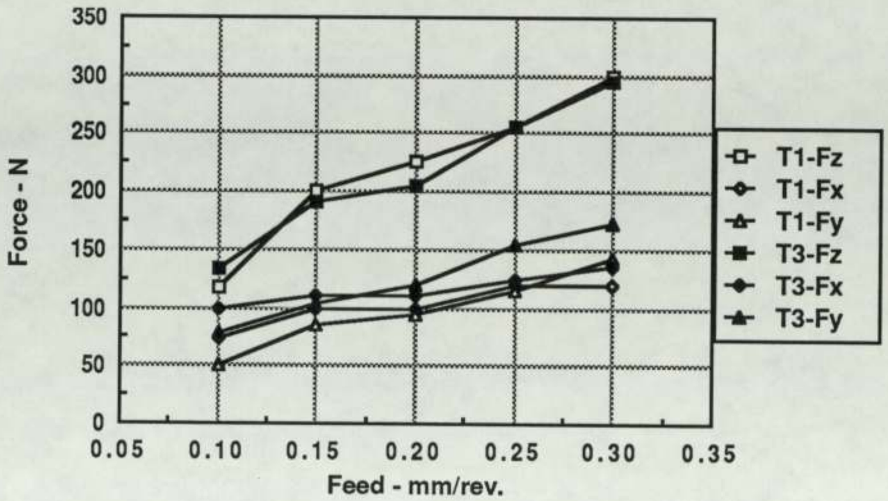


Fig. 4-21 : The Effect of Feed on Forces when Machining Mild Steel with Uncoated"T1" and Coated"T3" Turning Inserts-Finishing (Cut. Speed: 141 m/min ; Cut. Depth: 1.0 mm)

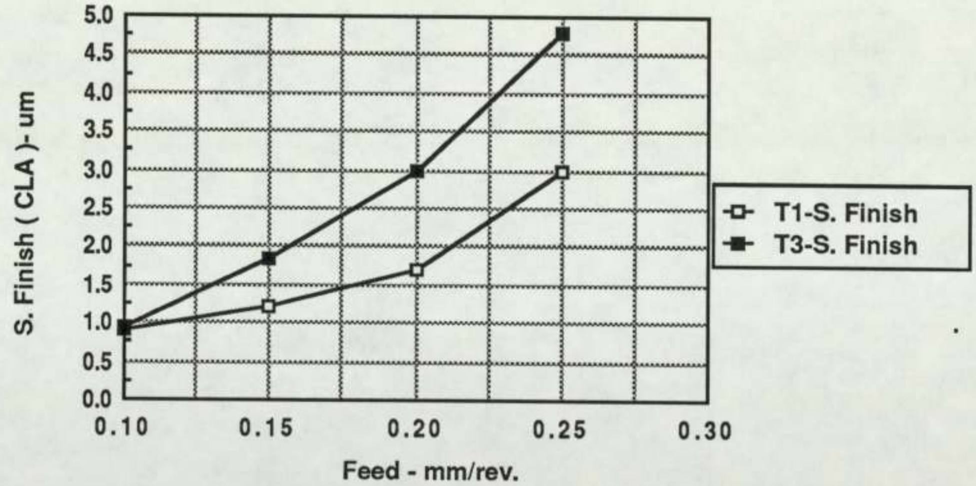


Fig. 4-22 : Effect of Feed on Surface Finish when Machining Mild Steel with Uncoated"T1" and Coated"T3" Turning Inserts-Finishing (Cut. Speed:141 m/min ; Cut. Depth : 1.0 mm)

Table 4.3: Data obtained during cutting of mild steel at cutting speed 141m/min; depth of cut 1.0mm, and variable feed rate

Cut Operations	Feed mm/rev	Forces on tools (N)						Workpiece S finish CLA (μm)	
		Tangential Fz		Axial Fx		Radial Fy			
		T_1	T_3	T_1	T_3	T_1	T_3	T_1	T_3
1	0.1	118	133	73	100	50	78	0.90	0.95
2	0.15	200	190	100	110	85	103	1.20	1.85
3	0.20	225	205	100	110	95	120	1.70	3.00
4	0.25	255	255	120	125	115	155	3.00	4.80
5	0.30	300	295	120	135	143	173	-	-

T_1: Uncoated tool

T_3: Coated tool

Figure 4.21 shows the effect of feed on the forces when cutting mild steel with the uncoated tool T_1 and the coated one T_3. The results show that there is little difference in the performance of these types of tools during finish turning, where the forces involved under such mild machining conditions are very low. On considering the quality of finish produced by these two types of tools during the same finishing operations, the performance of the uncoated tool was clearly better than that of the coated one (Figure 4.22).

4.3 Cutting Tests when Machining En8-Steel

A series of rough and finish cutting operations were carried out on En8 steel using turning inserts of the same types employed in cutting mild steel. Tests of long duration were performed to evaluate the behaviour of coated tools in comparison with the uncoated ones when machining on moderately hard steel. These cutting trials proved to be important before commencement of the comprehensive test programme planned using stainless steel as the work material. The results of cutting tests on En8 steel are displayed in two different ways. Firstly, by considering the variation of forces as a function of cutting time, and secondly by examining microscopically the characteristics of worn tool surfaces after machining.

4.3.1 Rough turning results

The force measurement results of rough turning tests presented in Table 4.4, and Figure 4.23 show a significant effect of TiN-coatings on tool performance. The forces related to the coated tool showed relatively low values which remained constant for a long period of cutting, whilst the force values related to the uncoated tool showed a substantial increase with the increase of the cutting time. The forces on the uncoated tool, after 27 minutes cutting, showed the following increases in excess of the corresponding forces on the coated tools:

Table 4.4: Values of cutting force 'tangential'-Fz; feed force 'axial' - Fx; and 'radial' force Fy obtrained during rough turning of En8 steel

Cut Operations	Cumulative time (sec)	Forces on tools (N)					
		Tangential Fz		Axial Fx		Radial Fy	
		T_2	T_4	T_2	T_4	T_2	T_4
1	4	900	875	600	550	175	160
2	8	975	875	750	600	200	180
3	12	1050	875	750	550	215	185
4	15	1125	875	875	550	230	180
5	18	1125	900	875	575	250	185
6	21	1125	875	835	550	260	190
7	23	1125	900	925	550	270	190
8	25	1225	900	1000	600	290	185
9	27	1200	875	900	600	290	190

T_2: Uncoated tool

T_4: Coated tool

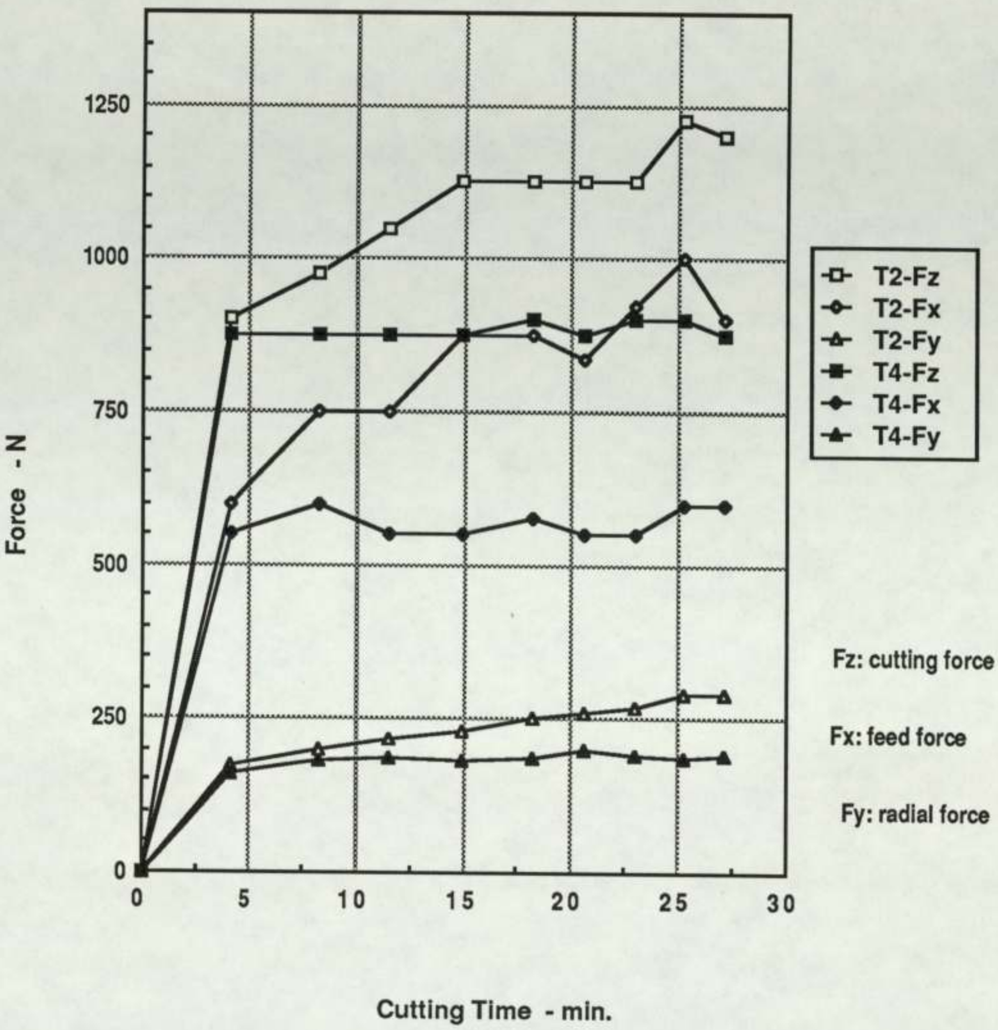


Fig.4-23: Variation of Forces with Time in Rough Cutting En8 Steel

with Uncoated "T2" and Coated "T4" Turning Inserts

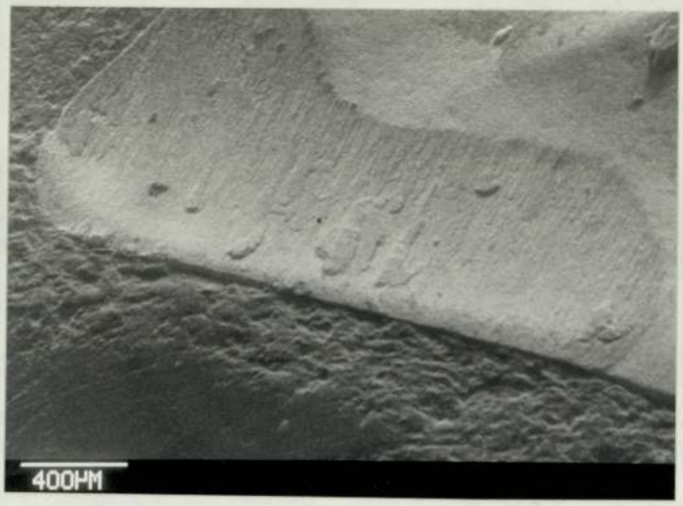
(Cut. Speed:100 m/min; Feed: 0.15 mm/rev ; Cut. Depth: 2.5 mm)

Cutting force Fz:	37%
Feed force Fx:	50%
Radial force Fy:	53%

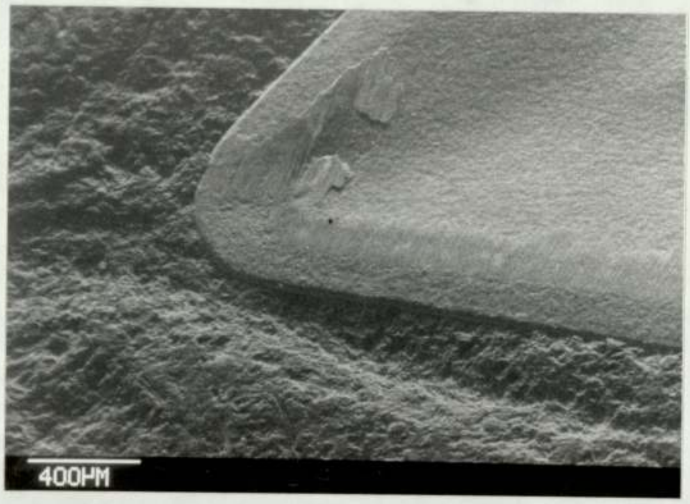
The metallurgical studies undertaken on the surfaces of the coated tool T_4 and the uncoated one T_2 showed a large difference between the two inserts regarding crater wear (Figure 4.24) and flank wear (Figure 4.25). Crater wear on the uncoated insert (Figure 4.24a) was very serious covering a large area on the rake face and clearly affecting the cutting edge and the nose radius. On the other hand the coated tool exhibited very little crater wear parallel to the cutting edge or near the nose (Figure 4.24b). Figure 4.25 shows optical micrographs for the flank surfaces of the same tools as those illustrated in Figure 4.24. Figure 4.25a illustrates the large width of flank wear on the uncoated tool (0.6mm) and the deep notch at the cutting depth end. In contrast, Figure 4.25b shows only a shallow mark at the notch site and flank wear on the TiN-coated tool was almost six times less than that for the uncoated tool.

4.3.2 Finish Turning Results

Finish turning of En8 steel was carried out with the uncoated tungsten carbide insert T_1 and the TiN-coated insert T_3. The test was run for a cumulative time of 67 minutes, for each tool. The results of forces measured at different intervals during machining are shown in Table 4.5, while the relationships of these forces with time are shown in Figure 4.26. The values of both the cutting force and the radial force are very low, and there is no significant difference between the uncoated tool and the coated tool performance. The performance of both types of turning inserts is almost the same at the end of the test, but it is noticable that the uncoated tungsten carbide insert performed better than the TiN-coated one in the early stages of the test. These results are somewhat similar to those obtained for finish turning of mild steel.

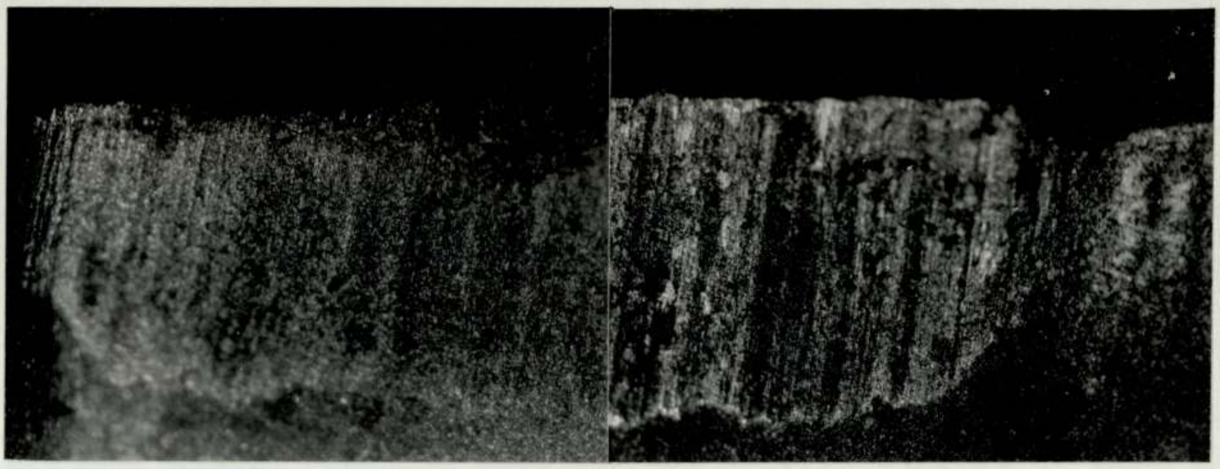


(a) Severe crater wear associated with adherent chip material on rake surface of uncoated tool T_2

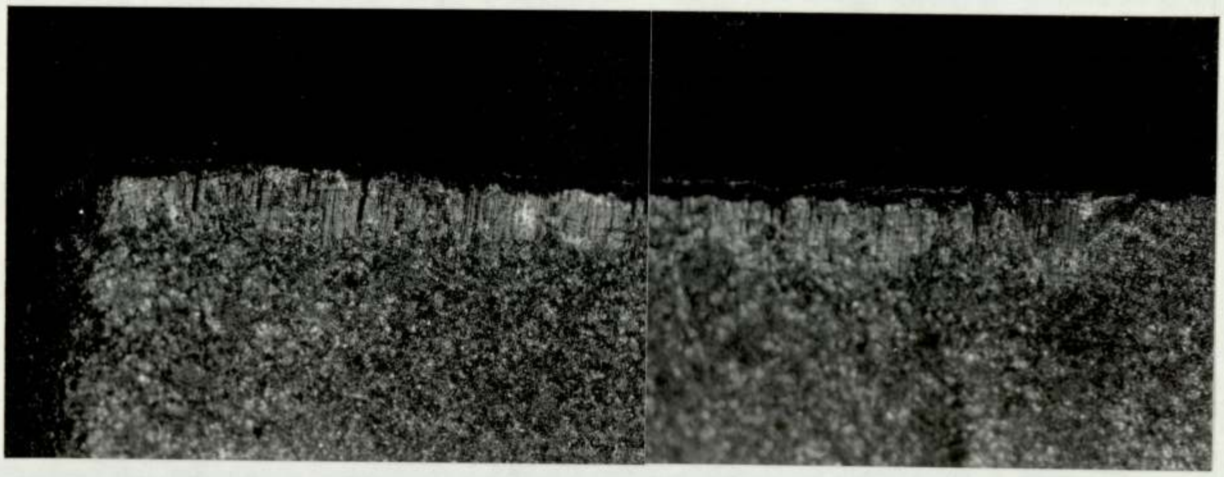


(b) very light tracks of chips shown as scratches on the rake face of the coated tool type T_4

Figure 4.24: Scanning electron micrographs showing the crater wear of the uncoated WC insert T_2 and the TiN-coated WC insert T_4 after light roughing of En 8 steel for 27 minutes



(a) flank wear land (about 0.6mm width) showing grooving of the flank face of the uncoated tool type T_2



(b) flank wear land (about 0.1mm width) of the coated tool type T_4 with much less grooving

Figure 4.25: Optical photomicrographs showing the flank wear of the uncoated insert T_2 and the coated insert T_4 after light roughing of En8 steel for 27 minutes (x 60)

Table 4.5: Values of cutting 'tangential' force Fz and 'radial' force Fy obtained during finish turning of En8 steel

Cut Operations	Cumulative cut time (sec)	Forces on tools (N)			
		Tangential Fz		Radial Fy	
		T_1	T_3	T_1	T_3
1	2	160	235	95	125
10	24	240	235	105	120
20	45	240	230	105	120
26	56	240	240	110	130
32	67	250	240	115	130

T_1: Uncoated tool

T_3: Coated tool

* Axial force not recorded due to a dynamometer fault

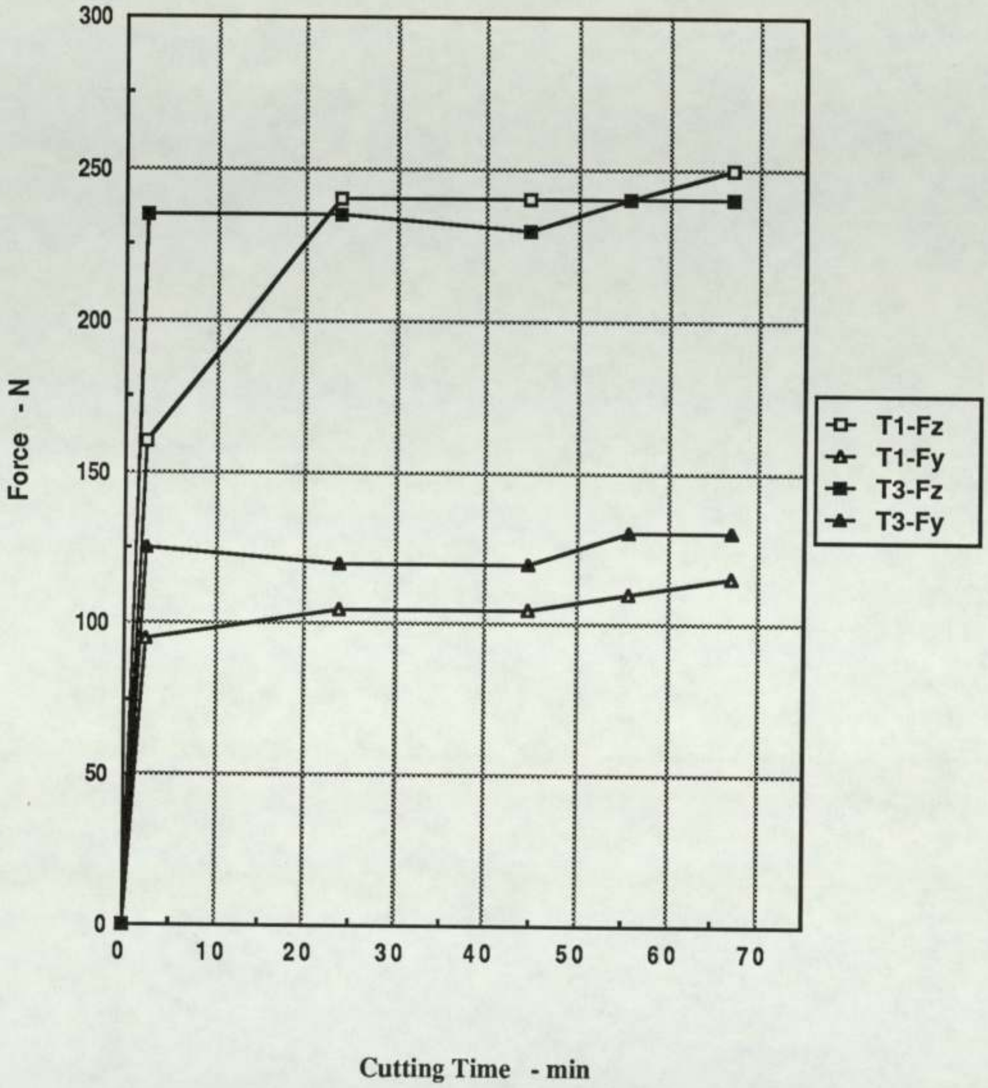


Fig.4-26: Variation of Forces With Time in Finish Cutting En8 Steel

with Uncoated"T1" and Coated"T3" Turning Inserts

(Cut. Speed: 150 m/min ; Feed: 0.15 mm/rev ; Cut. Depth: 1.0 mm)

Figure 4.27 shows the extent of crater wear developed on the working tips of both tools. Figure 4.27a shows the tip of the uncoated tool revealing a big notch on the main cutting edge and a smaller one on the minor cutting edge. A crater of significant size developed between the two notches, at a region beyond the nose radius. Figure 4.27b shows the tip of the coated tool revealing wear features totally different from those of the uncoated tool. There is no clear notch on the cutting edge, but a considerable amount of oxides and dark coloured products cover, almost, the whole rake face of the tip, with an indication of crater wear but the characteristics are different from those of the uncoated tool (Figure 4.27a). Higher magnifications of regions inside each crater wear area are shown in the micrographs c and d, where the difference in wear mechanisms is evident.

Figure 4.28 shows optical micrographs of rake faces of the two inserts. Figure 4.28a shows the worn tip of the uncoated tool with a deep notch associated with a crack in its bottom. Figure 4.28b shows the worn tip of the coated tool with a shallow notch and a smoothly polished surrounding zone.

4.4 Machining Stainless Steel at Medium Cutting Speeds

4.4.1 Introduction

Low production rates, poor product quality, and rapid deterioration of the cutting tool are usually associated with the machining of stainless steels. Low cutting speeds are normally employed as these materials are difficult to machine. Consequently, coatings applied to conventional cemented carbide inserts were expected, either to provide beneficial results compared with those achieved with uncoated tools subjected to the same cutting tests, or to enable machining of stainless steel at speeds higher than those used when uncoated tools were involved. Moreover, the way in which machining tests were conducted might have notable effect on tool wear and workpiece surface finish. The results presented in this section were obtained in one series of coontinuous rough and finish cutting operations, and in another series of interrupted ones, employing a number of uncoated and coated tool tips as described in the previous chapter.

4.4.2 Continuous and Interrupted Rough Turning

The results obtained after measurement of flank wear width and nose deformation length are shown in Table 4.6. Data corresponding to continuous rough cutting operations are presented in Table 4.6(a), and those corresponding to interrupted rough operations are presented in Table 4.6(b). Two types of tools were used: the uncoated tool S6 P40 (T_2) and the coated tool GC4 35 P35 (T_4) which was coated with triple layer of TiC, Al_2O_3 and TiN.

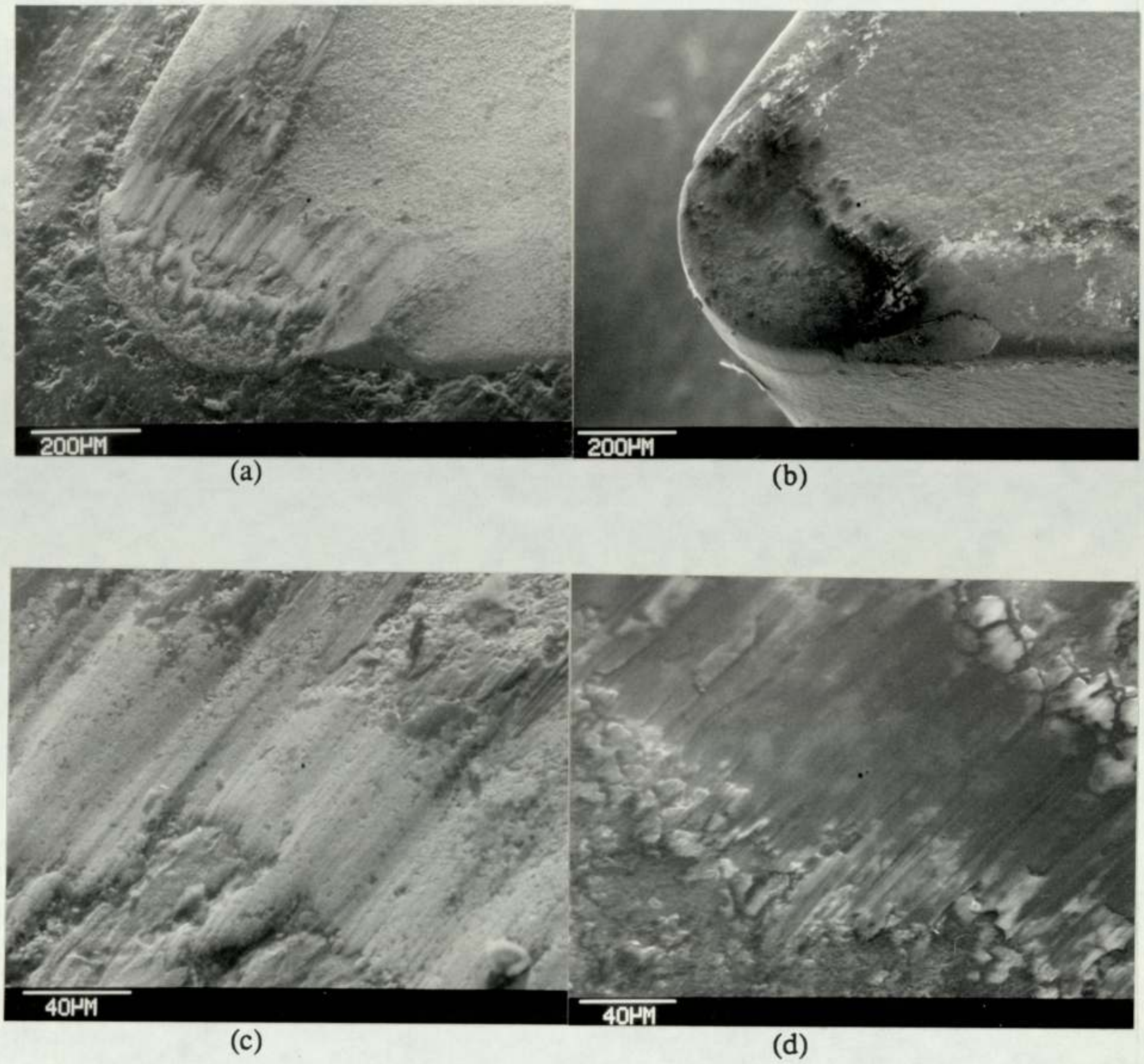


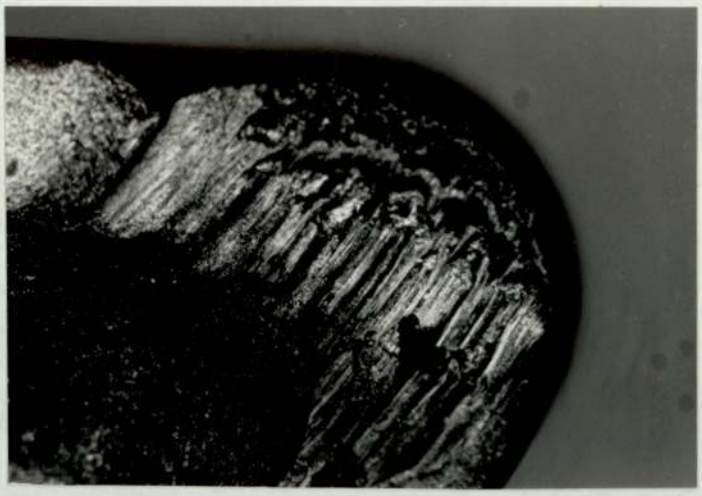
Figure 4.27: Scanning electron micrographs of the working tip of the uncoated tool T_1 and the coated tool T_3 after finish turning of En8 steel for 67 minutes.

(a) crater wear of T_1, a big notch on the main cutting edge has joined up to a smaller one on the minor cutting edge

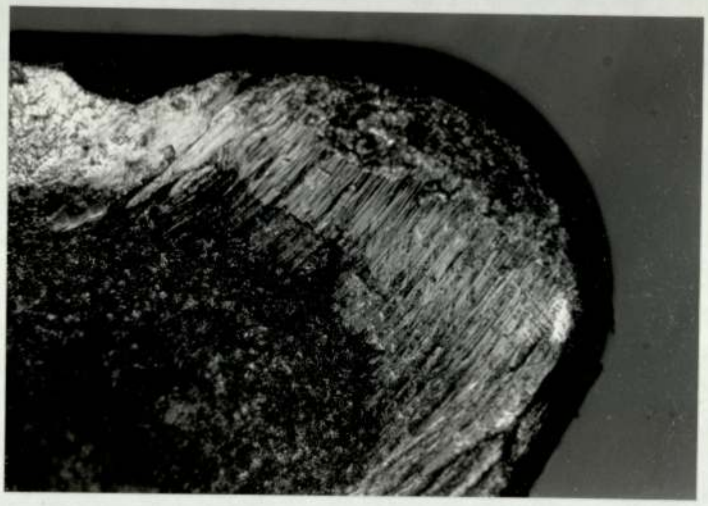
(b) shallow crater wear of T_3, significant oxides and adherent particles are visible

(c) plastic deformation and heavy abrasion tracks in the crater wear region of T_1

(d) oxidative wear and light abrasion tracks in the crater wear region of T_3



(a) rough crater wear and deep notch on uncoated tool T_1



(b) smooth crater wear and shallow notch on coated tool T_3

Figure 4.28: Optical photomicrographs of the uncoated and coated tool rake face showing the crater wear characteristics after finish turning of En8 steel for 67 minutes

Table 4.6: Data obtained during rough cutting of stainless steel with uncoated 'T_2' and coated 'T_4' turning inserts: (a) continuous roughing (no stoppages); (b) interrupted roughing (5 equidistant stoppages)

Cut Operation	Cut speed (m/min)	Cut time (sec)	F Wear Width (mm)		Nose deformation (mm)	
			T_2	T_4	T_2	T_4
R	62	100	0.064	0.057	0.432	0.487
R	78	80	0.067	0.080	0.503	0.575
R	94	60	0.114	0.086	0.659	0.589

(a)

Cut Operation	Cut speed (m/min)	Cumu-lative cut time (sec)	Flank Wear (mm)		Nose deformation (mm)	
			T_2	T_4	T_2	T_4
R1	62	20	0.055	0.046	0.268	0.086
R2	62	40	0.080	0.071	0.358	0.105
R3	62	60	0.083	0.078	0.369	0.118
R4	62	80	0.089	0.083	0.377	0.121
R5	62	100	0.115	0.091	0.452	0.156
R1	78	16	0.055	0.065	0.319	0.065
R2	78	32	0.108	0.065	0.484	0.082
R3	78	48	0.108	0.071	0.517	0.101
R4	78	64	0.111	0.086	0.528	0.133
R5	78	80	0.134	0.093	0.632	0.192
R1	94	12	0.076	0.059	0.524	0.032
R2	94	24	0.085	0.069	0.568	0.113
R3	94	36	0.112	0.082	0.680	0.153
R4	94	48	0.118	0.085	0.739	0.183
R5	94	60	0.118	0.095	0.762	0.242

(b)

4.4.2.1 Effect of Continuous and Interrupted Cutting on Flank Wear

Figure 4.29(a) shows comparison between flank wear width after continuous cutting and interrupted cutting with uncoated tool type T_2 at a set of three different speeds. Figure 4.29(b) shows the corresponding values when cutting with a coated tool, type T_4. Interrupted cutting was more detrimental than continuous cutting to both uncoated and coated tools. However, the coated tools were clearly more wear resistant than the uncoated ones in both cases of continuous and interrupted operations.

4.4.2.2 Effect of Continuous and Interrupted Cutting on Nose Deformation

Figure 4.29(c) shows the length of deformation that occurred on the nose of uncoated tools T_2 after continuous and interrupted cutting operations. Similarly Figure 4.29(d) shows the corresponding values of nose deformation detected on the coated tools type T_4. The uncoated tools deformed at the nose during interrupted cutting more than during continuous cutting operations. Nose deformation of the coated tools was reduced significantly in interrupted cutting. On comparing the nose deformation during continuous cutting, the uncoated tool performed better at the two lower speeds while the coated tool performed better at the higher speed. However, in both cases the difference in performance between the two types of tools is very small. On the other hand, when comparing the lengths of nose deformation that occurred on the coated and uncoated tools during interrupted cutting the difference in performance is quite significant. The nose deformation of coated tools was only 32% of that occurring on uncoated ones.

