WEAR RESISTANCE OF SURFACE TREATED METAL-WORKING TOOLS

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SUMMARY

Tools in metal-working applications experience considerable amounts of wear that lead to degradation of tool performance, reduction in production and limitation of tool life. By using surface treated tools to combat wear, improvement in production quality, increase in production and reduction in down-time in repair and replacement can be achieved.

Since hot forging subjects dies to some of the most severe conditions experienced in metal-working, it was chosen as the wear resistance test in this investigation. The two types of steel employed were No. 5 die steel and H.13 hot work steel. The surface treatments chosen for wear study were titanium nitride coatings deposited by chemical vapour deposition, and vanadium carbide coatings deposited by the Toyota Diffusion process.

The experimental dies were used to forge 50, 100 and 200 En.3B steel slugs on the uncoated and coated dies. An extended forging trial using 400 and 600 slugs was carried out on VC-coated No. 5 dies.

The effect of surface treatment on die performance was studied and the wear mechanisms involved were considered.

The wear evaluations and assessments were performed by the following methods:

1. The use of a surface analyser to determine changes in surface profiles and to measure wear volumes.

2. The use of an optical microscope and a scanning electron microscope to examine damage to the die surface and sub-surface.

The coatings and coating techniques employed proved to be successful in increasing the wear resistance of hot forging dies made from both types of tool steel. On the extended forging trial evidence of abrasive wear and slight localised erosion could be detected. The mechanism of failure which started as void nucleation and crack formation at early stages of forging stepped up successively and led to delamination wear, which proved to be the most dominant mechanism of failure in the surface treated hot forging dies.

KEY WORDS: WEAR; COATING; HOT FORGING DIES; VOIDS; CRACKING

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1. INTRODUCTION

Tool steels, readily workable in the soft state and certain types after hardening, possess favourable mechanical properties, such as good hardness and toughness. With the rising cost of material and labour, there is a growing need in almost all cases to produce tools economically and with high grade of quality. One of the major objectives in metal working industries is to lengthen the life of tools and to increase their reliability through the application of various wear-resistant coatings and by using different surface treatment techniques. Within universities and industrial research establishments, in recent years, there has been increased interest in the study of the subject of wear-resistant coatings, particularly the wear performance of surface treated hot forging dies. This is an attractive field for researchers since the most severe service conditions in the metal working industry are associated with hot forging, where many wear mechanisms interact, leading to failure of dies which limit their service life.

Many surface treatments and different coating techniques have been proposed by researchers to combat wear, and most of them have resulted in varying degrees of improvement in wear performance. These wide variations during hot forging were partly due to the complicated wear mechanisms associated with the process, and partly to the effect of the coating properties on the original properties of the die materials. However, an interesting outcome of one of the previous investigations was the evidence for the delamination type of wear. This mechanism has been ignored largely by most researchers since its proposal by 'Suh' in 1973,, and it still awaits more exploration.

The continuous developments in industry and interest in the subject of wear-resistance of tools necessitate further investigation of wear performance and behaviour under different service conditions utilizing newly adopted coatings and surface treatment techniques.

The investigations on die wear of coated and uncoated tools, carried out at Aston University [1-3], were based on a standard test involving the forging of 1000 billets of En 3B mild steel. Consequently previous studies have dealt with wear behaviour and mechanisms after a large number of forging operations when a significant amount of wear had occurred. Such studies proved to be useful for predicting the extent of service life improvement. Die failure may start at early stages of service despite the application of good wear-resistant coatings, and sometimes these initial stages of damage are difficult to detect.

The aim of the present work is to study wear after a few forging cycles and extend the previous investigations on surface treated hot forging dies, employing new wear-resistant coatings and surface treatment techniques.

The dies were prepared from two types of hot work steels, namely, the Electem No. 5 die steel (B.S.224-1938) and BH 13 tool steel. These steels are widely used in the metal working industry, not only for their good hot work properties, but also for economical considerations. The two surface treatments utilized were titanium nitride (TiN) deposited by chemical vapour deposition - CVD - and vanadium carbide

(VC) by the Toyota Diffusion Process - TD. The test equipment employed was a standard upset hot forging press originally devised by the Drop Forging Research Association and used for previous researches at Aston University [4]. The techniques employed for the assessment of wear were:-

(1) Measurement of wear volume using the "Talylin" surface analyser.

(2) Microstudies of the surfaces using the optical microscope and the Scanning Electron Microscope (SEM).

(3) Microstudies of the subsurfaces using taper sections and vertical sections, examined under the optical microscope and the SEM.

According to the wear volume considerations both of the coating systems used in this investigation performed excellently and in most cases surface wear could not be quantified since it was so small. Hence, the two coatings can be considered as promising and useful candidates for hot forging die treatments.

However, the surface and subsurface studies revealed fluctuating wear conditions and interesting features of die failure at early stages of service. The domination of delamination wear and its association with the initial failure at the early stages was evident.

2. LITERATURE REVIEW

2.1 General Aspects of Wear

2.1.1 Significance of Wear Studies

Wear leads to reduction in operating efficiency by increasing the power losses, oil consumption and the rate of component and tool replacement. With the growing importance of economy as a governing factor in industrial development, wear, together with its intimately related subject 'tribology', started to receive more attention from investigators recently. Advancement in wear technology appears to be based on protecting machines and tools, conserving energy, saving lubricants and improving plant performance. In engineering and industrial establishments wear studies are considered as a real investment. As far as this work is concerned, the application of wear resistant coatings on the surfaces of hot forging dies will lead to increased efficiency and reduced maintenance costs; but more significantly through enhanced reliability and increased productivity.

2.1.2 Definition of Wear

Wear is not a true property of material like tensile stress or modulus of elasticity, but it is an attribute of the engineering system. It occurs as a result of many simple and complicated interactions between different environmental conditions and other material properties. Any change in load, speed or surface properties may cause catastrophic changes in the wear rate of one or both of the surfaces in contact [5]. The fact that wear can be caused by widely varying conditions and various interacting factors had led to large differences between earlier researchers in their attempts to establish basic definitions and characterizations for the numerous types of wear. Different definitions have been reported and a large number of terms, used occasionally, to describe the same type of wear. For example, scoring, scratching and gouging, all refer to abrasive wear, while galling and scuffing are only some forms of adhesive wear.

Some international technical bodies and professional institutions have adopted their own terminologies and definitions. These include the Institute of Mechanical Engineers (I.Mech.E.), the American Society of Lubrication Engineers (A.S.L.E.) and the (O.E.C.D.) [7] committee on terms and definitions in tribology. However, the general definition of wear in its broad scope stated in the Tribology Handbook [8] seems to be more acceptable. It defines wear as 'the progressive loss of substance resulting from mechanical interaction between two contacting surfaces.' In general, these surfaces are likely to be in relative motion, either sliding or rolling, and under load. These are some of the main factors creating a wear situation that occurs because of the local mechanical failure of highly stressed interfacial zones. The failure mode will often be influenced by the environmental factors.

2.1.3 Mechanisms of Wear

The subject of wear is known for its complex nature. Various and extensive studies have been carried out to understand this phenomenon. Most investigators [6,9-11] have reported wide variations in the details of their results. However, there is assumed to be general agreement that about half of all industrial wear situations are essentially abrasive in nature, about 15% involve adhesive wear and the remaining 35% consists of a combination of fatigue, fretting, erosion and cavitation, and chemical attack and oxidation. These types are thus the modes of wear most likely to be encountered. It is worth emphasizing, however, that in practice several of the wear mechanisms may occur simultaneously and can interact to form the failure of a certain situation. These mechanisms represent a traditional classification of wear, however one of the recently proposed, but not yet fully explored, mechanisms is the delamination type of wear which represents a good example of the interaction between the different modes of failure.

As a background for further discussion in this research it is useful to consider the general principles of the wear mechanisms experienced in the metal-working industry.

2.1.3.1 Adhesive Wear

Adhesive wear may be called, in certain engineering applications, galling, scuffing or seizing. These different types of failure occur as a consequence of adhesive wear under different conditions; for example, scuffing of pistons and seizure of shafts. In general adhesive wear occurs when two surfaces slide against each other. Early studies of the subject of wear agree on the main features of the adhesion theory where plastic deformation is the governing factor [12-14].

The force between two surfaces in localised contact results in adhesion and a process of solid phase welding. During relative motion between the contacting asperities on the mating faces of the two metals further plastic deformation results in a process of junction growth until shearing occurs. The process of adhesive wear starts and progresses in mating surfaces depending on the different conditions that favour the adhesion. These conditions, in most cases, are cleanliness of surfaces, non-oxidising conditions and the chemical and structural similarities between the sliding surfaces [10].

The strength of adhesion between two metals reflects the degree of possibility of solid-solubility of one metal in another, and this shows the extent to which matching can occur between the crystal lattices [10].

It was noted by Roach et al [15] that pairs of metals having low mutual solubility have less tendency to scuffing during sliding than soluble pairs. Later the theory was extended by Rabinowicz [14,16] to confirm the link between this mutual solubility and adhesive wear. The actual establishment of a bond in adhesion is only the first stage of a wear mechanism, and there is no instant loss of material to bonded asperities which may strengthen by work hardening.

Shearing may occur within the body of one of the surfaces in contact, thus allowing fragments of one material to transfer to the other surface.

Metal-working operations, in general, exhibit varying adhesive wear situations. If the mating surfaces are of different metals, which is the normal case in tools, the harder surface becomes covered with a thin transferred film of the softer metal and at some instant the sliding tends to be between two layers of similar metals instead of between the original surfaces of different pairs (17). It is known that pairs of different metals generally wear less than when one metal is slid on itself (14). However, in like metal couples wear and friction may decrease if a thick film of oxide is formed (provided that the oxide is not much harder than the metal), or if a metal has a hexagonal structure. Sikorski (18) demonstrated that whilst there is a general inverse trend between the coefficient of adhesion and hardness the precise relationships depend on the particular crystal structure of the metals involved. Close packed hexagonal metals, such as Cd, Zn, Be and Co generally exhibit relatively low adhesion because their restricted slip properties during plastic deformation limit the growth of intermetallic junctions (10).

However, under any combination of pairs of sliding metal surfaces, most wear processes commence as adhesive mechanisms but as the wear process leads to the generation of debris the mechanism may change to abrasive. Wear debris becomes or is formed of oxides, which are very hard (8). Due to the instability of the surfaces in contact, especially in complicated situations where many factors interact, the adhesive wear at its later stages may disappear and new modes of failure start to dominate.

Quantitative estimates of adhesive wear performance are prepared by calculating the wear parameter k, from the primary concept that the friction is related to the true area of contact.

$$k = 3 (v) H/_{\ell s} \quad (19,20)$$

where v, H, ℓ and s are the volume of material removed, the hardness, the applied load and the sliding distance respectively. Archard [19] considered this parameter as a probability factor, depending on how many junctions lead to the formation of wear debris for one encounter.

Other attempts at the estimation of wear in many other cases have been reported [9, 10, 21]. The formula used by Eyre[6] for finding the volume of material lost per unit distance of sliding (wear rate) was:-

$$\text{Wear Rate (R)} = \frac{v}{s} = \frac{KL}{H}$$

where v is the volume of wear, s is sliding distance, L the applied load and H the hardness.

2.1.3.2 Abrasive Wear

Abrasive wear is one of the most common forms of damage in practice. It occurs when hard particles penetrate a softer surface and displace material in the form of elongated chips or slivers. It is sometimes described as scratching, scoring or gouging; the difference being mainly in the degree of severity. Abrasion is usually caused either by particles which are embedded or attached to some opposing surface, or by particles which are free to slide and roll between two surfaces. The latter arrangement causing far less wear than the former [8]. Khrushchev and Babinchev [22] assumed that the abrasive wear mechanism starts with the formation of plastically impressed grooves with no metal removal involved. The second stage is the separation of metal particles in the form of microchips. They stated that pure metals tend to show proportionality between wear resistance and hardness, whereas hardened steels behave differently and wear more rapidly than a pure metal of a comparable hardness (Fig. 1). In other earlier work of the same researchers it has been concluded that when the abrasive hardness is very much greater than the hardness of the wearing material, the wear is independent of the abrasive hardness, but it decreases as the wearing material hardness approaches that of the abrasive [23]. On the other hand if the hardness of the abrasive is less than that of the wearing material, wear decreases rapidly as the difference increases. Richardson [24,25] emphasized this relationship by defining hard abrasives as those whose hardness exceeds that of the worn surface material; and soft abrasives as those whose hardness is less than that of the worn surface. These assumptions have been translated into a simple mathematical relationship as follows:

$$K_T = \frac{H_v \text{ of surface}}{H_v \text{ of abrasive}}$$

where K_T is the relative hardness factor for which Richardson [25] has put a lower limit of 0.5 while Eyre [6] considered that the ratio over 1.3 is of no use, as no

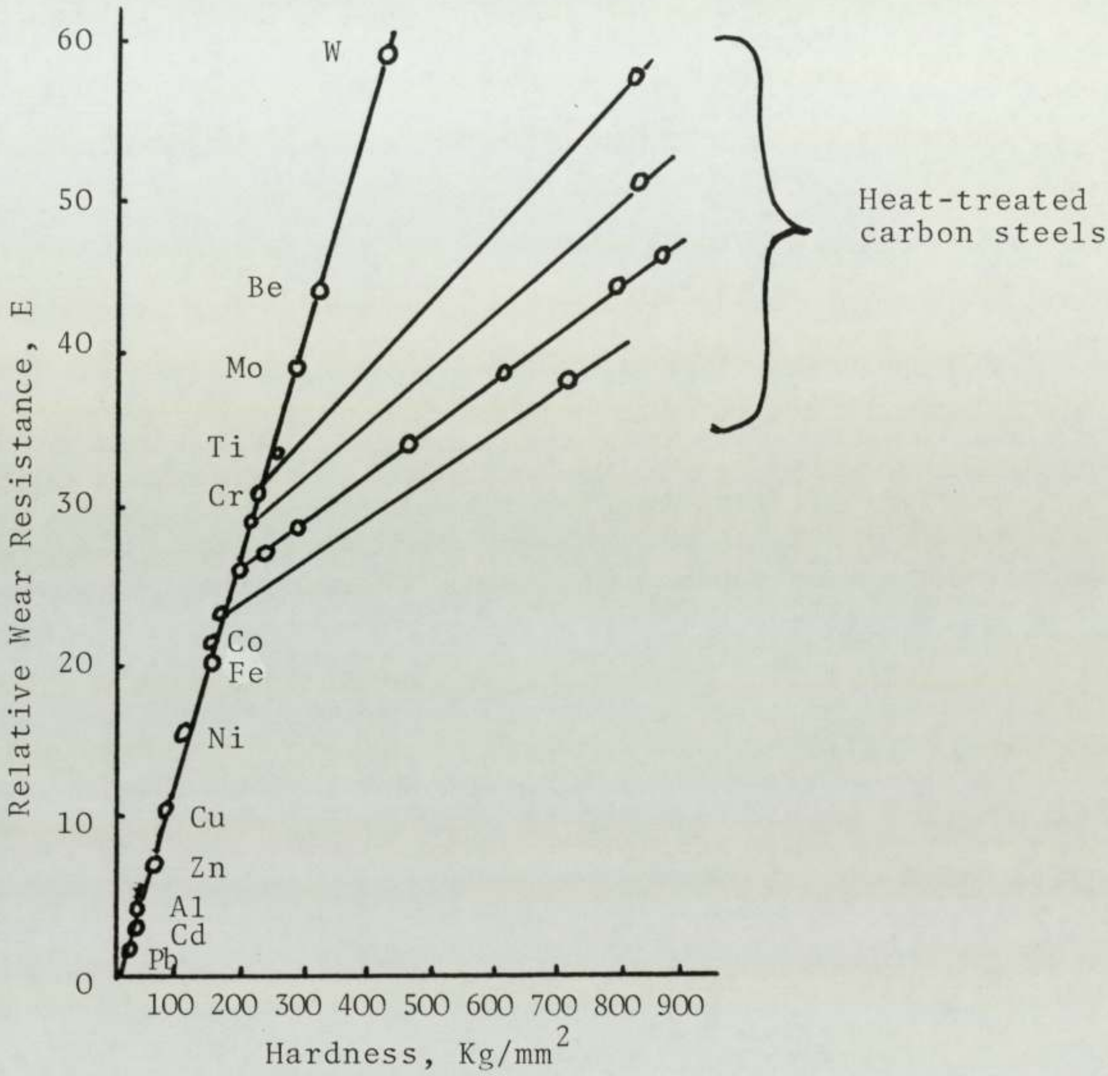


FIGURE 1: Relative abrasive wear resistance of metals vs hardness (after Krushchev and Babichev) (22).

significant improvement will be obtained. However, a more important relation between load on the particle and hardness of the surface shows the degree of penetration in a groove as $\frac{W}{H_V}$, hence the volume of wear = $\frac{W}{H_V}$ AL

where A = area of cross section of groove

L = length of groove.