4.4.2.3 Development of Wear During Interrupted Cutting

Figure 4.30 illustrates flank wear development with cutting time, and the effect of a coating system on tool wear compared with wear of uncoated tools used at

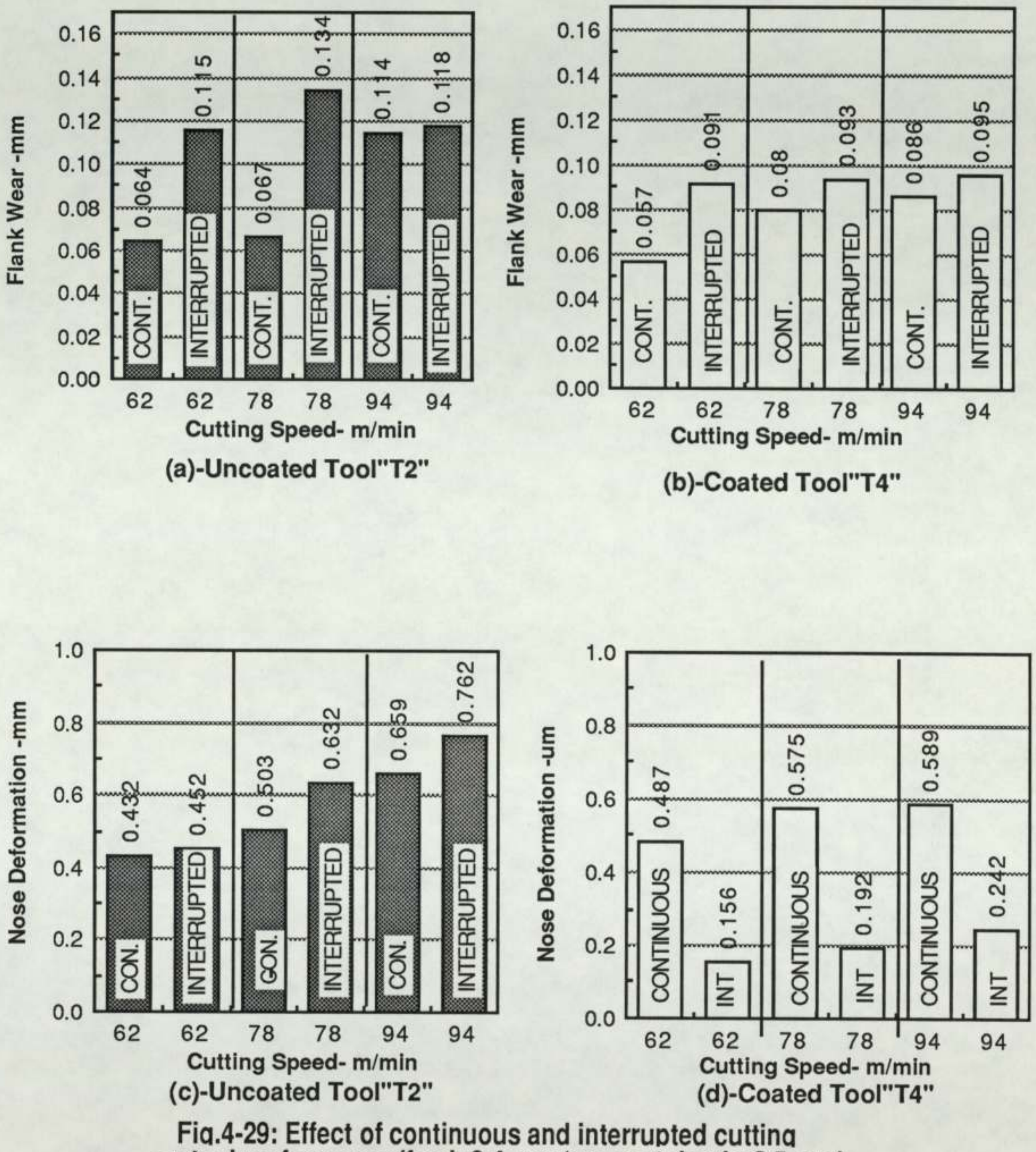


Fig.4-29: Effect of continuous and interrupted cutting on tool performance (feed: 0.4 mm/rev ; cut depth: 2.5 mm)

different speeds. Performance of coated tools at the three cutting speeds was better than that of the uncoated tools. In both cases flank wear increased with the increase in cutting time but as the cutting time increased wear of uncoated tools developed more rapid than of coated tools. The curves related to uncoated tools showed typical tool wear curve shapes, especially in Figures 4.30(a) and 4.30(b) where three zones of wear were detected:

(1) initial wear zone (wear-in period)

(2) normal wear zone (uniform wear period); and

(3) accelerated wear zone (excessive and rapid wear period).

On the other hand, the shape of wear curves of the coated tools showed a continuous, but slow progression with time and no distinct periodical wear zones.

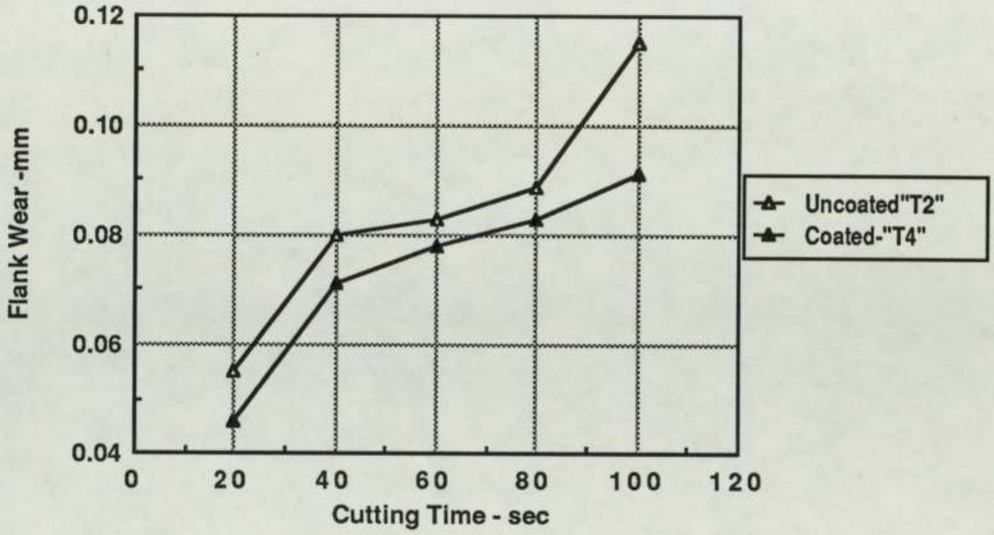
4.4.2.4 Development of Nose Deformation During Interrupted Cutting

Figure 4.31 illustrates the progress of nose deformation length with respect to cutting time for interrupted operations using uncoated T_2 and coated tool T_4. Nose deformation of uncoated tools increased significantly with the increase of cutting speed and the increase of time, while that of coated tools recorded a very small increase with both speed and time.

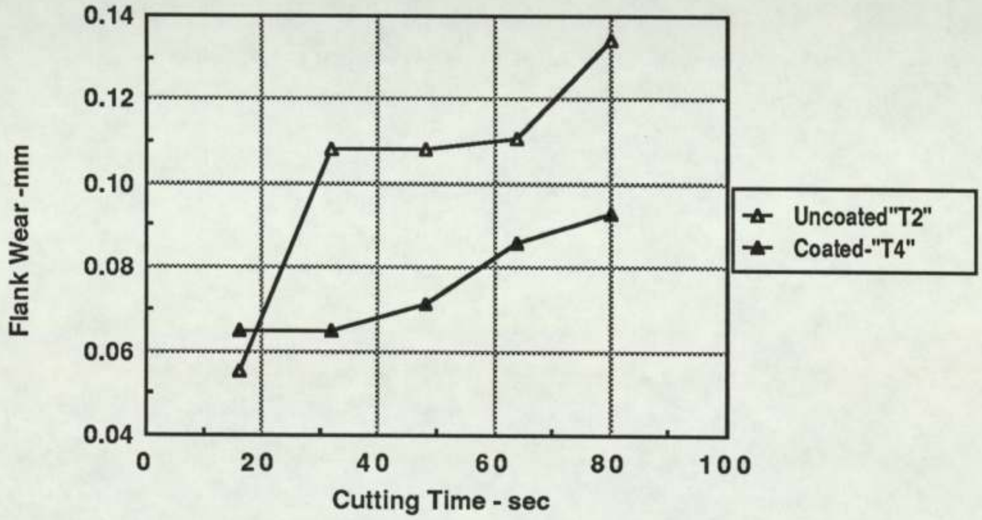
The shape of the nose deformation curves related to the uncoated tools were similar to those of the flank wear of the same type of tools. This indicated a probability of correlation between flank wear and nose deformation particularly in the case of uncoated cemented carbide tools.

4.4.3 Continuous and Interrupted Finish Turning

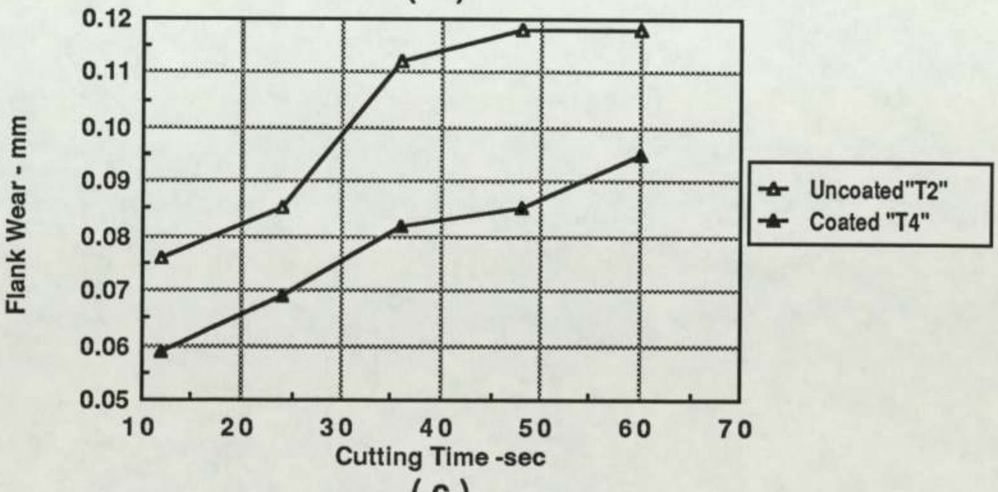
The results obtained after measurement of flank wear width and workpiece surface finish are shown in Table 4.7. Data of continuous finish cutting operations



(a)



(b)



(c)

Fig.4-30: Variation of Flank Wear with Time During Interrupted-Rough Cutting At Cut. Speeds (a) 62 (b) 78 (c) 94 m/min (Work Mat.: Stainless Steel; Feed : 0.4 mm/rev ; Cut. Depth : 2.5 mm)

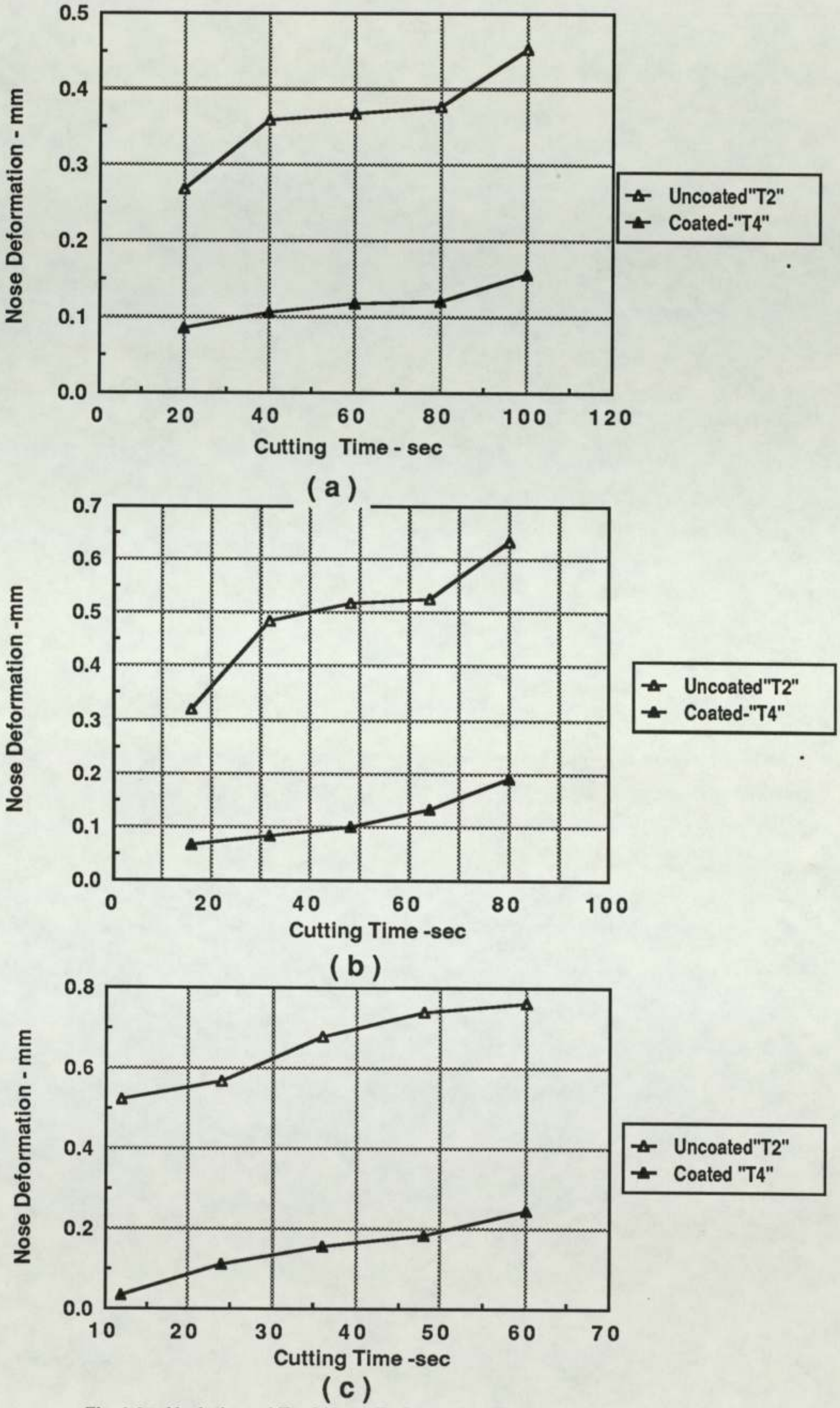


Fig.4-31: Variation of Tool Nose Deformation During Interrupted Rough Cutting At Cut. Speeds (a) 62 (b) 78 (c) 94 m/min
(Work Mat.: Stainless Steel; Feed : 0.4 mm/rev ; Cut. Depth : 2.5 mm)

are presented in Table 4.7(a), and those for the interrupted finish operations in Table 4.7(b). However, it was very difficult to measure the initial wear values at the lower two speeds especially the wear related to the uncoated tool due to a considerable amount of oxides in the vicinity of the working tips. The tools used in the test were the uncoated tool type T_1 (S1P-P10) and the coated tool type T_3 (GC415-P15), coating layers TiC-Al_2O_3-TiN.

4.4.3.1 Effect of Continuous and Interrupted Cutting on Flank Wear

Figure 4.32(a) shows values of flank wear of uncoated tool T_1 measured at the end of each continuous and interrupted finish operation at three different speeds. Figure 4.32(b) shows similar wear values concerning the coated tool T_3 after the same testing programme as that used for T_1. It was evident that the cutting technique had no significant effect on flank wear values, but there is a considerable degree of fluctuation in the results related to the coated tool T_3. However, the uncoated tool performed much better than the coated tool in both continuous and interrupted finishing operations. Considering each tool, the interrupted finish cutting was less harmful to both the uncoated and coated tool than the continuous cutting technique.

4.4.3.2 Effect of continuous and interrupted cutting on surface finish

Figure 4.32(c) shows surface finish values after finish cutting with uncoated tool (T_1), while Figure 4.32(d) shows surface finish after cutting with the coated tool T_3. The same fluctuation detected with flank wear occurred with surface finish in both uncoated and coated tools. However, in continuous finishing the uncoated tools performed slightly better than the coated tools at the three cutting speeds, while in interrupted cutting the coated tool performed better at the lower speed

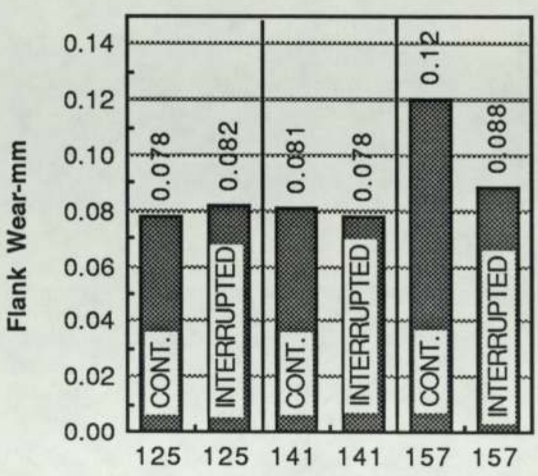
Table 4.7 Data obtained during finish cutting of stainless steel with uncoated 'T_1' and coated 'T_3' turning inserts: (a) continuous finishing (no stoppages); (b) interrupted finishing (5 equidistant stoppages)

Cut Operation	Cut speed (m/min)	Cut time (sec)	Flank Wear (mm)		S finish - CLA (μm)	
			T_1	T_3	T_1	T_3
F	125	150	0.078	0.138	3.27	3.37
F	141	135	0.081	0.178	3.13	3.27
F	157	115	0.120	0.140	2.63	3.00

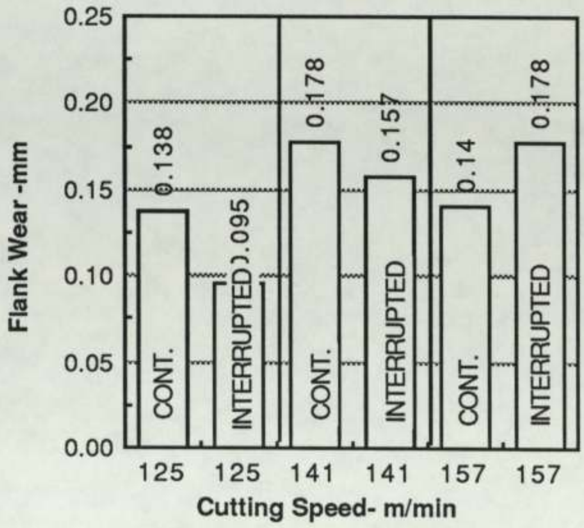
(a)

Cut Operation	Cut speed (m/min)	Cumu-lative cut time (sec)	Flank Wear (mm)		S finish - CLA (μm)	
			T_1	T_3	T_1	T_3
F1	125	30		0.081	2.80	2.83
F2	125	60		0.092	2.73	2.68
F3	125	90		0.085	2.70	2.80
F4	125	120		0.089	2.90	2.63
F5	125	150	0.082	0.095	3.00	2.48
F1	141	27		0.083	2.50	4.80
F2	141	54		0.090	2.68	4.00
F3	141	81		0.106	2.73	4.08
F4	141	108		0.107	2.90	383
F5	141	135	0.078	0.157	3.05	3.95
F1	157	23	0.043	0.087	2.73	3.85
F2	157	46	0.056	0.125	2.90	3.78
F3	157	69	0.062	0.138	2.85	3.85
F4	157	92	0.065	0.143	2.73	3.60
F5	157	115	0.088	0.178	3.03	3.55

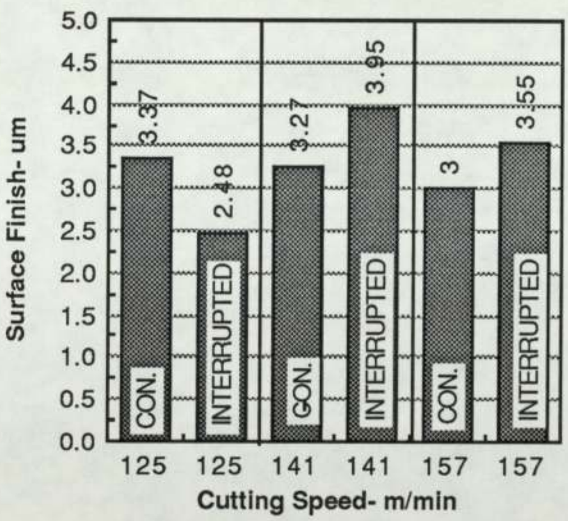
(b)



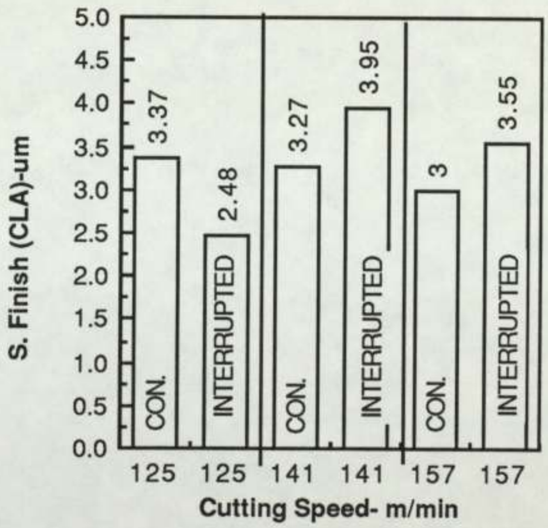
(a)-Uncoated Tool"T1"



(b)-Coated Tool"T3"



(c)-Uncoated Tool"T1"



(d)-Coated Tool"T3"

Fig4.32: Effect of cutting operatin on tool during finish cutting of stainless steel(feed:o.15mm/rev;depth of cut:1.0mm)

better than the uncoated tool which performed marginally better at higher speeds. Most probably, behaviour of both types of tools during finish turning, whether continuous or interrupted, is influenced by the high temperature generated at the workpiece/tool interface. There was considerable inconsistency in the results obtained which was largely due to the effect of the transient conditions of the tool working tip.

4.4.3.3 Variation of Surface Finish with Cutting Time

Figure 4.33 shows finish performance of uncoated and coated tools used in interrupted finishing operations carried out at three different speeds. Up to 100 seconds of cutting at speed 125 m/min performance of the two tools was the same, then the surface finish produced by the uncoated tool degraded rapidly while that produced by the coated tool improved with the increase of time. At the other two speeds, 141 m/min and 157 m/min the surface finish corresponding to the coated tool was rougher than that of the uncoated one, but it showed a trend of improvement the longer time it remained in use. On the other hand, the quality of the workpiece surface machined with the uncoated tool was far better than that of the coated tool at the start of cutting, with the exception of the lowest speed. After longer times of tool engagement the workpiece surface finish produced using coated tools improved while that produced by the uncoated tool deteriorated.

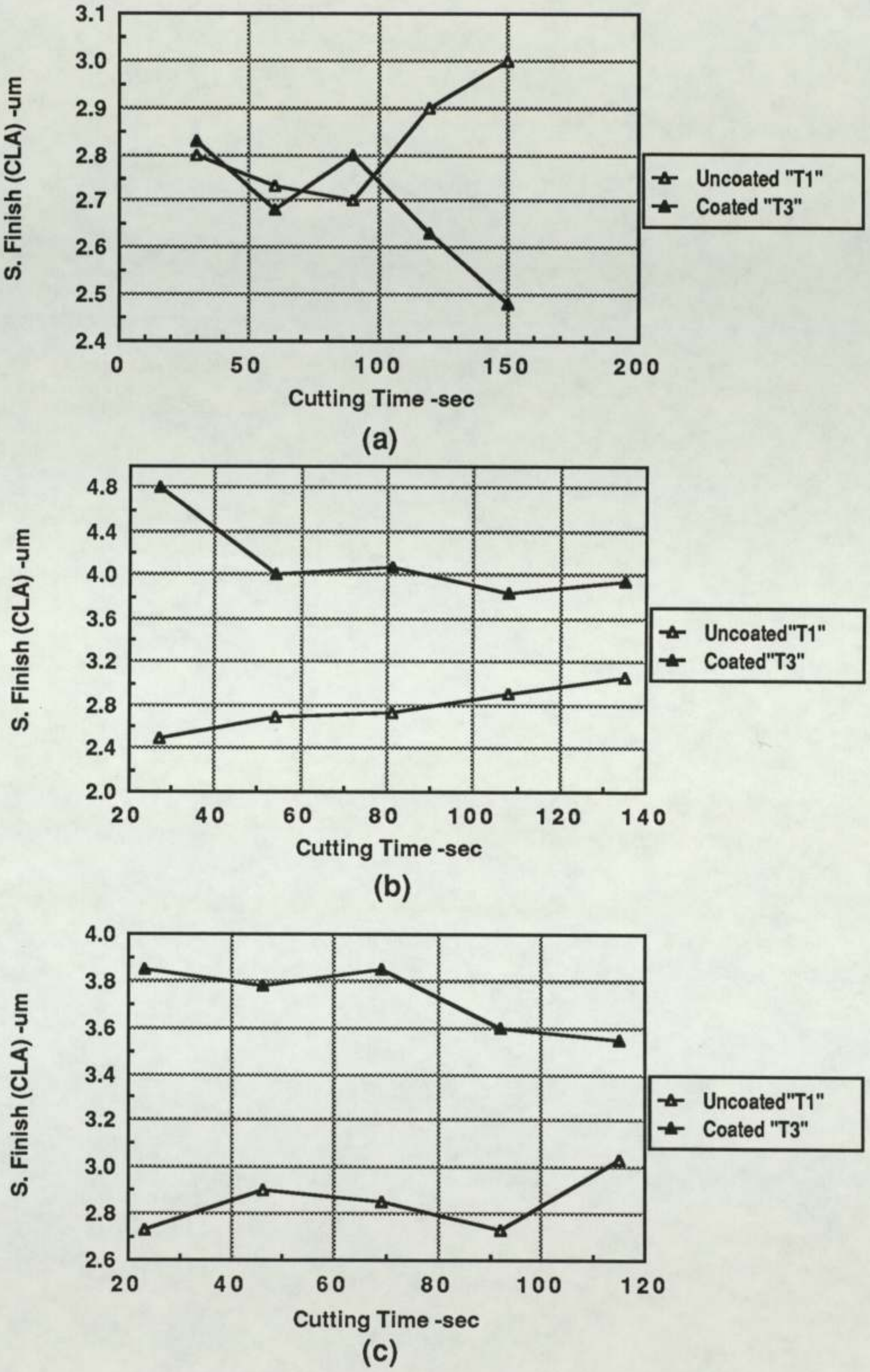


Fig.4-33: Variation of Surface Finish During Interrupted
Finish Cutting at Speeds (a)125 (b)141 (c)157 m/min
(Work Mat.: Stainless Steel ; Feed: 0.15mm/rev ; Cut. Depth: 1.0 mm)

4.5 Machining Stainless Steel at High Cutting Speeds

4.5.1 Introduction

Although the experimental design and objectives of this phase of the research programme have been discussed in the previous chapter, it is worthwhile indicating that the results presented in this section were expected to be more comprehensive than the previous ones. These results are related to rough and finish machining at higher cutting speeds, conducted with seven types of indexable turning inserts which could be categorized in different groups according to their substrates, geometries, coating systems and coating thicknesses. A strong foundation for constructive assessment has been established by including results from an extensive metallurgical examination of different parts of the tools' working tips.

4.5.2 Rough Turning Operations

4.5.2.1 Forces on the Cutting Tools

Results of measurement of the three components of forces acting on the tool during cutting are given in Table 4.8. F_Z represents the tangential or vertical force which is often called the cutting force, F_X represents the axial force or the feed force, and F_Y represents the radial force which acts against the tool. The latter is usually the smallest of the three and has no significant effect on the machining system, consequently it it usually ignored during metal cutting research. However, it is clear that it has a significant value when cutting stainless steel. The data corresponding to the uncoated tool type T_1 in the table are not complete because this tool failed suddenly by fracture of the working tip after performing the first cutting operation in 50 seconds and broke after just three seconds in the second operation thus indicating its unsuitability for this type of cutting operation.

Figures 4.34, 4.35 and 4.36 show the variation of the cutting force, feed force, and radial force respectively. The force-time curves illustrate the significant

Table 4.8: Summary of forces measured during rough cutting with uncoated tools T_1, T_2 and coated tools T_3, T_4, T_5, T_6 and T_7

Cut No	Cum cut time (sec)	Forces of T_1 (N)			Forces of T_2 (N)			Forces of T_3 (N)			Forces of T_4 (N)			Forces of T_5 (N)			Forces of T_6 (N)			Forces of T_7 (N)		
		F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y
R_1	50	2250	875	638	2450	1153	1019	2300	900	544	2350	975	650	2500	950	600	2500	1000	650	2500	1000	700
R_2	95				2838	1481	1438	2250	975	582	2375	1130	775	2700	1120	670	2700	1100	650	2700	1200	800
R_3	135				2863	1750	1575	2375	1250	638	2425	1230	825	2700	1150	750	2700	1100	700	2750	1250	800
R_4	170				2888	1738	1438	2325	1263	607	2375	1215	800	2700	1200	750	2700	1150	750	2750	1250	850

Machining conditions: Workpiece mat: 316 Stainless steel; Cut speed: 100 m/min; Feed: 0.4 mm/rev; Cutting depth: 2.5mm

R_1-R_4: Consecutive rough operations from 1 to 4.

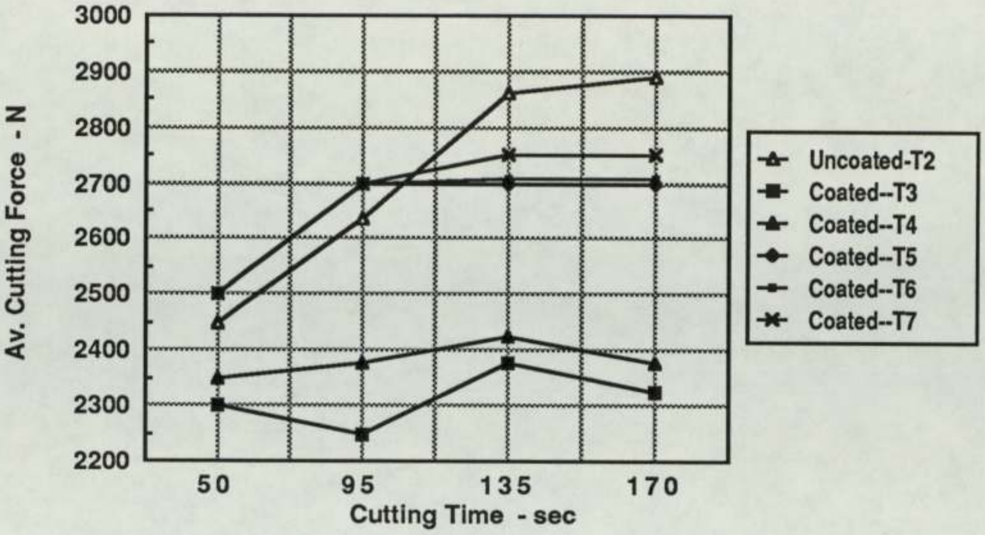


Fig.4-34:Variation of cutting force with cutting time during rough turning of Stainless Steel

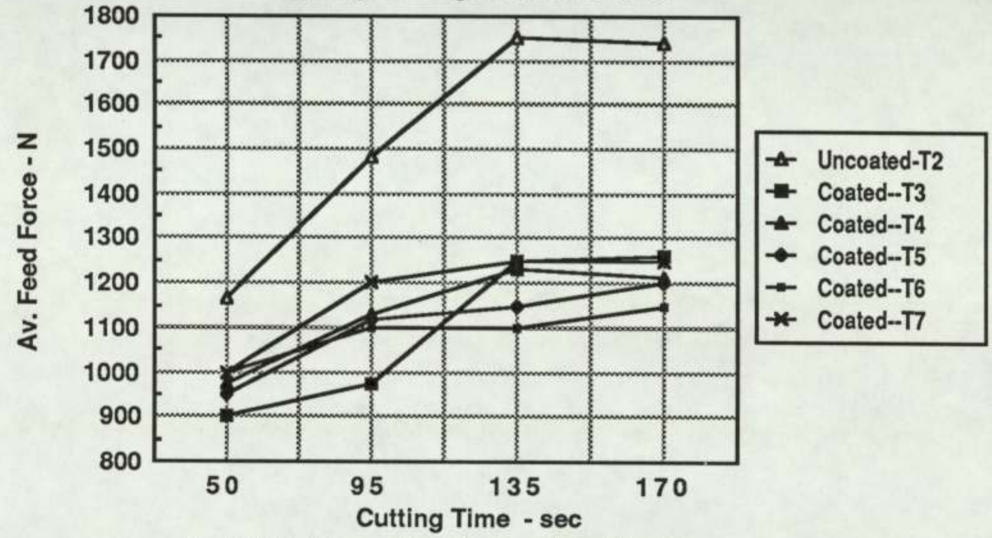


Fig.4-35:Variation of feed force with cutting time during rough turning of Stainless Steel

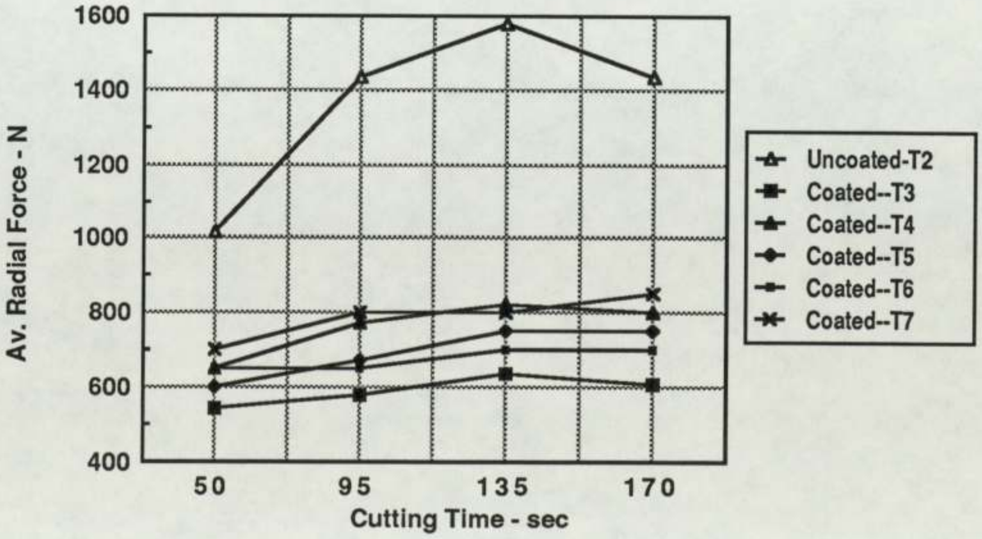


Fig.4-36:Variation of radial force with cutting time during rough turning of Stainless Steel

improvement in performance of the coated tools in comparison with that of the uncoated tool T_2 which did survive these same roughing operations. However, it was subjected to high forces which increased with the increase in cutting time. It was noticeable that all the force curves, even those related to the uncoated tool, changed in behaviour after 135 seconds cutting, when they either remained at constant values or reduced slightly.

4.5.2.2 Flank Wear Measurements

The flank wear widths were measured on the six working tips and the results are shown in Table 4.9. Figure 4.37 illustrates the development of wear with time and reveals the excellent performance of the different coatings in comparison with the uncoated cemented carbide tool. The different coatings reduced flank wear by a percentage ranging from 62 to 80%. The curve shapes and trends are almost the same as those of force-time curves, suggesting a strong relation between forces and flank wear of cutting tools.

4.5.2.3 Metallurgical Studies

Wear characteristics and related features which occurred during rough cutting of stainless steel with uncoated tools (T_1 and T_2), and coated tools (T_3 - T_7), were revealed after close examination by optical and scanning electron microscopy. The uncoated tool type T_1 could not withstand the severe cutting conditions and failed by sudden fracture after 53 seconds of turning. The other tools did survive until the end of the four cutting operations of the test, but significant wear features of differing severity occurred.

Figure 4.38 illustrates optical photomicrographs of the surfaces of the tools' working tips. Figure 4.38(a) illustrates heavy crater wear and nose deformation on the uncoated tool T_2. Figures 4.38 (b), (c) show similar wear characteristics on the rake

Table 4.9: Average flank wear measured progressively during rough cutting with uncoated tools T_1, T_2 and coated tools T_3, T_4, T_5, T_6 and T_7

Cut No	Cum cut time (sec)	Average flank wear width (mm)							Machining conditions
		T_1	T_2	T_3	T_4	T_5	T_6	T_7	
R1	50	0.170	0.328	0.115	0.071	0.079	0.115	0.114	Workpiece mat: 316 Stainless steel
R_2	95	*	0.452	0.186	0.089	0.144	0.125	0.141	Cutting speed: 100 m/min
R_3	135		0.617	0.203	0.120	0.199	0.173	0.165	Feed: 0.4 mm/rev
R_4	170		0.638	0.242	0.125	0.207	0.188	0.177	Cutting depth: 2.5mm

* Working tip broke after 53 seconds cutting time.

R_1 - R_4: Consecutive rough operations from 1 to 4.

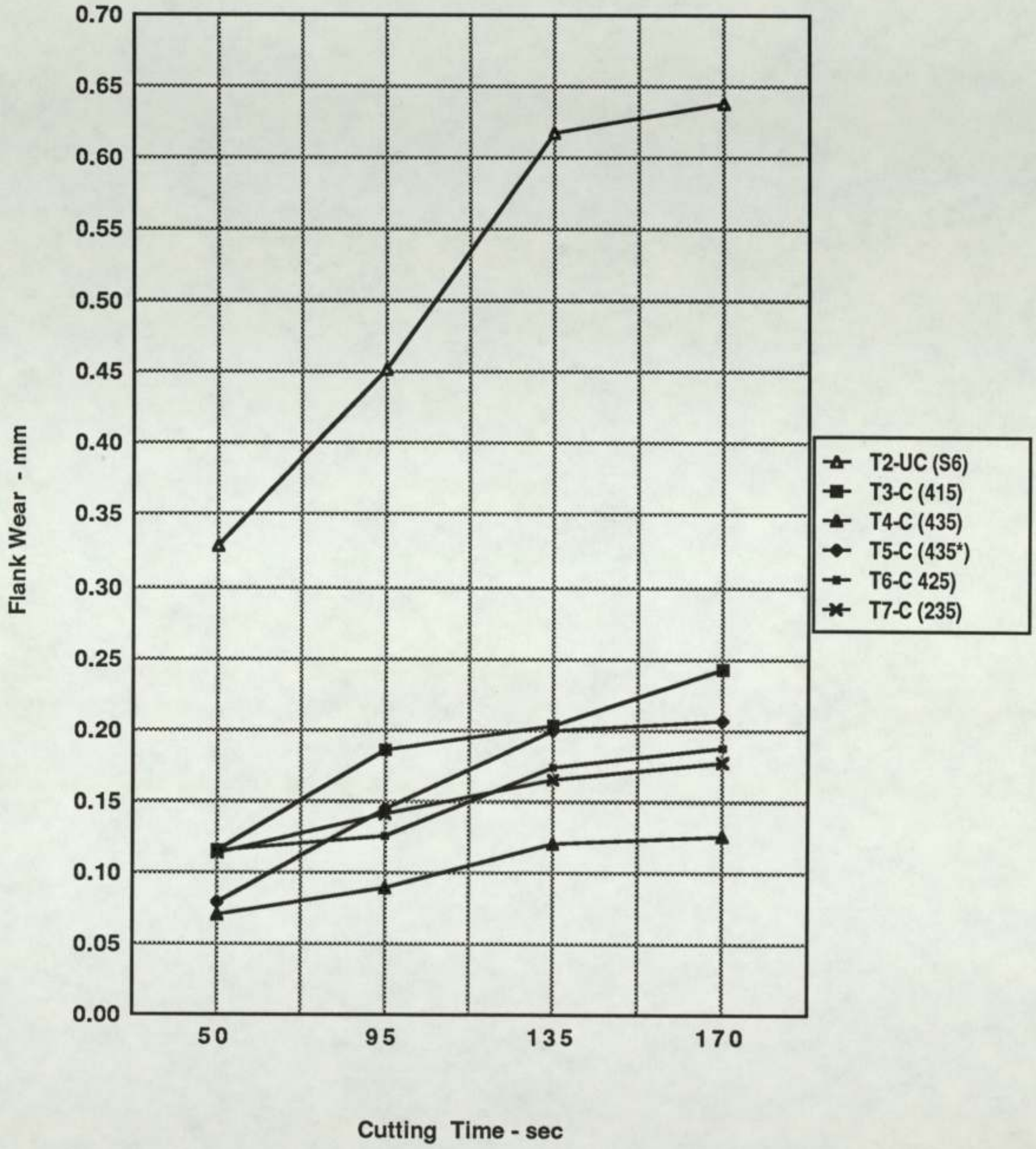


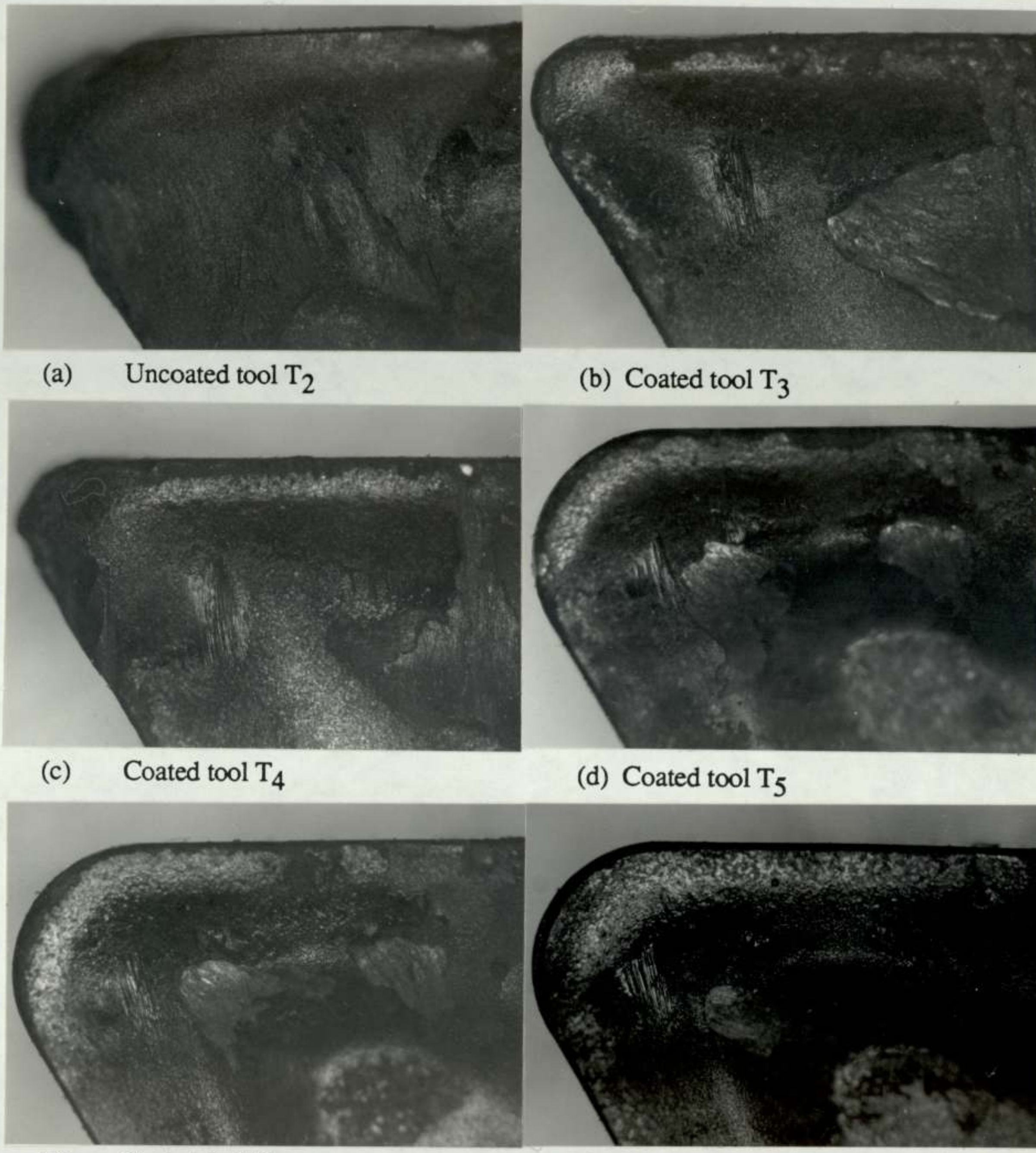
Fig.4-37:Development of Flank Wear with Cut Time During Rough Cutting

Stainless Steel with Uncoated(UC) and Coated(C) Indexable Turning Inserts faces of the similarly coated tools T_3 and T_4, plus slight deformation of tool T_4's nose. Figure 4.38(d) shows the crater wear of tool T_5 which was coated with the same type of coating as T_3 and T_4, and only differs from them in its geometry. Figure 4.38(e) shows the worn rake surface of the coated tool type T_6, and Figure 4.38(f) illustrates the corresponding surface of the coated tool type T_7.

Figure 4.39 illustrates scanning electron micrographs of a fractured tip of the uncoated tool type T_1. The breakage occurred away from the tool nose, straight across the working tip, as shown in Figure 4.39(a). Figure 4.39(b) exhibits some features detected on the fractured edge. The small notch (arrowed) is the remaining part of the primary notch formed on the cutting edge before the occurrence of catastrophic failure. Figure 4.39(c) illustrates secondary crater wear, built-up edge, and notching which existed after fracture of the tool tip.

Figure 4.40 shows the wear characteristics on the working tip surface of the uncoated tool type T_2. The micrographs a, b and c illustrate the presence of a significant amount of adherent substance covering the surface of the tool after cutting, whilst the corresponding micrographs d, e and f show the appearance of the same tool after chemical cleaning. The extent of crater wear, nose deformation and wear, and adherent work material on the rake face were masked partially in the uncleaned state, but these features were revealed fully after cleaning.

Figure 4.41 illustrates scanning electron micrographs of the same tool surface as Figure 4.40 at higher magnification revealing some features which signify the severity of wear of the uncoated tool T_2. The micrograph in Figure 4.41(a) shows the cracked and plastically deformed nose, and notch formation on the end clearance edge (arrowed). Figure 4.41(b) shows a significant amount of workpiece material adhered to the tool rake face at the centre of the crater wear zone. Figure 4.41(c)

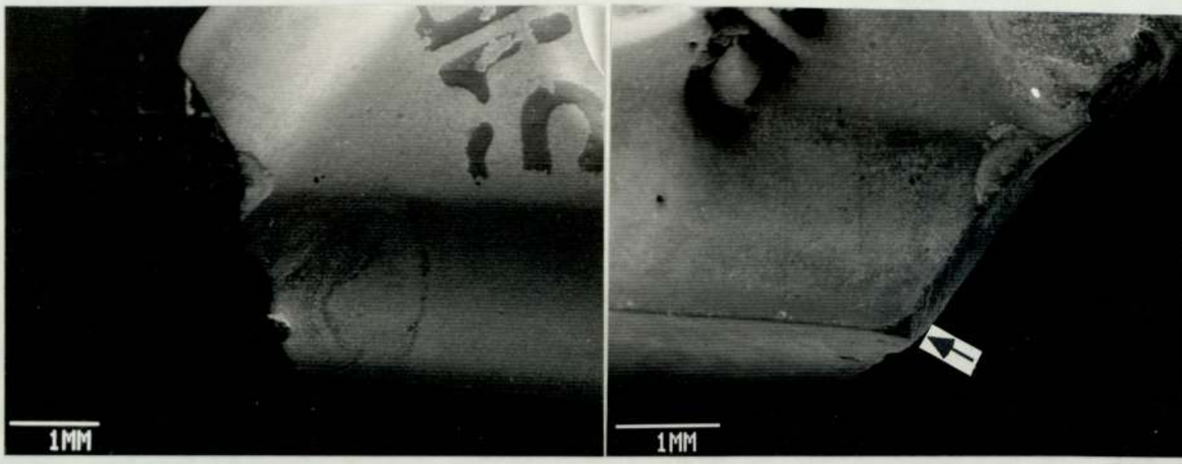


(a) Uncoated tool T_2 (b) Coated tool T_3

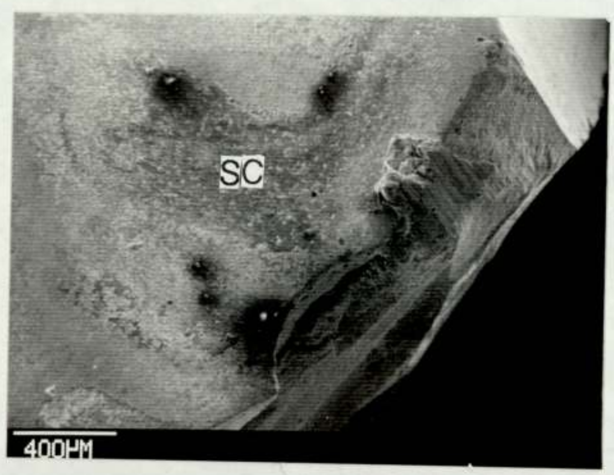
(c) Coated tool T_4 (d) Coated tool T_5

(e) Coated tool T_6 (f) Coated tool T_7

Figure 4.38: Optical photomicrographs of the rake surfaces of the experimental cutting tools showing the different features of crater wear after rough machining of stainless steel for 170 seconds



(a) (b)



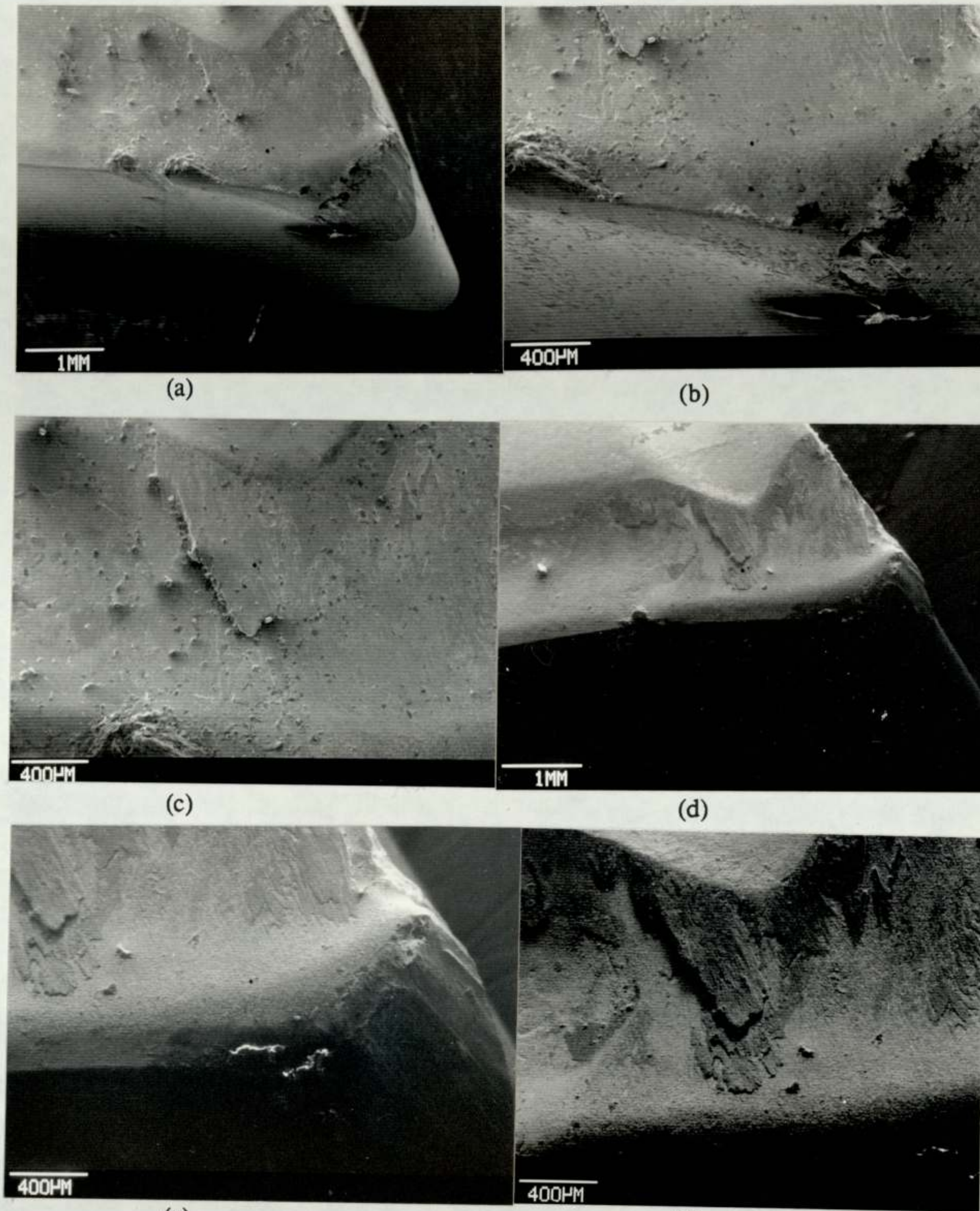
(c)

Figure 4.39: Scanning electron micrographs of the fractured tip of the uncoated tool T_1 showing the different features associated with tool failure after 53 seconds of rough cutting stainless steel;

(a) top view of fractured tip

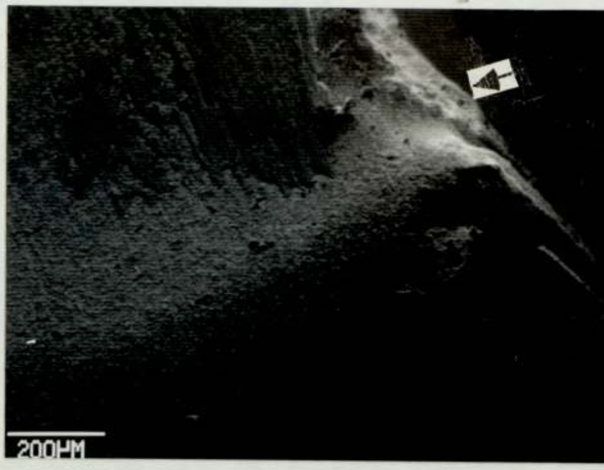
(b) indication of primary notch (arrowed) and chipping of the fractured tip

(c) chipping, BUE and formation of secondary crater (SC) due to cutting after fracture

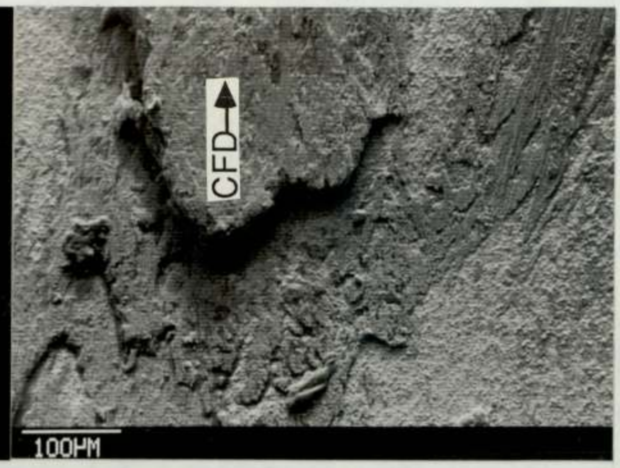


(a) (b) (c) (d) (e) (f)

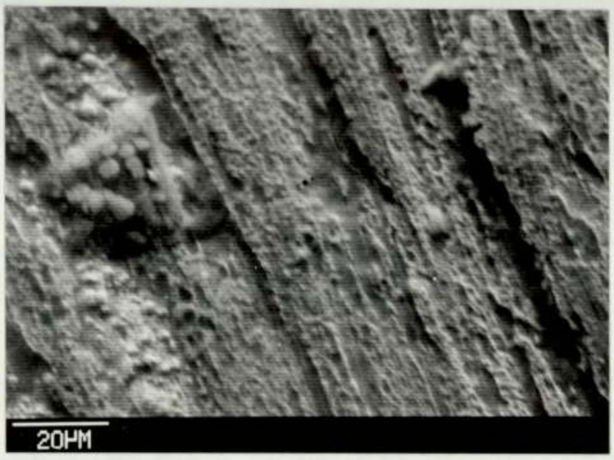
Figure 4.40: Scanning electron micrographs of the uncoated tool T_2 after rough turning of stainless steel for 170 seconds: a, b and c showing the partially masked wear features before chemical cleaning; d, e and f showing the same areas of the working tip after chemical cleaning revealing more wear features



(a)



(b)



(c)

Figure 4.41: Scanning electron micrographs of the same tool surface as Figure 4.40 at higher magnification showing wear of the uncoated tool T_2:

(a) cracked and plastically deformed nose, and notch formation on the end clearance edge (arrowed)

(b) adherent chip material at the centre of the crater wear zone (CFD = chip flow direction)

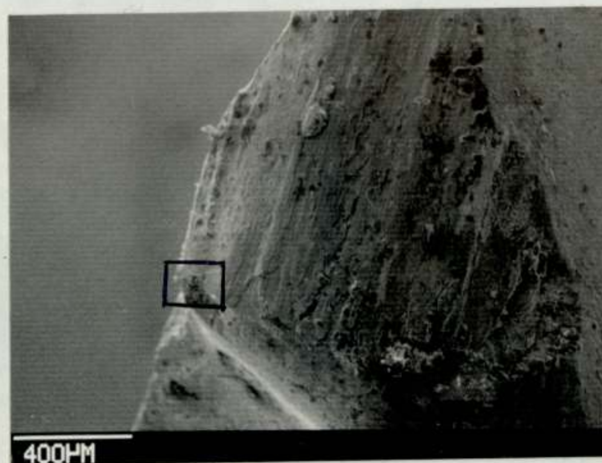
(c) deformation of the adherent metal in the chip flow direction forming 'ridges' and 'valleys' shows adherent metal deformed in the direction of chip flow, forming tracks of long 'ridges' and 'valleys'.

Figure 4.42 illustrates scanning electron micrographs of the working tip of the uncoated tool T_2. Figure 4.42(a) shows the heavily worn nose. The heat generated in this vicinity promoted nose wear and severe plastic deformation in the direction of workpiece rotation (WRD), Figure 4.42(b). Figure 4.42(c) shows localised fracture at the top corner of the nose edge.

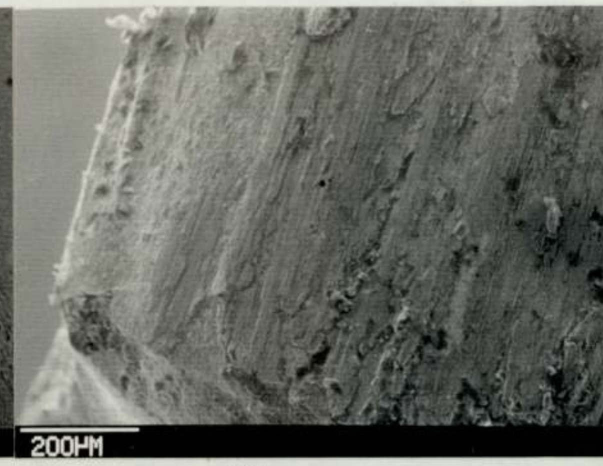
Figure 4.43 shows the extent of cracking and deformation of the cutting edge of the uncoated tool T_3. Figure 4.43(a) exhibits the smoothly deformed edge which contains microcracks of different sizes. Figure 4.43(b) shows a deep longitudinal crack underneath the cutting edge (CE) and just above the flank wear (FW). Figure 4.43(c) displays a magnified view of the crack which is indicated by an arrow in Figure 4.43(a).

Figure 4.44 shows scanning electron micrographs of a cross section through the cutting edge of the uncoated tool T_2. Figure 4.44(a) illustrates the cutting edge deformation observed on both faces of the tool where the dotted lines represent the original face boundaries. Figure 4.44(b) shows the extent of flank wear (FW) under the cutting edge near the end of the cutting depth. Figure 4.44(c) exhibits the worn and void-enriched subsurface of the rake face adjacent to the cutting edge. The same features are shown at the subsurface of the flank wear region (Figure 4.44(d)).

The wear characteristics detected on the coated tools are shown in the scanning electron micrographs in Figure 4.45 to 4.60. Figure 4.45 illustrates different features on the working tip surface of the coated tool type T_3. Figure 4.45(a) shows the front part of the tip where a considerable amount of built-up edges accumulated on the cutting edge and the nose, while crater wear has just initiated on the rake face far from the cutting edge. Figure 4.45(b) shows the rear part of the cutting edge where a



(a)



(b)

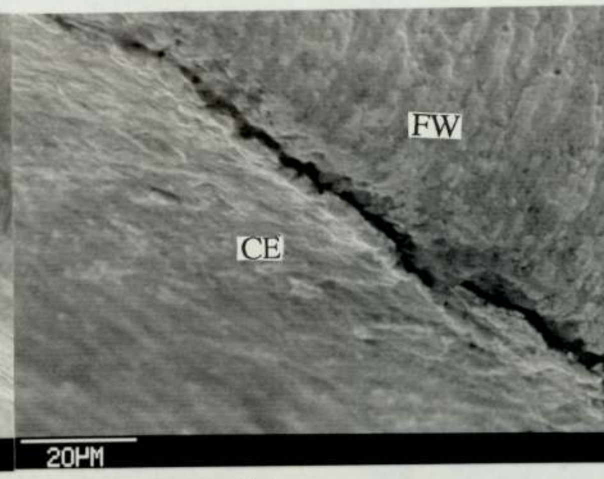
(c)

Figure 4.42: Scanning electron micrographs of the working tip of the uncoated tool T_2 after rough cutting of stainless steel showing the characteristics of wear detected at the nose radius:

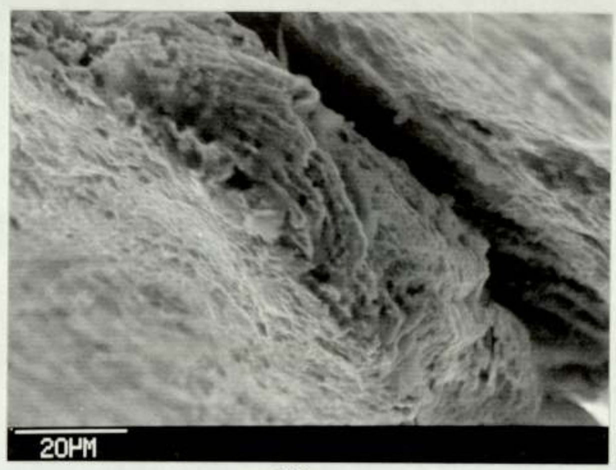
(a,b) the severe plastic deformation of the tool nose;

(c) a region of localised fracture at the nose top edge (squared in micrograph (a))

(a)



(b)



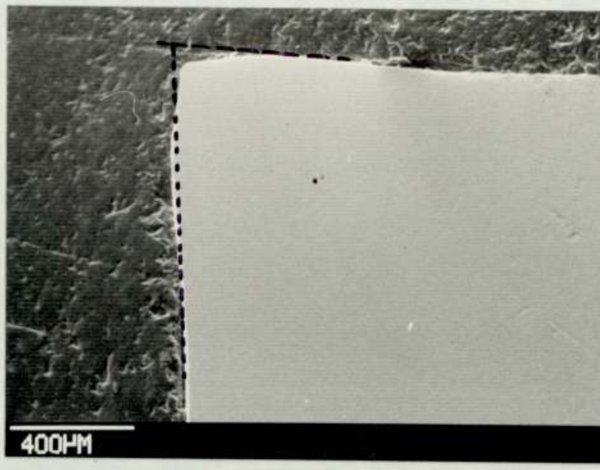
(c)

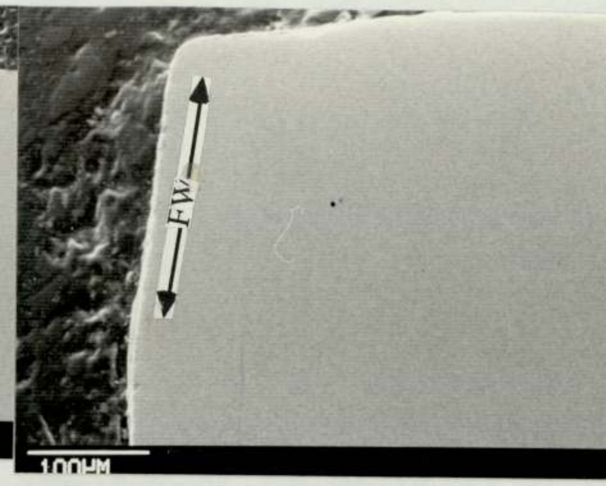
Figure 4.43: Scanning electron micrographs of the cutting edge surface of the uncoated tool T_2 after rough machining stainless steel showing:

(a) cutting edge deformation and microcracking;

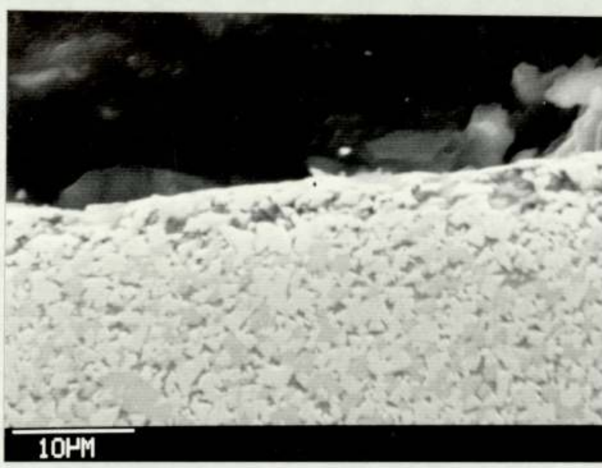
(b) deep longitudinal crack underneath the cutting edge (CE) and just above the flank wear (FW);

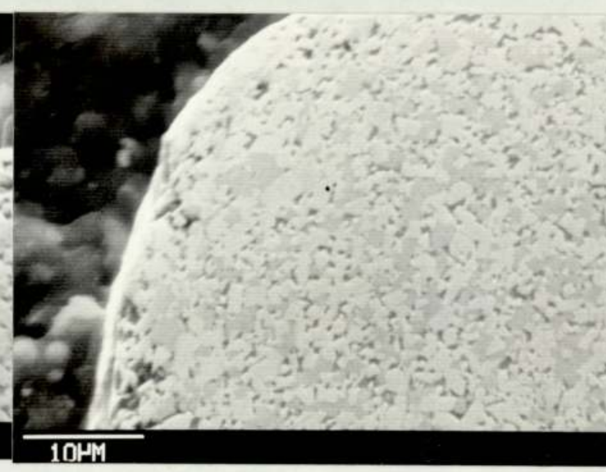
(c) magnified view of the crack in (a) arrowed





(a) (b)





(c) (d)

Figure 4.44: Scanning electron micrographs of a cross section through the cutting edge of the uncoated tool T_2 after rough cutting stainless steel showing the following features:

(a) bulgingly deformed cutting edge (dotted lines represent the original faces)

(b) flank wear site under the cutting edge (FW = flank wear)

(c) subsurface deformation and voids in the rake face near the cutting edge

(d) wear and deformation in the flank face.

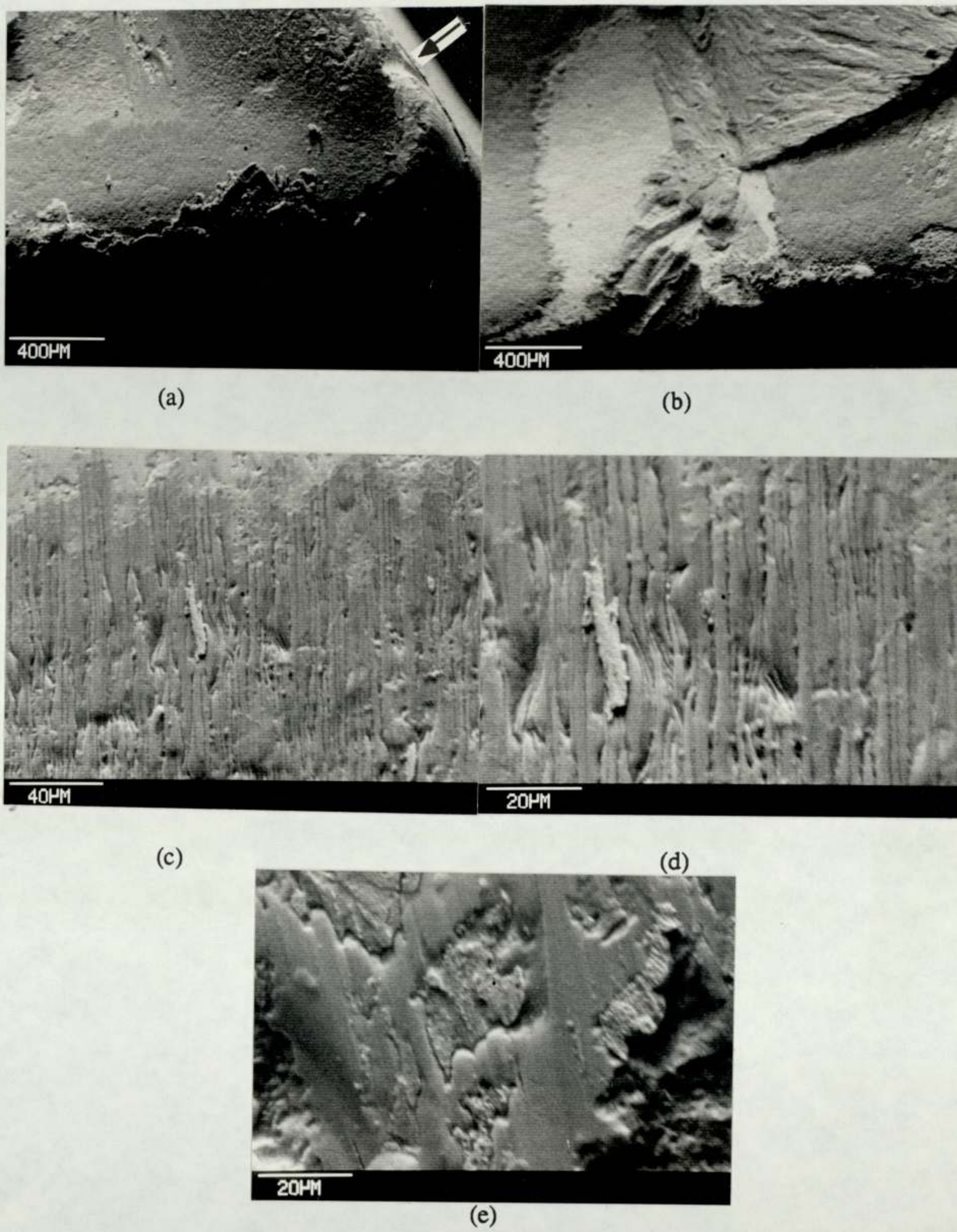
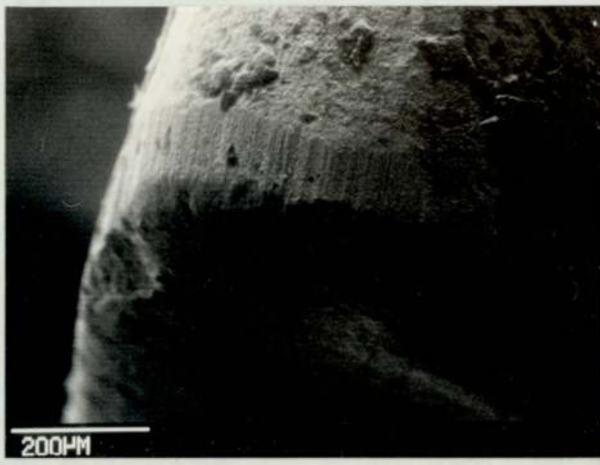


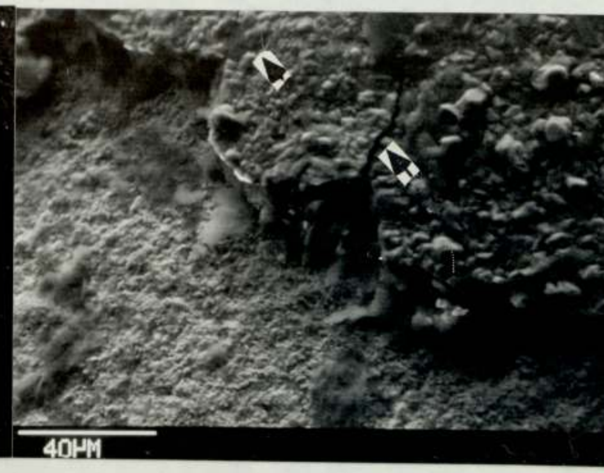
Figure 4.45: Scanning electron micrographs of the working tip surface of the coated tool T_3 after rough cutting stainless steel showing: (a) BUE, crater wear, small notch of the minor cutting edge, and a worn nose, (b) notch at the cutting depth extremity; (c,d) smooth wear region with deformed inclusions in the rake face, (e) rough crater wear with adherent material, erosion and plastic deformation in a region of heavy chip/tool contact

significant notch is formed at the cutting depth extremity, and extended on the rake face. Moreover, a large piece of chip material is welded to the edge of the notch, whilst spots of flaked-off coating are observed the cutting edge. Figure 4.45(c) shows the tracks of the flowing chips on the rake face adjacent to the cutting edge. Fine abrasion grooves, small voids, and microscopic wear debris are evident. Some inclusions deformed longitudinally in the smoothly grooved surface (Figure 4.45(d)). Figure 4.45(e) shows a magnified view of a spot at the bottom of the cratered region. It illustrates the plastically deformed coating associated with adhesive wear and welded fragments of the flowing chips. These features suggest heavy contact between the chips and the tool's rake surface. Figure 4.46 shows the wear features at the nose of tool T_3, where abrasive wear occurred at the front of the nose, appearing as an extension of flank wear (Figure 4.46(a)). Cracking of the coating (indicated by arrows) occurred at the edge of a chipped-off area (Figure 4.46(b)), whilst microcracking of an exposed substrate is shown in Figure 4.46(c).