Rabinowicz [13] used geometrical considerations based on model asperities of conical shape to obtain the relationship

$$V = \frac{KLS}{H} \left(\frac{2}{\pi} \tan \theta\right)$$

where V is the volume of wear, L is the applied load, S is the distance of sliding, H is the indentation hardness and θ is the base angle of the cone. The constant K expresses the fact that only a proportion of the groove volume appears as loose wear debris, typically ranging between 0.1 and 0.3.

Two points should be noted about this relationship [10]:-

1. It introduces the concept of a "specific wear rate", volume removed per unit distance of sliding per unit load, $^V/SL$.

2. This specific wear rate depends on a material property, hardness and on a geometrical factor defining the conditions of sliding.

2.1.4 Wear of Hot Forging Dies

The two types of wear reviewed so far are regarded to be the most influential mechanisms in the metal-working tools in general, but when wear behaviour of hot forging dies is taken into account, it must be emphasized that this situation is an exceptionally interesting one, where numerous suggestions and new theories have been put forward. Due to the involvement of factors like high operating temperature of the flowing metal, the high compressive and shearing forces, the sticking friction and many other factors, the wear modes expected to prevail are mostly of a fatigue nature. Many investigators have studied the wear performance of hot forging dies and they attempted to categorize and identify the main mechanisms involved. Elfmark [(26)] considered erosive wear as the most important cause of die failure, and Kannapan [(27)] underlined the importance of thermal fatigue. Dennis and Lodge [(28)] emphasized that the failure of hot forging dies is due to a combination of mechanisms such as erosion by hot metal flow over the surface intensified by the presence of abrasive oxides. They are also subject to repeated thermal and mechanical shock, besides the strong compressive forces. Ewere [(29)] reported that the mechanisms in operation are erosion, abrasion, oxidation and delamination. He suggested that the delamination type of wear was the dominant mode of failure in hot forging dies. Halling et al [(30)] favoured the traditional types of wear (adhesive-abrasive) and added the delamination wear as a macroscopic fatigue failure.

From all the previous published work on the failure of hot forging dies, the importance of erosive wear is quite obvious. However, the delamination wear theory deserves further consideration since it is a mode of failure strongly linked with fatigue and deformation.

2.1.4.1 Erosive Wear

Failure of metal surfaces by erosive wear was originally related to the deformation caused by the impact of liquids or gases at high velocities. The damage appears as tiny ring cracks or small plastic depressions in the metal surface (8). Numerous researchers have studied the characteristics of erosive wear. Avery (31) described it as a kind of abrasion that implies a velocity factor, and he sub-divided it into more than one type, like impingement erosion, abrasive erosion and low stress erosion.

Wright (8) considered it as some form of fatigue damage, building his views on the appearance of the eroded surface. He considered the flow of the liquid from the deformed zone to be accompanied by strong shear deformation leading to pitting and roughening of the surface. There are certain areas in practice which suffer from the erosive type of wear. Fluid erosion frequently occurs in steam turbines and fast flying aircraft through the impact of water droplets, but in fact erosive wear can also be caused by impact of solid particles incorporated in, or accompanying, a carrying liquid.

Zahafi and Schmitt (32) have studied solid particle erosion of coatings and reported that local microcracks were formed and propagated to intersect each other, causing the formation of local coating fragments both at low and high angles. Fragment removal depends on the quality of adhesion and on the impact angle.

Sometimes erosion occurs by a fluid of high temperature flowing on a hard surface. This type of erosion is likely to occur on hot metal-working surfaces. Metal in its hot state and under high compression spreads on the surface acting in the same manner as a fluid, and eventually causes the same effect. A typical example of this situation is the forging of a hot billet, where scale and wear debris are squeezed and forced to flow radially by the approaching press ram. This results in surface and subsurface deformation by cutting and ploughing action [(29)].

2.1.4.2 Fatigue Wear

Fatigue in its general conception is just one of the major mechanical failures that occur on the surfaces of engineering components and tools after repeated loading and unloading. Recent studies have given new interpretation of fatigue failure in relation to wear mechanisms. Sarkar [(33)] in his investigation of friction and wear in rolling contact, has defined fatigue wear as the removal of surface layers by spalling. He differentiated it from sliding wear which is progressive with the number of revolutions, by implying that spalling occurs suddenly and the rolling element loses surface layers. In Sarkar's opinion the adhesive wear may represent a first step prior to a fatigue wear situation.

At an early stage of the mechanism the true areas of contact yield plastically under the high contact stresses and they can be removed by shearing due to sliding. Then a thin surface layer soon work hardens and contact may become largely elastic. The effect of an elastic encounter is that it provides a situation where the micro-cracks may fail by fatigue wear. Most of the previous researchers agreed on the idea that fatigue cracks occur at the subsurface. It has been indicated [8] that the most probable critical stress in contact fatigue is the maximum cyclic orthogonal shear stress rather than the unidirectional shear stress which occurs at somewhat greater depths. The maximum cyclic stress occurs in the subsurface origin.

Cracks nucleate in the subsurface and propagate to the surface. This feature may be found mostly in rolling contacts, e.g. ball and roller bearings, cams and gears. A possible contact fatigue failure in tool surfaces, particularly in forging dies, is that which follows the suggestion of Lancaster [34]. He assumed that under repeated contacts, a subsurface layer becomes progressively weaker until any weak adhesion across a junction can become sufficient to detach a fragment and transfer it to the opposite surface. This process introduces the concept of localised fatigue as a contributory factor in hot forging die wear.

2.1.4.3 Delamination Wear

The delamination theory of wear was proposed by Suh in 1973 (35), and overviewed and revised in 1977 (36). It explained the nature of sliding wear and suggested a new wear mechanism based on the dislocation theory and the plastic deformation and fracture of metals near their surfaces. The fundamental mechanisms involved in the theory are:-

1. Transmission of forces
2. Deformation
3. Void and crack nucleation
4. Crack propagation
5. Wear sheet separation.

These processes develop as follows:-

1. When two surfaces in contact slide on each other, normal and tangential forces are transmitted through the contact points by adhesive and ploughing actions. Asperities of the softer surface are easily deformed and some are fractured by the repeated loading action. A relatively smooth surface is generated and the contact becomes stronger. Each point of contact along the softer surface is subject to cyclic loading as the asperity of the harder surface presses on it.

2. The surface traction exerted by the harder asperities on the softer surface induces plastic shear deformation which builds up with repeated loading.

3. As the subsurface deformation continues, cracks are nucleated below the surface.

4. Once cracks are present (owing either to the crack nucleation process or to pre-existing voids), further loading and deformation causes cracks to extend and to propagate, joining neighbouring ones. The cracks tend to propagate parallel to the surface.

5. When these cracks finally shear to the surface (at certain weak positions) long and thin wear sheets "delaminate".

The validity of the theory and the mechanisms involved, has been confirmed through extensive analytical and experimental work [37-39].

Johanmir and Suh [37] proposed that the wear rate can be controlled by void nucleation or crack propagation, depending on the material and sliding conditions. Teixeira et al [38] concluded that the delamination theory of wear predicts adverse effects if the hardness is increased by introducing inclusions which act as crack nucleation sites. Thus raising the hardness while suppressing crack nucleation and crack propagation is a good method for decreasing the wear rate of a material. The delamination theory provides guidelines for minimization of wear in components and tools, through control of metallurgical structure and chemistry of sliding surfaces, modification of the surface and machining practices. The theory may also be used in creating composite structures for minimum wear [39].

The theory received more interest in recent studies of wear performance of uncoated and coated metal surfaces and very recently the theory has been used as guidelines for materials selection [40]. Lancaster [10] considered that the 'delamination' theory is an extension of localised fatigue failure although he follows, in his analysis, the same lines proposed by Suh. He pointed out that as a result of repeated contacts and subsurface deformation, dislocations are generated beneath the surface and pile up around discontinuities such as impurity particles. The dislocations unite leading to voids, stress concentrations and crack formation. The subsurface layer weakens until fragments can be detached via adhesion or simple mechanical interlocking.

The severe conditions experienced in hot forging proved to bring failure to die surfaces by delamination wear. The flow of hot metal of upset billets subject die surfaces to similar conditions. Ewere [29] concluded that the delamination wear mechanism "deformation-type wear" is the dominant mode of failure in hot forging dies. He used untreated and surface-treated dies in his study. However, more study of wear performance of surface treated dies may reveal additional information about the delamination theory of wear, and new procedures to combat this type of wear in metal-working tools may be discovered.

2.2 Previous Use of Hot Forging Dies

The actual wear imparted to the forging dies depends upon two main factors. The first factor is the forging process environment which includes: the wearing action of the flowing metal on the die surface, the time of contact between the hot metal and the die surface, the proper heating the die design, the quantity of forgings produced at a time and the skill of the operator [41].

The second factor is the die material and surface quality. This factor has been a subject of continuous investigation by the Drop Forging Research Association and by various workers at Aston University. The researches have included studies of steels suitable for hot forging dies, and studies of the wear performance of different coatings and surface treatment techniques to improve die life.

2.2.1 Steels for Hot Forging Dies

An essential function of any hot-work die steel is its capacity to retain sufficient hardness at elevated temperatures. The hardness is a subject for compromise. Although high hardness values often give good wear resistance, they may lead to premature thermal cracking. Dies must not break under repeated mechanical stress or soften or erode or delaminate after short runs of forgings. Hocke [42] considered that the selection of the best material to resist wear, in general, is a compromise between hardness and toughness, then come the other properties to vary according to the different applications. In most cases no one alloying element in steel will satisfy all requirements. An element enhances the beneficial effects of the other special elements, but may produce an adverse effect if alloyed over a certain percentage.

However, in hot forging die steels the main alloying elements are nickel, chromium, molybdenum, tungsten and vanadium. Apart from No. 5 die steel which is the standard steel recommended (BSS.224) for drop forging dies, there are many hot work steels available for selection to resist die wear. Hot work steels of 5% Cr are usually used for press dies [1,43]. In general the types of 5% Cr steel that contain Mo designated as H10, H11, H12 and H13 are the most widely used of all hot work steels [44]. It has been reported that the effect of the alloying elements of the 5% Cr steel in improving wear resistance decreases in the order of V>Mo>W>Cr [45]. They show good resistance to thermal fatigue cracking and erosive wear which are important criteria in relation to die life. These steels rely on their secondary hardening by the carbide forming elements with vanadium showing its superiority over the others (molybdenum and tungsten).

Aston et al [1] have reported that No. 5 die steel has the least wear resistance when compared with the other grades of highly alloyed steel, and this has been confirmed by investigations on coated No. 5 and BH 13 die steels [29]. It has been concluded [1] that improved wear resistance is obtained by the addition of more than 3% total alloy content, particularly 3-5% Cr may be valuable but the best benefit was achieved by Mo and that agreed generally with Thomas [46], who found that the life of dies is proportional to the square root of the Mo content in steel.

2.2.2 Coatings for Hot Forging Dies

Selecting the bulk material of tools and dies to combat wear is one of the early methods of prolonging their service-life. Certainly, the best steels to fulfil this function are the highly alloyed grades which proved to be very costly. Although the choice needs to be based mainly on a compromise between material cost, machining costs and die life (43), savings should not be achieved at the expense of the essential properties required for the material performance. This attempt will lead indirectly to additional losses as a consequence of shorter die life. High technical performance of tools and dies must be achieved since it has a direct relationship with productivity so the only way to minimize costs is to look after the required properties of the material surfaces instead of the bulk materials. In hot forging dies, where the most arduous conditions are experienced, the use of coatings on a relatively cheap die steel base seems to be one of the most promising (28).

For selecting a surfacing treatment, in general, there will be a requirement in the surface layers for strength, hardness and toughness. However, high hardness tends to be associated with low impact resistance, notch sensitivity and poor resistance to crack propagation (11). The coated surface of hot forging dies must possess sufficient strength to resist the imposed loads and enough toughness to avoid failure due to surface imperfections or fatigue cracks. Structure is also important in the ability to withstand abrasive wear. Most surfaced layers derive their wear resistance from the presence of carbides or nitrides. The type, amount, shape and distribution of these as well as their support in the matrix affect the actual wear performance. Under pure abrasion a coarse carbide seems desirable but where there is impact a finer, well distributed carbide is probably preferable [11]. Additionally the die steel needs a carefully selected surface treatment to ensure that sub-surface cracking, or cracking at the interface between the coating and substrate, is avoided. Many coating systems have been extensively studied previously. They vary widely in terms of the methods of their formation, the coating types themselves and the degree of effect they produce on die surfaces to meet the wear resistance requirements. It is not easy to enumerate these coating systems. The available reports and literature on the subject can be used as guidelines for general use of coatings on tools and dies [28,47,48].

To enhance wear resistance of forging dies, a wide variety of heat treatments and coatings have been used by forgers [47,48]. Many of these were unsuccessful, especially when related to hot forging. However, some treatments have been reported to be extremely successful in extending die life. The most extensive work done in this field by Dennis and Co-workers [2,3,49-53], was based on the use of cobalt alloys. They used the conventional electroplating techniques with varying compositions of alloying elements of Ni, Mo and W. They also employed the brush plating technique which is a well established coating method. Cobalt has good hot hardness properties in comparison with nickel [54].

Early existing cobalt alloy plating solutions were investigated but were found to be unsuitable for hot forging [55]. The excellent results have been reported after adding complexing agents and varying the compositions of the alloying elements (Mo and W), while nickel was unsuccessful. It has been concluded that cobalt alloy electrodeposits containing up to 10% of either tungsten or molybdenum improved the life of hot pressing tools by 60% and drop hammer dies by 50% [28]. The alloys were relatively hard and did not scale during the forging test; both these factors assisted in reducing erosion of the die surface [3]. Cobalt alloys, particularly those deposited by brush technique, have shown that significant increases in die life can be obtained with subsequent reduction in production costs [52]. This is an additional merit with the several other advantages that characterize the brush plating technique. Ewere [29] reported that No. 5 die steel plated with electrodeposited hard chrome performed better than brush plated Co-Mo alloy. However, Dennis and Still[3] suggested that the performance of a particular coating may be influenced by the shape of the die or the test procedure.