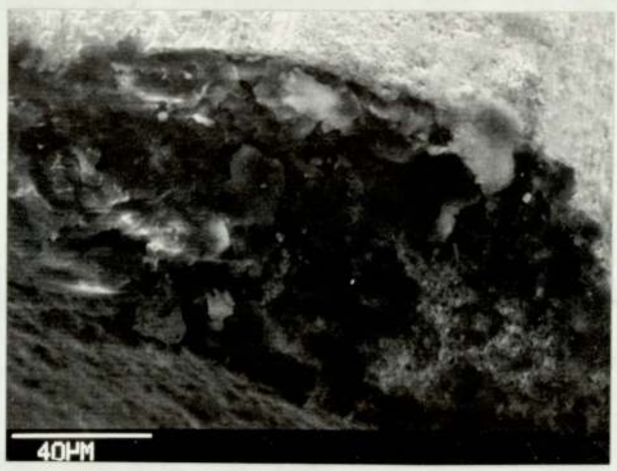
Figure 4.47 shows cross section through the cutting edge of the coated tool type T_3. Figure 4.47(a) illustrates the built-up edge (BUE) and a notch-like flank wear (arrowed). Figure 4.47(b) shows the chip material welded to the cutting edge and curved in the direction of chip flow over the rake face of the tool. The outer edge of the chip is fairly smooth, while the inner side with smaller curvature is quite rough. Figure 4.47(c) indicates the strong adhesion of the built-up edge (BUE) to the cutting edge and no coating layer is detected at this region. However, it seems that the welded chip material has protected the interface from further deterioration such as the features observed at the two corners of the built-up edges as indicated by arrows. Figure 4.47 d, e and f illustrate magnified views of an eroded area on the flank face just under the buiilt-up edges, where 'd' shows the whole curved shape of the notch, 'e' shows the localized void concentration in the subsurface ahead of the notch bottom, and 'f' shows the angular carbides remaining 'loose' in the deformed subsurface with the



(a)



(b)



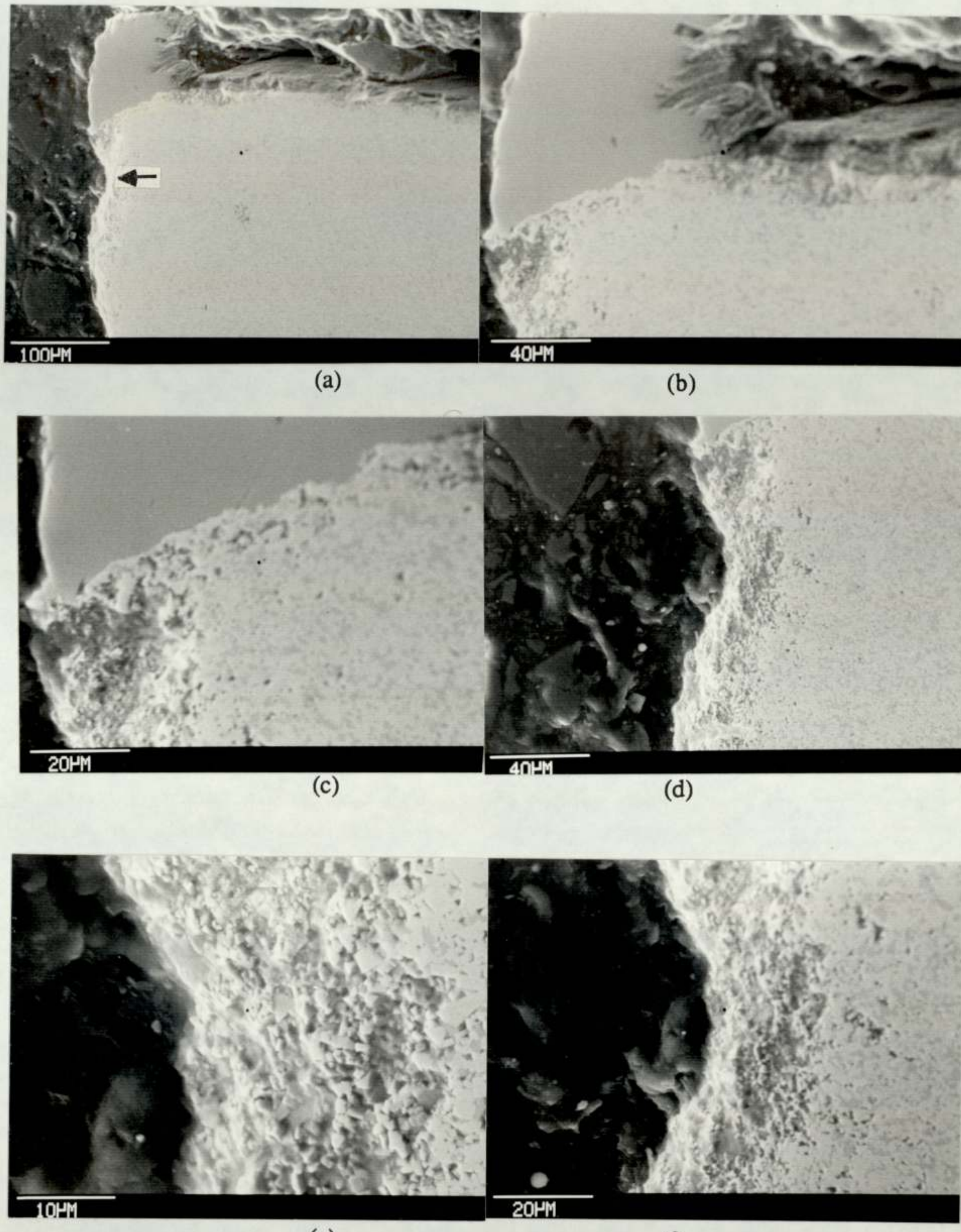
(c)

Figure 4.46: Scanning electron micrographs of the coated tool T_3 after rough cutting of stainless steel showing the different characteristics of nose wear:

(a) nose wear with peeled-off coating and nothing of the minor cutting edge

(b) cracking of the coating (indicated by arrows) at the edge of a chipped-off area

(c) microcracking and subsequent frature of an exposed substrate



(a) (b) (c) (d) (e) (f)

Figure 4.47: Scanning electron micrographs of a cross-section through the cutting edge of the coated tool T_3utrating wear features near the cutting edge: (a) BUE and notch-like flank wear (arrowed); (b&c) localised wear at the sides of BUE which bonds firmly to the cutting edge (d,e,f) show magnified views of localised deformation and binder matrix disintegration

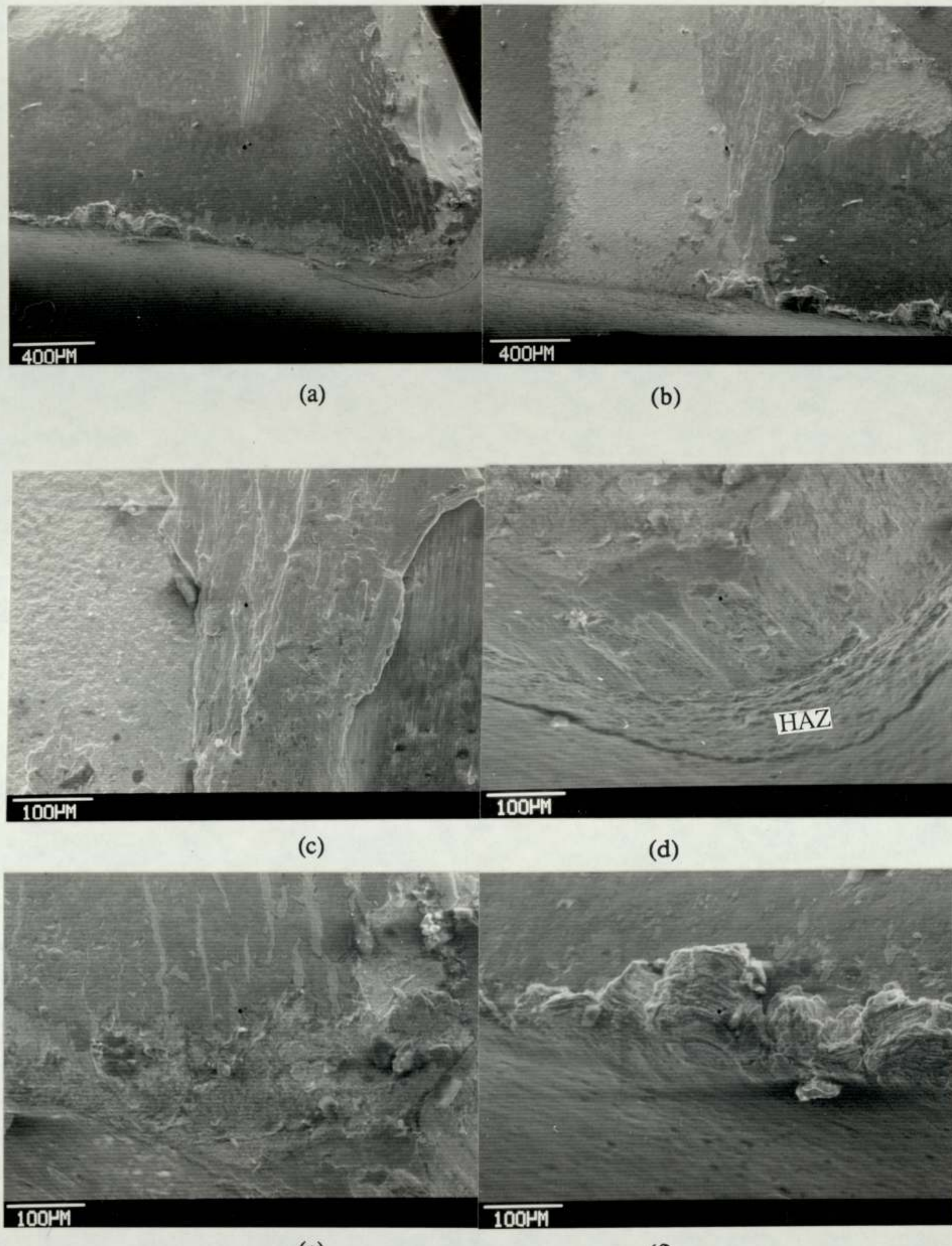


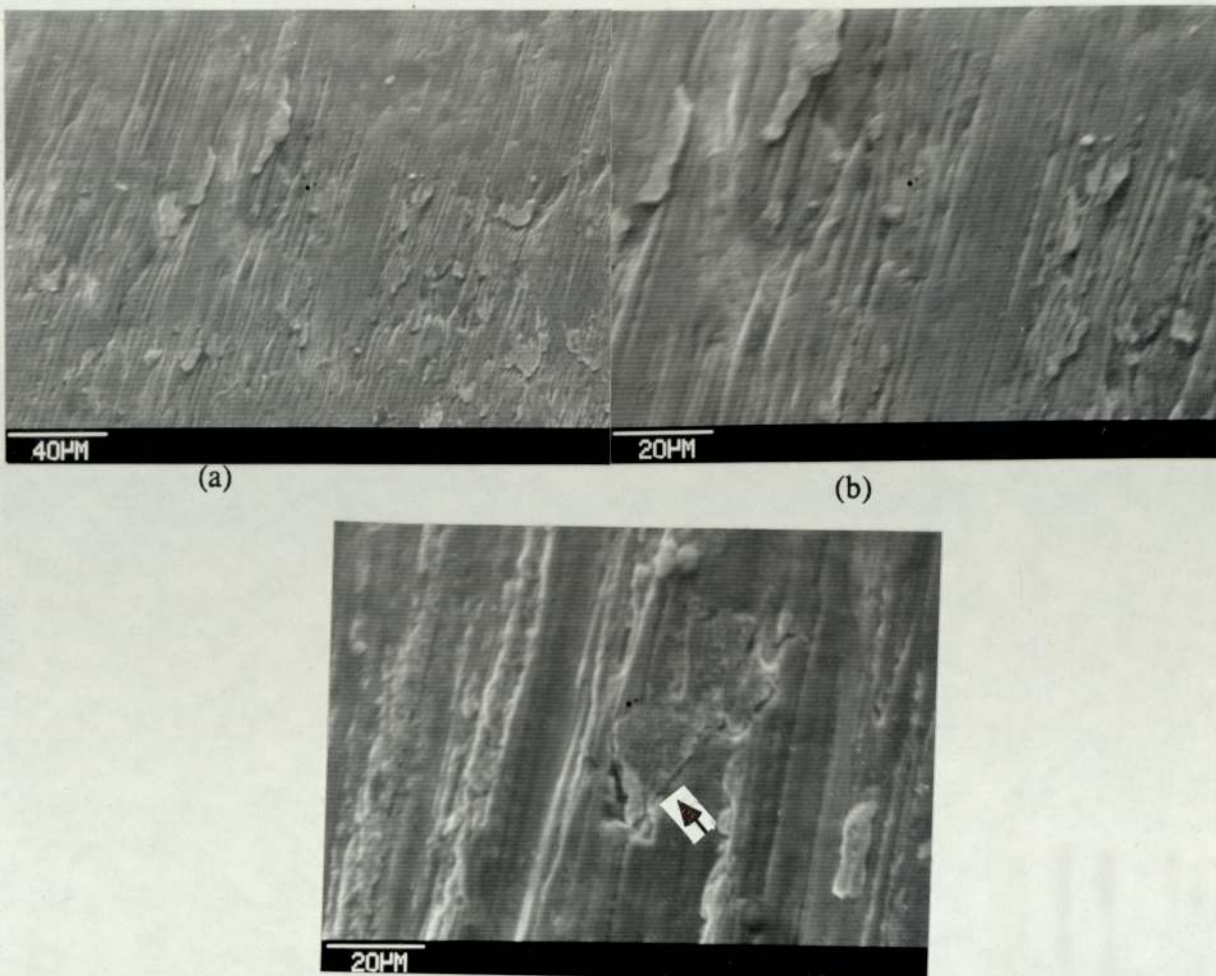
Figure 4.48: Scanning electron micrographs of the working tip surface of the coated tool T_4 after rough cutting stainless steel showing (a) wear characteristics at nose, cutting edge, and rake face, (b) heavy notching and BUE, (c) welded chip smeared over a large area of the notch, (d) plastic deformation of the nose on top of a large heat affected zone (HAZ), (e) nose microcracks above deformed are, (f) BUE of chip material

disintegrated binder matrix.

Figure 4.48 displays the wear features observed on the surface of the coated tool type T_4. The micrograph (a) shows the front part of the working tip with significant nose wear and end clearance face notching, coupled with built-up edge at the cutting edge and an isolated area of crater wear on the rake face. The micrograph (b) shows the cutting edge close to the cutting depth extremity characterized by heavy notching and built-up edges. The micrographs (c) exhibits a welded chip material smeared over a large area of the notch. The micrograph (d) shows the tool nose with heavy wear and plastic deformation on top of a large heat affected zone (HAZ). The micrograph (e) depicts the existance of microcracks above the deformed area (indicated by arrows), while (f) shows part of the built-up edges welded to the cutting edge and small fragments left behind the flowing chips, adhered to the rake face (arrowed).

Figure 4.49 shows details of the crater wear at two different zones on the rake face of the coated tool T_4. Micrograph (a) shows adhering particles and light abrasive grooves in the worn area parallel to the cutting edge. Micrograph (b) displays the deformation of the adherent debris in the direction of chip flow (from bottom to top). Micrograph (c) illustrates the heavily abraded area at the bottom of crater wear away from the cutting edge. Note the deep abrasive grooves embedded with small wear debris and a large inclusion (arrowed), surrounded with microcracks (CFD = chip flow direction).

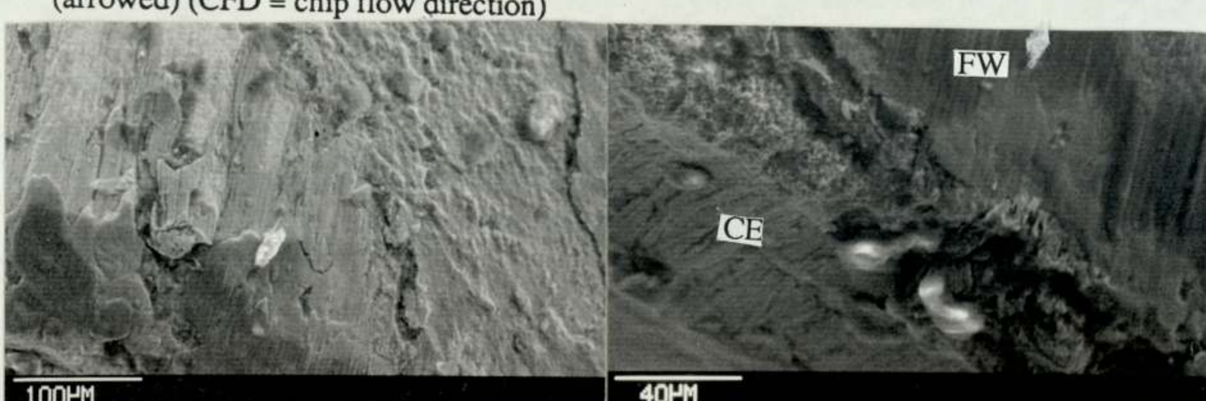
Figure 4.50 shows the flank face of the coated tool type T_4 at the cutting edge close to the nose. Wear features detected on the surface in the nose vicinity are illustrated in Figure 4.50(a) where microcracking and deformation took place in the rough wear 'land' above an area of stripped-off coating as a result of thermal fatigue cracking. Figure 4.50(b) revealed deep and long cracks beneath the cutting edge (CE) and above the smooth flank wear region (FW).



(a) (b)

(c)

Figure 4.49: Scanning electron micrographs of the coated tool T_4 showing the crater wear at two different zones: (a,b) mild wear with inclusions deformed in the direction of chipflow (from bottom to top) (c) heavily abraded area. Note surface inclusion (arrowed) (CFD = chip flow direction)



(a) (b)

Figure 4.50: Scanning electron micrograph of the coated tool T_4 showing wear features of cutting edge near the tool nose.

(a) Microcracking and deformation above an area of stripped-off coating due to thermal fatigue cracking

(b) Cracked and rough region between cutting edge (CE) and flank wear (FW)

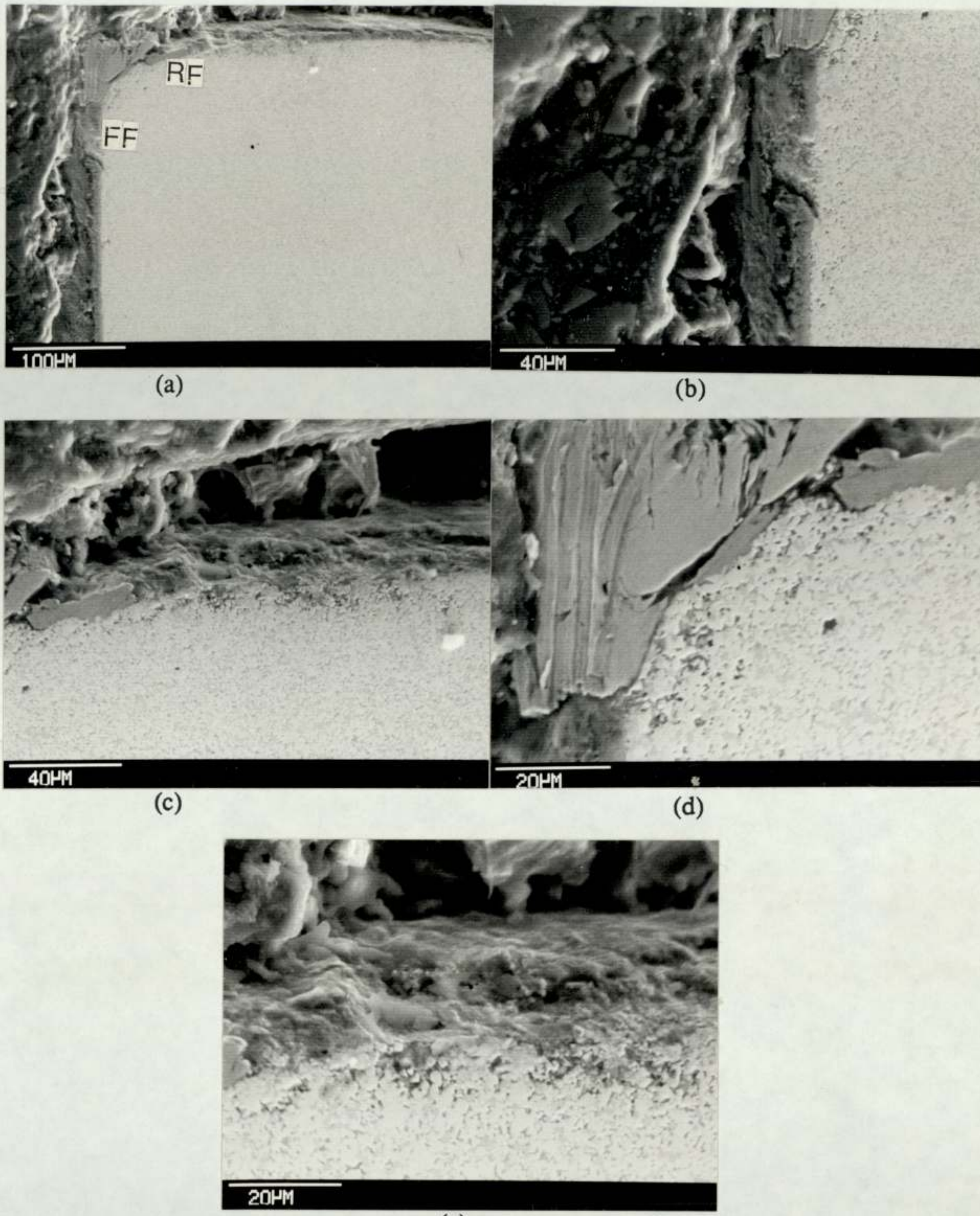


Figure 4.51: Scanning electron micrographs of a cross section through the cutting edge of the coated tool T_4 showing the wear features near the BUE (a) the cutting edge and neighbouring zones at rake face (RF) and flank face (FF); (b) cracking of the coating at the flank face; (c) cracked and deformed coating at the rake face; (d) loose attachement of chip fragments; (e) magnified view of (c) illustrating coating/substrate interface deformation and void concentration

Figure 4.51 shows a cross section through the cutting edge of the coated tool T_4. The scanning electron micrographs reveal wear features of tool subsurface in the vicinity of built-up edges on the cutting edge. Micrograph (a) shows the cutting edge and the neighbouring zones on the rake face (RF) and flank-face (FF). Micrograph (b) shows cracking of the coating at the flank face, whilst micrograph (c) shows cracked and deformed coating at the rake face adjacent to the cutting edge. Micrograph (d) illustrates chip fragmemts loosely attached to the cutting edge where the workpiece material covered the partially spalled coating. Micrograph (e) displays a magnified view of (c) showing the extent of subsurface cracking and coating deformation above a region of void concentration at the coating/substrate interface.

Figure 4.52 shows the wear characteristics observed on the surface of the working tip of the coated tool type T_5. Figure 4.52(a) illustrates the extent of chipping of the nose and the cutting edge. It also shows a large fragment of chip material adhereing to the rake face away from the cutting edge. Micrograph (b) shows a considerable size of built-up edge (BUE) accumulated at the foot of a significant notch which was formed at the cutting edge rear and extended along the rake face. Micrograph (c) illustrates the size of chipping of the cutting edge, and a magnified view is shown in Figure 4.52(d) where the stripped-off coating exposed the associated microcracks of the coating surface and subsurface on both the rake and flank faces of the tool as indicated by arrows. Figure 4.52(e) shows the chipped coating at the nose, the exposure and abrasion of the underlying layers of coating plus the microcracking of the coating subsurface. Figure 4.52(f) shows a magnified view of micrograph (e) depicting the abrasion marks inside the chipped coating region, coupled with fine cracks at the coating edges and on the surface.

Figure 4.53 illustrates the wear features observed on the surfaces of the coated tool type T_5. Figure 4.53(a) shows the flank wear under the rear part of the cutting edge where edge chipping, cracking and built-up chip material are evident.

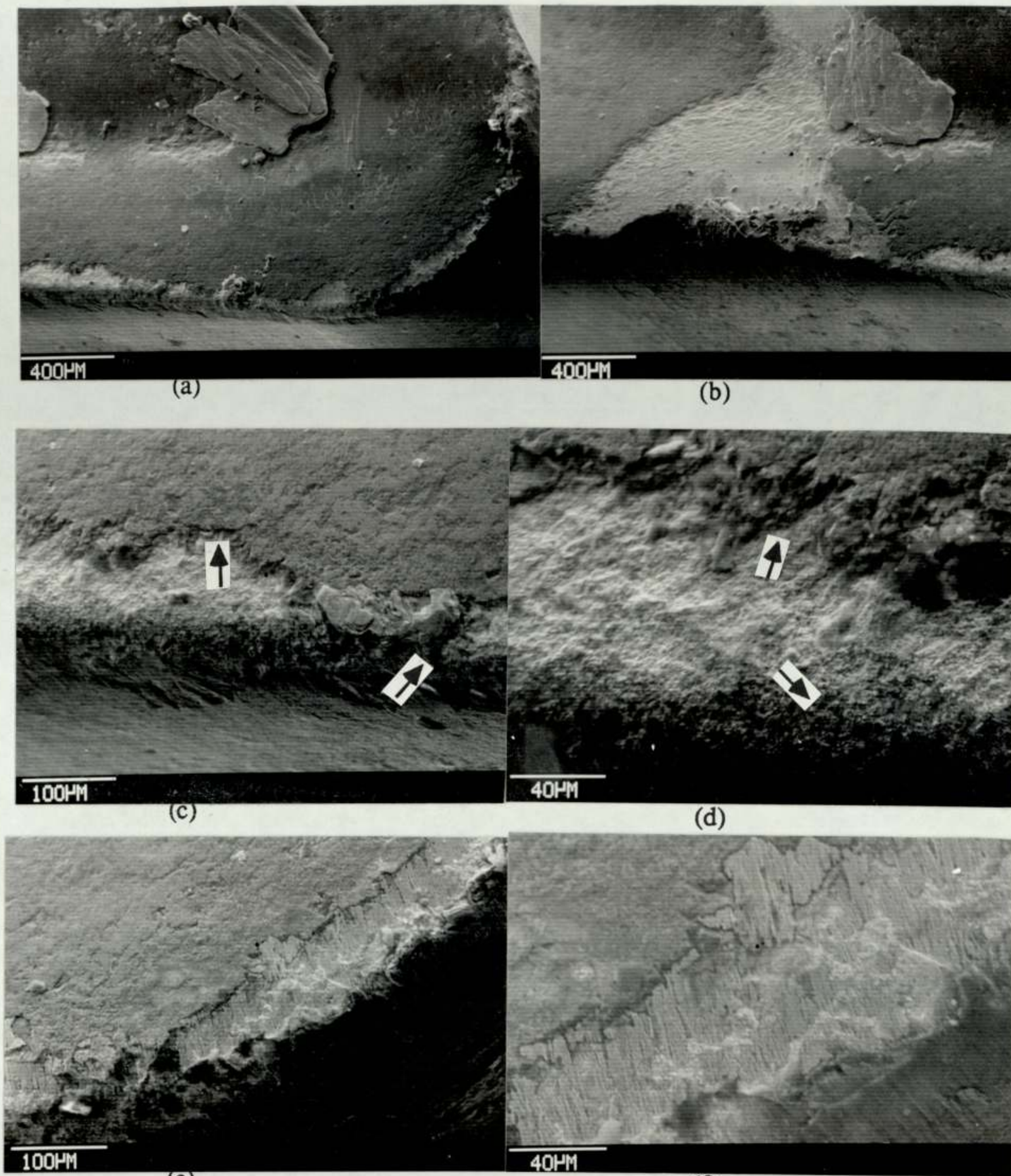
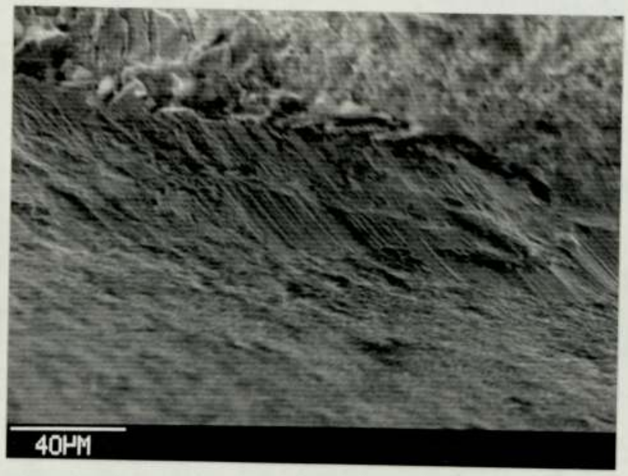
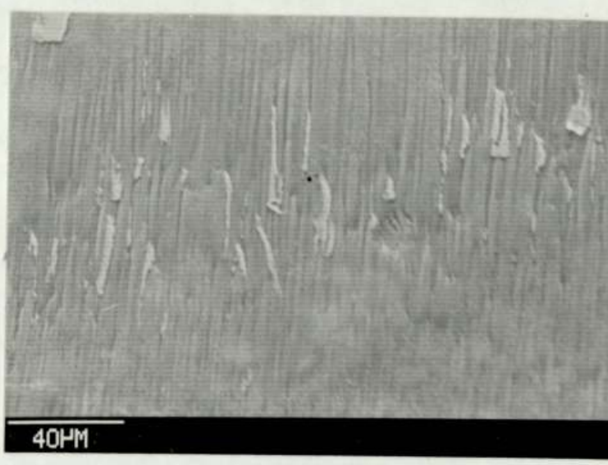


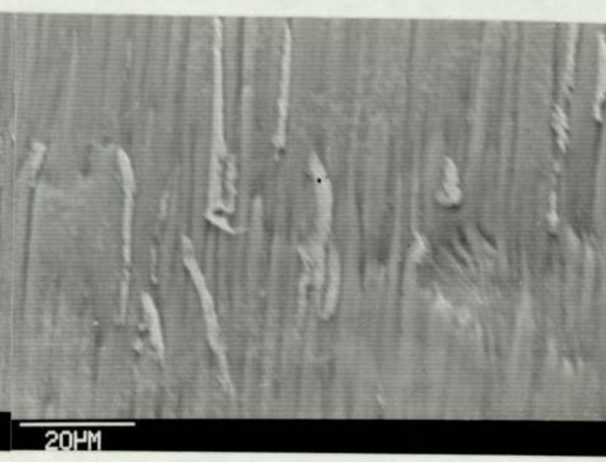
Figure 4.52: Scanning electron micrographs of the coated tool T_5 surface showing the dominant wear characteristics after rough machining of stainless steel:

(a)	chipping of the nose and the cutting edge
(b)	significant notching, BUE and welded chip fragments
(c,d)	magnified views of the chipped edge illustrating microcracked edges of stripped-off coating (arrowed)
(e,f)	magnified views of the chipped-off coating at the nose exposing the underlying layers to heavy abrasion



(a)



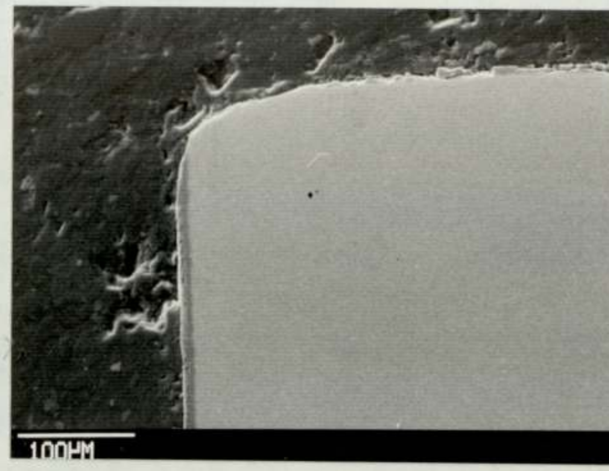


(b) (c)

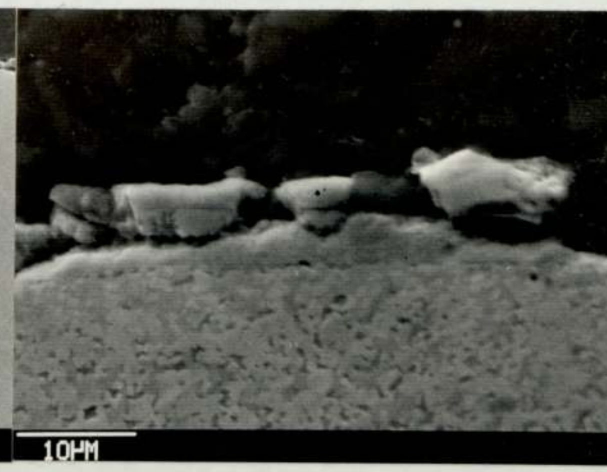
Figure 4.53: Scanning electron micrographs of the surface of the coated tool T_5 showing the wear characteristics in the flank and rake faces;

(a) flank wear under the rear part of the cutting edge with microwelds and microcracks;

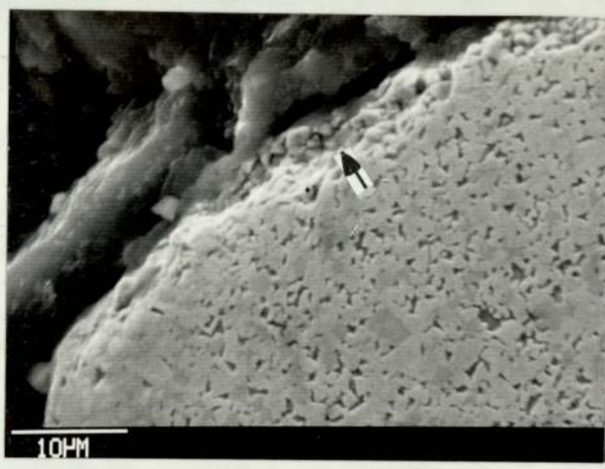
(b,c) shallow and thin grooves of abrasive wear in the rake face adjacent to the cutting edge. Note the adherent particles deformed longitudinally in the chip flow direction (from bottom to top)



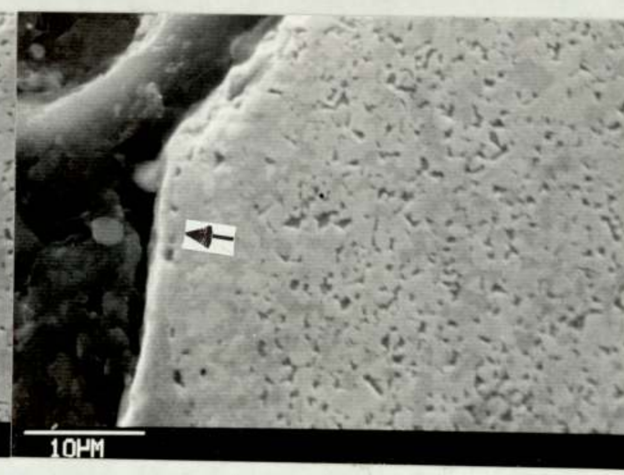
(a)



(b)



(c)



(d)

Figure 4.54: Scanning electron micrographs of a cross-section through the cutting edge of the coated tool T_5 at a region of a chipped away coating:

(a) full view of the sectioned cutting edge
(b) damaged coating in the rake face near the cutting edge
(c) microcracks and voids in the exposed substrate of the chipped area (arrowed)
(d) smooth flank wear (arrowed)

Figure 4.53(b) exhibits shallow and thin grooves of abrasive wear in the rake face adjacent to the cutting edge. Figure 4.53(c) shows a magnified view of micrograph (b). The adherent particles at the centre of the chip/tool face contact area, were plastically deformed alongside the smoothly worn ridges in the chip flow direction.

Figure 4.54 shows cross-section through the cutting edge of the coated tool type T_5 at a region of a chipped away coating. The region of chipping located above the cutting edge and extended towards the rake face of the tool as indicated by arrows in Figure 4.54(a). Figure 4.54(b) illustrates a disintegrated coating at the edge of the chipped area on the rake face. Figure 4.54(c) displays details of the chipped area as the arrows indicate the microcracks and voids in the exposed substrate. Figure 4.54(d) shows the smoothly worn coating at the flank wear zone (arrowed).

Figure 4.55 shows the wear characteristics of the working tip surface of the coated tool type T_6 . Figure 4.55(a) illustrates the notably low wear at the nose and the cutting edge, yet, a significant amount of chip material was welded to the tool's rake face away from the cutting edge. Figure 4.55(b) illustrates a notch at the cutting edge rear, similar, in size and shape, to the one observed on the coated tool type T_5. A large area of flaked-off coating extended from the notch vicinity to the rake face where a considerable amount of material was built-up on the notch edge. Figure 4.55(c) shows the rough cutting edge above the flank wear, whilst Figure 4.55(d) shows the rough and crack-free nose. However, evidence of localised smooth wear and microwelds at the nose top is shown in Figure 4.55(e). Microvoids and crack-like features were also detected.

Figure 4.56 shows the surface features of flank and crater wear obseved on the coated tool type T_6. Micrograph (a) illustrates the smoothly abraded flank face, and (b) shows the extremely smooth wear of the rake face. Figure 4.56(c) shows the same area in Figure 4.56(b) at higher magnification. The nodular nature of tool T_6

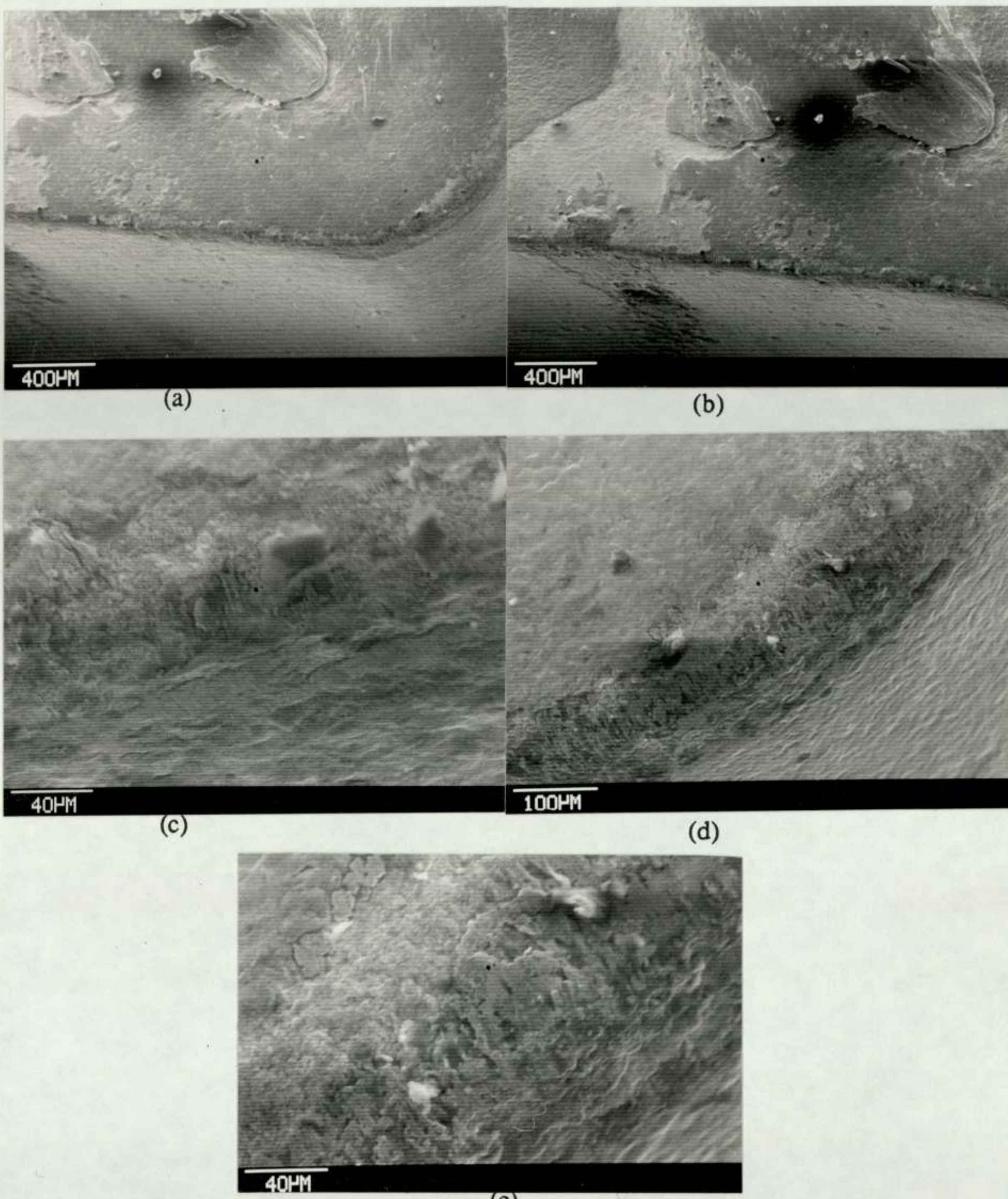
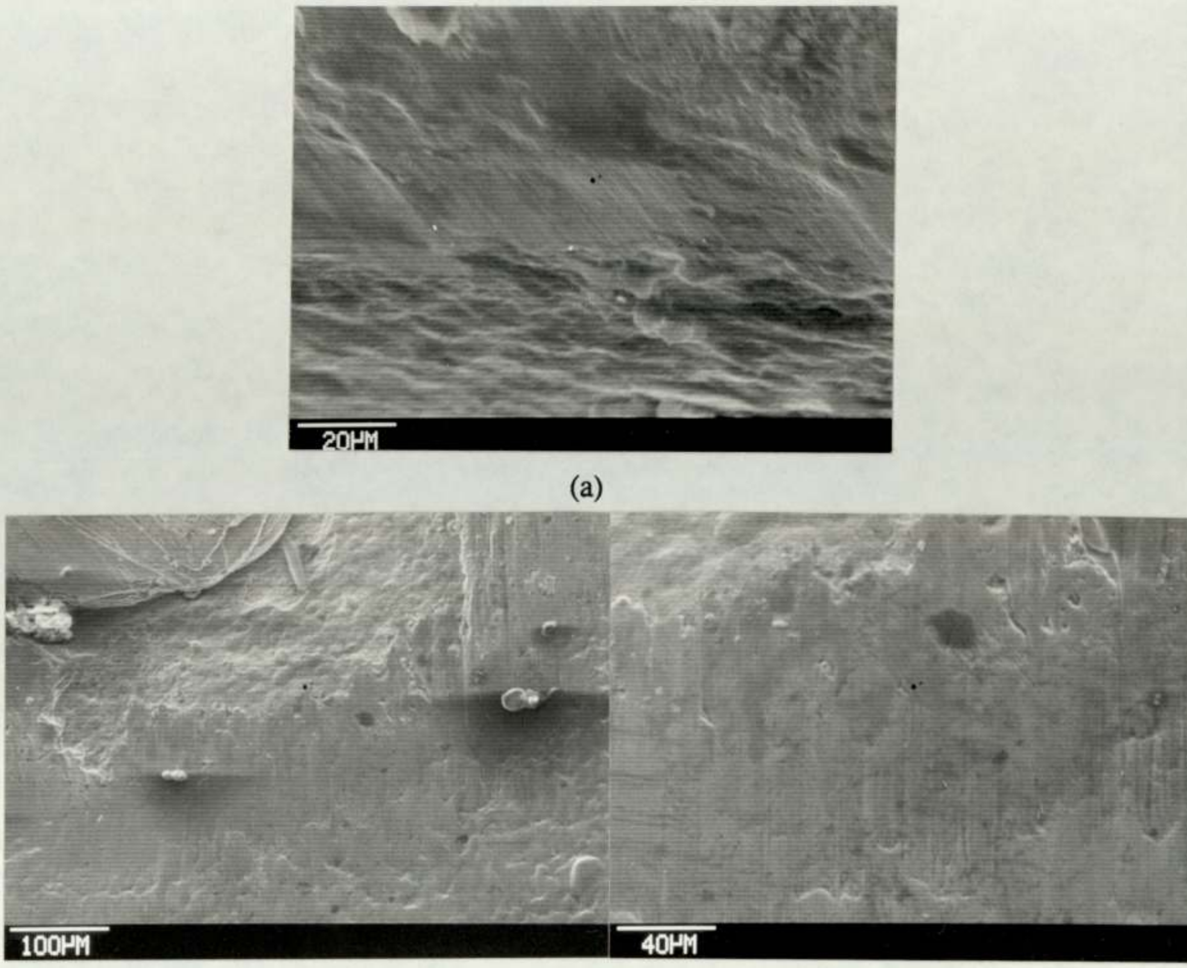


Figure 4.55: Scanning electron micrographs of the surface of the coated tool type T_6 showing the wear features after rough machining of stainless steel:

(a) view of the working tip illustrating low wear in the nose and cutting edge
(b) significant notching of the cutting edge, coating flaked off the notch area, and chip material welded on the rake face
(c) rough cutting edge
(d) rough and crack-free nose
(e) localised smooth wear and microvoids



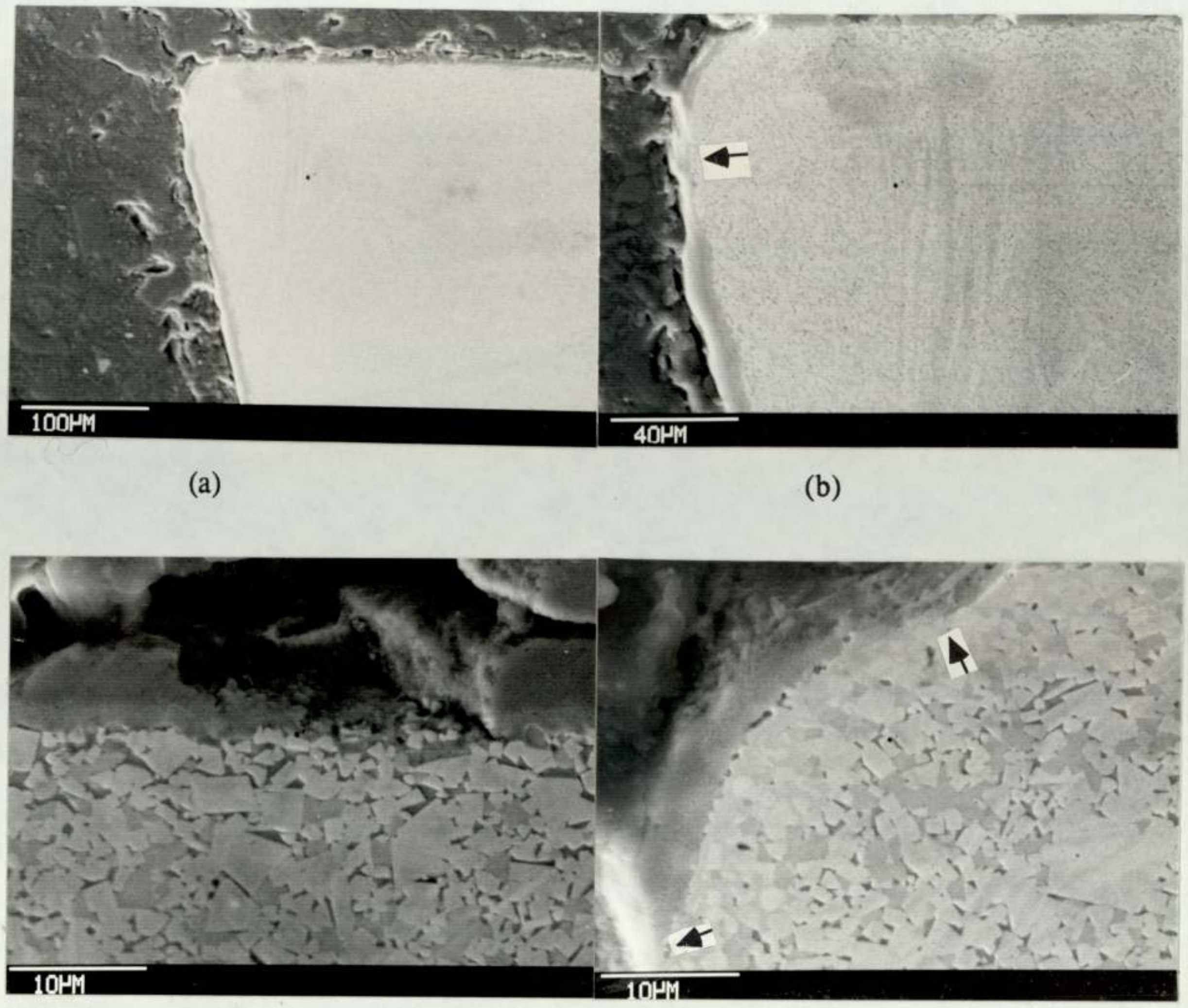
(a)

(b) (c)

Figure 4.56: Scanning electron micrographs of the surface of the coated tool T_6 showing the wear characteristics in the flank and rake faces;

(a) smoothly abraded flank face

(b,c) extremely smooth wear of the rake face



(a) (b)

(c) (d)

Figure 4.57: Scanning electron micrographs of a cross-section through the cutting edge of the coated tool T_6 at a region near the notch site

(a) general view of the sectioned cutting edge

(b) slightly worn flank face (arrowed), undamaged cutting edge, and partially damaged coating at rake face (top)

(c) localised cracking and deformation of the coating at the rake face

(d) undamaged coating at the cutting edge with worn spots at its two sides (arrowed) surface was highly smoothen as a result of the sliding chip/tool contact during the cutting operation.

Figure 4.57 illustrates scanning electron micrographs of a cross-section through the cutting edge of the coated tool type T_6 at a region near the notch site. Figure 4.57(a) shows a general view of the cutting edge bordered by the rake face (top) and the flank face (left side). Figure 4.57(b) shows the slightly worn flank face below the cutting edge (arrowed), and the partially damaged locality at the rake face, where a crack penetrates the remaining part of the inner coating layer reaching the micro voids of the interface Figure 4.57(c). Figure 4.57(d) shows the coating's strong adhesion to the substrate at the cutting edge, and partially broken at a few sites (arrowed) above and underneath it.

Figure 4.58 shows the wear features observed on the working tip surfaces of the coated tool type T_7. Figure 4.58(a) illustrates the uniform nose and cutting edge free of built-up material, but significant wear and built-up chip material are detected on the rake face. Moreover a notch (arrowed) was formed at the minor cutting edge (the end clearance face). On the other hand a large notch similar, in shape, to those observed on tools T_5 and T_6 is shown in Figure 4.58(b). However, the welded chip material is less, the cutting edge is smoother, and the shallow notch is smaller, in relation to those of the tools T_5 and T_6. Figure 4.58(c) illustrates the smooth flank wear near the tool nose, and Figure 4.58(d) illustrates smooth nose wear under a notably rough nose edge, which is shown in the magnified view in Figure 5458(e) where voids, and microwelds are evident.

Figure 4.59 shows the wear features observed on the surfaces of the coated tool T_7. Figure 4.59(a) illustrates the smooth flankwear at the rear of the cutting edge, and Figure 4.59(b) illustrates the worn rake face. Different characteristics are shown in two distant zones of the crater wear, where zone (S) indicates smooth mild abrasive

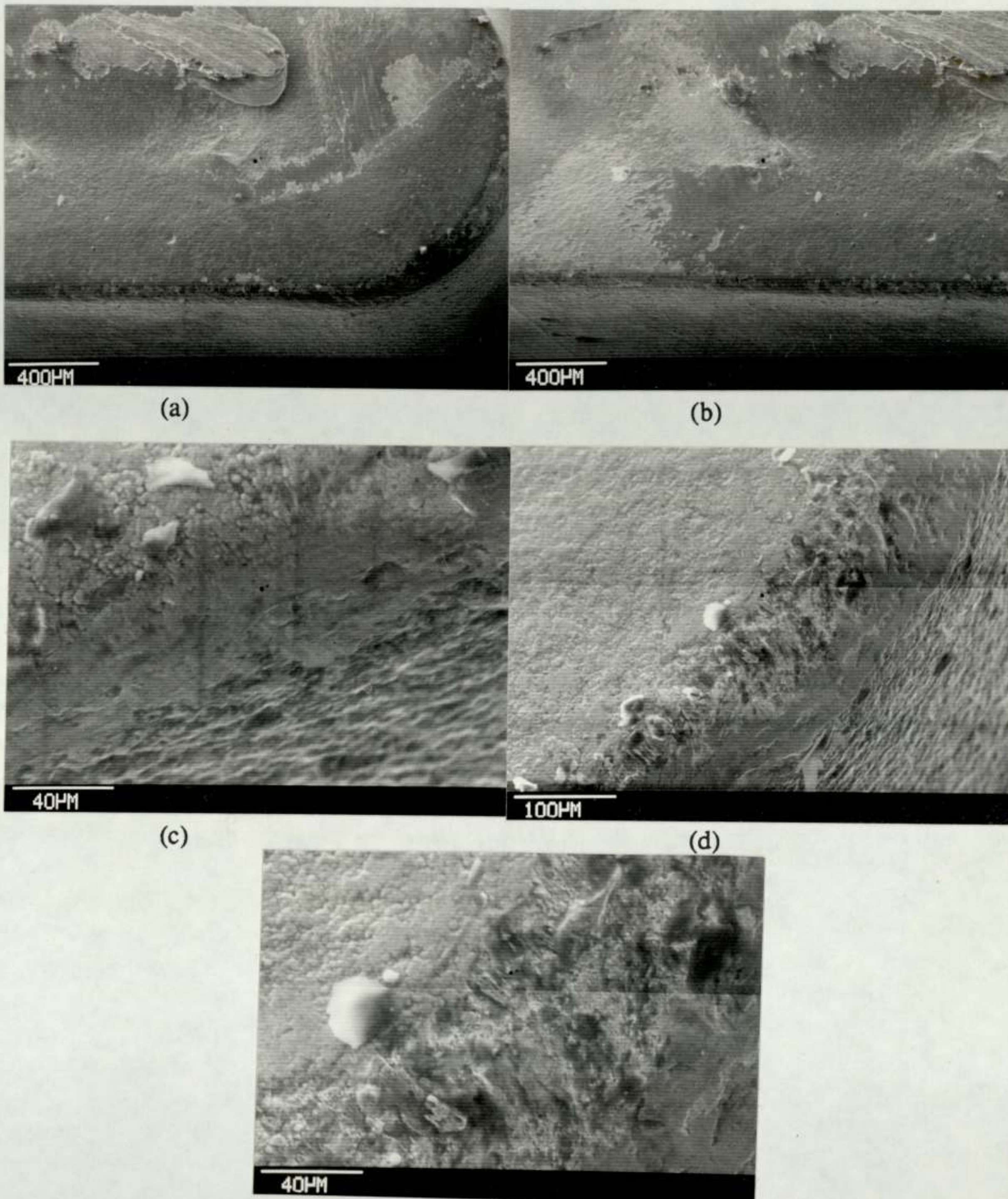
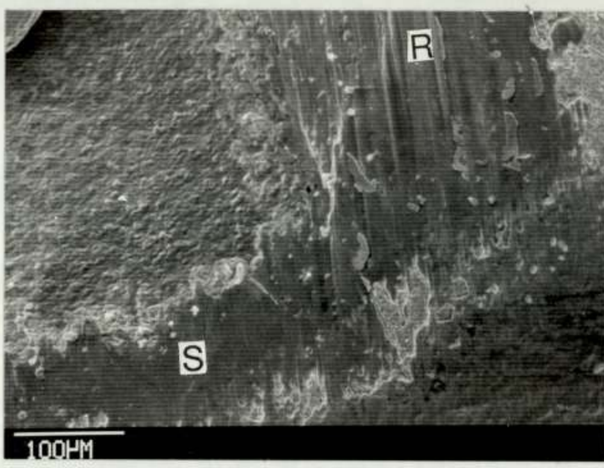


Figure 4.58: Scanning electron micrographs of the surface of the coated tool T_7 showing the wear features after rough cutting of stainless steel:

(a)	general view of the working tip illustrating a uniform cutting edge and nose, and the rake face wear
(b)	shallow notching of the cutting edge
(c)	smooth flank wear near nose
(d)	rough nose top and smoothly worn bottom
(e)	voids and microwelds at the nose

(a)



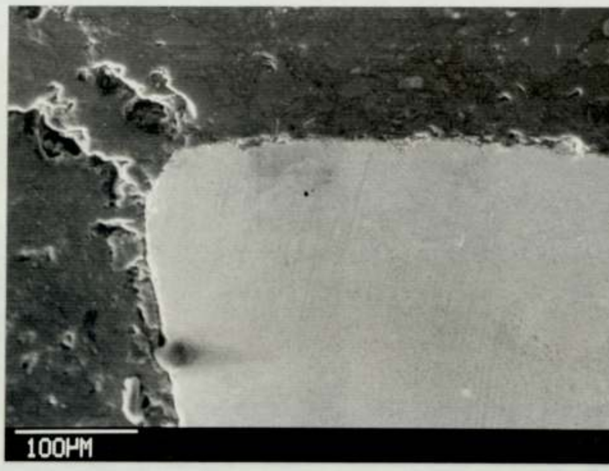
(b) (c)

Figure 4.59: Scanning electron micrographs of the surface of the coated tool T_7 showing the wear features of the flank and rake faces:

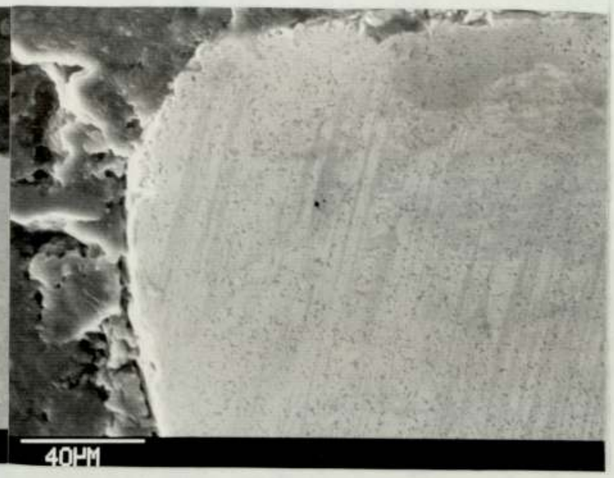
(a) smooth flank wear at the rear of the cutting edge;

(b) crater wear of different features, smooth (S) and rough (R);

(c) enlarged view of smooth wear zone with a cluster of eroded spots (arrowed)



(a)



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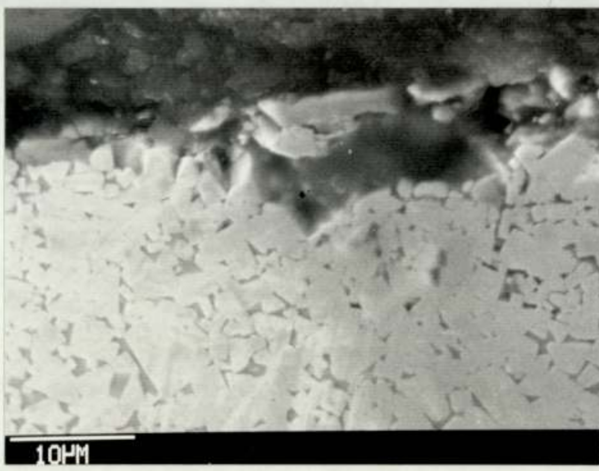
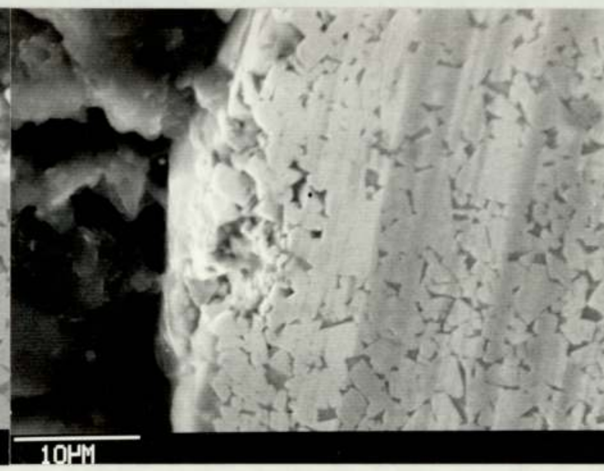


(c)



(d)

Figure 4.60: Scanning electron micrographs of a cross-section through the cutting edge of the coated tool T_7

(a) general view of thin coated cutting edge (corner), flank (left), and rake face (top)

(b) worn away coating at flank and a locally deformed coating at rake face

(c) details of the heavily deformed area of the rake face

(d) subsurface voids at a deformed area at the flank face wear, whilst the relatively rougher area (R) with its ridged features indicates the process of plastic deformation. Moreover heavy contact between the chip material and the tool surface led to the exposure of the underline coating layer at a region close to the small notch of the end clearance face (top right of the micrograph (b)). Figure 4.59(c) shows an enlarged view of the smooth wear zone where eroded spots (arrowed) interconnected along the crater side closer to the cutting edge, where the flowing chips started rubbing the rake face (CFD = chip flow direction).

Figure 4.60 shows a cross section through the cutting edge of the coated tool type T_7. Figure 4.60(a) illustrates a general view of the cutting edge (radiused zone), the adjacent rake face (top), and the flank face (left). Figure 4.60(b) shows the deformed and worn flank face, and the deformed coating at the rake face. Figure 4.60(c) shows details of the rake face where the heavily deformed interface is detected, while part of the thin coating is still bonded to some areas along the surface. Figure 4.60(d) exhibits a worn away coating at a deformed zone in the flank face just under the cutting edge. The subsurface voids at the localised deformation zone represent a weak side towards which further deformation might develop leading to a feature similar to that shown in Figure 4.47(a,e,f).

4.5.3 Finish Turning Operations

4.5.3.1 Forces on the cutting tools

Results of measurement of the forces acting on the tools' working tips during four consecutive finishing cuts are presented in Table 4.10. Although the cutting speed employed in this test is relatively high, 200 m/min, the three types of forces were notably low. This was attributed to the low feed and depth of cut used which resulted in a type of chip formation that was not harmful. Figures 4.61, 4.62 and 4.63 show the relationships between the cutting forces, feed forces and axial forces respectively. The seven types of coated tools and uncoated ones performed in a similar way as indicated by the curve shapes for forces vs cutting time for the three types of force. However, the forces related to the coated tools exhibited sharp increases initially but then they all tend to show constant or slightly increased values. The individual performance of each type of tool will be discussed later.

Table 4.10: Summary of forces measured during finish cutting with uncoated tools T_1, T_2 and coated tools T_3, T_4, T_5, T_6 and T_7

Cut No	Cum cut time (sec)	Forces of T_1 (N)			Forces of T_2 (N)			Forces of T_3 (N)			Forces of T_4 (N)			Forces of T_5 (N)			Forces of T_6 (N)			Forces of T_7 (N)		
		F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y
F_1	45	403	210	148	510	290	194	350	175	125	393	210	123	460	210	190	460	240	210	460	210	200
F_2	87	435	221	148	475	275	205	450	263	140	430	241	130	510	260	180	500	270	220	500	240	200
F_3	127	432	230	140	460	256	183	445	275	141	425	239	134	510	270	180	520	290	280	480	260	210
F_4	165	440	234	139	470	266	168	443	281	141	430	266	140	520	290	230	510	290	220	490	270	210

Machining conditions: Workpiece material: 316 stainless steel; Cutting speed: 200 m/min; Feed: 0.16 mm/rev; Cutting depth: 1.0mm

F_1 - F_4: Consecutive finish operations from 1 to 4.

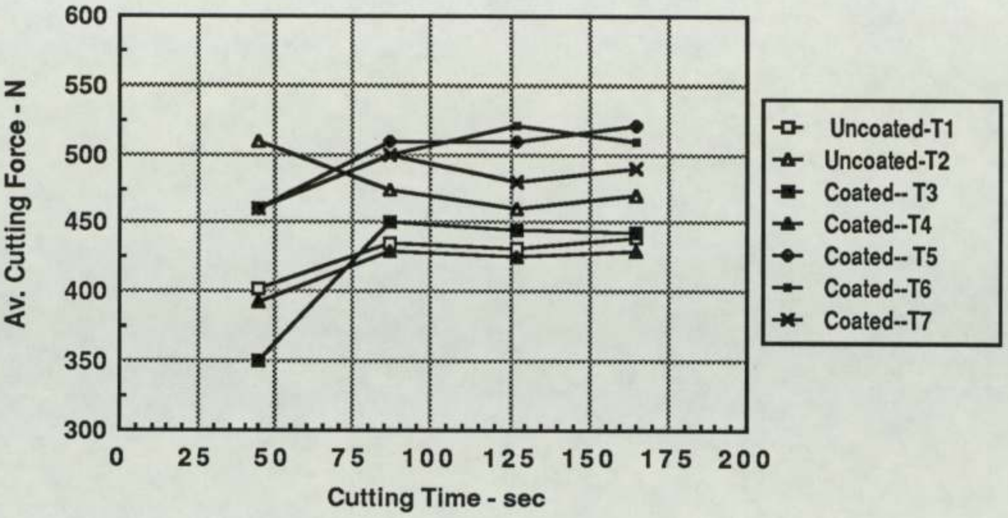


Fig.4-61:Variation of Cut. Force with Time During Finish Turning of Stainless Steel
(Cut. Speed: 200 m/min; Feed: 0.15 mm/rev; Cut. Depth: 1.0 mm)

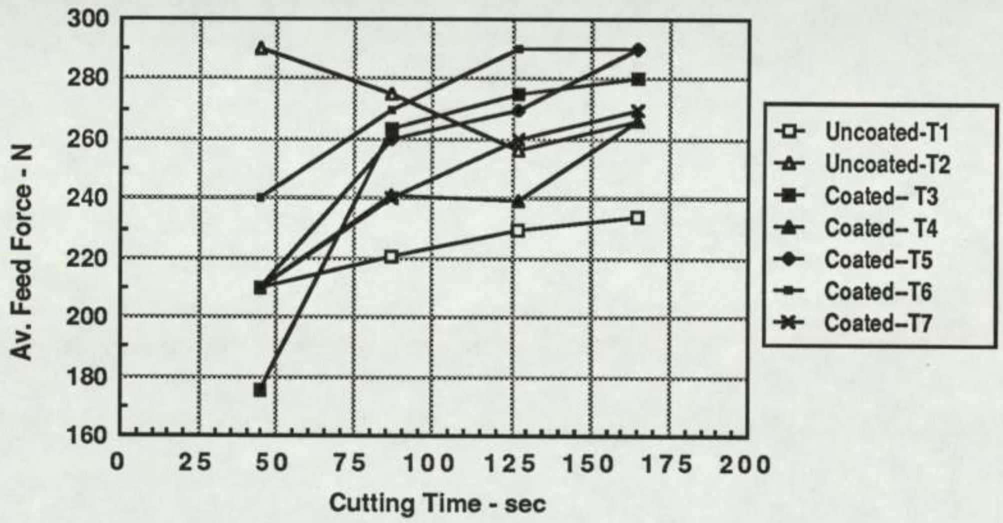


Fig.4-62:Variation of Feed Force with Time During Finish Turning of Stainless Steel
(Cut. Speed: 200 m/min; Feed: 0.15 mm/rev; Cut. Depth: 1.0 mm)

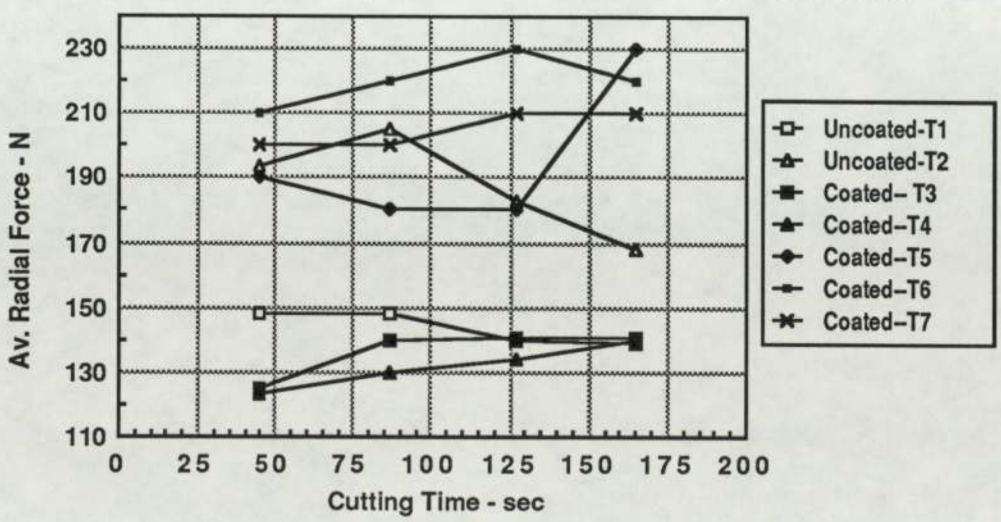


Fig.4-63:Variation of Radial Force with Time During Finish Turning of Stainless Steel
(Cut. Speed: 200 m/min; Feed: 0.15 mm/rev; Cut. Depth: 1.0 mm)

4.5.3.2 Flank Wear Measurements

Results of the flank wear measurements are given in Table 4.11 and illustrated graphically in Figure 4.64. The development of wear with time was evident in the case of uncoated tool T_2, but the other type of uncoated tool T_1 behaved in the same way as the coated tools. Most of the wear of coated tools occurred during the first 45 seconds cutting, then flank wear width remained almost unchanged until the end of the four cutting operations. Tools T_4 and T_3 performed better than the others.

4.5.3.3 Surface Finish Measurement

Results of workpiece surface finish are summarised in Table 4.12. Measurements were taken at different zones along the workpieces, to follow the development of the finish quality. Average finish values for each operation were calculated after a set of three readings. Figure 4.65 illustrates the progress of surface finish with respect to time and Figure 4.66 shows average values of the same results of Figure 4.65. The curves indicate continuous changes in surface finish which suggests that periodic changes must occur at the workpiece/tool interface during cutting. However, some of the tools, particularly the coated tool type T_7 performed exceptionally well throughout.

4.5.3.4 Metallurgical Studies

In order to achieve comprehensive evaluation of tool performance on machining stainless steel with TiN-coated tools, the results presented in this section were obtained after metallurgical examination of the uncoated tools (T_1 and T_2), and the coated ones (T_3 to T_7) after conducting a series of finish cutting operations. The wear characteristics of the tool surfaces observed by optical and scanning electron microscopy have confirmed the validity of the features detected on the same types of

Table 4.11: Average flank wear measured progressively during finish cutting with uncoated tools T_1, T_2 and coated tools T_3, T_4, T_5, T_6 and T_7

Cut No	Cum cut time (sec)	Average flank wear width (mm)							Machining conditions
		T_1	T_2	T_3	T_4	T_5	T_6	T_7	
F_1	45	0.089	0.138	0.094	0.087	0.142	0.120	0.094	Workpiece mat: 316 Stainless steel
F_2	87	0.109	0.191	0.103	0.090	0.154	0.126	0.103	Cutting speed: 200 m/min
F_3	127	0.109	0.220	0.103	0.092	0.159	0.170	0.126	Feed: 0.15 mm/rev
F_4	165	0.123	0.263	0.103	0.095	0.168	0.174	0.127	Cutting depth: 1.0mm

F_1 - F_4: Finish operations from 1 to 4 consecutively

Table 4.12: Average surface finish (CLA) of workpiece material during finish cutting with uncoated tools T_1, T_2 and coated tools T_3, T_4, T_5, T_6 and T_7.