The exact mechanisms by which the coatings extend the die life are not known, but it seems likely that the solid film acts as a lubricant [28]. The initial thickness of a coating is worn away down to minimum optimum thickness of between 0.1 and 1.0 μm. This acts as a solid lubricant and holds back wear until the film is broken and normal wear of the die steel commences. This slow erosion period may also give time for the die to 'bed-in' and so prolong its life [56].

The success of cobalt alloys as excellent coatings for hot forging dies has been achieved through a long period of trials since the early unsatisfactory attempts [57-60] up to the latest most successful work [61]. This success has encouraged trials of other coating systems. The results reported by Dennis et al [62] after the use of electroless composite coatings indicate that the coatings produced, particularly after appropriate heat treatment, perform in a similar manner of brush plated Co-Mo alloys. The only defect observed was an unharmful amount of porosity on the surface.

Several combinations of composite coatings have been tried and proved to be quite successful in extending die life, while others are still under investigation at Aston University.

2.3 New Coatings and Techniques to Combat Wear in Hot Forging Dies

There are many surface treatments available to resist wear in tool steels, but they vary very widely in their suitability for coating metal-working tools. Many coatings may be unreliable in certain applications due to their poor performance under severe wear conditions or due to their high costs in comparison with the available alternative coatings. The severity of wear in metal-working tools has led to a rapid development in the trend of adopting new surface treatments and new coating techniques to resist wear and improve economies and productivity.

Chemical vapour deposition (CVD) and the Toyota Diffusion (T.D.) process, are two of the surface coating systems which have emerged as having outstanding potentials for combating wear in the metal-working industry, in recent years.

2.3.1 Titanium Nitride by Chemical Vapour Deposition

Chemical Vapour Deposition (CVD) is defined as the deposition of a solid material on to a heated substrate surface as a result of chemical reactions [63]. Any chemical reaction in which the primary products are gaseous and one of the resulting products is solid, is considered a CVD reaction. 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 steel surface.

CVD is a well developed process [64-66], and it was the original process used for coating sintered carbide inserts and remains dominant in that application [67]. However, in recent years new fields for CVD application have attracted attention. It is growing rapidly in certain countries such as U.S.A., Japan, Switzerland and U.K. where a wide variety of industries is using this coating process to prolong tool life.

The use of CVD coatings in metal cutting is now well established [30,68], and it has proved to be promising for treating tools such as punches, dies, forming tools, screw machine tools, machine parts and wear components [68-70]. The process is capable of depositing coatings of a wide range of metals, carbides, nitrides, oxides and borides [28]. However, the most widely used coatings for metal-working tools are titanium carbide (TiC) and titanium nitride (TiN) [63,67-76].

Figure 2 shows a diagram of CVD installation for depositing TiC and TiN coatings on tool steel. The TiC is formed by the reduction of gaseous titanium tetrachloride ($TiCl_4$) in the presence of methane (CH_4), using hydrogen (H_2) as reducing agent and carrier gas:

$$TiCl_4(g) + CH_4(g) \xrightarrow{H_2(g)} TiC(s) + 4HCl(g)$$

In practice this reaction is usually made to take place at a relatively low pressure (about 90 mbar) and at a temperature of 950-1050°C. The TiC coating has an appearance ranging from bright silver to dull grey. The yellowish-gold TiN coating is accomplished in a mixture of titanium tetrachloride ($TiCl_4$), hydrogen (H_2) and either nitrogen (N_2) or ammonia (NH_3):

$$TiCl_4(g) + 2H_2(g) + \tfrac{1}{2}N_2(g) \xrightarrow{H_2(g)} TiN(s) + 4HCl(g)$$

This reaction is usually made to take place at almost atmospheric pressure (about 900 mbar) and at a temperature of 850-950^oC. The hydrochloric acid gas (HCl) liberated in the above reactions as by-product is very corrosive and must not enter the atmosphere. It is transported by the carrier gas (H_2) to a liquid ring pump filled with caustic soda solution, which neutralizes it.

In a typical CVD 'reactor' (Fig. 2), once the carefully cleaned tools are loaded the reactor is sealed, evacuated and an inert gas (Ar) introduced during heating. When the coating temperature is attained, the reactive gases are introduced for the duration of the coating period. Cooling takes place in an inert gas.

Although the process can be carried out at atmospheric pressure, operation at reduced pressure favours the desorption of hydrogen chloride from the surface of the part to be coated [68], and it has other advantages:- [71,72]

- improves the uniformity of coatings,
- minimizes contamination,
- increases gas speed to allow coating of large surfaces,
- decreases hydrogen embrittlement.

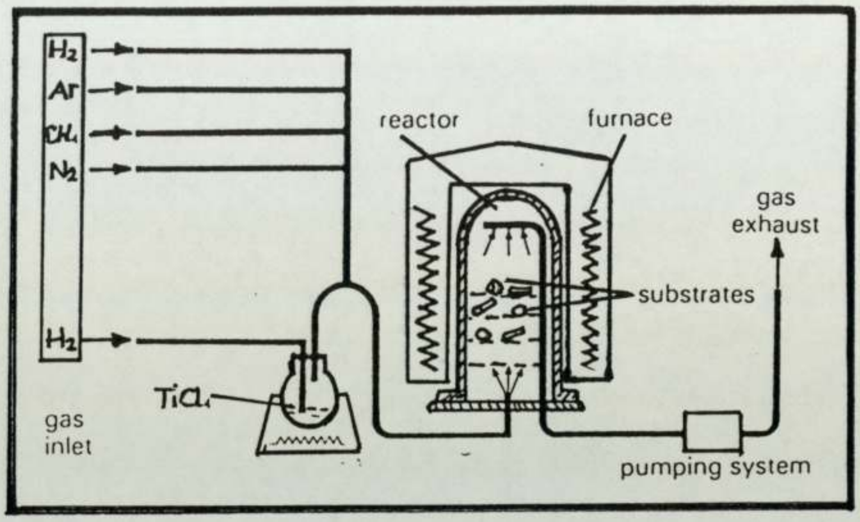


FIGURE 2: Schematic arrangement of a CVD installation for applying a TiC or TiN coating (72)

The coating on tool steels grows at a rate of 1-2 μm/h to give a typical layer thickness of 5-10 μm depending 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 variation in thermal expansion stresses of the substrate and the coating.

Coatings of 5-10 μm thickness can take up these stresses and can even withstand some impact and shock. The desired increase in wear and corrosion resistance can be obtained with coatings which can adhere well to tool steel (71).

The hardness of TiC coating is 3300-4000 Hv and that of TiN coating is 2500-3000 Hv (69). Because of their great hardness, TiC and TiN coatings by CVD offer good protection from abrasion; and due to their high melting point (>2500^{o}C), 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.

Apart from hardness, the TiN coating is somewhat better than the TiC, additionally it has little tendency to galling, fretting and erosion (71), and has a lubristic quality that resists metal pick-up (69). Moreover, TiN resists elevated temperature, retaining all of the above properties to an excellent degree at the high temperatures encountered in metal-working (67).

These properties which characterize the TiN coatings deposited by the CVD process suggest an excellent performance under wear situations like those of hot forging where the dies are exposed to different interacting wear mechanisms. This coating technique has already proved its superiority in applications such as cutting tools, back extrusion tools and applications for protective/decorative purposes like watch cases and watch-bands. American Machinest [(67)] has reported that TiN-coated cutting tools have shown remarkable extension of service life and comprehensive increase in both feeds and speeds in comparison with the uncoated tools. A Swiss screw manufacturer has found that high-speed steel punches used for forming slots and recesses in screw heads required changing after an average of 25,000 screws. When coated by a double layer of TiC and TiN life increased to between 80,000 and 120,000 items with individual punches attaining peak outputs of up to 180,000 [(73)].

The use of TiC and TiN coatings deposited by CVD has led to substantial savings through increase of tool life, high product quality, decrease in labour costs, reduction in machine down-time, reduction in consumption of metal-working fluids, reduction in maintenance costs, reduction in expensive base material costs and many other savings [(30)].

The main features of CVD process that led to its wide acceptance in the tool industry can be summarized as:-

- The ability to produce good quality coatings which are both coherent and adherent at temperatures which can be tolerated by steel substrates.

- The possibility to coat a wide range of engineering components (dies, cutting tools, punches, bearings, automobile components, etc...)

- The excellent throwing power.

- The uniform coating without complicated jigging and regardless of the tool geometry.

- The suitability for handling a large number of small components at a time.

In spite of the several advantages of CVD process there are some limitations which should be considered. It is often associated with problems of distortion, parts-dimensional changes and softening of the tools to be coated, due to the high temperature required for the deposition. For this reason tools must be heat treated after coating to restore their 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. For this reason there is a considerable restriction in substrate choice. Halling et al have referred to this brittle transition layer as 'eta phase'[30]. 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 ($TiCl_4$) has a tendency to take carbon from the substrate as well as from the gas phase. This decarburized brittle layer is formed directly beneath the TiC coating (74,75). In addition to the restrictions in substrate choice, pre-plating by other methods is sometimes used to solve this problem. However, subsequent development has eliminated this brittle phase and suggested coatings such as titanium nitride [30,76], while the most recent development proposed the use of multi-layer coating such as TiC and TiN [70].

Practically, even under such coatings, decarburization is possible since $TiCl_4$ is the main reactant used and a certain amount of carbon is essential in tool steel substrates. So there is always a need for a proper selection of the substrate steel and a considerable percentage of carbon in steel may be needed.

Despite these limitations, the chemical vapour deposition technique offers a good prospect for domination as an excellent wear resistant coating process in the metal-working industry, and is worth consideration for hot forging dies.

2.3.2 The Toyota Diffusion Process

The Toyota Diffusion (TD) process is one of the latest developments in metal surface treatment techniques, which are used widely to modify the properties of engineering components and tool-surfaces. Although it is a thermochemical process, it differs somewhat from the conventional thermochemical surface treatments such as nitriding, carburising and nitrocarburising. It differs in terms of the type of change it produces to the substrate surface, and in the way by which this change occurs. Coatings produced by the TD process have proven to perform successfully under varying wear conditions, and the process can be regarded as a strong competitor with alternative processes such as chemical and physical vapour deposition, CVD and PVD [77].

The TD process carries the name of the Toyota Company in Japan, where it was developed, and it has been evaluated comprehensively within that organisation [78-80].

The process is used for coating tool surfaces by pore-free compound layers of alloy carbides capable of extending tool life significantly. It has been reported that, under certain conditions, pure carbide layers of thickness of the order of 5-12 μm can be developed on the surfaces of steels that have considerable carbon contents [77,81].

The carbides commonly produced by TD process are those of vanadium, titanium, chromium and niobium. The process has been applied to most tool steels, and the carbide coating efficiency has been demonstrated for most types of die and tool applications including press work, cold and hot forging, powder compaction, glass moulding, die-casting dies and cutting tools [82,83].

The process is carried out in a salt bath of composition based on borax; the carbide-forming element is added as a ferro-alloy of the required coating (e.g. ferro-vanadium). Pure carbide is formed at the surface of carbon-bearing steel by maintaining the temperature of the bath in the range of 950-1050^{o}C. The coating grows by reaction between the carbide-former and carbon diffusing from the substrate. Treatment times are between 2-10 hours depending on the temperature and the layer thickness required. The rate of layer formation depends upon bath temperature, composition of the substrate (particularly carbon content) and the type of carbide produced. The tool or die may be quenched directly from the salt bath and then tempered, except in the case of high-speed steel and tool steels of high hardening temperature [81,84]. The distortion expected during the process may be controlled by pre-hardening and tempering, thus minimizing dimensional changes during the surface heat treatment [82].

Very high hardnesses are achieved depending on the type of carbide formed. It has been reported that vanadium carbide which has a hardness of 3200-3700 Hv is favoured for most applications. It increases the wear and corrosion resistance, retains its hardness at elevated temperatures, and maintains the tool's fatigue strength and toughness [81,82,85].

Studies of the T.D. process mechanism at Aston University suggested that bath conditioning depends on oxidation of the carbide former, e.g. vanadium to V_2O_3. The solubility of the reactive oxides is low and the time taken to reach a maximum depends on a number of factors. The rate of dissolution is affected by the percentage addition of ferro-alloy (typically 10% by wt). Other parameters have been found to include the physical form of the alloy (mesh size or powder), the temperature of the bath, oxidising conditions prevailing and bath agitation [81,86].

The T.D. process is quite a reliable surface treatment with its main limitations being the need to allow for distortion during the treatment, hence its use on ultra-hard surfaces is restricted. With the possibility of dimensional changes the process is restricted to relatively small parts.

3. EXPERIMENTAL

The experimental work consists of three main parts which have been sub-divided into a series of different activities. The successive stages were directed to the final evaluation and assessment of the die surface wear performance under the experimental forging conditions employed.

3.1 Die Preparation

3.1.1 Die Manufacture

The two steels used in this investigation were obtained as forged round bars of diameter 57-65 mm, in their annealed conditions. The manufacturer's chemical specifications of these steels are shown in Table 1.

The Ni-Cr-Mo grade designated as 'Electem'* No. 5 die steel was bought from Walter Somers Limited, while H.13 steel was obtained from Udeholm Limited.

The bars were turned to 50 mm diameter, and discs of approximately 12.5 mm thickness were sliced from that stock. These were then ground prior to hardening which had been carried out according to the manufacturer's heat treatment directions.

The Electem No. 5 dies were pre-heated to 840^{o}C, quenched in oil and air cooled to about 200^{o}C (oil adhering to die surface still has a tendency to smoke). The dies were then tempered at 480^{o}C for 60 minutes.

* The producer's trade name for this grade.

TABLE 1

CHEMICAL COMPOSITIONS OF DIE STEELS

Elements	Steels	
	No.5 'Electem'	H.13
C	0.55	0.37
Ni	1.50	-
Cr	0.65	5.00
Mo	0.30	1.50
V	-	1.00
Mn	0.65	0.30
Si	0.30	1.00
P	0.04	-
S	0.04	-

H.13 dies were pre-heated to 840°C then heated quickly to 1030°C, oil quenched for about 30 minutes and finally tempered at 550°C for 90 minutes. These heat treatment operations produced hardnesses of the order of 405-464 Hv for the Electem No. 5 dies, and 509-589 Hv for H.13 dies. The two types of steel are widely used industrially in these conditions. After heat treatment the die surfaces were reground, first to ensure the removal of any decarbonised layer which may have formed during tempering and secondly to develop a fine surface finish prior to the surface coating.

3.1.2 Die Surface Treatments

3.1.2.1 Titanium Nitride (TiN) by Chemical Vapour Deposition

Chemical vapour deposition has not been widely used in the U.K. until recently, but it is continually finding new areas of application in metal working industries [68]. There is no equipment in Aston University to produce CVD coatings, and even commercially such facilities are very limited. PFD Limited, a subsidiary of the GKN Group, has recently introduced the process for coating dies and machine tools. The firm's new operation is based on CVD coating equipment from 'Scientific Coatings Inc.', one of the world's major suppliers of CVD process plant and finishing technology.

Twenty four of the prepared dies were sent in two batches to PFD Limited for TiN coating by the CVD process. Each batch contained 6 'Electem' dies and 6 H.13 dies. The TiN coatings produced were yellowish-gold in colour. The thickness was in the range of 6 to 8 μm for the Electem dies and of 5 to 7 μm for the H.13 dies. The hardness of the coating was of the order of 2800-3000 Hv.

The coating produced was actually a three-layer system. The layers were in the following sequence, starting from the substrate surface: a grey TiC layer, a pink and very thin layer of Ti(C-N) and the goldish TiN layer. This multi-layer coating agrees with the information reviewed in the previous section [70,75].

3.1.2.2 Vanadium Carbide (VC) by the Toyota Diffusion Process

The successful application of vanadium carbide deposited by the T.D. process has led to a wide recognition of this surface treatment technique in the tool industry. Moreover, the simplicity of the preparation and procedure has encouraged its commercial development. A set of 6 'Electem' dies, and another of 6 H.13 ones were coated at British Heat Treatment, New Bond Street Factory, Birmingham [84]. Vanadium carbide layers were deposited on the die surfaces, by the T.D. process which was carried out at 1000^{o}C for four hours. The coating produced was of thickness 5-8 μm and hardness 3100-3450 Hv.

The small scale installation for the T.D. process available at Aston University has been in use at times to coat experimental pins and small test samples with VC. The salt bath was used for coating samples of the two steels employed in this investigation keeping the same temperature and time used in the commercial coating of the dies. The layers of VC obtained were quite similar to the commercial ones.

3.1.3 Post-Coating Heat Treatment

The heat treatment carried out prior to surface coating of the dies is essential to produce the substrate hardness and toughness required for optimum wear characteristics in service. However, the substrate properties may be destroyed if the operating temperature of the surface treatment is very high. In such cases a post-coating heat treatment must be carried out to restore the original hardness and toughness of the die steel, hence the pre-coating heat treatment could be eliminated. For this investigation, in which high temperature coating processes were employed, both pre- and post-coating heat treatments were accomplished, since the initial hardening and tempering has no adverse effect on the coating and the substrate. Additionally it could control distortion and minimises dimensional changes [82].

Usually many restrictions are associated with post-coating heat treatment, especially when C.V.D. coatings are involved, and to some extent T.D. process coatings.

The first batch of titanium nitrided dies was hardened after the C.V.D. process, with the same pre-coating heat treatment system, while the dies of the second batch were heat treated under more controlled conditions using a vacuum furnace. The post-coating heat treatment carried out in the protective atmosphere was based on the original hardening procedure (Table 2), but to protect the hard thin coating of TiN gas quenching was used. More restrictions were imposed on tempering [84,87,88]. H.13 dies were pre-heated at 850°C for 45 minutes, hardened at 1010°C for 40 minutes, gas quenched for 30 minutes, then tempered twice at 550°C for 90 minutes. Between the first and second tempering periods the die temperature was allowed to reach room temperature before commencing the second tempering. The 'Electem' dies were hardened at 840°C for 45 minutes, gas quenched for 30 minutes and finally tempered at 480°C for 60 minutes. During tempering all dies were wrapped in shim-metal to stop further oxidation of the coated surface.

This heat treatment procedure helped in controlling the dimensional and metallurgical properties of the dies, as well as the coating appearance.

The dies which were coated with VC by the T.D. process were quenched directly from the salt bath and then tempered using the procedure employed for the other coatings.

TABLE 2

POST-C.V.D. COATING HEAT TREATMENT

Steel	Heat treatment sequence
No. 5 'Electem'	1. Harden at 840°C - 45 min 2. Gas quench - 30 min 3. Temper at 480°C - 60 min
H.13	1. Pre-heat at 850°C - 45 min 2. Harden at 1010°C - 40 min 3. Gas quench - 30 min 4. Temper twice at 550°C - 90 min

3.2 Hot Forging Test

Many die wear studies at Aston University have been carried out by using a simulated hot forging test. By employing the same equipment and following the same procedure, results obtained from the present work can be compared with those of the previous investigations.

The test used was an upsetting hot forging press which represents a simple and practical metal-working process. The equipment used and the forging mechanism were fully described elsewhere (1-4), nevertheless, a brief description in this work may be convenient.

3.2.1 The Mechanical Press

The essential features of the 10-tonne crank press used are shown in Figs. 3 and 4. The feeding cycle was controlled by a cam timing device which was started or stopped by a switch on the front of the press. Consecutive operations were each controlled by a pair of cams acting on microswitches, which directed compressed air to the appropriate cylinder to activate the corresponding part of the feed mechanism. A high frequency induction heating system was used to heat the slugs. As the time of heating was fixed and controlled by the cam timing device, the slug temperature was determined by the power output of the high frequency set. The forging ram descended at the end of the feeding cycle. An air cylinder engaged the flywheel and ram. The forged slug was then automatically ejected. The complete operating cycle took 10 seconds and was then repeated. The forging time is about 0.15 seconds.

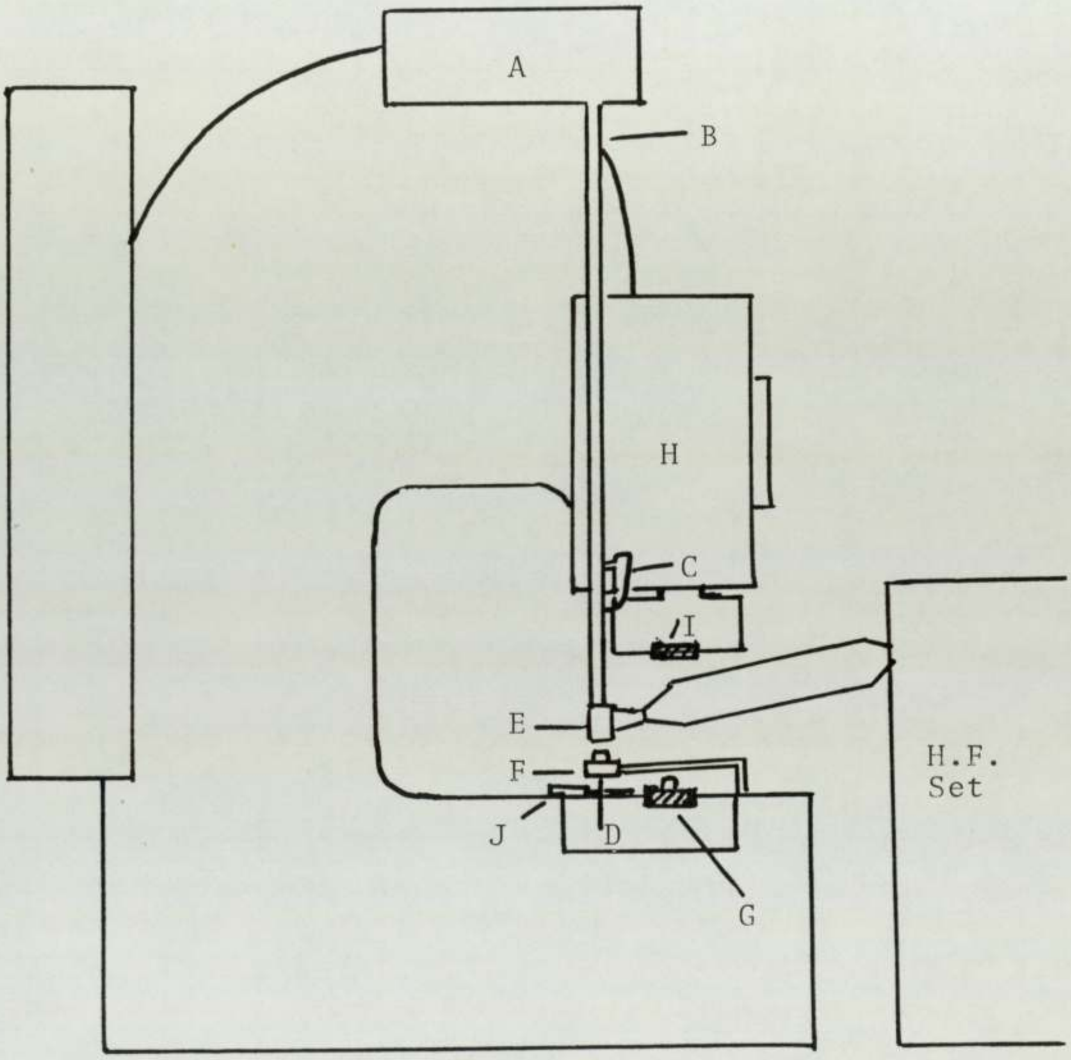


FIGURE 3: Schematic drawing of the experimental press showing the feed mechanism

FIGURE 4: A general view of the forging equipment showing the forging operation arrangement

3.2.2 The Forging Mechanism

En.3B slugs of 12 mm diameter by 18 mm length are discharged from a vibratory bowl feeder A (Fig. 3) into the pipe B where they fall into an air-operated regulating mechanism C. A ceramic peg D is raised in the silica tube surrounded by the high frequency (H.F.) induction coil E and the regulating mechanism allows one slug to drop on to it. The H.F. set remains on throughout the operation so that heating begins immediately. After the pre-determined heating time the ceramic plug is lowered to drop the slug between the jaws of the feed tongs F. Then the tongs swing through 90^{o} to place the slug in the centre of the bottom die face G. The retaining arm is then withdrawn and the tongs return to their original position under the H.F. heating coil, leaving the slug ready for forging. On return of the tongs a microswitch is tripped to activate the air cylinder and engage the press ram and fly wheel. The ram H moves down and compresses the slug between the surfaces of the top die I and the bottom die G. The ram on its movement down activates a switch on its side to allow air into the ejector J which moves forward until stopped by the position of the ram. Thus air pressure is built up behind the ejector so that, when the ram begins to rise it moves rapidly forward and ejects the compressed slug into a side bin. As the ram ascends it activates two switches, one to retract the ejector and the other to disengage the clutch, allowing the ram to come to rest at the top of its stroke.

3.2.3 Forging Operations and Control

The surface treated dies under test were mounted in pairs. One die in the upper holder and the other on the lower holder. The dies were secured tightly in their bolsters and the die pre-heating system was adjusted to 130°C. The system consisted of cartridge type resistance heaters each supplying 400 watts at 250 volts A.C. The heaters were inserted into the die holders which were surrounded by insulating materials. The temperature was controlled by thermocouples connecting the dies to the controllers/recorders which displayed the temperature and kept it within the selected range.

The slug temperature was kept in the range 1110-1140°C by setting the reading of the recorder/controller of the high frequency heating set. A counter mechanism operated by the forging stroke determined the number of forgings by counting from the pre-set reading down to zero.

In a forging cycle an En 3B slug was upset forged from 18 mm to 6 mm in height and the forged billet ejected and a new cycle commenced.

Pairs of different surface treated dies were tested by performing different groups of upset forging cycles. Between one forging run and another, the press and the heating system was switched off so that the temperature dropped and new die inserting was possible.

3.3 Die Wear Studies

The study of the uncoated and coated die surface performance after different operations of upset hot forging was carried out through different methods:

1. Quantitative evaluation;
2. Die surface examination;
3. Die sub-surface examination.

3.3.1 Quantitative Evaluation of Wear

Several methods are used to evaluate wear. The different methods followed may largely depend on the type of wear test performed. For example, wear weight of removed material (weight loss) is used for measuring wear of pins in a 'pin-on-disc' test, while the depth of penetration measurement is used in scratch tests. One of the more reliable methods of wear evaluation is the wear volume measurement, i.e. the volume of the material loss due to wear. This method is more useful in situations where wear is large enough to leave a scar that can change the die surface profile. It is one of the most frequently used for die wear evaluation, particularly when large numbers of forgings are made. This method has been used in the present investigation, despite the fact that a small amount of wear was expected to occur since the die surfaces were protected with wear resistant coatings, and relatively low numbers of forgings were employed.

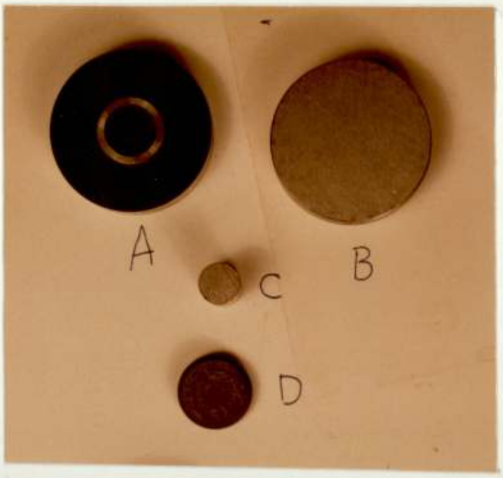
However, the wear volume measurement may draw guidelines for comparison with the uncoated die's wear and may reflect any failure of the coated surfaces resulting from unsuccessful surface treatments or testing preparations.

3.3.1.1 Descaling

After forging, most of the dies showed considerable amounts of scales adhering to their surfaces at the wear area. In order to evaluate this wear quantitatively the surfaces should be descaled. The descaling was done electrolytically. The dies' back surfaces and sides were coated with a suitable lacquer, and the solution was prepared by measuring a suitable volume of water with addition of 5% by volume sulphuric acid (H_2SO_4) and 0.1% by weight O-tolylthiourea as an inhibitor. By using a carbon rod as anode, the die surfaces were cleaned cathodically one after another. The solution temperature was maintained at about 75°C and the applied current density varied between 20 and 30 A/dm^2. The descaling time for each die was kept around 1.5 minutes divided into 30 second periods separated by swift and vigorous brushing of the surface with a hard brush. By this method all the adhering scale was removed except the firmly bonded ones.

3.3.1.2 Wear Volume Measurement

After descaling, and sometimes before, in cases of scale-free surfaces, a ring shaped wear pattern was observed on the die surface. This shape which was known as the 'wear ring' [1-4] represented the wear scar which was formed as a result of sticking friction and flow of forged metal on the die surface. Practically the shape of the scar depended on the shape of the forged slug [89]. The 'wear ring' of cylindrical slugs (Fig. 5C´) consisted mainly of two areas; the wear region and the central plateau (Figs. 5E,6) the central plateau region was of approximately the same size as the billet diameter which was 12.5 mm. This represented



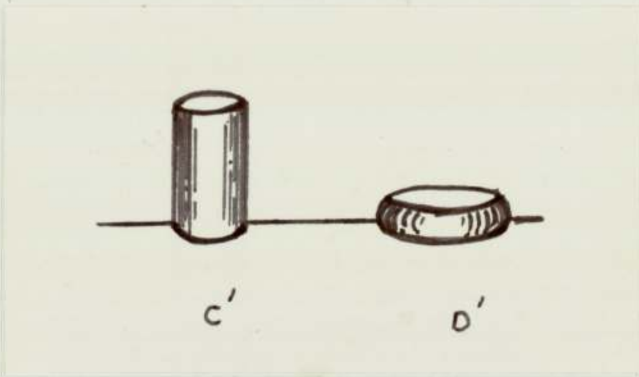


FIGURE 5: Illustrations of the experimental dies and slugs before and after forging -
A - shaped die;
B - flat die (before forging);
C - top view of an unforged billet
D - top view of a forged billet
C´- sketch of an unforged billet
D´- sketch of a forged billet
E - wear ring on a flat die surface after forging

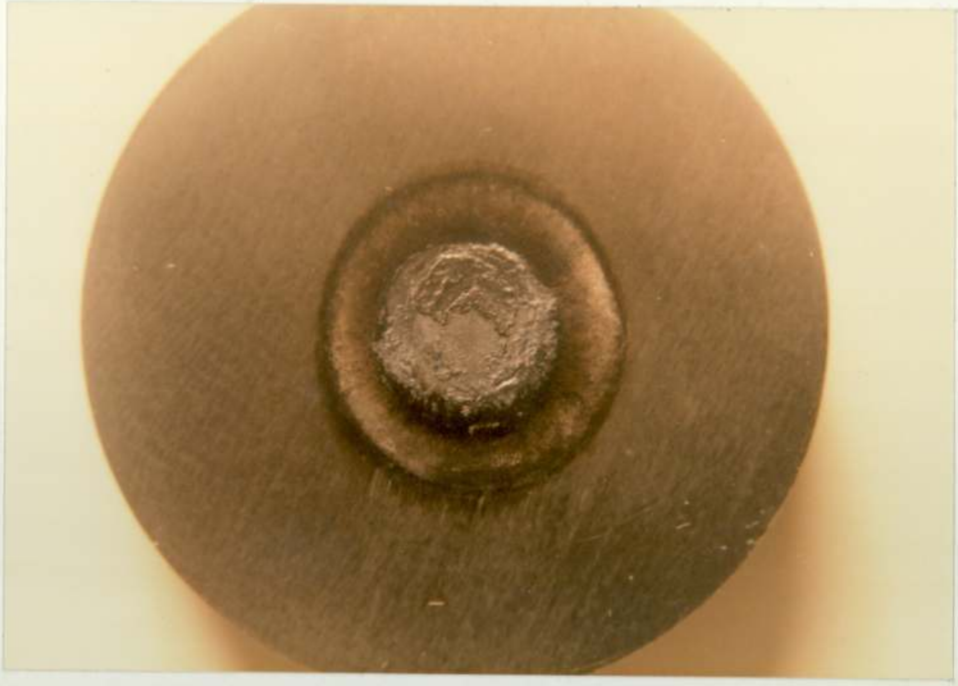


FIGURE 6: Undescaled TiN coated flat die after forging 200 billets showing the wear ring and the central plateau.