Cut No	Cum cut time (sec)	S Fin of T_1 (µm) (µm)		S Fin of T_2 (µm)		S Fin of T_3 (µm)		S Fin of T_4 (µm)		S Fin of T_5 (µm)		S Fin of T_6 (µm)		S Fin of T_7	
		Cont	AV	Cont	AV	Cont	AV	Cont	AV	Cont	AV	Cont	AV	Cont	AV
	15	2.70		1.40		2.60		3.10		1.10		1.20		0.95	
F_1	30	2.80	2.77	1.40	1.47	2.60	2.53	3.80	3.27	1.30	1.17	1.20	1.20	0.95	0.93
	45	2.80		1.60		2.40		2.90		1.10		1.20		0.90	
	59	3.00		1.70		2.80		2.70		1.30		1.20		0.90	
F_2	73	3.30	3.27	1.90	1.83	3.10	2.83	3.20	2.97	1.30	1.27	1.20	1.20	0.90	0.90
	87	3.50		1.90		2.60		3.00		1.20		1.20		0.90	
	100	3.30		1.70		2.80		3.10		1.30		1.40		0.90	
F_3	113	3.20	3.30	1.50	1.83	2.50	2.77	4.20	4.10	1.30	1.30	1.40	1.37	0.85	0.88
	127	3.40		2.30		3.00		5.00		1.30		1.30		0.90	
	139	3.00		2.70		2.60		3.00		1.40		1.70		0.90	
F_4	152	3.70	3.37	2.90	2.87	2.50	2.67	3.30	3.37	1.80	1.60	1.80	1.67	1.00	0.93
	165	3.40		3.00		2.90		3.80		1.60		1.50		0.90	

MACHINING CONDITIONS: Workpiece mat: 316 stainless steel; cutting-speed: 200 m/min; 0.15 mm/rev; cut depth: 1.0mm

F_1 - F_4: Consecutive finish operations from 1 to 4.

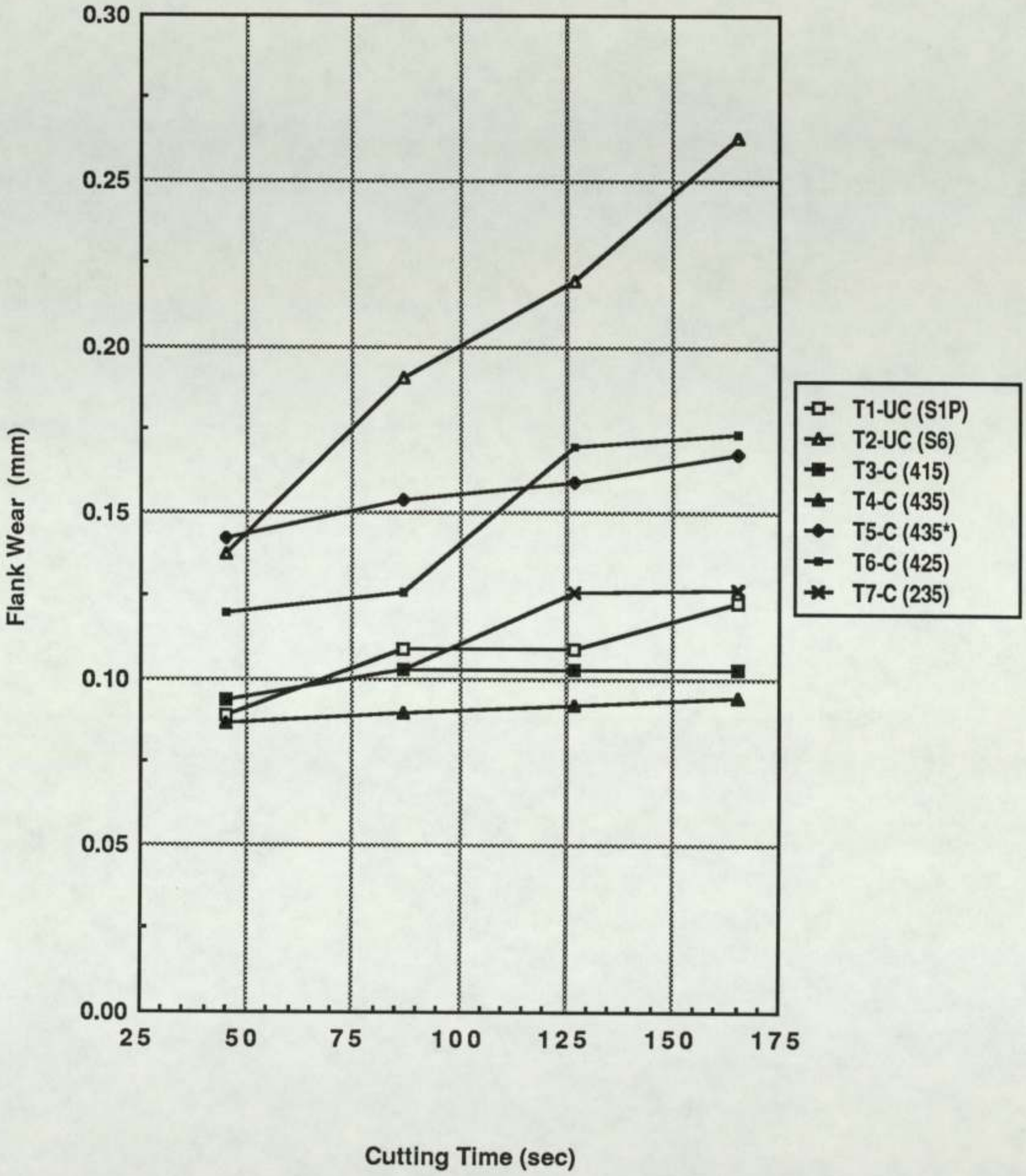


Fig4.64:Development of Wear With Time During Finish Turning of Stainless Steel

(Cut. Speed: 200 m/min ; Feed: 0.15 mm/rev; Cut. Depth: 1.0 mm)

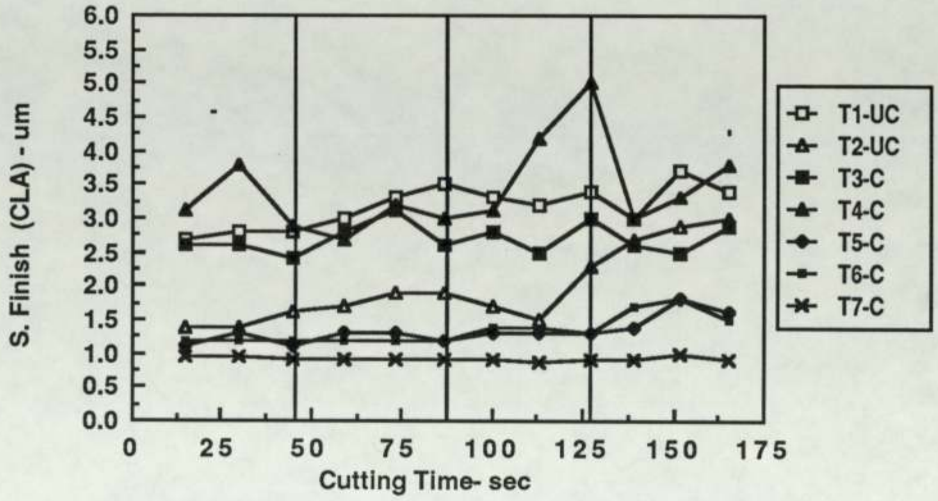


Fig.4-65:Comparison of Uncoated (UC) and Coated (C) Tool Performance based on Progressive Surface Finish during Four Cutting Operations
(Cut. Speed: 200 m/min; Feed: 0.15 mm/rev; Cut. Depth: 1.0 mm)

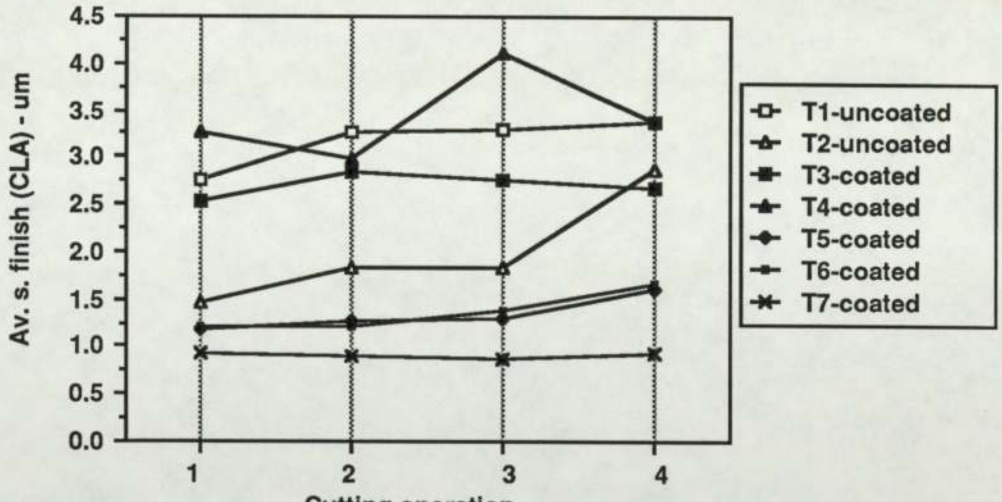
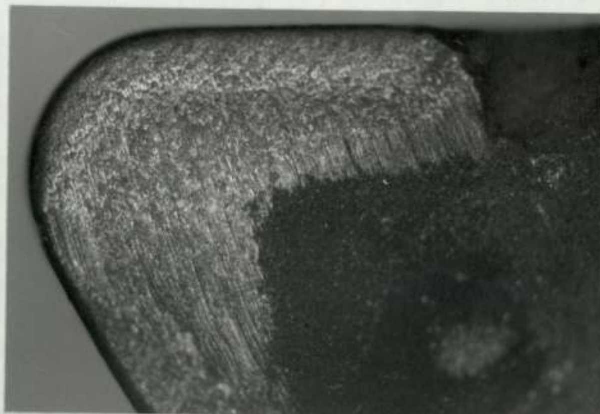


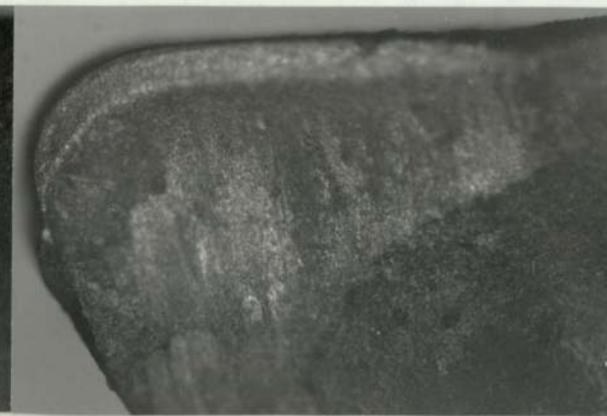
Fig.4-66:Comparison of tool performance based onaverage surface finish during each of the four consecutive cutting operations
(cut. speed: 200m/min; feed:0.15mm/rev; cut. depth: 1.0 mm)

tools when used in rough cutting operations. However, certain wear characteristics, were found to be associated with finishing operations more than roughing ones and vice versa.

Figure 4.67 shows optical photomicrographs illustrating the variations in wear characteristics observed on the surfaces of uncoated and coated tools after their use in finish cutting of stainless steel. Figure 4.67(a) shows the notching and crating of the uncoated tool T_1. Figure 4.67(b) shows excessive cratering, nose wear, and small notch of the uncoated tool T_2. Figure 4.67(c) shows irregular crater wear and significant notching together with considerable built-up chip material on the rake face of the coated tool type T_3. Similar features are detected on the coated tool T_4 (Figure 4.67d) but the size of both the notch and built-up edge are smaller in T_4, than in T_3. Figure 4.67(e) illustrates the wear features of the coated tool type T_5. A thin and long crater wear is shown as a curved track adjacent to the curvature of the tool nose. A large notch was formed at the rear of the rough cutting edge (top of micrograph). Figure 4.67(f) shows the crater wear features of the coated tool T_6. The wear tracks are very shallow, covering a narrow area beyond the tool nose. The size of the notch is smaller than those formed on other tools. The rake face region between crater wear and the cutting edge is shiny due to the rubbing action which took place between the sliding chips and the tool's surface. Figure 4.67(g) illustrates the wear characteristics of the coated tool type T_7, where a comparatively large notch was formed at the cutting depth end on the tool's edge. Shallow marks of abrasion were detected in the crater wear zone and a lustrous highly polished surfce is shown covering a large area included between the cutting edge, the nose, and the curved wear tracks pattern.

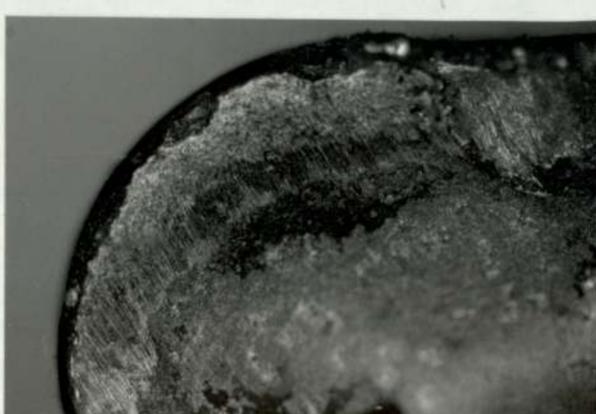
Figures 4.68 to 4.74 are scanning electron micrographs illustrating the details of wear observed on the surfaces of the seven types of tools employed in the finish turning operations of the test programme. Figure 4.68 shows the wear features


(a)


(b)


(c)


(d)


(e)


(f)

(a) uncoated tool T_1; (b) uncoated tool T_2

(c) uncoated tool T_3; (d) coated tool T_4

(e) coated tool T_5; (f) coated tool T_6

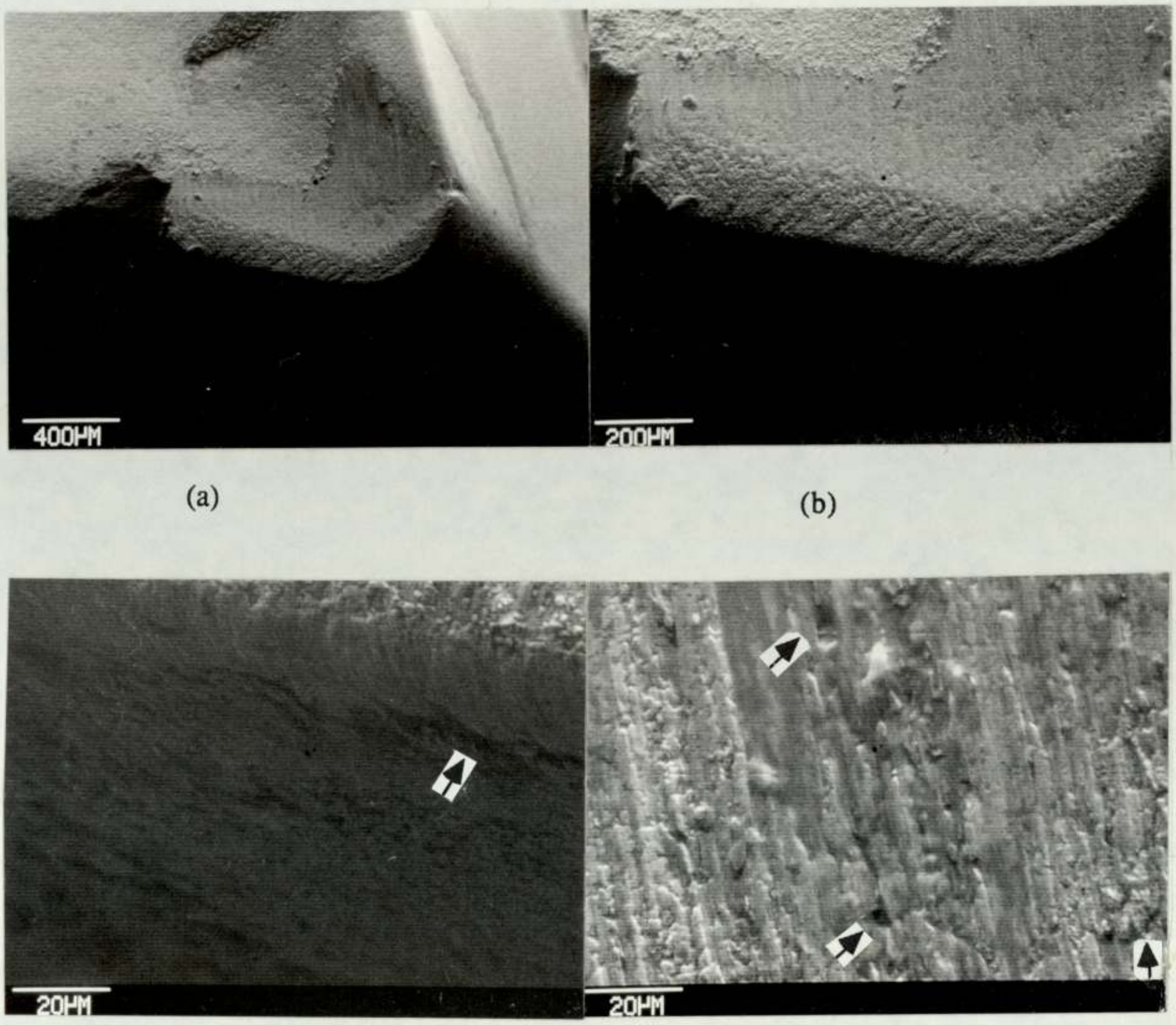
(g) coated tool T_7

Figure 4.67: Optical photomicrographs of the surfaces of the experimental tools showing the working tips after finish machining of stainless steel for 165 seconds

of the uncoated tool T_1. Micrograph (a) exhibits deep and large notch, deep and large area of crater wear, small notch on end-clearance face and welded chip material beyond the crater. Micrograph (b) shows the smooth crater wear with patches of adherent workpiece material, and the smooth cutting edge and nose free of built-up edges. Figure 4.68(c) shows the smooth flank wear with microcracks above and below the 'wear land' as indicated by arrows. Figure 4.68(d) illustrates the occurrence of microcracks and microvoids (arrowed) together with smoothly worn ridges alongside the wear tracks in the bed of the crater (CFD = chip flow direction).

Figure 4.69 shows the wear characteristics of the working tip surface of the uncoated tool T_2. Figure 4.69 (a) illustrates severely worn rake face; slight notching of the major cutting edge (arrowed) and the large notch of the minor cutting edge. The crater covers a wide area between the two notch sites, with its deepest side nearer to the end clearance face. Figure 4.69(b) shows accumulated wear debris near the worn nose; cutting edge free of built-up edges, and large islands of adherent workpiece-material besides scattered debris in the crater region. Figure 4.69(c) displays the extent of fragmentation of the adherent material in the bottom of the crater, and formation of microcracks in the strongly adhered and plastically deformed material. Figure 4.69(d) illustrates another area at the crater's bottom where large inclusins and small debris were embedded in the cracks and voids of the deformed metal.

Figure 4.70 shows different views of the working tip surfaces of the coated tool type T_3. Figure 4.70(a) exhibits the whole features which consist of crater wear, notching, coat flaking, edge chipping and built-up edges at the notch site and nose. Figure 4.70(b) illustrates two areas of crater wear: the narrow strip of smooth wear parallel to the cutting edge and the wider area of rough wear beyond the nose and near the small notch of the minor cutting edge. Built-up edge was accumulated at the foot of the notch where a significant area of peeled-off coating extended on the rake face.



(a) (b)

(c) (d)

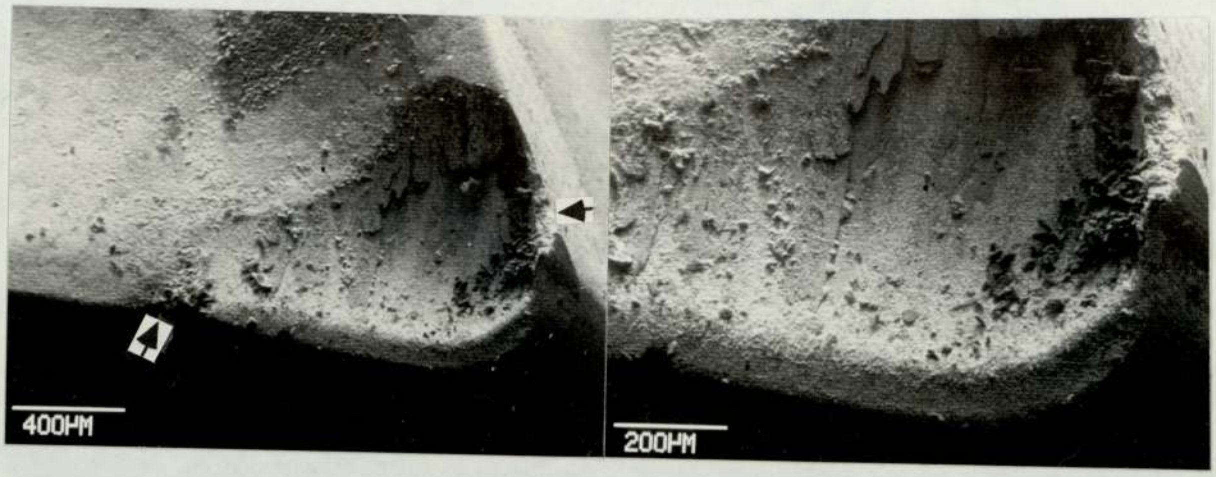
Figure 4.68: Scanning electron micrographs of the surface of the uncoated tool T_1 showing its wear characteristics after finish machining stainless steel;

(a) deep and large notch, deep crater, and small notch on the end clearance face

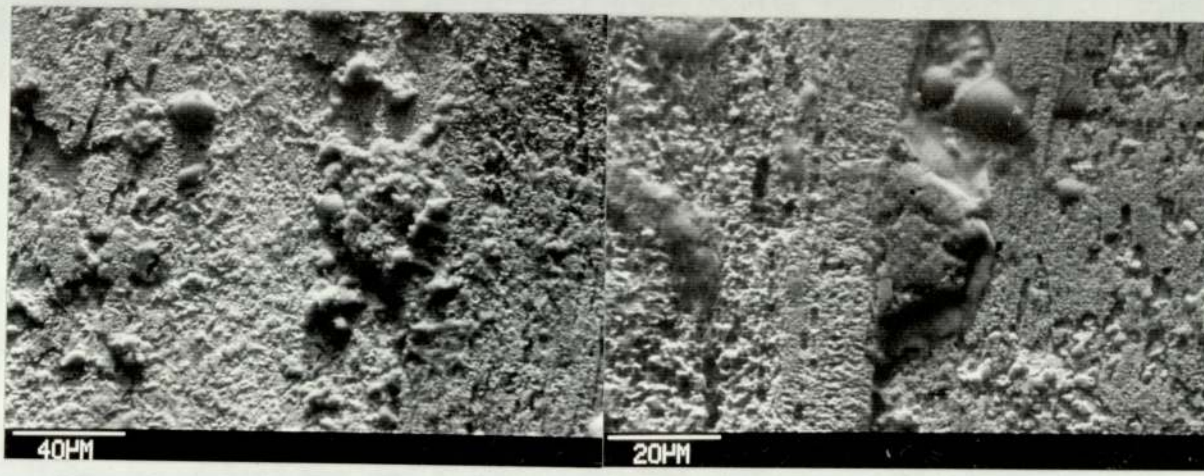
(b) regular cutting edge and nose, and smooth crater wear

(c) smooth flank wear with fine cracks (arrowed)

(d) microcracks and microvoids (arrowed) with smoothly worn ridges of the wear track in the bed of the crater



(a) (b)



(c) (d)

Figure 4.69: Scanning electron micrographs of the surface of the uncoated tool T_2 showing the wear characteristics after finish machining of stainless steel:

(a) severe crater wear with small notch of the major cutting edge (arrowed) and large notch of the minor cutting edge

(b) adherent material and wear debris in the deep crater, and slightly deformed cutting edge but free of BUE

(c) cracked and deformed adherent material

(d) embedment of wear debris in the voids and cracks of the deformed metal in the crater bottom

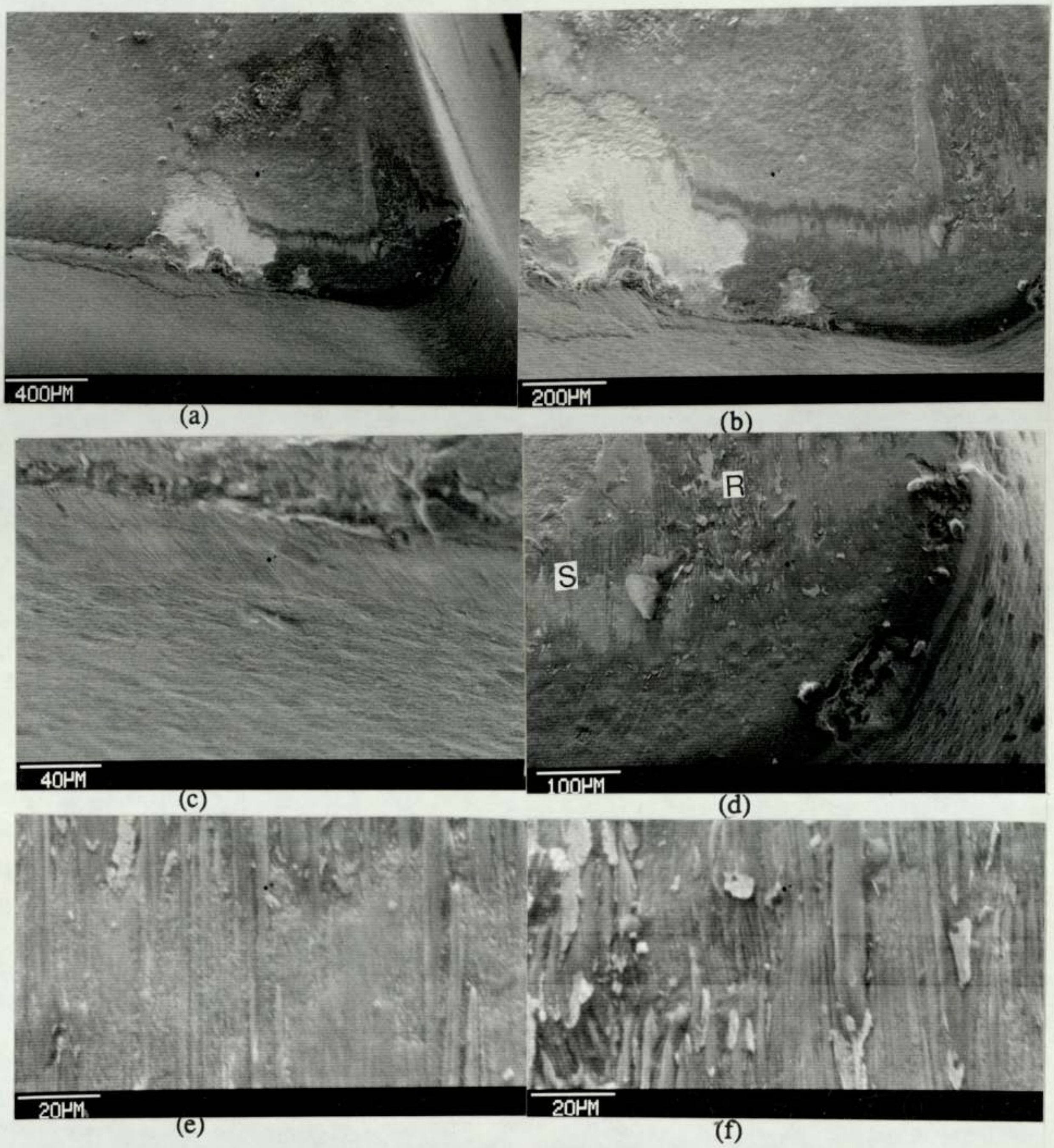


Figure 4.70: Scanning electron micrographs of the surface of the coated tool T_3 showing different wear features after finish machining of stainless steel

(a) general view of the worn working tip
(b) notch wear, crater wear, flank wear (under notch), chipped coating and BUE at notch site
(c) flank wear
(d) localised nose fracture and notching of minor cutting edge
(e,f) details of smooth S, and rough R crater wear areas in micrograph 'd'.

Besides these wear features, it is worth noting that a large area of the rake face between the cutting edge and the crater wear site remained intact. Figure 4.70(c) shows the occurrence of flank wear under a cutting edge region characterised by cracking and chipping features. Figure 4.70(d) shows localised fracture at the nose and the small notch on the minor cutting edge, connected to the neighbouring crater on top of it. Figure 4.70(e) shows a magnified view of a smooth crater wear zone with its fine grooves and minute debris (area S in micrograph (d)). Figure 4.70(f) shows details of the rough crater wear zone (area R in micrograph (d)), illustrating different size of mixed particles deformed in the direction of chip flow.

Figure 4.71 shows different views of the working tip surfaces of the coated tool type T_4. Figures 4.71(a,b) illustrate the similarity of the wear characteristics observed on this tool and those shown in Figures 4.70(a,b) for tool T_3. The only difference between the two sets of wear features appears to be the slight chipping of T_3. Figure 4.71(c) shows the flank wear under the crack-free cutting edge, despite the evidence of micro void formation in the subsurface. Figure 4.71(d) shows a view at the nose where localised build-up of chip material took place, and the small notch occurred on the minor cutting edge (top right corner of the micrograph). Moreover crater wear regions of different topography are illustrated. Figure 4.71(e) shows the smooth crater wear with its fine abrasion tracks, whilst Figure 4.71(f) exhibits the features of the rough crater wear region with its high concentration of adherent chip fragments deformed in the direction of chip flow (CFD), associated with fine cracks and voids (arrowed) oriented longitudinally in the same direction.

Figure 4.72 shows the wear features observed on the surface of the coated tool type T_5. Figure 4.72(a) illustrates the moderate wear characteristics detected on the working tip, where significant change in the shape and size of crater wear took place. Figure 4.72(b) shows flank wear under the built-up chip material above which a small but rather deep notch was formed at the rake face. Figure 4.72(c) exhibits a

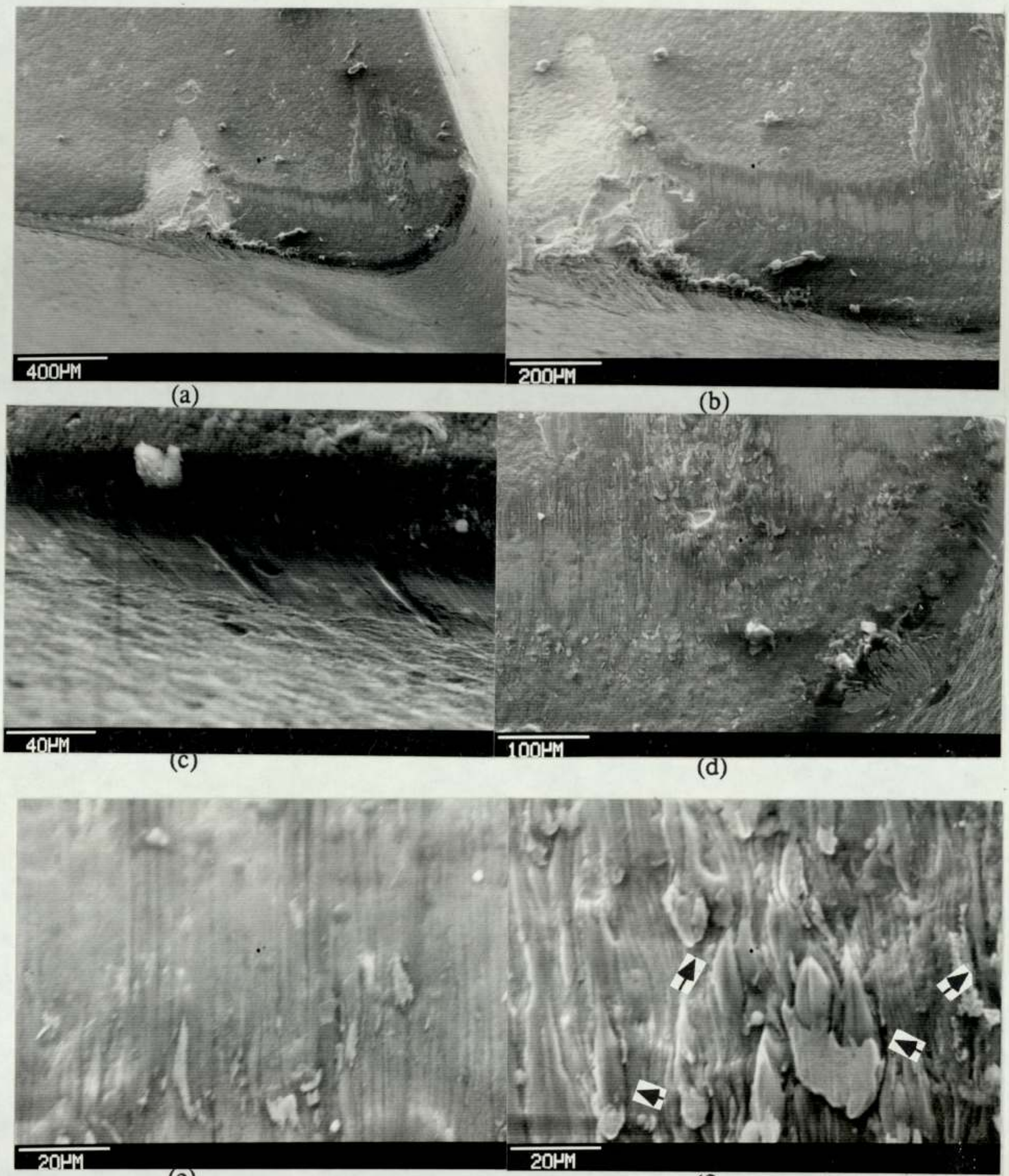


Figure 4.71: Scanning electron micrographs of the worn working tip of the coated tool T_4 after finish machining stainless steel showing wear characteristics similar to those observed on tool T_3 as illustrated in Figure 5.70. The crater wear is rougher than that of T_3 with evidence of larger deformed fragments associated with microcracks and voids as arrowed in (f).