N.B. Scales adhering to the central plateau before electrolytic descaling the area of sticking friction associated with the upset forging operations of the cylindrical slugs. It was therefore an area of almost zero metal flow and remained virtually unworn on finishing the forging test [47]. In spite of the different ideas about this region [29,41,89], any metal movement if it existed, was negligible. The wear ring represented the track of the metal flow on the die surface outward under impact pressure. Its diameter was slightly less than the diameter of the forged billet which was approximately twice as big as the original slug's diameter. The wear volume was evaluated by determining wear profiles on the die surface using a Taylor Hobson Talylin surface analyser. Four lines were drawn across the die surface intersecting at the midpoint of the wear scar, at 45^{o} to each other. The four wear traces were obtained by passing the Talylin stylus along each of the four lines. Different horizontal and vertical magnifications could be selected to produce the adequate size of graph representing the die wear. Figure 7 shows how to obtain wear traces on the Talylin surface analyser. The two ends of the trace showed the original surface level. Any depression in the graph represented metal removed, i.e. wear, while peaks, if there were any, would represent built up scales or picked up metal.

The ideal Talylin profile of a worn die would show horizontal levels for the unworn surface and central plateau, and two 'v'-shape depressions for the two sections of the wear ring where the stylus crossed it.

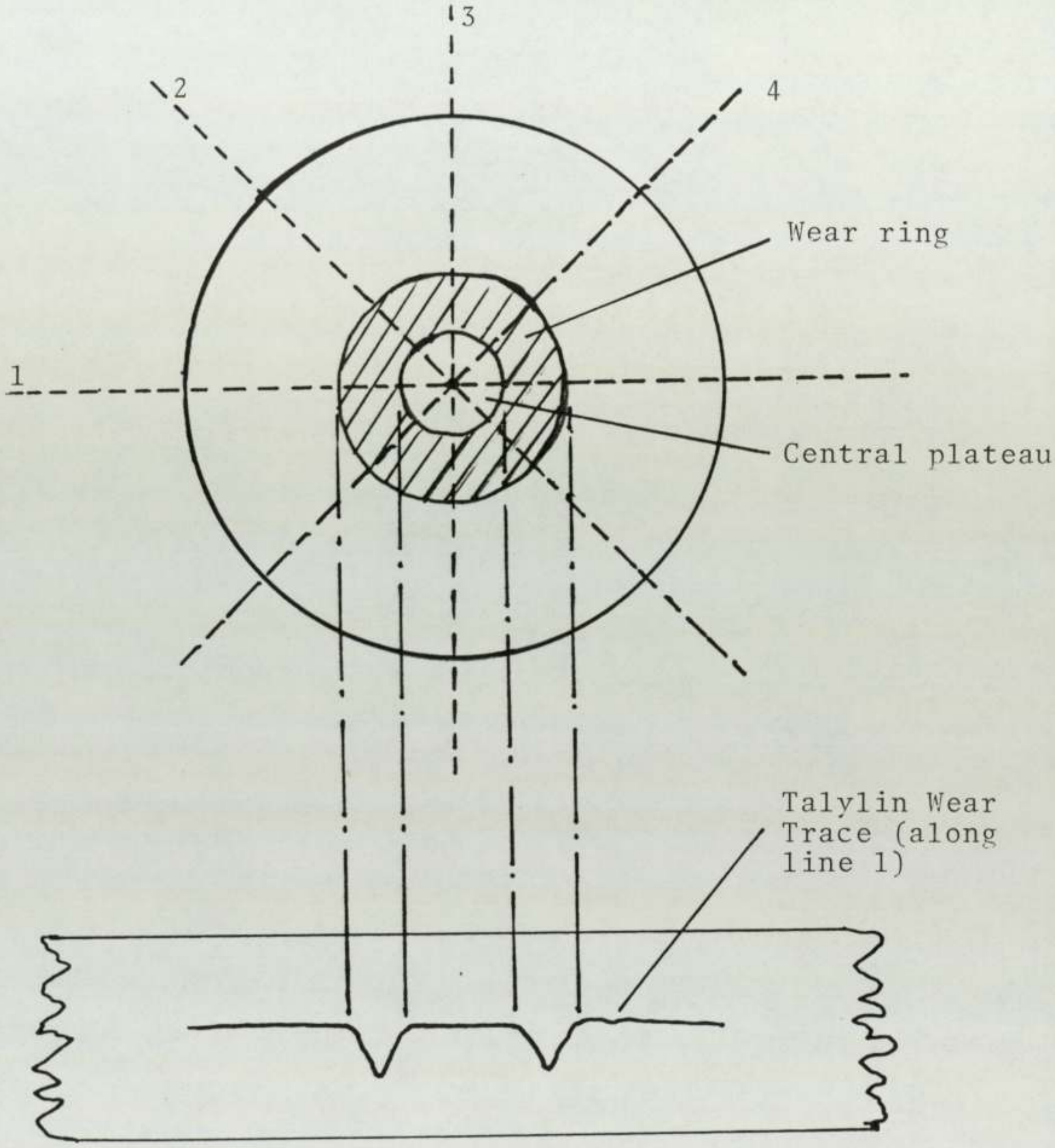


FIGURE 7: Illustration of the wear scar on a flat die surface showing the positions at which Talylin wear traces were obtained

In order to measure the worn area a line was drawn along the wear trace joining the two original surfaces, Fig. 8. The external and internal extremities of the wear ring were marked, hence the outer and inner diameters were measured. The mean wear diameter was then calculated using the expression:-

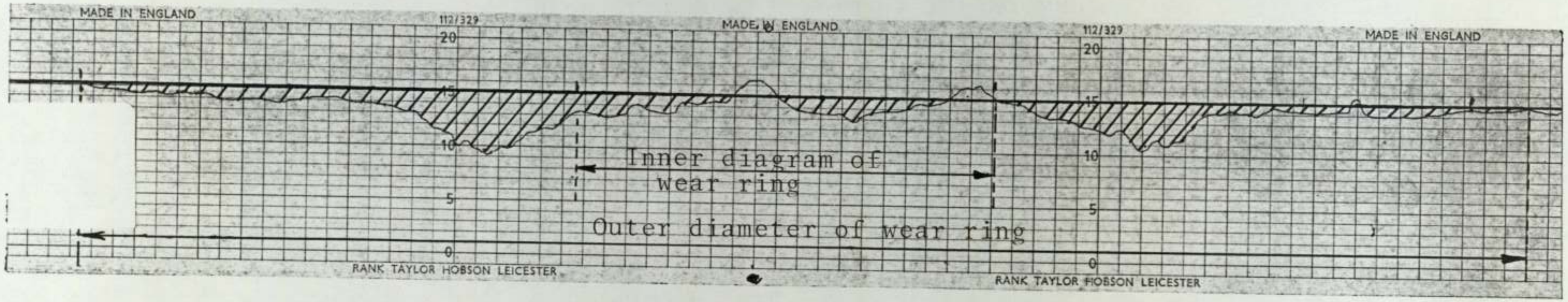
$$\text{Mean Wear Dia.} = \text{Inner Dia.} + \left(\frac{\text{Outer Dia.} - \text{Inner Dia.}}{2}\right)$$

The area bounded by the wear trace and the original surface line (the shaded area shown in Fig. 8) was then determined using a Planimeter (a tracing device used for measuring map and technical figures' areas and for other similar purposes). The real wear area was calculated in cm^2, using the planimeter apparent area values and the magnification employed in producing the graph. The wear volume in cm^3 was then found by rotating half the wear area about the mean wear circle, thus:-

$$\text{Wear Volume} = \frac{\text{Wear Area}}{2} \times \text{Mean Wear Dia.} \times \pi$$

The average value of the four wear values calculated in this way, gave the wear volume of one die. For accurate wear volume calculation average values for both top and bottom flat dies were found and the average of the two averages gave the final wear volume.

However, this technique was only possible when distinct wear occurred on the surface such as on the wear of uncoated dies or after a large number of forging operations. In the case of wear resistant coatings, although wear scars were visible, the wear depression could be very shallow and no demarcations



a

b

FIGURE 8: Typical wear traces obtained on uncoated Electem flat dies.

a) 200 billets forged;

b) 1000 billets forged.

between the regions were possible even when high magnification was used.

More description of wear volume calculation employing the Planimeter is given in Appendix 1.

3.3.2 Die Surface Examination

After quantitative tests were completed qualitative assessment of wear was carried out through microscopical studies. Visual observation was carried out during forging and before and after descaling, but for close examination a Scanning Electron Microscope (SEM) and an Optical Microscope were used. To examine the surface conventional preparation of samples was followed. Samples from each type of steel, each type of coating and each forging operation group were slit from the forged dies. The samples' surfaces after bakelite mounting showed part of the wear ring, the central plateau and a small part of the unworn surface outside the wear ring. The specimens were examined directly under the SEM.

3.3.3 Die Sub-Surface Examination

3.3.3.1 Taper Sections

It was intended to undertake a more detailed examination to study the underlying sub-surface and near-surface features of the worn dies. To do this the taper sectioning technique was used. That approach could reveal more die failure mechanisms especially on theoretical suggestions about crack formation and propagation and their relation with die surface failure.

The taper sections were prepared in a similar manner to that devised by Samuels [90] and used by other investigators [2,29,55]. Samples from the different worn dies were cut by the abrasive slitting wheel and prepared in the usual manner but a special jig was used to develop the taper section, Fig. 9. The thermosetting plastic carrying the specimen with its worn surface upwards was clamped in the steel block jig of a parallel face approximately 18 mm thick with a hole designed to accommodate the bakelite in a configuration permitting surface grinding at a tilted angle of 5^{o} 44' to the vertical. This angle produced a magnification of 10:1 to the coating layer and coating/substrate interface. By this magnification clear observations of sub-surface changes were possible after etching the samples in 2-4% Nital.

3.3.3.2 Conventional Cross-Sections

Although the taper section was used as a successful technique for detection of the sub-surface failure, the conventional cross-sections role could not be ignored. They were needed to reflect the real dimensions and size of failure at the coating-substrate interface, and to participate in the interpretation of results obtained from taper sections. The vertical cross-section samples were prepared in the usual manner and finally etched in 2-4% Nital, then examined under the optical microscope and the Scanning Electron Microscope.

3.3.4 The Use of Optical Microscope

Preliminary surface examination was carried out for dies after forging and descaling but before sectioning. Some forged billets were also viewed under the optical micro-

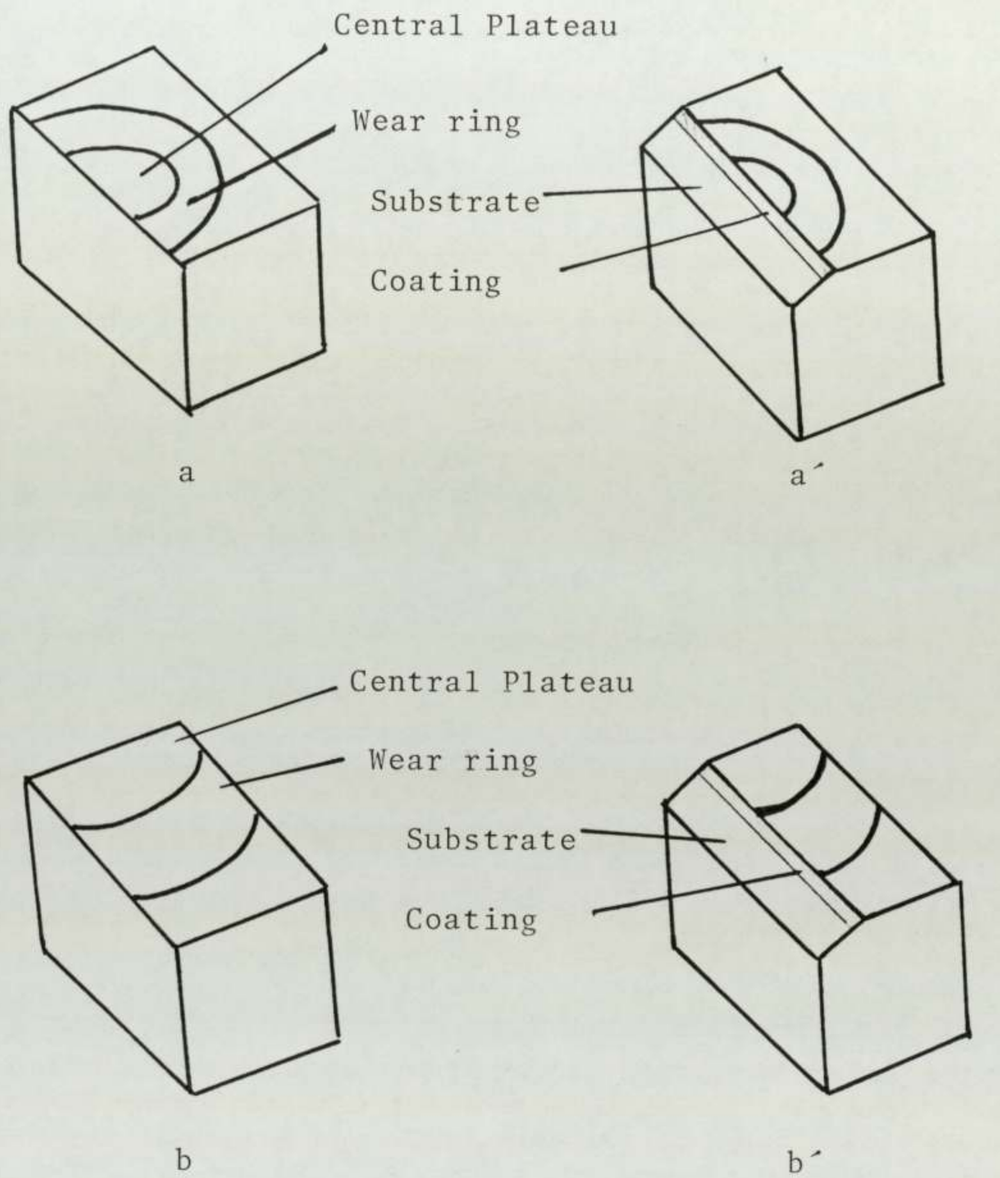


FIGURE 9: Taper section preparation.

a, b) samples as cut from die surface

a´, b´) Taper sectioned samples

scope. Then, after metallographic preparation of taper sections and conventional cross-sections, careful examination was accomplished using magnifications ranging from X20 up to X1000.