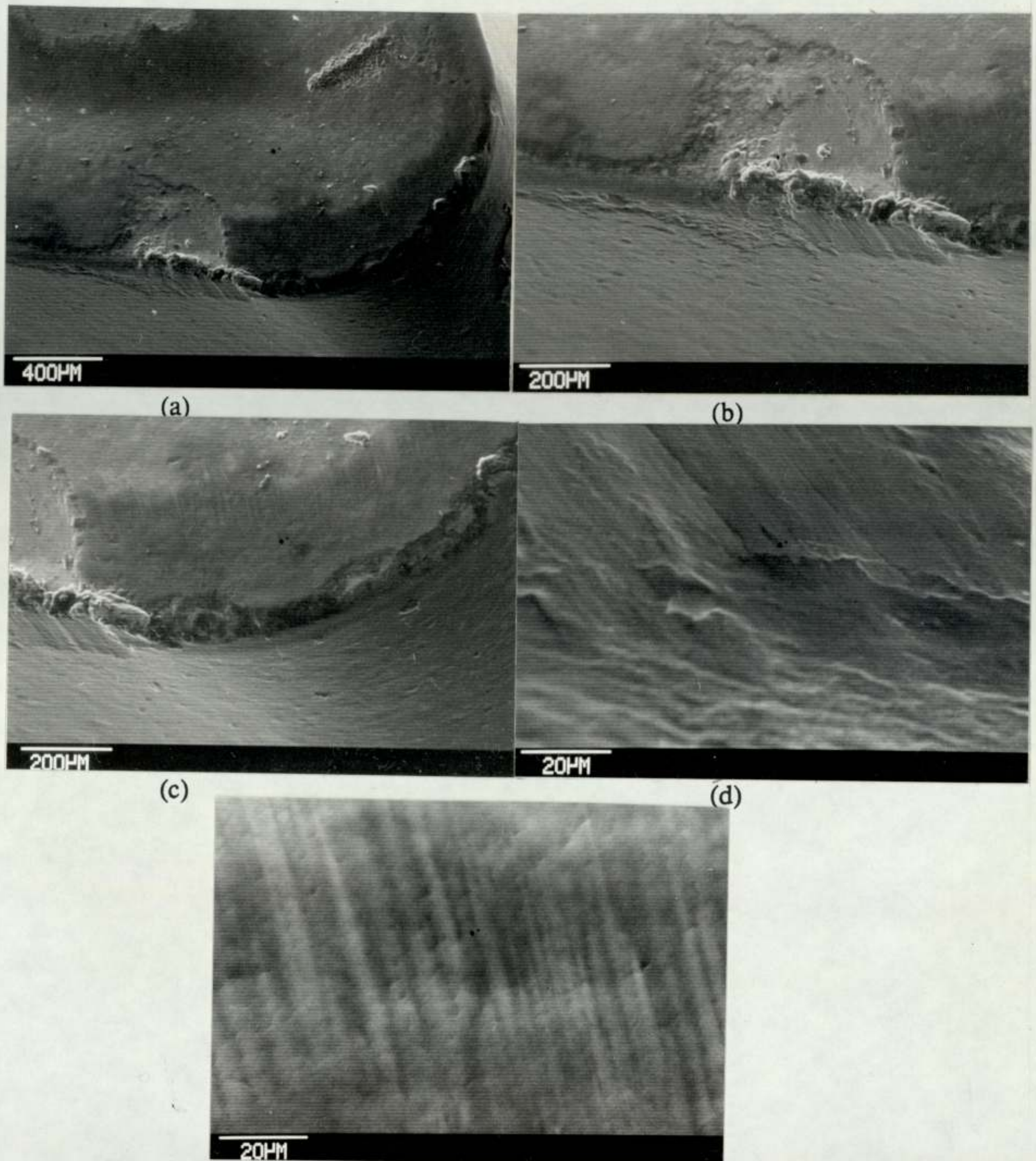


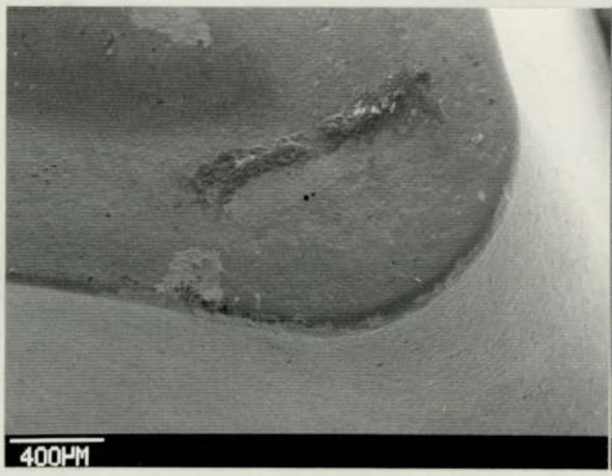
Figure 4.72: Scanning electron micrographs of the surface of the coated tool T_5 after finish machining of stainless steel showing the moderate wear features

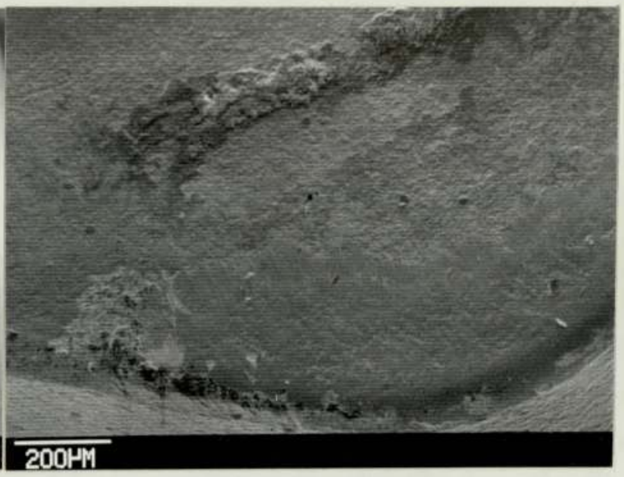
(a) general view of the working tip
(b) notching (groove wear) and BUE
(c) rough cutting edge and cracked nose
(d) smooth flank wear
(e) smooth rake face wear

smooth pattern of fine abrasive wear tracks alongside the curvature of the tool's nose. The nose is markedly cracked, with a rough cutting edge. Figure 4.72(d) shows smooth flank wear with fine tracks of the revolving workpiece during cutting. Figure 4.72(e) illustrates the considerably smoother tracks of the flowing chips initiating crater wear, very close to the rough nose and the cutting edge.

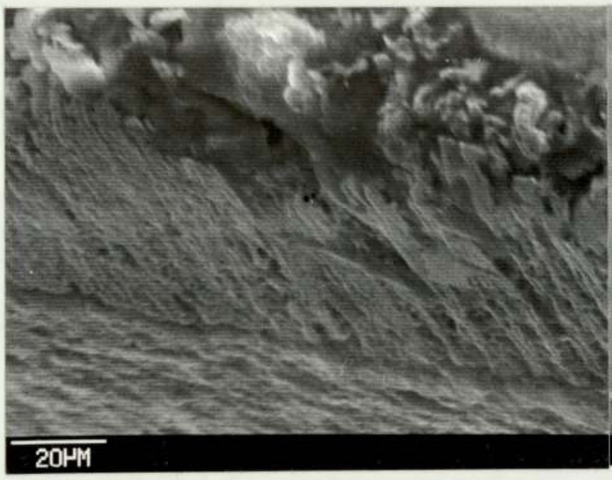
Figure 4.73 shows the surface of the working tip of the coated tool T_6. Figure 4.73(a) illustrates the smooth and sharp nose, small and shallow notch, negligible crater wear, and significant amount of chip material welded on the rake face far away from the nose and the cutting edge. Figure 4.73(b) shows a small flank 'wear land' under the cutting edge, uniform nose edge and lightly polished rake face near the nose. Figure 4.73(c) exhibits a rough and microcracked edge above course flank wear close to the notch. Figure 4.73(d) shows the smoothly polished crater wear.

Figure 4.74 shows the wear characteristics observed on the working tip surface of the coated tool type T_7. Figure 5.74(a) displays the wear features which are, comparatively of larger magnitude, than those detected on tool T_6, except the size of the welded chip material at the rake face which is smaller in tool T_7. Figure 4.74(b) shows the smoothly polished rake surface region adjacent to the cutting edge and nose, and the extension of the notch to the boundaries of the smoothly worn region. Figure 4.74(c) illustrates the formation of voids and microcracks at the cutting edge (arrowed) above the coarse flank wear nearer to the notch site. Figure 4.74(d) shows the remarkably smooth wear of the rake face with scattered voids under shallow wear tracks of the sliding chips (CFD = chip flow direction).





(a) (b)



(c) (d)

Figure 4.73: Scanning electron micrographs of the surface of the coated tool T_6 showing wear characteristics after finish machining of stainless steel:

(a) general view of the working tip
(b) intact cutting edge and nose, and shallow small notch
(c) rough and microcracked cutting edge close to the notch site above rough flank wear
(d) smoothly polished rake face wear

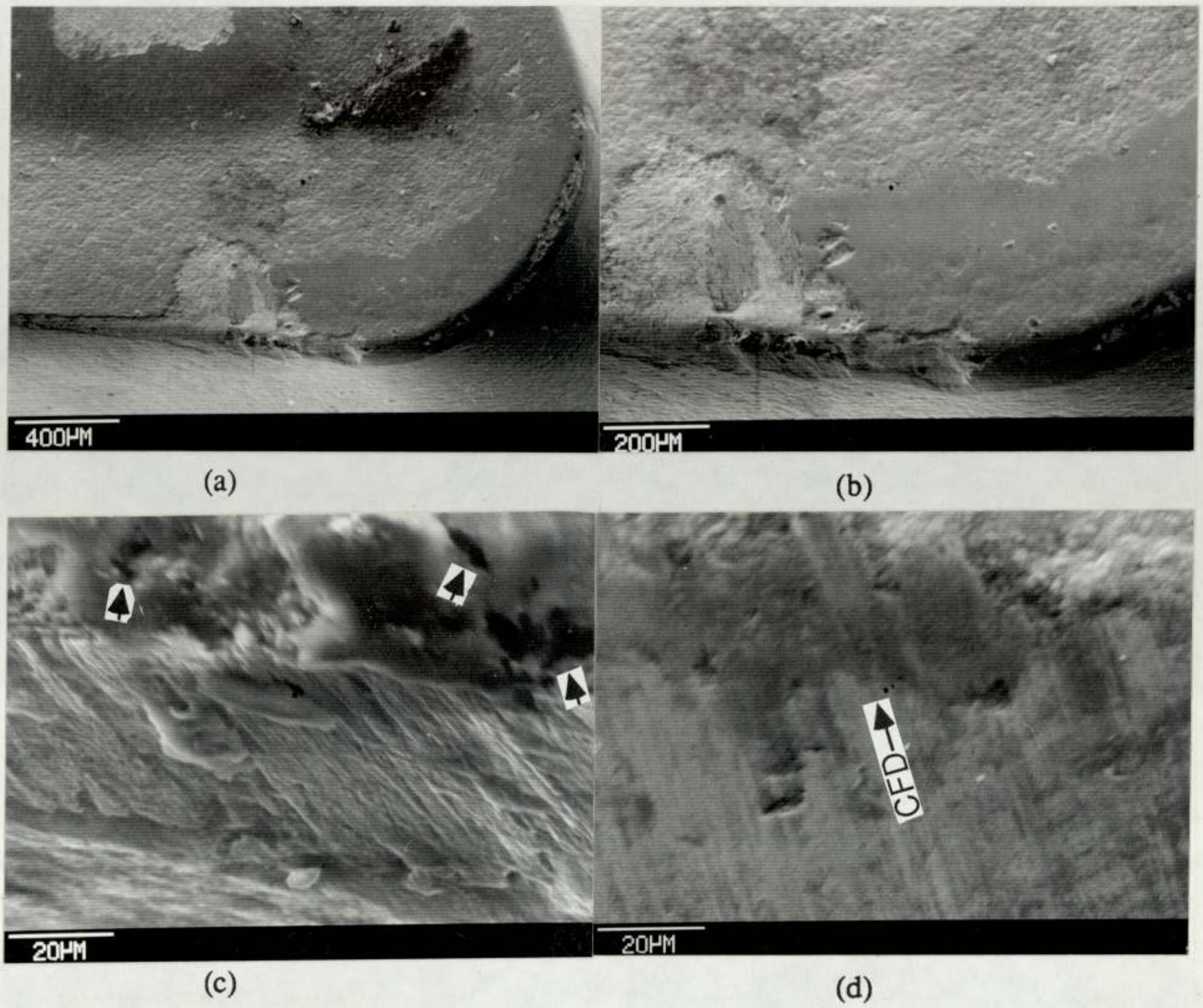


Figure 4.74: Scanning electron micrographs of the surface of the coated tool T_7 showing wear characteristics after finish machining of stainless steel:

(a) general view of the working tip
(b) notch, flank wear, and damaged cutting edge
(c) voids and microcracks of the cutting edge (arrowed) above rough flank wear near notch site
(d) scattered voids in the extremely smooth rake face wear (CFD = Chip Flow Direction)

CHAPTER FIVE

RESULTS. ANALYSIS AND DISCUSSION

CHAPTER FIVE

5 RESULTS ANALYSIS AND DISCUSSION

5.1 Introduction

The experimental machining results presented in the previous chapter, have covered a preliminary microscopic study of the cutting tools prior to machining, machining programmes employing mild steel and En 8 carbon steel as work materials, and an extensive programme of machining 316 austenitic stainless steel.

Apart from the pre-machining examination which has been undertaken for all the tools involved in the investigation, each phase of the experimental work has had its own features which were distinctive from those of the other phases. The different properties of the three work materials employed were one of the key factors that dictated the use of particular machining conditions in each phase.

Unlike the approach of most of the previous investigators, who assessed tool performance by only one or two means of evaluation, this research has attempted to utilize more methods in order to establish an interrelationship between the different factors that can be used to monitor tool performance. In the first three phases of the experimental work, tool performance was evaluated by two of the following means at the same time:

(i) Machining force measurement

(ii) Surface finish measurement

(iii) Flank wear measurement, and

(iv) Metallurgical examination.

However, the four means of performance evaluation were used together, when stainless steel was machined with the seven different grades of uncoated and coated tools. Consequently, a more comprehensive assessment was possible, and the specific performance of each of the various tools was distinguishable.

This discussion aims to feature the significance of the experimental results obtained in this investigation relative to the theory and to the results obtained by other researchers in the same field. Eventually, the findings of this investigation are utilized for establishing constructive conclusins and useful recommendations.

The special aspect in this research is the use of some cutting tools with new coating systems whose potentials are yet to be explored, and new geometries whose abilities are to be discovered, in addition to the relatively earlier grades whose behaviour and modes of failure are still awaiting recognition and understanding.

5.2 Pre-Machining Studies of Tools

The recognition of cemented carbides as some of the best tool materials, and their domination of the metal cutting industry are due mainly to their peculiar properties and ability to withstand the arduous conditions of the cutting process. The recent rapid development of surface coatings has enabled even better performance to be achieved by coating carbides. However, the need for the unique properties of carbides dictates their use as substrates for coating systems, and as entire tool materials for certain types of applications.

The status of cemented carbides as a well established cutting tool material has made them the obvious choice as substrates for coatings and the standard material against which the evaluation of coating performance is carried out.

Close microscopic examination of the experimental tools, before commencement of the machining tests in this investigation, has revealed interesting details of these tool materials.

Examination of the substrates of the five types of coated cemented tungsten carbide turning inserts and the two uncoated ones, revealed that the most distinguishable features which were expected to affect tool performance were as follows:

(i) Size and distribution of porosity

(ii) Grain size, distribution and uniformity of microstructure

(iii) Size and distribution of carbide particles in the binder (cobalt), and

(iv) Chemical composition.

All the above factors may have an influence on tool performance and thus contribute to variations in tool wear. The first three factors were detected easily by the scanning electron micrographs of the cross-section through each tool, while the chemical composition revealed by the EDX analysis gave semi-quantitative results with considerable inaccuracy due to the wide variation in composition from area to another.

A cutting tool substrate must be strong and tough. Strength is needed for wear-resistance and toughness for resistance to breakage by mechanical shocks and impacts. It is worth noting that these two basic requirements are opposite to each other, or, in other words each one can only be achieved at the expense of the other. Consequently, an adequate balance must be achieved by a compromise between the two properties. This is one of the main factors that has led to the alloying of the substrates and to the advancement of surface coating technology for this purpose. All the turning inserts under investigation in this work were of the steel cutting grade (P). This category is characterized by the addition of a small percentage of titanium carbide to resit crater wear which usually occurs in the case of the strong and tough WC-Co alloy. The ISO and manufacturer's numbers associated with the letter P are used as standards indicating the degrees of toughness and wear resistance. High numbers indicate high toughness and low wear-resistance, while low numbers refer to high wear resistance and low toughness.

It is known that the toughest tungsten carbides are those of large particles alloyed with a high percentage of cobalt, and the most wear resistant ones are those of small particles with a low percentage of cobalt. Turning insert users and researchers, used to practice machining and investigate tool performance without being certain of the preliminary information supplied with the large number of commercially available tools. The lack of information in the technical data supplied by the various manufacturers may be deliberate in order to avoid disclosing proprietory aspects of production techniques, or it may be due to ignorance about their products behaviour in the wide and ill-defined fields of application. It has been emphasised that this uncertain information may provide a useful guide for production engineers, but is not adequate for research purposes[99,117,118].

This has been proved true by the preliminary studies undertaken in this investigation. The insert type T_1 (S1P-P10) which was considered a standard turning insert of highly concentrated WC particles with a small percentage of Co (binder), and TiC additive to enhance resistance of crater wear, seems to possess a significant feature in its microstructure. This, as shown in Figure 5.1 was the large area of the substrate which was covered by the rounded structure of TiC-based solid solution known as the mixed crystal phase. This rounded mixed crystal occupied most of the micrograph volume with only a few scattered angular WC grains which were evenly distributed over a relatively narrow bands of cobalt. It seems that this tool consisted mainly of TiC with a much lower percentage of WC. However, the chemical analysis has not confirmed this idea, and showed a composition of TiC less than 10%. Consequently, the mixed crystal phase must be a combination of TiC with WC and the solid mixture possesses a good resistance to crater wear. Trent has attributed a similar feature to the low specific gravity of TiC and the high solid solubility of WC in TiC (70% by weight at 1500°C)[212].

The structure of the uncoated tool T_2 (S6-P40), was expected to show coarse grains of WC as it was supposed to be extremely tough. It did show that microscopical feature but fine grains of other additives were also incorporated. The most significant characteristic, however, was the evidence of pores and voids which must have an adverse effect on its high toughness (Figure 4.2).

The structure of the substrate of the coated tool T_3 (GC 415-P15), was expected not to differ much from that of tool T_1 (S1P-P10), but it showed quite a different microstructure with some porosity (Figure 5.3). The coated tools T_4 and T_5 (GC432-P35) which were of the same substrate and coating system and only differed in their geometry had a structure similar to that of T_2 (S6-P40) in the carbide size and distribution but porosity was not detectable (Figure 4.4).

The coated tool T_6 (GC425-P25) had a very homogeneous structure, especially the binder phase which was evenly distributed, but the extent of porosity in this type of tool was quite significant (Figure 4.5). This feature which seems to be a common defect in most of the substrates was totally absent in the coated tool T_7 (235-P45) which was one of the latest Sandvik turning inserts. The coarse WC grains were densly arranged on the narrow islands of the cobalt matrix (Figure 4.6).

The effect of the tool's bulk material on the machining performance is more likelay to occur either in very rough operations, or in later stages of a normal cutting operation after the progressive wear reaches a stage of severity and the tool's life approaches its end. However, wear may be accelerated if the substrate defects are close to the interface with the coating layers, or a localised defect lies under them.

The part of the tool that comes into direct contact with the work material and which is subjected to the high heat generation and frictional force is the surface. This is the part that needs to be protected from the wearing conditions encountered in metal cutting. Coated or uncoated, the tool's surface must have the minimum number of defects because almost any kind of surface defect can have a serious effect on the wear situation, and consequently on the cutting performance and tool life.

The pre-machining inspection of the experimental tool's surfaces has revealed significant surface defects. These were related to the topography of the rake face, the cutting edge and the nose radius conditions.

The uncoated tools were generally free of defects other than the scattered voids on the nodular surfaces. On the other hand, the coated tools showed more than one type of surface defect. These included voids, nodules, surface irregularities, microcracks, surface inclusions and roughness. However, the most serious defects were the microcracks and surface inclusions. These were detected in tools T_3, T_4 and T_5. The common feature about these tools was the coating system which consisted of a bottom TiC layer, intermediate Al_2O_3 layer and top layer of TiN. These defects were unlikely to be associated with the top layer of TiN since there were no such defects on the other coated tools which all had TiN as the top layer.

It is most likely that these defects were associated with the Al_2O_3 due to chemical interaction that took place during the deposition process or due to the nodular nature of impurities which appear beyond the extremely thin layer of TiN. These inclusions and star-shaped microcracks were a significant feature of the tool type T_4. Such defects would create weak localities in the tool surface and accelerate wear during a cutting operation.

The quality of the coating systems and the conditions of the coating/substrate interface of the coated tools is one of the important aspects that contribute directly to the performance of the coating and the life of the tool. Irrespective of the properties of a specific coating material, performance of coated tools may be influenced largely by the existence of defects within the coating layers or at the interface with the substrate. Such defects usually occur as a result of inadequate preparation of the substrate prior to the coating process, or as a result of chemical interactions during the process which should be operated under careful control.

The scanning electron microscopy study carried out on the carefully prepared cross-sections of the coated tools has revealed various defects which could have a significant influence on tool wear during machining.

With the exception of tool T_7 which was coated with very thin layers of TiN+TiC+TiN, with total thickness of about 3μm, all the coated tools appeared to have an additional layer between the substrate and the bottom layer of TiC. This layer, which could easily be mistaken for the TiC layer on top of it, was shown by chemical analysis to consist of tungsten and cobalt, the main constituents of the base material, in addition to titanium. This layer is termed eta phase and has been discussed by several investigators(9,57,168). It is a brittle layer which is formed due to the decarburization of the substrate surface during the early stages of the deposition of TiC coatings. Besides the occurrence of this brittle decarburization phase at the base material/coating interface, regions of micropores and localities of high void concentration were also evident in some tools. The void-enriched zones create weak areas under the weak brittle layers where damage to the coating may be initiated and accelerated to result in total tool failure at early stages of machining. However, the coating defects may be present even before commencing a cutting operation. Microscopic examination has revealed different forms of serious cracking of some coatings, mainly in the brittle layer zone at the coating/substrate interface. Tool T_4 had the highest frequency of these defects and was the one with most surface defects as mentioned earlier. The tool with the least number of defects was T_7 which was coated with extremely thin layers of TiN+TiC+TiN. The coating itself seemed to be free of any defect, covering the substrate homogeneously with an evidently excellent adhesion, except at very few localities of void formation beneath the coating.

5.3 Tool Performance when Machining Mild Steel

Tool performance study was undertaken by considering the behaviour of the forces and the surface finish of the workpiece during light roughing and finishing with two pairs of coated and uncoated turning inserts. These types of tool materials were not designed to machine the readily-machinable work materials such as mild steel which could be machined economically and efficiently by traditional tool material of medium hardness. However, it was felt that it might be a logical approach towards a proper evaluation of tool performance if short machining trials were conducted on an easy to machine material before dealing with the more difficult. Regardless of the comparative results and their significance in evaluating the coating performance, the trials have proved to be useful in providing a reasonable estimation of the appropriate selection of the machining conditions.

Despite the fact that there was no significant difference between the performance of coated and uncoated tools, there was evidence that coated tools tended to perform better at higher feed rates and depths of the cut. This has been demonstrated by the trend of the force curves when light roughing operations were undertaken.

As the pairs of coated and uncoated tools used in each of the two sets of machining conditions were different, the comparison has been made between coated and uncoated tool performance in each single situation. However, the selection and allocation of certain tools for particular operations was made on a constructive basis. Besides the recommendations of the manufacturers the ISO designation provided suitable guides for application selection, eg. rough or finish operations.

Although the coated tool T_4 and the uncoated one T_2 were designed for relatively rough cutting, they performed quite satisfactorily at feeds below 0.2 mm/rev where reasonable surface finish has been attained (Figure 4.20). Above that feed the surface was rough. The same observation applied to the tools T_3 and T_1 used for finish turning. There was no difference between the performance of the coated tool T_3 and the uncoated one T_1 when considering the three force components of low values (Figure 4.21). However on comparison between the surface finish results, it was clearly evident that the uncoated tool performed better than the coated one (Figure 4.22). At a feed rate of 0.25 mm/rev the surface finish of the uncoated tool was 37%

better than that of the coated one.

The common features observed after these machining trials were that:

* Both machining forces and surface roughness increased with the increase of feed rate.
* Coated tools tended to perform better than the uncoated ones at high feeds and large depths of cut.
* The surface finish was acceptable up to feed rate of (0.2-0.25 mm/rev) above which the workpiece surface was quite rough
* There was no advantage in cutting with coated tools when finishing operations were undertaken.
* The uncoated WC inserts performed better than the TiN-coated inserts during finish turning.
* Regarding mild steel as an 'easy-to-machine' material, there may be no special requirements in the properties of the cutting tools to be used for machining this steel. This fact together with the inconsistent results shown by the force/feed relationships and the surface finish values did not justify the use of coated tools for cutting mild steel. Even the use of the uncoated tungsten carbide tools might be uneconomical when general-purpose turning is to be carried out.

5.4 Tool Performance when Machining En 8 Steel

The turning tests conducted on En 8 steel have covered rough and finish turning operations followed by a study of the development of the forces involved with respect to cutting time. A metallographic study was then undertaken using the optical and the scanning electron microscopes. This enabled the coated tools performance, T_4 and T_3 to be compared with the performance of the uncoated tools T_2 and T_1

respectively.

The results of rough turning En 8 steel under the machining conditions used have shown the outstanding performance of the coated tool T_4 reflecting a remarkable reduction in the forces related to the uncoated tungsten carbide tool T_2(Figure 4.23). Both the cutting force and the feed force showed no increase from the beginning to the end of the tool for a cutting period of nearly thirty minutes. In contrast, the forces behaviour when using the uncoated tool T_2 was clearly different. The steady increase in the forces with the increase in the cutting time, was quite substantial. The cutting force for the uncoated tool started 3% higher than that of the coated tool and ended with a difference of 37%, while the feed force difference started at 9% and ended 50% higher than that of the coated tool. The same behaviour has been shown in the radial force value which changed from 9% to 53% in excess of the coated tool radial force. However, both radial forces were notably of low values in comparison with the cutting and feed forces.

Usually, a rapid increase in forces is an indication of the transformations that take place at the tool's surface. When excessive wear occurs at the flank face, cutting edge and nose radius, an increase in the cutting force is likely to occur, and when excessive wear takes place at the rake face, the feed force will respond by an immediate increase. The radial force, which is the component of force that acts against the tool, will increase as a result of excessive vibration or chatter, or as a result of nose wear or deformation.

The comparative results for the wear characteristics associated with both the uncoated and coated turning inserts were illustrated by the scanning electron micrographs of the crater wear (Figure 4.24), and flank wear (Figure 4.25). The wear features of the uncoated tool rake face, were totally different from those detected at the rake face of the coated tool. The significant crater wear of the former covers an area extending from the nose radius to the cutting depth extremity, with a clear depth and a width nearly reaching the cutting edge (Figure 4.24a). This significant size of the crater was caused by the mechanical stresses and high temperatures that arose due to high frictional contact between the flowing chip and the tool's rake face surface. Welding and pick-up of metal between the sliding chip and the tool, and the subsequent tearing-off of the loose fragments resulted in a progressive increase in the crater depth and width. Some fragments of different sizes were left behind by the chips where they could easily be observed adhering to the tool rake face, mainly on the crater side nearer to the cutting edge. Usually the high stresses and the heavy metal flow take place beyond this zone and the crater wear develops and deepens progressively. Eventually the tool fails when the crater reaches the cutting edge, and no further efficient cutting takes place.

As has been demonstrated by the force results and the metallographic illustrations, there seems to be a direct relationship between crater wear and force behaviour, and each one could be used to monitor the occurrence of the other. In this particular test the extent of the progressive wear was indicated by the steady rise of the cutting forces. However, the wear situation certainly involved several factors of different effects. As the cuttig period was increased, the cutting temperature, tool wear and cutting forces also increased.

The cratering resistance of TiN coatings is demonstrated by Figure 4.24b where the cutting edge of the coated tool subjected to the same cutting tests as the uncoated tool shown in Figure 4.24a was smooth and remained entirely intact. Moreover, the tool nose is almost untouched, and there are very light tracks caused by the sliding chips on the rake face with only one or two adhering fragments situated away from the cutting edge.

The absence of crater wear after nearly thirty minutes of cutting time, associated with the constant low cutting forces (Figure 4.23) revealed the potential of TiN as an excellent wear resistant coating for cutting En 8 steel under the machining conditions employed.

TiN coatings reduce or eliminate other features which are usually experienced during the cutting process. For instance, BUE 'build-up-edge' is one of the characteristics frequently generated during metal cutting, and has a significant effect on the product quality and tool wear. The surface finish measurement has not been undertaken in the present tests on En 8 steel, but flank wear was measured and presented metallographically in Figure 4.25.

Originally, TiN coatings were developed to combat crater wear when they were first introduced in the early seventies. Its low coefficient of friction and anti-weld properties reduce the heavy frictional contact between the chip and tool rake face. This enhances smooth sliding of the flowing chip and stops its adhesion to the tool surface. As one of the most dominant wear mechanisms in metal cutting is wear by diffusion between the tool material and the work material, it is believed that most coatings, and TiN in particular, resists this mechanism. Nevertheless, it is widely accepted that TiN coatings resist crater wear and TiC coatings resist flank wear. However, it is evident that TiN as a top layer in the coating systems investigated in this research has a beneficial influence on more than one aspect of wear. Its elimination of excessive BUE has already been demonstrated, but of more significance is the reduction of flank wear which is regarded by many as the most important type of tool wear. It is frequently used as the tool-life criterion and consequently receives particular attention.

Considering Figure 4.25a, flank wear of the uncoated tool is substantial, while that of the coated tool (Figure 4.25b) is very small. After nearly thirty minutes of cutting En 8 steel, the coated tool T_4 performed notably better than the uncoated tool T_2, as judged by the extent of flank wear width 'wear land'. The wear on the uncoated tool flank was 6 times greater than that on the coated one, indicating an improvement of 83% achieved by the use of the TiN coating.

Comparative results for finish turning of En 8 steel with the uncoated tool T_1 and the coated tool T_3 are presented graphically in Figure 4.28 and metallographically in Figures 4.27 and 4.28.

The force/cutting time relationship has shown low values for both cutting and radial forces for both the coated and uncoated tools. The cutting force for the uncoated tool started very low, then increased markedly during the first 24 minutes of cutting after which it remained at a constant value for the next 32 minutes then started to rise again in the last 11 minutes of the cutting time. On the other hand, the cutting force for the coated tool started with a relatively higher value than that of the uncoated tool, but it kept almost, a horizontal path until the end of the full 67 minutes of cutting time. The very low values of the radial force have shown very little increase from the start to the end of cutting. Higher values were recorded for the radial force associated with the coated tool than with the uncoated one but at the end of the test there was a tendency of the uncoated tool radial force to approach and exceed that of the coated tool. It was not possible to record the behaviour of the feed force due to a sudden drift of the feed force recorder as a result of a dynamometer defect. However, the results obtained have shown no significant improvement brought about by finish turning En 8 steel with the coated tools, especially at early stages of cutting where the uncoated tools did show lower forces during the first 20 minutes. These results are somewhat similar to those obtained for finish turning of mild steel. Probably the coated tools perform better at higher speeds or after longer cutting times, but, under the conditions used for this finishing operation there is no justification for using TiN-coated inserts. However, a coated tool's performance and potential might not be assessed solely by the cutting force results since there are many other factors that that can reflect the advantages of using a certain type of tool. Moreover, tool performance is a function of many interacting parameters involved in turning processes such as the work material and the machining conditions employed.

The wear features shown in Figure 4.27 demonstrate the difference between the behaviour of the uncoated tool (Figure 4.27 a&c) and the coated tool (Figure 4.27 b&d). The extent of crater wear which is quite significant in both types of tools, suggests that the assessment of tool wear and tool performance necessitates microscopic inspection since the cutting force relationships might not reflect the exact situation as is evident in this investigation. There is a considerable amount of adherent material on the rake face of the uncoated tool, and a magnified view of it (Figure 4.27c) reveals plastic deformation which had taken place in the vicinity of the crater. This working tip which was subjected to a substantial increase in temperature during the long cutting period, has been notched on both front and back edges with the crater wear joining the two grooves. Despite the fact that the nose remained unworn and did not suffer from built-up material, this tip is liable to breakage after further turning operations as a result of excessive notching and cratering.

The wear mechanisms likely to dominate in the case of this uncoated tool are a combination of diffusional, adhesive, abrasive and plastic deformation types of wear. On the other hand, the coated tool operated under the same cutting conditions showed an indication of oxidative type of wear. Oxidation of the surface took place at the chip/tool contact zone as well as at the edge of the nose. Because TiN is susceptible to oxidation when subjected to high working temperatures, it frequently experiences the formation of a thin oxide layer characterized by a dark colouration. This did not occur in the cutting trials discussed earlier because of the relatively low speeds. However, in these long cutting time tests, where high speed is involved, the extent of oxidation indicates the importance of the cutting speed and its role in dictating the wear mechanisms. Although many wear features can be masked by such oxide films, it is more likely that the poor performance of the coated tools in comparison to the uncoated ones in finish turning was due to the excessive wear that occurred beneath the dark oxide layer. When inspecting the rake face of the same worn tip, illustrated in Figure 4.27b, at the higher magnification shown in Figure 4.27d, it was evident that the TiN coated tool had undergone cratering similar to the uncoated tool but due to a different wear mechanism. Separate coating islands or nodules were formed at the edges of the wear scar, probably due to loss of bond strength caused by the high temperature associated with the high speed process. However, the nodules nearer to the cutting edge have deformed plastically as indicated by the elongated ridges parallel to the tracks of the flowing chips. Grooving and abrasive wear occurrence was indicated by the presence of the scratches and grooves across the crater in the direction of chip flow.

Notch wear seems to be associated with finish machining of En 8 steel more than rough machining. This mode of wear was revealed in more detail in the optical photomicrographs illustrated in Figure 4.28. Notching of the uncoated tool T_1 was coupled with a serious crack at the bottom of the deep notch (Figure 4.28a). The shallow notch of the coated tool T_3 was highly polished and crack-free. The former notch is liable to increase and ultimately might lead to total tool tip breakage. The same figures demonstrate the difference between the rough crater of the uncoated tool and the smooth shallow one of the TiN-coated tool.

5.5 Tool Performance when Machining 316 Stainless Steel

On machining stainless steel, forces on the tools are expected to be very high, tool wear is anticipaetd to develop in a short cutting time, several wear mechanisms are forecast to occur to limit tool life and the work surface finish is likely to be of poor quality.

The difficult conditions associated with machining stainless steel impose great restrictions on the cutting operations and necessitate strict control of the operating factors.

Probably, the most important aspects that affect tool performance are the maching tool itself, the machining conditions to be used, and the technique with which cutting is to be conducted.

In this investigation the problems of machine tool rigidity and efficiency, which are normally encountered in the use of conventional lathes, have been solved by the use of a powerful CNC lathe. The other two aspects were left for the coated tools to challenge and exercise their potential in solving the inherent problems involved in machining stainless steel.

5.5.1 Machining at Different Medium Speeds

Results were obtained after performing cutting tests as follows:

* Continuous roughing at 62, 78 and 94 m/min
* Interrupted roughing at 62, 78 and 94 m/min
* Continuous finishing at 125, 141 and 157 m/min
* Interrupted finishing at 125, 141 and 157 m/min.

The tools employed for roughing operations were the coated insert T_4 and the uncoated insert T_2, while those employed for finish operations were the coated insert T_3 and the uncoated insert T_1.

Evaluation and comparison of tool performance was based on flank wear and nose deformation measurement after roughing; and on flank wear and surface finish after finishing.

Generally, the results for rough machining were more significant than those for finish machining. These will be discussed separately. Considering the effect of continuous and interrupted roughing on flank wear, it was quite clear that interrupted cutting was more detrimental than continuous, to both uncoated and coated tools (Figures 4.29 a&b respectively). This was most likely to be due to the fluctuation of changing conditions and temperature during interrupted cutting, where heating and cooling with subsequent softening and hardening take place at the tool/workpiece interface and cause excessive wear. On comparison between the coated and the uncoated tools, the better results correspond to the coated tool in both continuous and interrupted operations.

The effect of continuous and interrupted cutting on nose deformation is shown in Figure 4.29 c&d. The uncoated tool has deformed more due to the interrupted cutting than as a result of continuous cutting. Flank wear was similar in both cases. However, the most significant observation was that the coated tool experienced very little nose deformation during interrupted cutting, while the same tool deformed during continuous cutting about three times as much as in the interrupted cutting (Figure 4.29d). It is likely that the stressed nose recovers during intermittent cutting and only elastic deformation takes place. This indicates the possibility of a longer tool life when a coated tool is used for intermittent cutting.

It is well known that during interrupted or intermittent cutting the loading on the tool's cutting edge and nose is characterised by severe mechanical stressing and cyclic temperature fluctuations at the tool/workpiece contact zone. Eventually this accelerates microcracking, flank wear and plastic deformation, or even causes sudden fracture as a result of impacts during edge engagement and disengagement with the workpiece.

Accordingly, the excessive flank wear, caused by interrupted cutting with the uncoated tool T_2 and to a lesser degree with the coated tool T_4 was quite predictable, as was the nose deformation of the uncoated tool T_2. However, one would expect the coated tool to perform better than the uncoated one. The coated tool T_4, did perform better by showing slightly less nose deformation than the uncoated tool T_2, but the most significant improvement was the substantial reduction in nose deformation during the interrupted cutting; this ranged between 65% to 70% at the three speeds used (Figure 4.29d).