3.3.5 The Use of S.E.M.

More detailed die failure was exposed by using the Scanning Electron Microscope. Intensive examination revealed wear particles, tiny localised cracks and many other wear features.

Samples from different coated dies, from different regions of the die surface and after different numbers of forging operations were examined. Several photographs of surfaces and sub-surfaces were taken using magnifications ranging from X50 to X5000.

4. ANALYSIS OF RESULTS

4.1 Wear Volume Measurements

4.1.1 Uncoated Dies

Flat die sets from the uncoated stock of Electem and H.13 dies were used in the first forging test run. Annealed dies were subjected to 100 forging operations and the wear volume measured to check the forging press and measuring equipment. Hardened and tempered sets were used for forging 100 and 200 billets to establish a reference against which the performance of the coated dies could be compared.

Previous investigations had established a standard wear volume for the uncoated Electem No. 5 die steel based on 1000 forging operations. A pair of Electem dies used to forge 1000 billets in this programme gave a wear volume 4.22×10^{-3} cm^3 which is in fairly close agreement with the standard value of 4.37×10^{-3} cm^3 obtained previously. Having established that the equipment was working satisfactorily the coated and surface treated dies were tested. The wear volumes obtained for the uncoated dies are given in Tables 3-5.

4.1.2 Titanium Nitride Coatings by C.V.D. Process (I)

The first batch of dies, titanium nitrided by chemical vapour deposition, was subjected to post-coating heat treatment and to various forging operations. Flat dies were used for forging 100 and 200 billets, while pairs of shaped on flat dies were employed to forge 50, 100 and 200 billets. Shaped dies like those designed by Still and Dennis [(2)] were used as top dies in the press for accelerating

TABLE 3

WEAR VOLUME OF FLAT DIES AFTER FORGING 100 BILLETS

Type of Steel E, H	State of Dies	Wear Volume ($x10^{-3}cm^{3}$)		
		Top Die T	Bottom Die B	Mean
No.5 'Electem' - E	As Annealed	2.387	1.251	1.819
	As Hardened and Tempered	0.930	1.522	1.226
	Titanium Nitrided by CVD	0.744	0.913	0.829
H.13 - H	As Annealed	1.024	1.266	1.145
	As Hardened and Tempered	1.425	0.744	1.085
	Titanium Nitrided by CVD	0.794	0.651	0.723

TABLE 4

WEAR VOLUME OF FLAT DIES AFTER FORGING 200 BILLETS

Type of Steel E, H	State of Dies	Wear Volume ($x10^{-3}$ cm^3)		
		Top Die T	Bottom Die B	Mean
No.5 Electem - E	As hardened and Tempered	1.961	3.108	2.535
	Titanium Nitrided by CVD	1.495	1.695	1.595
H.13 - H	As Hardened and Tempered	2.100	1.863	1.982
	Titanium Nitrided by CVD	0.816	2.476	1.646

TABLE 5

PERFORMANCE OF THE TWO TYPES OF STEEL USED (PAIRS OF FLAT DIES)

Type of Steel	No. of Billets Forged	As Annealed	Wear Volume ($x10^{-3}$ cm^3)	
			As Hardened and Tempered	Tit. Nitrided by CVD
No. 5 Electem	100	1.819	1.226	0.829
	200	-	2.535	1.595
	1000	-	4.22	-
H.13	100	1.145	1.085	0.723
	200	-	1.982	1.646

wear so that worthwhile results could be drawn to show the effect of increasing the number of forging operations. The use of shaped dies was previously employed to increase the severity of the forging test for easy estimation of die life. Since this research is dealing with wear related to low numbers of forgings, the shaped dies were not intended to be used further in the investigation, and only the flat ones have been employed for the rest of the experimental work.

The results obtained from the wear volume measurement concerning the first batch of TiN coated dies are shown in Tables 3-6.

The shaped dies used are illustrated by Fig. 5A, which shows the circular flash-land, on which wear volume could not be measured by the Talylin surface profile analyser. Relative metal movement was assessed by obtaining 'Talyrond' traces, Figs. 10, 11.

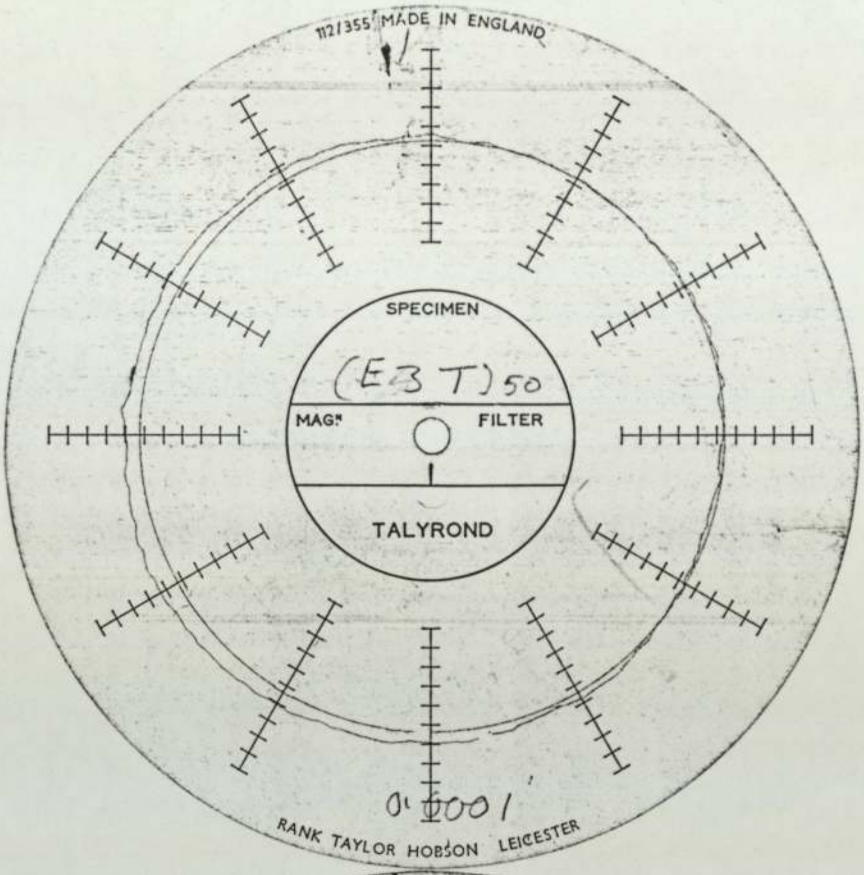
4.1.3 Titanium Nitride Coatings by C.V.D.(II)

The second batch of titanium nitrided dies were used for forging 50, 100 and 200 billets. During forging flakes of scales from the forged billets instantly cleared off the die surface during the ejection of the forged billet. For both types of dies (Electem and H.13) there was very little scale formed on the working surface. The dark colour was easily cleaned off in the electrolytic descaling solution and the wear ring could hardly be detected. The wear traces obtained by the Talylin surface analyser were slightly irregular, Figs. 12, 13.

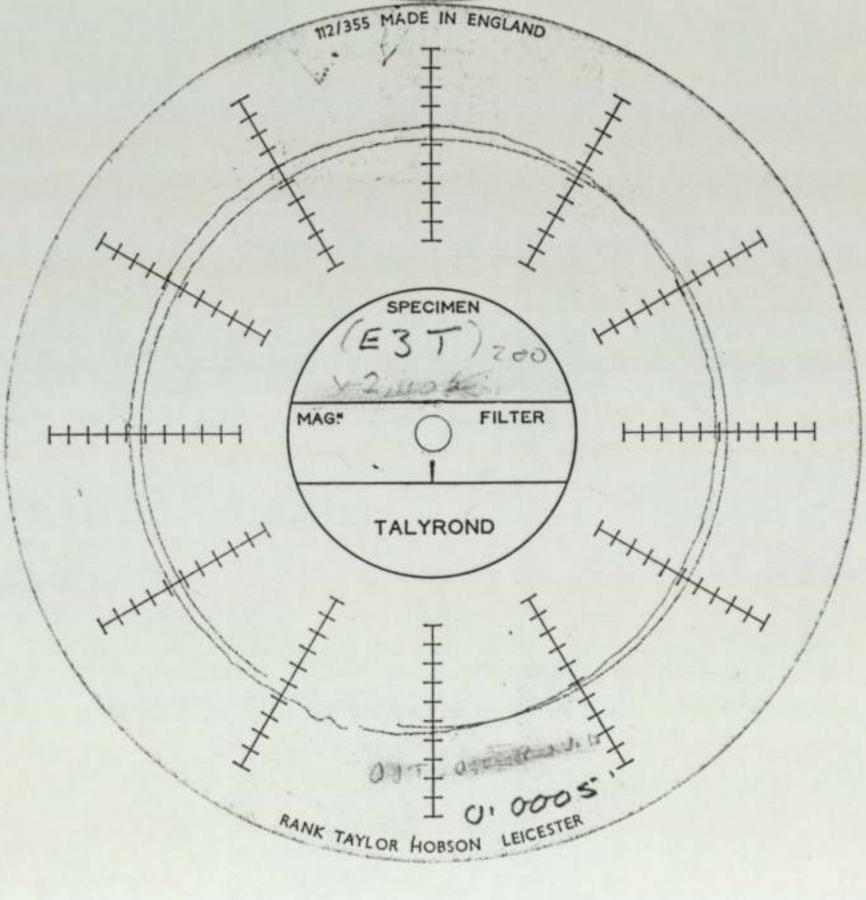
TABLE 6

WEAR VOLUME OF TiN COATED (I) FLAT DIES (TOP DIES SHAPED) AFTER FORGING 50, 100 AND 200 BILLETS

Type of Steel	Wear Volume ($x10^{-3}$ cm^3)		
	50 Billets Forged	100 Billets Forged	200 Billets Forged
No. 5 Electem	0.595	0.823	2.088
H.13	0.251	0.603	2.307



a

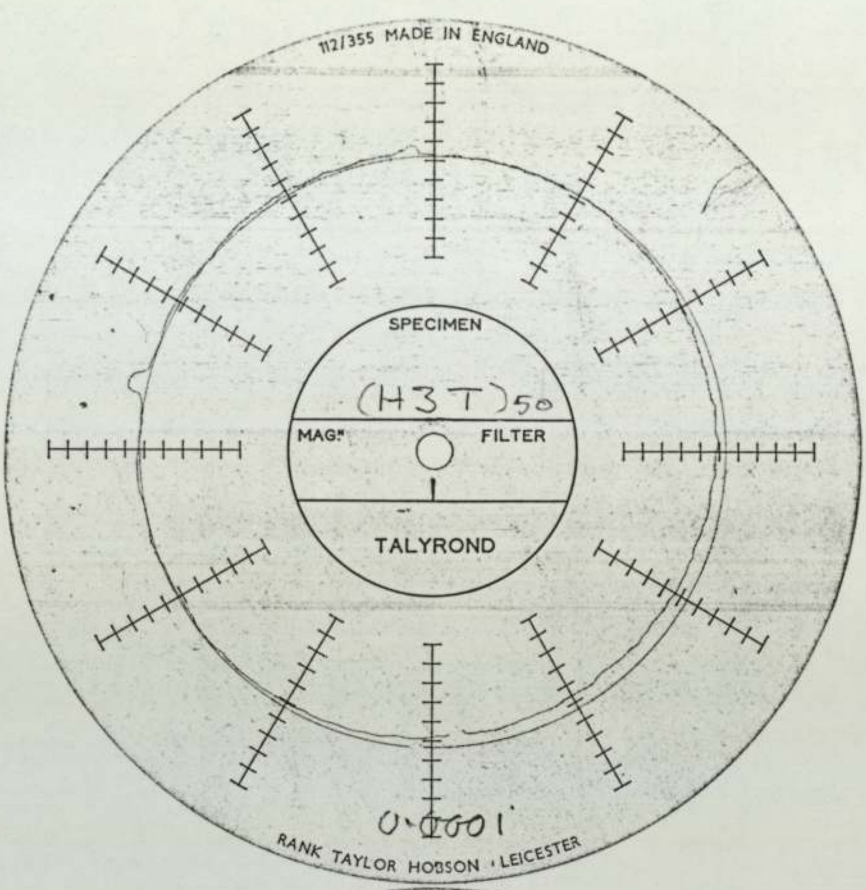


b

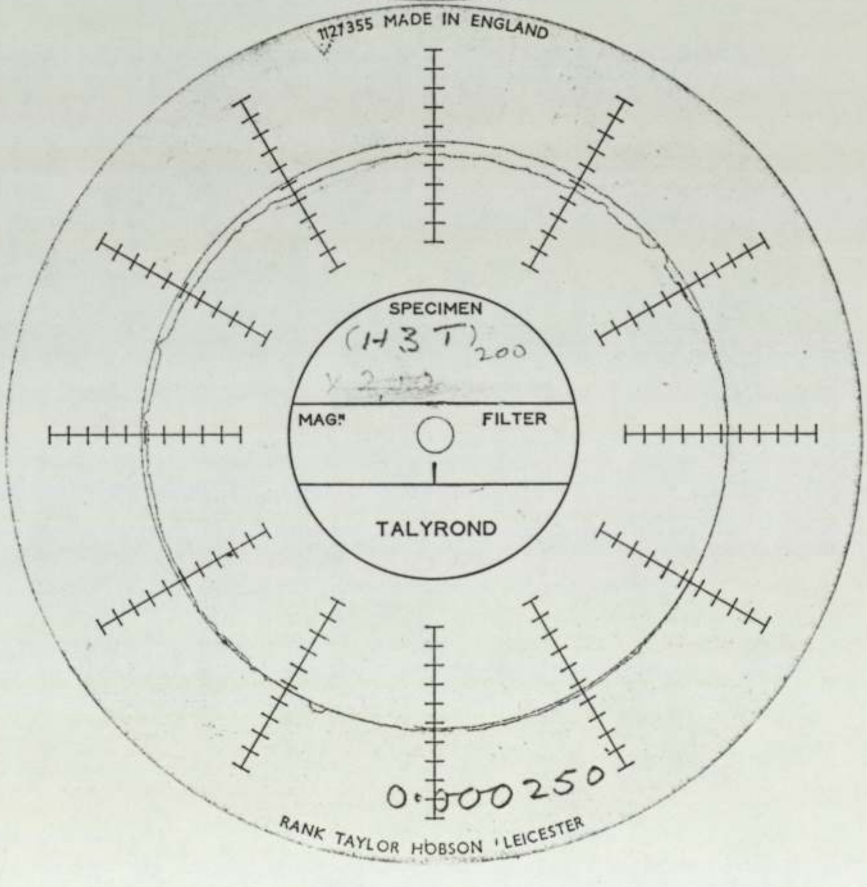
FIGURE 10: Typical Talyrond traces of TiN coated CVD (I) Electem dies (shaped)

a) 50 billets forged

b) 200 billets forged



a



b

FIGURE 11: Typical Talyrond traces of TiN coated CVD (I) H.13 die (shaped)

a) 50 billets forged

b) 200 billets forged

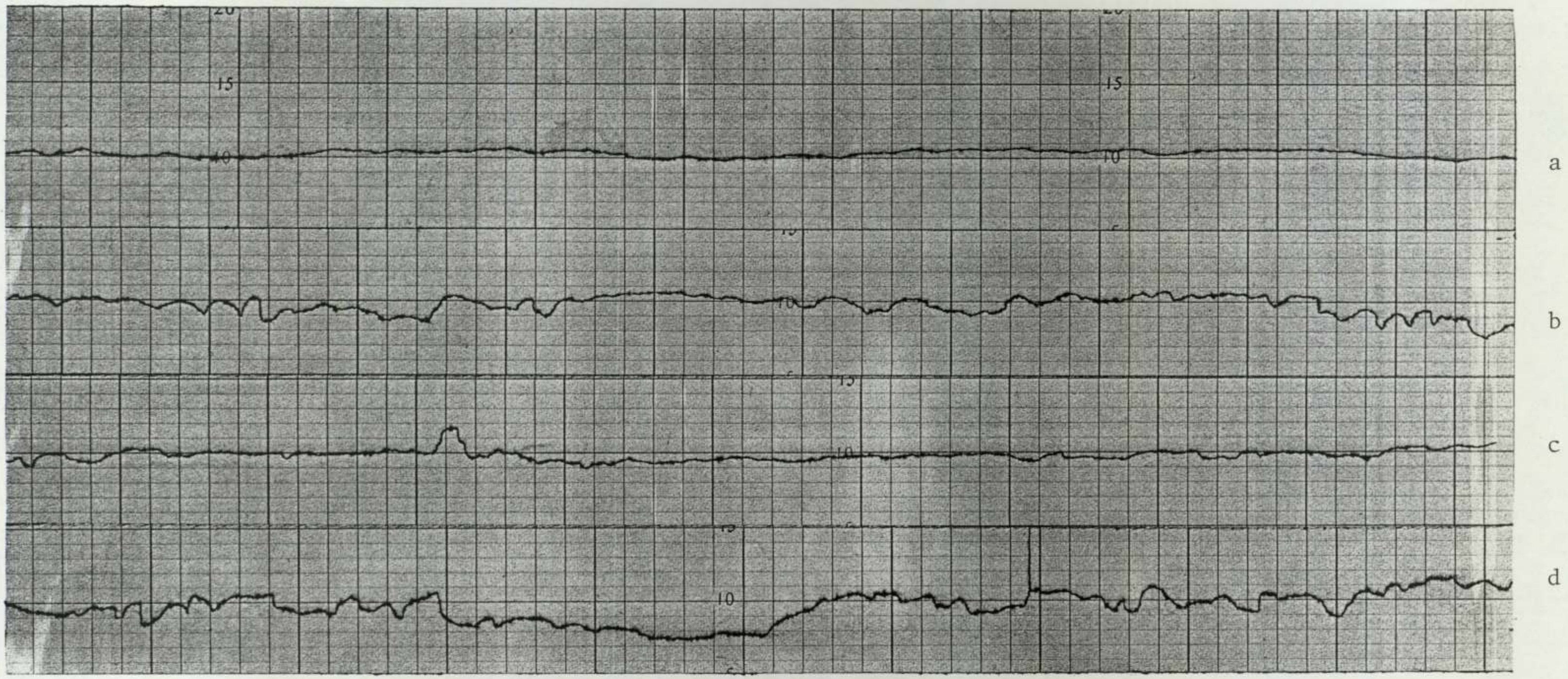


FIGURE 12: Typical Talylin traces of TiN coated CVD(II) Electem dies (flat)

a) Before forging
b) After forging 50 billets
c) After forging 100 billets
d) After forging 200 billets

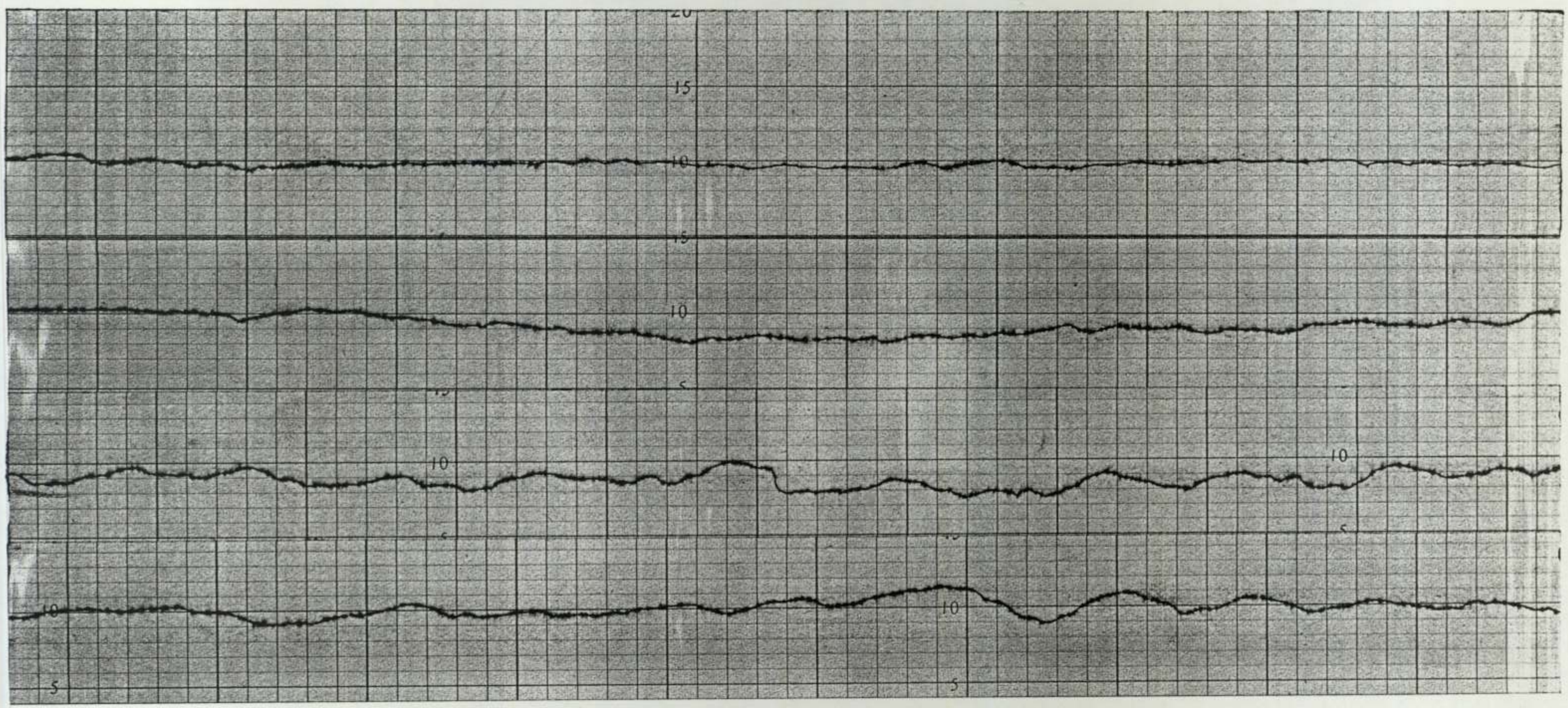


FIGURE 13: Typical Talylin traces of TiN coated CVD (II) H.13 dies (flat)

a) Before forging
b) After forging 50 billets
c) After forging 100 billets
d) After forging 200 billets

4.1.4 Vanadium Carbide Coatings by T.D. Process

Coated dies of both Electem and H.13 steels were used for forging 50, 100 and 200 slugs. Visual observation during and after forging showed that thick scale adhered to the central plateau of both the top and the bottom die, some of which could easily be removed by slight rubbing especially those of the top dies. However, on descaling all the scales were cleaned off leaving a shiny highly polished wear ring region and a brownish central plateau with dark edges. On both Electem and H.13 dies there were clear indications of cracks encircling and, in some cases, crossing the wear area. All the Talylin traces were protruding above the original surface in the wear ring and central plateau zones with peaks at crack locations, Figs. 14,15.

In an attempt to increase the severity of wear and detect any significant increase in wear volume, the same flat dies of Electem were employed to carry out additional forging operations of 300, 400 and 600. Up to this stage there was no significant wear volume loss or change in the Talylin traces, Fig. 14 c, d. However, the wear ring became more shiny and lustrous.

4.1.5 Evaluation of Wear Volumes

4.1.5.1 Uncoated Flat Dies

The two pairs of flat dies used in their annealed condition for forging 100 billets, showed the highest wear volume for both types of steel, Table 3. However, steel in this condition is not used for wear resistance purposes. It was used at the beginning of this test to check the experimental equipment, so the annealed condition will not be considered further.

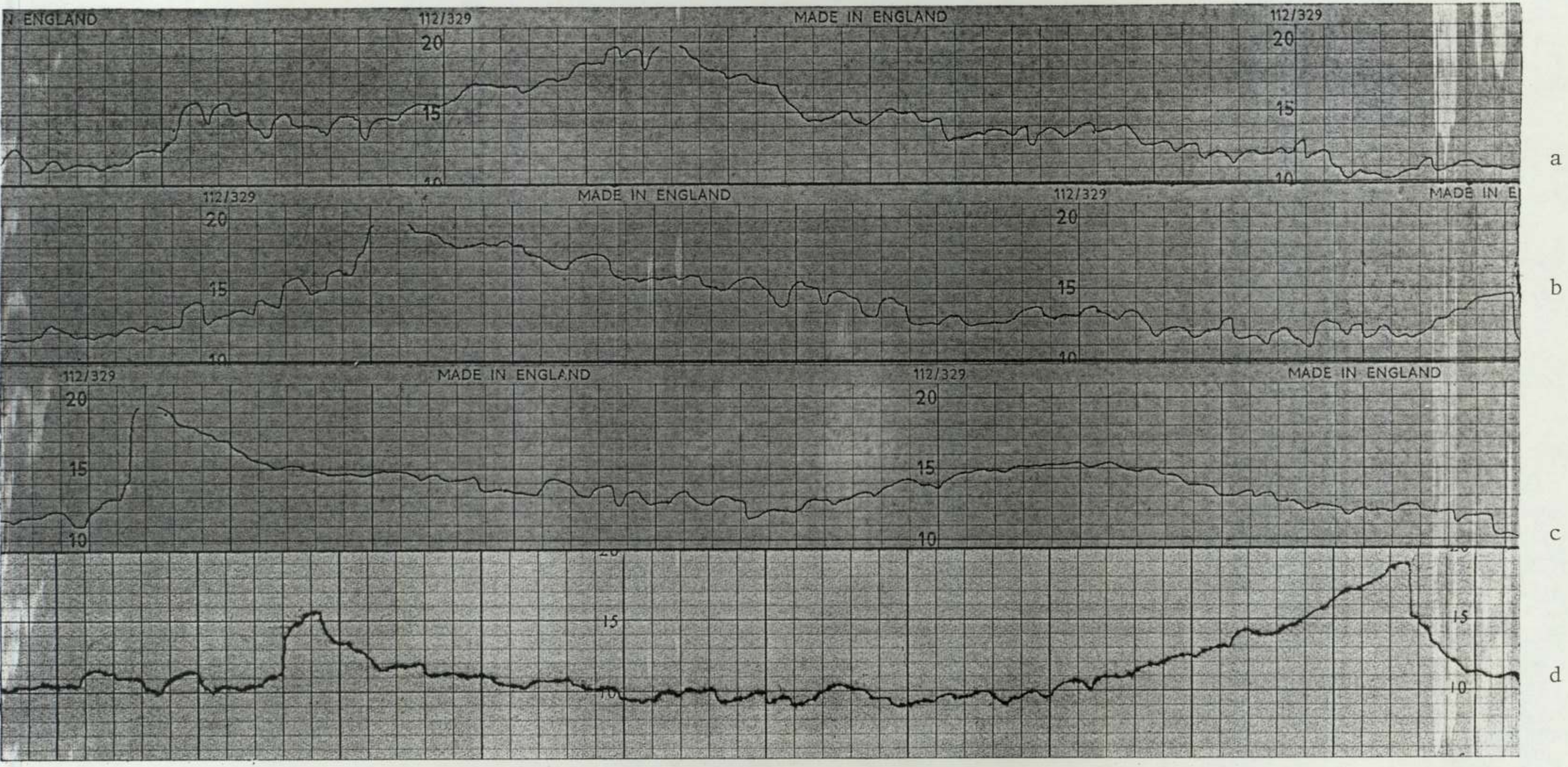


FIGURE 14: Typical Talylin traces of VC coated Electem dies (flat)
a) 100 billets forged; b) 200 billets forged;
c) 400 billets forged; d) 600 billets forged

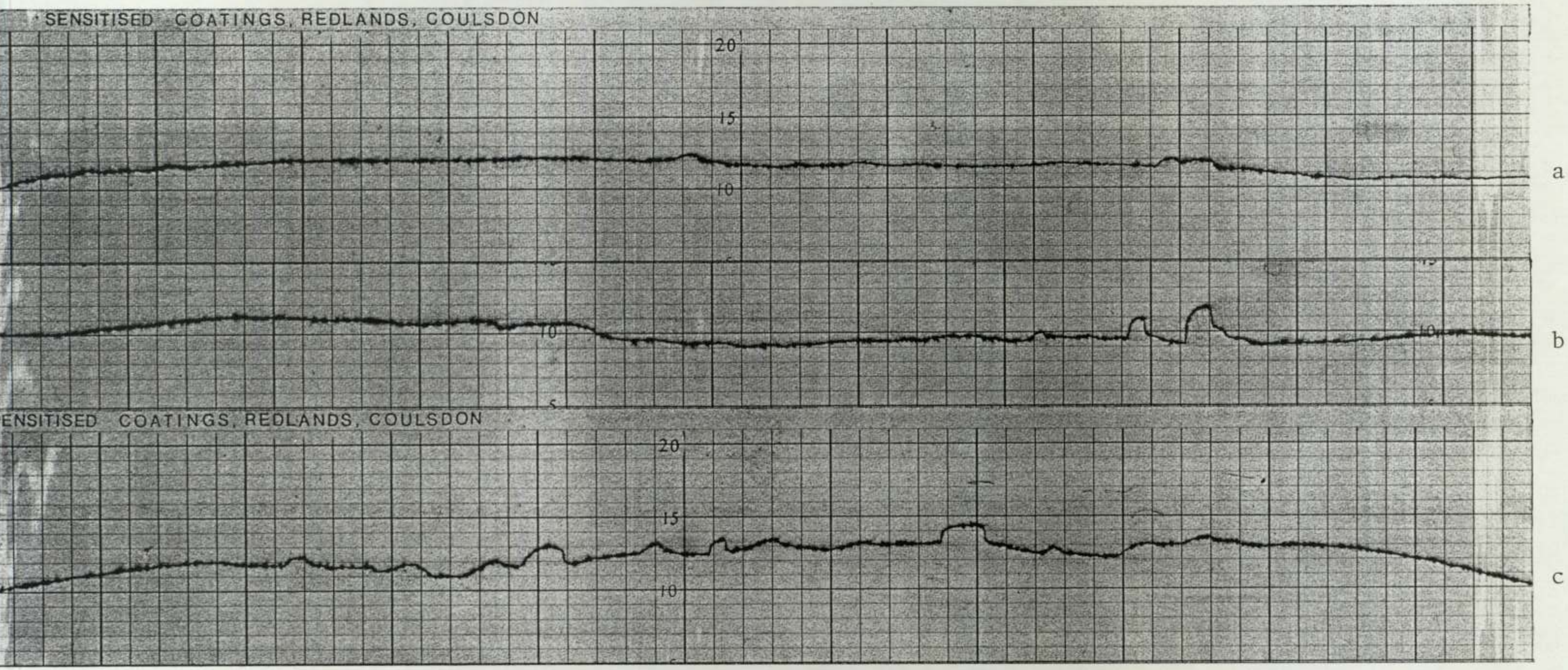


FIGURE 15: Typical Talylin traces of VC coated H.13 dies (flat)

a) 50 billets forged; b) 100 billets forged;
c) 200 billets forged

The wear volumes of the hardened and tempered flat dies are shown in Tables 3 and 4. After forging 100 and 200 billets the uncoated dies exhibited wear volumes higher than those of the surface coated dies, with the highest values related to Electem. The wear variation of the bottom and top dies (Fig. 16) shows that the bottom dies of Electem No. 5 steel wear more than the top dies, while in the case of H.13 the reverse was true.