It must be emphasised that results obtained at different speeds cannot be compared directly because the volumes of metal removed during the machining tests were different. This applies to the results shown in Figure 4.29 which were determined at the ends of the complete cutting operations. However, the progressive measurement of flank wear and nose deformation undertaken during the short time interrupted cutting could be used for comparison between tool performance at different speeds (Figures 4.30 & 4.3l). Both flank wear and nose deformation increase with the increase in the cutting speed. Nevertheless, within each speed, flank wear and nose deformation developed with the increase in cutting time. The improvements achieved by the coated tools was greater at the higher speeds and longer cutting times. The curves of flank wear/cutting time (Figure 4.30), and nose deformation/cutting time (Figure 4.3l) demonstrate the comparative behaviour of the uncoated and coated tools. It is of interest to note that the curves related to the uncoated tool showed typical wear/time curve shapes with three distinctive zones, initial wear, normal wear and accelerated wear regions. Similar behaviour for nose deformation was reflected by deformation/time curves. It is clear that the excessive and rapid wear or deformation periods during which tool failure is expected to occur appear after longer times of cutting at low speeds than at higher speeds. This implies the association of shorter tool life with higher speeds which are obviously more aggressive than lower speeds.

On considering the performance of the uncoated tool T_1 and the coated tool T_3 after continuous and interrupted finish turning at three different speeds, the results indicate an insignificant difference between the two tools. Interrupted and continuous cutting had the same effect on flank wear of the uncoated tool which showed relatively low values (Figure 4.32a). The flank wear results related to the coated tool have shown a considerable degree of inconsistency. Continuous cutting seemed to be more detrimental than interrupted cutting at lower speeds, while at higher speeds interrupted cutting appeared to be more damaging than continuous cutting (Figure 4.32b).

However, flank wear of the coated tool was clearly higher than that of the uncoated tool.

The surface finish of the workpieces after continuous and interrupted cutting was generally poor, showing the same fluctuation observed in the flank wear results for both the uncoated and coated tools. However, the surface finish achieved by the uncoated tool was marginally better than that associated with the coated tool (Figure 4.32 c&d).

It was evident that the use of the coated tools for the finish machining of stainless steel showed no advantages over uncoated ones. This has some similarity to the results obtained earlier with the machining of mild steel and En 8 steel. However, the only significant observation in favour of the coated tools is indicated by the trend of the surface finish time curves shown in Figure 4.33. Despite the considerable variations of the surface finish values obtained during interrupted cutting, there is a clear indication that the coated tools improve surface finish after long cutting times. The curves show a small but steady drop in the surface finish values the longer the time the cutting tool remains in use. On the other hand, the uncoated tool showed poorer performance at higher cutting time, but the situation changes at a very slow rate, except at the lower speed (Figure 4.33a) where the opposite behaviour of the two tools took place relatively fast.

5.5.2 Machining at High Cutting Speeds

The results discussed in this section have been obtained after attempting a comprehensive machining programme in which both rough cutting and finish cutting were undertaken. All the seven types of tools were used in each type of cutting operation. The evaluation was intended to cover a wide range of testing techniques which included the measurement of machining forces, flank wear and surface finish, plus an extensive metallographic examination. The machining tests themselves were based on practical machining conditions for general purpose cutting, practiced to attain economical achievements by a compromise mainly between high metal removal rates, reasonable product quality and long tool life.

5.5.2.1 Rough Machining

The quantitative assessment of tools performance during rough cutting revealed a wide variation in each of the three components of machining forces (Figures 4.34-4.36) and the flank wear width (Figure 4.37). The six curves shown in each figure are related to the uncoated tool T_2 and the five coated tools T_3-T_7. The uncoated tool T_1 (S1P-P10) failed catastrophically after 53 seconds. The working tip fractured suddenly in the first three seconds of the second cut. According to the pre-machining studies which have been carried out and discussed earlier, this tool was characterized by its high wear resistance and low toughness. Its lack of adequate toughness has led to rapid termination of its life by fracture as it could not withstand the difficult conditions of rough machining stainless steel. The other uncoated tool T_2 (S6-P40) which was very tough in contrast to T_1, did survive the machining test but was subjected to high forces which developed very rapidly suggesting a rapid deterioration and high wear rate. The five coated tools showed significant improvement in the three components of force in comparison to the performance of the uncoated tool T_2. The improvement in the cutting force ranged from 5% to 19% at the end of the 170 seconds in roughing, while the improvement in the other force components were 27%-34% feed force and 41%-58% radial force. However, both the feed and radial forces are very low in comparison to the high cutting force (vertical force).

On considering the flank wear results (Figure 4.37) the advantage of using coated tools for rough cutting stainless steel was very clearly illustrated by the very low flank wear width in the coated tools compared with the extremely high wear uncoated tool. After 170 seconds of rough cutting the different coatings reduced flank wear by 62% to 80%. The progressive wear behaviour which was comparable to that of the force/time relationships suggests a direct correlation between flank wear and the forces acting on the tool during cutting.

According to the evaluation of the forces and flank wear of the coated tools in comparison to the uncoated one, it was quite clear that the coatings under investigation were very successful in machining stainless steel, and the improvement in performance was remarkable. However, there was some variation in the coated tool performance in relation to each other (Table 5.1).

There are several factors which cause these variations in performance:

(i) different bulk material or substrates;

(ii) different tool geometries;

(iii) different coating systems;

(iv) different coating thicknesses.

Table 5.1: Tool performance after 170 second rough turning stainless steel

Order of merit	Cutting force	Feed force	Radial force	Flank wear
1	T_3	T_6	T_3	T_4
2	T_4	T_5	T_6	T_7
3	T_5	T_4	T_5	T_6
4	T_6	T_7	T_4	T_5
5	T_7	T_3	T_7	T_3
6	T_2	T_2	T_2	T_2
7*	T_1	T_1	T_1	T_1

* T_1 broke after 53 seconds cutting time

Cutting tools deteriorate at their rake face, flank face, cutting edge and the nose. Tool deterioration causes degradation of the workpiece surface finish and increases the forces acting on the working tip of the tool. Moreover excessive wear terminates the tool's service life.

On evaluation of tool performance, the forces may be high or low, and the surface finish may be rough or smooth and inconsistent along the workpiece surface. Likewise, wear may be high or low but it is of most importance to study the wear characteristics and mechanisms by which wear has taken place. As there are various characteristics and modes of wear that lead to tool failure, it is very important to identify and understand the failure mechanisms involved in each single situation.

So far in this investigation, the different coated tools under study have shown excellent performance in comparison to the uncoated tools used under the same machining conditions. However, there have been wide variations in performance when compared to each other. It should be pointed out that neigher the cutting forces, nor the surface finish, can reflect the exact wear features that occur on the cutting tool surface. Despite the importance of flank wear as a tool life criterion, its measurement is not fully informative about the wear situation.

The metallographic examination of the worn tools after rough cutting of stainless steel showed different wear characteristics for each of the different turning inserts.

The optical photomicrographs of the working tips (Figure 4.38) illustrate the rake face wear and nose deformation of the uncoated tool T_2 and the coated tools T_3-T_7. The figure gives a limited idea about the features of wear, but it is interesting to observe the plastic deformation of the uncoated tool T_2 (S6-P40) and the coated tool T_4 (435-P35). Both tools are supposed to be tougher than the others, particularly T_3 (415-P15) which was of the same geometry and coating as T_4. The tools with larger nose radii (0.8 mm) have not experienced any deformation at the nose.

The uncoated tool T_1 fractured at an early stage of rough cutting. After surviving the first cut which took 50 seconds, it cut for 3 seconds only in the second operation. It is interesting to note that the forces measured against this tool in the first cutting operation were the lowest of all corresponding forces of the other 6 tools (Table 4.8). However, the flank wear width was second highest after the uncoated tool T_2 which did survive the four cutting operations but with very high forces and significant flank wear. This indicates that failure was not due to high forces or excessive wear, but to a mechanism related to the material properties. This tool T_1 is the standard S1P-P10 which is characterised by its high wear resistance and low toughness, so it is usually used for finishing operations[159]. The small remaining part of notch at the corner of the fractured tip (Figure 4.39b) represents the start of the fracture which propagated across the tip through the crater wear zone. Although the forces during cutting were not high, they were enough to cause the brittle fracture failure. The small secondary crater wear shown in Figure 4.39 together with chipped zone and built-up edge indicate that fracture did not occur suddenly but that it took a short time to be completed, with the possibility that cutting continued after fracture before the machine was stopped.

The other uncoated tool T_2 which is supposed to be very tough and highly rated as a turning insert capable of cutting difficult-to-machine materials with high efficiency, has exhibited various characteristics of wear as shown in Figures 4.40 - 4.44. These features were partially obscured before a light chemical cleaning with diluted HCl was undertaken to reveal the surface details. The very severe wear features suggest that failure of this tool was imminent when the cutting operations ended. This is supported by the extremely high forces and flank wear width discussed earlier in this section and demonstrated in Figures 4.34 - 4.37. The extensive wear mechanisms which dominated in the case of this tool took place on the whole working tip. The wear characteristics and mechanisms include the following:

(1) Deep cratering associated with a significant amount of work material welded to the rake face where some fragments of the chip adhered strongly to the surface. Other chips of thicker and larger sizes were loosely attached to the rake face. Adhesive wear took place across the surface while the plastically deformed material supported this mechanism during the crater formation. Moreover, it is widely accepted that diffusion wear plays a great part and interacts with other wear mechanisms on the rake face.

(2) Plastic deformation of the cutting edge is evident by the bulging appearance of the flank face of the edge as shown in Figure 4.40a&b, Figure 4.43a, and Figure 4.44a&b. Built-up edge also occurred as shown in Figure 4.40a&b, but some of the built-up edge might be formed and broken away by the moving chip where part of it stuck to the rake face and participated in the crater development. Most of the remaining part on the cutting edge was removed by chemical cleaning.

(3) Plastic deformation of the tool nose was very severe as demonstrated by Figures 4.40a,d,e; 4.41a; and 4.42a&b.

(4) Serious cracking occurred at the cutting edge (Figure 4.43) as a result of the extensive deformation and the brittle nature of the tool materials.

(5) Microcracking and localised fracture was observed on the nose; this was associated with extensive plastic deformation (Figure 4.42).

(6) Notch wear occurred at the minor cutting edge beyond the nose as shown in Figure 4.40d&e, and Figure 4.41a.

(7) Subsurface deformation was detected on the rake face and the flank face as shown in Figure 4.44c&d.

All these modes of failure characterise wear of the uncoated tungsten carbide insert when machining 316 stainless steel at the conditions specified earlier in Chapter Four. Moreover diffusion wear is likely to be operative as indicated by the smooth crater wear illustrated in Figure 4.40 and Figure 4.41.

None of the coated tools which were subjected to the same test and assessment, performed in the same way as the uncoated tool T_2. Their remarkable reduction of the cutting forces and the flank wear has already been discussed. However, the wear characteristics revealed by the scanning electron microscope were very interesting. All the coatings reduced, and in some cases eliminated certain wear mechanisms, but new wear features, totally different from those detected on the uncoated tools were evident. Nevertheless each tool behaved in a way different from the other coated ones.

The wear characteristics associated with the coated tools may be induced by their different substrates, coating systems, geometry or the coating thickness. Furthermore, they may be affected significantly by the quality of the coating and variation of surface inclusions even within the otherwise identical situations. Consequently, each tool will be considered separately, then to facilitate proper interpretation the different wear characteristics will be treated in categories.

The coated tool T_3 (415-P15) which was coated with a triple layer of $TiC+Al_2O_3+TiN$ showed very little crater wear, but the following mechanisms and features are evident:

1 Excessive built-up edges accumulated on the cutting edge (Figure 4.45a).

2 Notch wear linked with groove wear and welded work material extending to the rake face side (Figure 4.45b).

3 Smooth abrasive wear with plastically deformed and elongated particles and surface inclusions (Figure 4.45c&d).

4 Crater initiation with evidence of erosion, and plastic deformation of built-up layers of chip material (Figure 4.45e).

5 Microcracking of the coating at the nose, flaking away and substrate exposure (Figure 4.46a&b).

(6) Abrasive wear of the exposed bulk material (Figure 4.46a), and localised microfracture at the nose (Figure 4.46c).

(7) Localised attrition wear at the flank face under the excessive built-up edge (Figure 4.47).

(8) Smaller notch was formed on the minor cutting edge, but this was much smalller than the big one on the uncoated tool T_2 that occurred in the same spot (Figure 5.45a).

Of all the characteristics mentioned above, the most significant ones are the BUE, groove wear and the nose wear. Both groove wear and nose wear featured coating damage, but in the first case the coating layers were worn away by continuous sliding of curled edge of the hot chip, whille in the latter case the coating was lost by mechanical damage or by brittle fracture following the surface microcracking by excessive loading and heat generation at the nose.

The coated tool T_4 (435-P35) was similar in geometry and coating system to the tool T_3, but different in substrate. It performed in a way similar to the tool T_3, and the dominant wear characteristics are summarised as follows:

(1) Notch wear on both the major cutting edge and the minor cutting edge.

(2) Built up edge accumulaetd at the major cutting edge, and some work material smeared over the groove wear zone formed on the rake side of the notch (Figure 4.48b,c&f).

(3) Plastic deformation and microcracking of the nose (Figure 4.48d&e).

(4) Abrasive wear of the rake face with smooth tracks, exposure of surface inclusions and plastic deformation of welded particles (Figure 4.49).

(5) Coat flaking and microcracking of deformed material at the nose (Figure 4.50a).

(6) Cracking of coating interface at the cutting edge (Figure 4.50b).

(7) Subsurface cracking at the flank and rake faces (Figure 4.51a-c).

(8) Coating disintegration and coating/substrate interface deformation (Figure 4.51d&c).

The most dominant wear mechanisms of the coated tool T_4 were the notch wear (grooving wear), the excessive built up edges, the nose deformation, abrasive wear of the rake face and the coating/substrate subsurface and interface deformation.

The wear characteristics observed on the coated tool type T_5 are summarized as follows:

(1) Notch or groove wear of the major cutting edge associated with substrate exposure and isolated patches of chip material welded to the rake face (Figure 4.52a&b).

(2) Extensive edge chipping associated with microcracking of the coating (Figure 4.52c&d).

(3) Chipping and abrasive wear at the nose (Figure 4.52e&f).

(4) Cracking of the coating at the cutting edge above flank wear land (Figure 4.534a).

(5) Abrasive wear of the rake face adjacent to the cutting edge (Figure 4.53b&c).

(6) Damaged coating layers at the rake face near the notch site (Figure 4.54a&b).

(7) Deformation of substrate surface at a chipped-off coating area.

(8) Smooth flank wear.

The most dominant mechanism was chipping of the cutting edge and tool nose, associated with microcracking of the coating layers.

It should be mentioned that tool T_5 had the same substrate and operating system as tool T_4. They only differed in their geometry, which appeared to have a significant effect on the wear behaviour.

The main wear features related to the coated tool T_6 are summarised as follows:

(1) Groove wear (notch wear) of the same shape and size as that of tool T_5 (Figure 4.55a&b).

(2) Smooth wear at the rake face adjacent to the cutting edge (Figure 4.56b&c).

(3) Localised cracking and deformation of the coating/substrate interface (Figure 4.57c).

Tool T_6 was coated with double layers of TiC+TiN with the same total thickness as the tripple layer system on tools T_3, T_4, and T_5. Its geometry was similar to T_5 and T_7 and the three of them represent some of the recently developed products of the manufacturer. However, it seems that the intermediate layer of Al_2O_3 on tool T_5 was the cause of the significant difference between the performance of the other two tools (T_6 & T_7).

The coated tool T_7 was a unique one, having the same geometry as T_5 and T_6 but different from both of them in its relatively tough substrate, and its extremely thin triple coating layer of TiN+TiC+TiN with an overall thickenss of 2-3 μm. When subjected to the same tests as the other tools, one would expect to observe wear characteristics totally different. However, it has already been shown that its machining forces and flank wear were comparable to the results shown by other tools. As far as the wear characteristics were concerned, T_7 demonstrated the following features:

(1) Rake face wear of different forms (Figure 4.58a and Figure 4.59b&c).

(2) Very shallow groove wear at the major cutting edge (Figure 4.58b).

(3) Void-enriched and rough nose (Figure 4.58d&e).

(4) Localised deformation of the coating/substrate interface at the rake face and flank face with very slight wear of the cutting edge (Figure 4.60).

5.5.2.2 Finish Machining

It is well known that performance of cutting tools during machining at low and medium speeds, is largely influenced by the presence of built-up edges. BUE is a characteristic of low speed machining which affects both crater wear and flank wear, in addition to the machind parts surface quality. When high cutting speed is involved the continuously changing conditions at the cutting edge during chip formation do not allow microwelds to occur. The swift movement of the chip on the tool surface hinders the formation of BUE whose absence is a characteristic of high speed machining. Tool performance and wear behaviour at high cutting speeds are a function of high temperature. The wear mechanisms that prevail in such conditions are mainly oxidative or diffusive types.

TiN coatings investigated in this research work were expected to improve the machining performance of stainless steel at such high cutting speeds. Although a surface cutting speed of 200 m/min may not be considered very high when other work materials are used, for stainless steel which is very damaging to the cutting tool, this speed is relatively high. The results of machining forces acting on the tools during finishing operations at 200 m/min Figures 4.61-4.63 showed behaviour totally different from the results obtained after rough machining. However, the coated tools did not show any significant improvements over the uncoated ones. Despite the fact that the three components of forces under the machining conditions used in this test were very low in comparison to those involved in rough machining, the forces related to the uncoated tools were clearly lower than the forces for the coated ones.

The behaviour of flank wear development with the cutting time (Figure 4.64) was notably different from the force/time relationships. The tools performed quite differently. While the uncoated tool type T_2 was worn away very rapidly at a wear rate of 96 x 10^{-3} mm/min, the other tools showed a comparatively low wear rate in the range of (35-63) x 10^{-3} mm/min. However, there was considerable variation in the wear of the different tools. The uncoated insert T_1 which failed to withstand the rough machining test for stainless steel as discussed earlier, performed well; its flank wear width was comparable to the coated inserts and even better than some of them. The coated inserts T_3 and T_4 performed exceptionally well in comparison to those with larger nose radii and chip breakers improved design which produced better surface finish and reduced creater wear.

The graphical representation of the workpiece surface finish variation with the cutting time showed significantly divergent behaviour for the various tools (Figures 4.65 and 4.66).

It was noticable that the three coated inserts with larger radii performed better than the other inserts with smaller radii, but the most significant results were related to the coated insert T_7, where the surface finish was very smooth and perfectly homogenous along the workpiece surface. Whilst there was a considerable fluctuation in the performance of the other inserts. The quality of different areas along a particular bar machined with the same tools was not consistent. This was due to the unstable condition of the tool/workpiece interface where the contact point conditions change due to excessive heat or surface wear of the tools flank and nose. As the nose radius of the tool is the part subjected to high stresses and continuous periodic changes during a cutting operation, these changes might be indicated by the variation in the finish/time curve. However, due to the continuous changes of the tool/workpiece interface condition, the surface finish may not reflect the wear situation of the tool, but only the point of contact with the workpiece. In some cases when the work material is very hard and the depth of cut is very small, the surface finish reading may not represent the tool's performance. This is due to the possibility of the tool pressing on the workpiece but no actual cutting or metal removal taking place. Surfaces generated in such situations are usually created as a result of metal deformation under the tool nose pressure. For this reason very large nose radii and very small depths of cut should be avoided when very hard materials are to be cut. However, that was not the case in this investigation, and as far as this work is concerned, the surface finish produced after the use of the tools under examination showed considerable variation. Starting with the best, the tools performed as follows:

T_7, T_5, T_6, T_3, T_2, T_1, T_4

It should be noted that T_7 which gave the best performance is the tool having the thin coating of TiN+TiC+TiN. On the other hand, T_4 which exhibited the worst performance is the tool with the triple coating layer of $TiC+Al_2O_3+TiN$. This tool is the one which contained the highest number of surface inclusions as discussed earlier.

Table 5.2: Performance of Cutting Tools on Finish Machining Stainless Steel

(165 second cutting time)

Order of merit	Cutting force	Feed force	Radial force	Flank wear	Surface finish
1	T_4	T_1	T_4	T_4	T_7
2	T_1	T_4	T_1	T_3	T_5
3	T_3	T_2	T_3	T_1	T_6
4	T_2	T_7	T_2	T_7	T_3
5	T_7	T_3	T_7	T_5	T_2
6	T_6	T_5	T_6	T_6	T_1
7	T_5	T_6	T_5	T_2	T_4

1 Indicates lowest force or lowest wear

From the foregoing discussion it is possible to draw some conclusions about the comparative performance of the experimental tools. However, the metallographic examination results after the finishing operations, were anticipated to reveal significant characteristics of TiN coatings' behaviour under the conditions used. It has, already, been proven practically that proper evaluation of tool performance necessitates detailed inspection of the worn tools.

The results demonstrated by Figure 4.67 have given a general idea about the wear features detected on the working tips. It was quite evident that the wear pattern was dictated by various factors:

* The properties of the bulk material, ie. the grade of the cemented tungsten carbide insert (Figure 4.67a&b; or c&d).
* The geometry of the tool; ie. the nose radius and chip breaker (Figure 4.67 d&e).
* The coating system, ie. triple or double layered (Figure 4.67e&f).
* The coating thickness (Figure 4.67f&g).

On considering the two uncoated inserts T_1 and T_2, the wear patterns and the details of wear detected, one might not believe that these tools were subjected to the same cutting operations since there was a great difference between the two worn surfaces. The main wear characteristics of the uncoated tool T_1 were, notch wear and crater wear (Figure 4.68). The smooth appearance of the crater in Figure 4.68b suggests the occurrence of wear by diffusion and abrasion. This is supported by the features detected in Figure 4.68d which shows the abrasion tracks along with micro voids which indicate a probability of delamination wear at later stages. The extent of notch wear together with the crater joining the two notches indicate the possibility of total failure by breakage through the crater after further cutting.

The main wear characteristics of the uncoated tool T_2 (Figure 4.69) include a deep and rough crater with its deepest side reaching the minor cutting edge which created a large notch beyond the nose. The significant amount of debris adjacent to the nose and inside the crater suggests the occurrence of an abrasive wear mechanism. However, the most significant feature of this large crater was the considerable amount of work material adhered to the rake surface, deformation in the chip flow direction and incorporation of the fragmented particles. These features suggest plastic deformation and adhesive "attrition" wear as the most dominant mechanisms.

The results presented in Figures 4.70 and 4.71 exhibits the wear pattern observed on the tools T_3 and T_4 respectively. Although these tools had different substrates, they behaved in a similar manner due to their similar coating systems. It was evident that the coatings of TiC+Al_2O_3+TiN have reduced tool wear markedly, particularly crater wear and notch wear which were the dominant mechanisms in the case of uncoated tools subjected to the same finishing tests. However, it should be noted that the modes of failure of the tools coated with this triple system, were most likely to be initiated as groove wear at the notch sites that joined by the crater wear. The governing factor is most likely to be the extent of coat flaking and development of the grooving together with the progress of the abraded crater.

According to the preliminary study undertaken and discussed in a previous section the top layer of TiN was extremely thin (<2μm), especially on tools T_3-T_5, where Al_2O_3 was deposited as an intermediate layer. Consequently, under conditions of high speed cutting of stainless steel it might easily be worn away by any mechanism in a short time to expose the Al_2O_3which was about 4 μm thick. In fact this seemed t be the case as illustrated by Figures 4.70 and 4.71 for the rough regions of the crater, where the surface inclusions revealed in the pre-machining studies were exposed deformed in the chip flow direction and promoted adhesive and abrasive wear mechanisms. In contrast to this, the slightly abraded region of the crater parallel to the cutting edge was only lightly polished, so it is most likely that a long cutting time will pass before a serious wear situation might occur. Another feature observed with these types of coatings was the longitudinal cracks (Figure 4.70c) formed at the cutting edge under a chipped area on top of a smooth flank wear of tool T_3. On the other hand tool T_4 showed rougher flank wear with deep grooves under a cutting edge consisting of scattered micro voids and fine cracks which might result in localised chipping of the edge after further machining.

It seems that the types of wear and the mechanisms by which wear of the coatings occurs depend to a great extent on the tool geometry. Comparing the wear characteristics of tool T_5 to those of tool T_4, the difference was immense. Apart from their geometry the two tools were similar. Figure 4.72 illustrates the details of the worn tip of the tool T_5. The notch of the cutting edge was smaller than those of T_3 and T_4 and the rake face wear was very low. The abrasive wear tracks were very light and smooth (Figure 4.72e) forming a curved shape beyond the nose curvature. Flank wear was very smooth but included crack-like grooves across the wear land width (Figure 4.72d). However, the significant feature was the rough and heavily cracked nose and cutting edge. Moreover, most of the flank wear was located under the notch site and very little was detected under the nose (Figure 4.72c).

It would obviously be expected that coating layers of the same type should perform in a similar manner when subjected to the same test, but this has been proved incorrect. The tool type T_6 was of the same geometry as tool T_5 but with a double layered coating of TiC+TiN. Indeed, to include a thick intermediate layer of Al_2O_3 coating would have a great effect on tool wear, but to increase the TiN layer thickness from about 1.5μm to about 4 μm instead of the Al_2O_3 coating must bring about a marked alteration in the wear characteristics.

Although the double layer system entered the market earlier than the triple layer, its performance was better than the latter, at least under the machining conditions of this investigation. The wear features illustrated in Figure 4.73 indicated that grooving wear, which was the most common characteristic of wear so far, has been reduced markedly in tool T_6. Nevertheless, the extremely smooth crater wear appeared to be lower than that of tool T_5; the cutting edge of tool T_6 and its nose wear clearly intact in contrast to the very rough and cracked nose of T_5. However, the flank wear of T_6 was rougher than that of T_5, and in a region close to the notch site the cutting edge on top of the flank wear had a significant number of voids and microcracks (Figure 4.73c). These are likely to develop and promote extensive notching or localised damage.

The thin triple layer coating system of tool type T_7 (TiN+TiC+TiN) performed as well as the other similarly designed tools T_5 and T_6. Although the groove wear was slightly larger than that of T_6, it was still smaller than the grooved region of tool T_5.

On comparing wear features of tool T_7 to those of tool T_6 it was evident that the rake face wear region of T_7 was larger and the nose was worn slightly more. The flank wear (Figure 4.74e) was smoother, but still the subsurface defects of the cutting edge were observed. Cracks and voids were evident, but were less severe than in tool T_6 (Figure 4.73c), where their pressure seemed to be linked with the use of Al_2O_3 as an intermediate coating layer.

It should be emphasised that the performance of coated tools when evaluated by force, flank wear width, and surface finish measurement might not reflect a coherent relations between them since a tool which gives the best result in one respect may not do so in another.

A tool might perform well by eliminating a specific mode of wear, but a new wear feature may appear. However, as far as this investigation is concerned, the various evaluation techniques followed to assess the performance of the TiN-coated turning inserts have proved to be of value as very interesting features have been revealed. The observations and comparative results have been discussed to enable constructive conclusions to be drawn about the behaviour of coated cutting tools and optimum machining conditions.

CHAPTER SIX

CONCLUSIONS

CHAPTER SIX

6 CONCLUSIONS

Although 'optimisation of machining' has more than one interpretation, its meaning in the present research is considered to mean low cutting forces, good surface finish and less tool wear.

Machining of Mild Steel

1 Coated tools provided no advantage over uncoated ones for the machining of mild steel except at high feed rates and large depths of cut. However, the use of coated inserts could not be justified even at these conditions because the forces were relatively low for uncoated tools and a slight reduction would only be a minor advantage.

2 For the two sets of machining conditions used, the surface finish of the machined parts was quite rough above a feed rate of 0.2 mm/rev. This indicated that the feed rate was the governining factor in finishing operations.

3 On comparing the surface finishes below a feed rate of 0.2 mm/rev, it was found that the uncoated tool produced better surface finish than the coated tool.

Machining of En 8 Steel

1 TiN coated tools (TiC + Al_2O_3 + TiN) proved to be very successful in rough machining of En 8 steel. The cutting forces remained constant at a low value for a long period of cutting time, while the forces involved in machining with the uncoated tools (S6-P40) increased steadily with cutting time.

2 The reduction in cutting forces related to the coated tools was attributed to the reduction of tool wear due to the presence of the CVD coatings. On the other hand, the rapid increases in the cutting forces for the uncoated tools were due to heavy abrasion of the flank face.

3 CVD coatings resisted more than one aspect of tool wear. They reduced crater wear and flank wear, and eliminated excessive BUE.

4 The substantial crater wear which occurred on the rake face of the uncoated tools indicated a direct relationship between the high cutting forces and the excessive wear. In the case of coated tools crater wear was absent after nearly 30 minutes of cutting time.

5 TiN-coated tools achieved 83% reduction of flank wear relative to the uncoated tools after a cutting time equivalent to the expected life of the uncoated tools. At this stage the coated tool was still in good condition but no attempt was made to determine its useful life.

6 The built-up edge formed when machining with uncoated WC tools was eliminated totally by machining with TiN-coated tools.

7 As in the case of mild steel no advantage was found in using coated tools for finish turning.

8 The metallurgical investigation revealed that on cutting En 8 steel with the uncoated tungsten carbide tools, the dominant wear mechanisms were a combination of diffusive, adhesive, abrasive and plastic deformation types.

9 TiN-coated tools deteriorated by oxidation at the rake face and the nose. This mechanism was dominant during high speed machining where the cutting temperature was high.

10 Notch formation and groove wear were found to be associated with finish machining more than with rough machining. Notching of the uncoated WC insert was promoted by significant cracking. In contrast the shallow and highly polished notch of the coated tool was formed by the continuous friction between the chip edge and the tool at the end of the cutting depth.

Machining of Stainless Steel at Medium Speeds

The following conclusions are based on turning tests made at cutting speeds of 62, 78 and 94 m/min for continuous and interrupted roughing; and at cutting speeds of 125, 141 and 157 m/min for continuous and interrupted finishing operations.

1 Interrupted rough cutting of stainless steel at medium cutting speeds was found to be more detrimental to the cutting tools, than continuous rough cutting at the same machining conditions.

2 The main modes of tool failure during rough cutting of stainless steel at medium speeds were plastic deformation of the nose and flank wear; both developed rapidly with increase in cutting time.

3 At lower cutting speeds there was no significant difference between the performance of uncoated and coated tools, but at higher speeds the latter showed their superiority over the former.

4 CVD coatings could not prevent deformation during continuous rough cutting but they reduced deformation during interrupted cutting, which is normally the more severe operation, very significantly.

5 During finish turning of stainless steel at medium cutting speeds there was no significant difference between the uncoated and coated tool's performances. However, continuous cutting seemed to be more detrimental than interrupted cutting at lower speeds, while at higher speeds the opposite was observed.

6 After both continuous and interrupted finish cutting of stainless steel it was found that flank wear of the coated tool was higher than that of the uncoated tool.

7 When cutting stainless steel at medium cutting speeds the surface finish of the workpieces after both continuous and interrupted operations, was generally poor showing the same fluctuatins and inconsistencies observed with flank wear. However, the surface finish produced by the uncoated tool was marginally better than that associated with the coated tool.

8 It was evident that the use of CVD coated tools for finish machining of stainless steel at medium speeds and other conditions employed, showed no advantages over the uncoated ones. This had some similarity to the situations of finish machining mild steel and En 8 steel at different cutting conditions. However, there were clear indications that at longer cutting times the coated tools performed better than the uncoated ones.

Machining of Stainless Steel at High Speeds

The following conclusions are based on turning tests carried out at speeds of 100 m/min for rough operations and 200 m/min for finish operations:

1 Tools of inadequate toughness are not suitable for cutting stainless steel as they can fail prematurely. The trials made at cutting speeds higher than 200 m/min or depths of cut more than 2.5 mm led to rapid termination of tool life by immediate fracture.

2 The coated tools, irrespective of their different substrates, coating systems, coating thicknesses, and geometries; performed excellently in comparison with the uncoated ones, particularly for roughing operations in which the standard uncoated tool (S1P) broke after 53 seconds.

3 Both the cutting forces and flank wear for the coated tools were reduced significantly in comparison with those for the uncoated tool (S6). After 170 seconds of rough cutting, the different coatings reduced the forces in the range of 5%-58% and the flank wear by 62%-80%.

4 The similar behaviour of force time curves and flank wear width-time curves suggested a direct correlation between the progress of flank wear and the development of the forces acting on the tools during cutting.

5 Tools having the same coating systems, the same geometry or of the same coating thickness did not necessarily perform in a similar manner.

6 The difference in the number of coating layers had no great effect on tool performance as there was no consistency in the results.

7 During rough machining, plastic deformation of the nose occurred to the tougher tools with smaller nose radii, while those with larger radii did not experience any deformation. This emphasised the influence of tool geometry.

8 Failure of the uncoated tungsten carbide tools during rough cutting of stainless steel, could be caused by one or a combination of several of the following mechanisms; brittle fracture, adhesive and diffusive wear at the rake face, plastic deformation of the cutting edge and the nose, microcracking and localised fracture at the nose, built-up edge, cracking of the cutting edge, and notching of the minor cutting edge beyond the nose.

9 CVD coatings reduced or eliminated, almost, all the above mechanisms, but new characteristics appeared to be associated with the coated surfaces.

10 The most dominant wear characteristics of the coated tools during rough cutting of stainless steel included the following:

* Groove wear (all tools)
* Nose wear (small radiused tools)
* Microcracking of the coating at the nose (all tools)
* Built-up edges (mainly small radiused tools)
* Nose plastic deformation (small radiused tools of tough substrate coated with TiC+Al_2O_3+TiN which had more defects at the coating/substrate interface).
* Notching of the minor cutting edge (small radiused tools).
* Microcracking and chipping of coating at the cutting edge and nose (TiC+Al_2O_3+TiN coating on the large radiused tool).
* Flaking off of coating at nose and notch site (TiC+Al_2O_3+TiN coating on small radiused tools).

11 Tool failure in finish machining of stainless steel occurred by progressive wear rather than by sudden fracture.

12 In terms of cutting forces, finish machining of stainless steel with coated tools showed no advantages over the uncoated ones.

13 With regard to flank wear/time results the uncoated tool S1P-P10 which failed in rough cutting, performed fairly well and even better than some of the coated tools. The coated tools generally showed a reasonable wear rate within the range (35-63) x 10^{-3} mm/min in comparison with the high wear rate of the uncoated tool S6-P40 which was 96 x 10^{-3} mm/min.

14 The best surface finish was produced by the large radiused inserts, particularly the one with the very thin layers of TiN+TiC+TiN whose surface had the least number of defects prior to machining.

15 The worst surface finish was produced by a triple layer coating of TiC+Al_2O_3+TiN whose surface had the highest number of defects and a cracked coating/substrate interface. The poor surface finish produced by this tool yet its excellent performance regarding the cutting forces and flank wear measurements indicated the adverse effect of Al_2O_3 on the surface finish, and the favourable effect otherwise.

16 Wear of uncoated tungsten carbide during machining of stainless steel occurred, mainly, by crater and notch types. The two notches on both edges of a working tip can become connected by a deep crater and develop to cause total failure. CVD coatings appeared to combat these types of wear which develop by diffusion and

abrasive wear mechanisms.

CHAPTER SEVEN

SUGGESTIONS FOR FUTURE WORK

CHAPTER SEVEN

7. SUGGESTIONS FOR FUTURE WORK

The CVD coatings investigated in this work have shown great potential in improving machining performance and reducing tool wear. Despite the various experimental approaches followed in this research programme, several other means of assessment can be attempted to extend the scope of the investigation.

1) The surface and interface examination carried out prior to machining has revealed certain coating defects which may contribute directly in the machining performance and the wear of the tool. Consequently it is of importance to investigate the occurrence of these surface and subsurface defects and and their association with the coating systems.Toundertake this type of study, it is essential for the coating process to be under the control of the investigator. It is not satisfactory to evaluate only commercially produced tools.

2) Tool life testing is one of the important evaluation methods which has not been covered in this research. However, there is conflict about the validity of the different tool life criteria. Nevertheless, ultimate tool life is a characteristic of commercial interest and should be investigated.

3) New wear characteristics were evident when cutting stainless steel with coated tools instead of uncoated ones. Further research is necessary to investigate these over a range of machining conditions.

4) Other parameters of significant influence on the machining performance and the wear of the cutting tool are the coolant, the tool geometry and the work material. Extended research is needed to study the effect of coolants other than the standard 1:10 oil-water, and the effect of cutting difficult-to-machine materials such as titanium alloys with various tool geometries.

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