4.1.5.2 TiN Coated Flat Dies (I)

Results are shown in Tables 3-5 and Figs. 16 and 17. In both steels the wear volume was less than that of the uncoated dies indicating improvement of the die wear resistance. The improvement after 100 billets forged was 33% for Electem and 34% for H.13, while after 200 forgings the wear performance improved by 37% for Electem and by 17.5% for H.13 dies. The bottom and top dies showed a large variation on comparing the two types of steels employed, Fig. 16. The Electem dies performance improved remarkably and the relationship between the bottom and top die remained stable with the higher wear associated with the bottom die. The coated H.13 dies exhibited unstable wear conditions. The highest wear volume was fluctuating between the bottom and top die alternately. After forging 200 slugs the bottom die showed an excessive wear.

4.1.5.3 TiN (I) Coated Shaped Dies

The accelerated test results of bottom dies are shown in Table 6 and Fig. 18. At low numbers of forging operations the two steels started with quite low wear. H.13 dies performance was far better than that of the Electem dies,

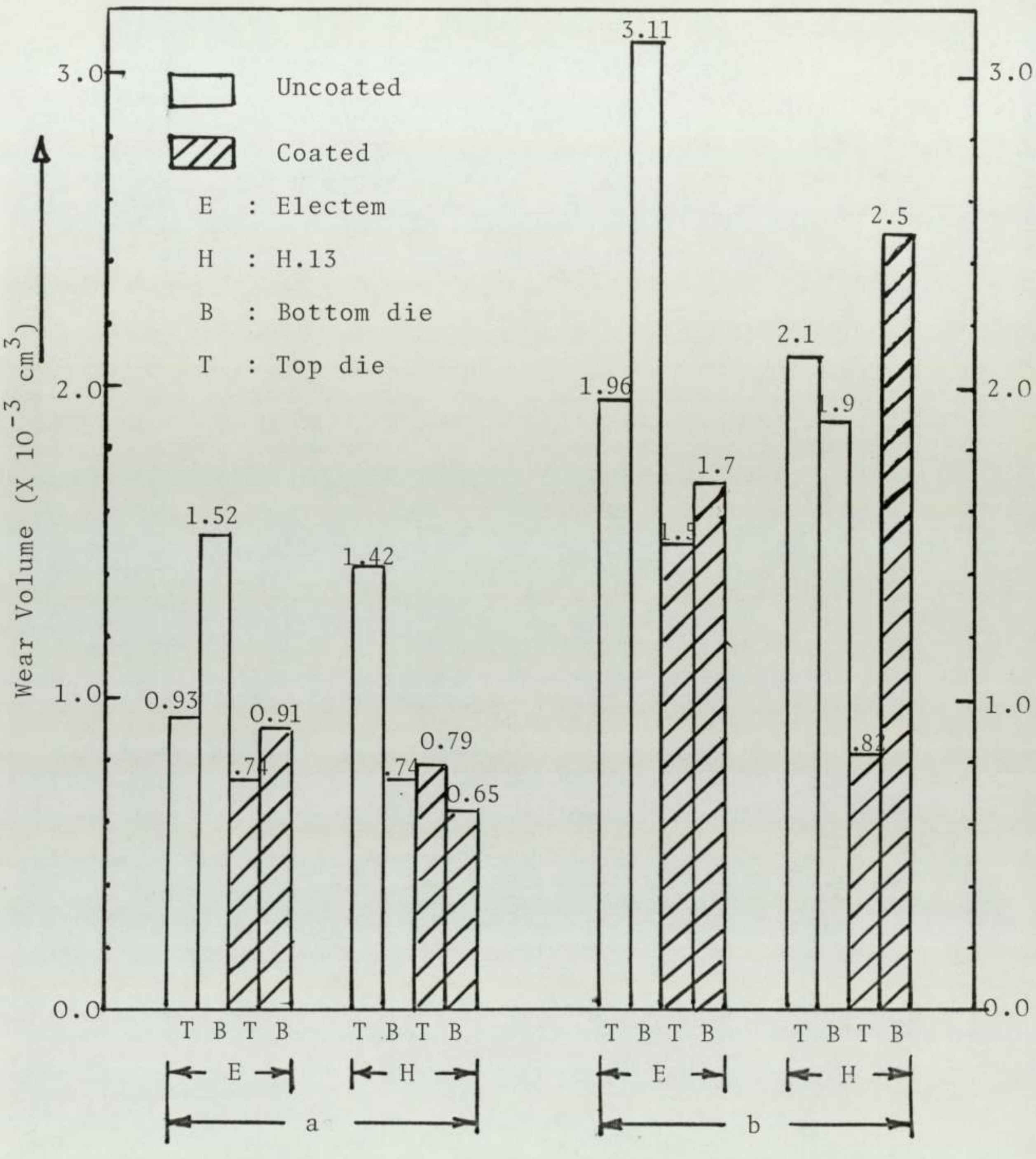


FIGURE 16: Wear variation of uncoated and TiN-coated dies

a) after forging 100 billets
b) after forging 200 billets

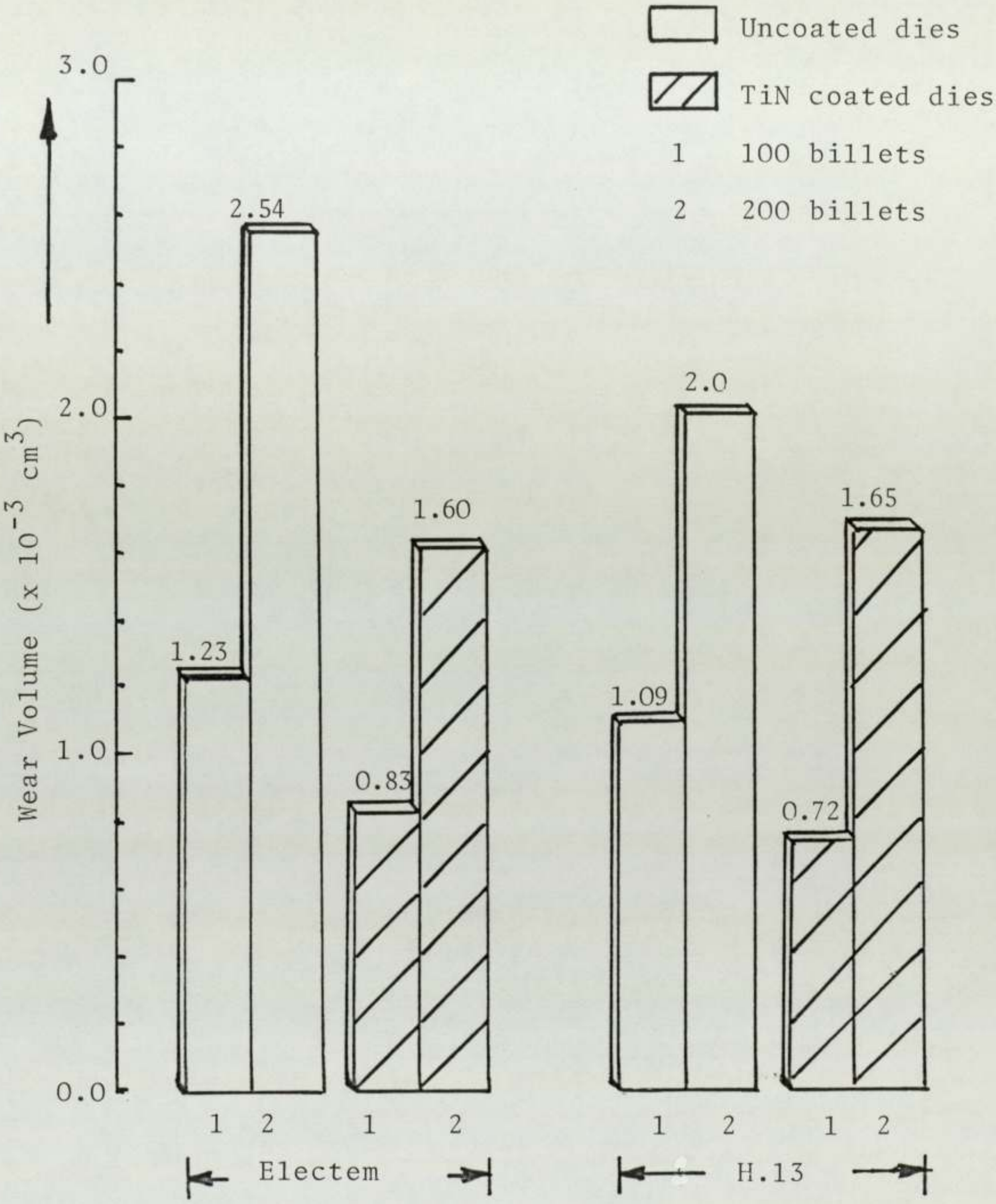
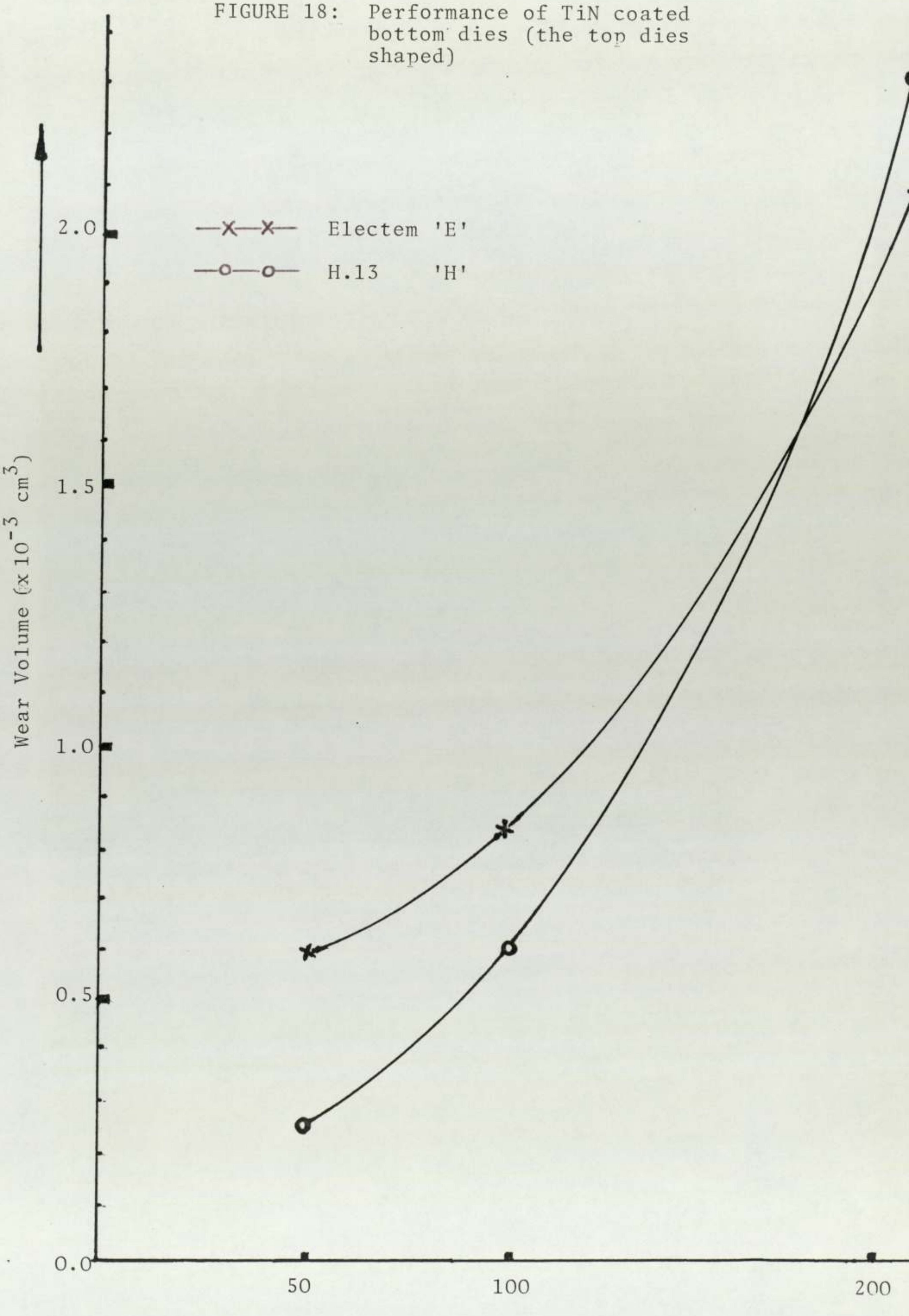


FIGURE 17: Wear volume of flat dies after forging 100 and 200 billets

FIGURE 18: Performance of TiN coated bottom dies (the top dies shaped)



but after forging about 175 billets the wear volume of H.13 exceeded that of Electem No. 5 steel. Wear volume for both types of steels increased with the increase of wear severity but wear of H.13 was more rapid. The use of the shaped dies resulted in high wear volumes after a relatively low number of forging operations on the flat dies. The top dies also suffered wear, the flash-land had the highly deformed metal flowing over its thin cross-section, eroding and deforming the edges of its surface. It is difficult to measure wear volume on the shaped dies. The Talyrond traces obtained (Figs. 10, 11) were used to give comparable results. The traces obtained for the coated Electem shaped dies (Fig. 10) and those for H.13 dies (Fig. 11) showed very shallow depths of wear and almost negligible deformation despite the remarkable increase and variation in wear volume of the associated flat dies.

The wear that occurred on these flat dies satisfactorily represented the accelerated test and fulfilled the present requirements. Moreover, previous researchers [2] who had employed similar test conditions in studying the performance of cobalt alloy coatings, suggested that erosion of shaped dies increased after 200 forgings, the highest number of forgings used here. However, it was decided to employ only the flat dies for the rest of this study.

4.1.5.4 TiN Coated Flat Dies (II)

Figures 12 and 13 show the changes that occurred in the Electem dies and the H.13 dies respectively. Figures 12a and 13a are the surface profiles of the dies before forging, while the traces b, c and d are those obtained by the

Talylin surface analyser after forging 50, 100 and 200 billets respectively. The traces (a) are smooth horizontal lines for both types of steels. These represent the reference against which the other traces were compared. All the traces showed no wear except the 200 forgings traces which indicated a very small wear volume which could not be measured. In both TiN coated steels the die surfaces became more rough at certain instances. The Electem No. 5 dies roughened after 50 forgings, but became smooth after 100 forgings, then after 200 forging operations became rougher again with more small and shallow depressions. The H.13 traces showed smoother profiles than the Electem traces, but they indicated a clear difference from the pre-forging trace (Fig. 13a). At 50 forgings the trace illustrated a long, but quite shallow depression, while after 100 and 200 forgings the traces showed some waviness across the wear profile.

Since the Talylin surface profile analyser did not illustrate detailed features of the failure mechanisms microscopic examination was also employed.

4.1.5.5 V.C. Coated Flat Dies

Figure 14 shows four wear traces after forging of

(a) 100 billets;

(b) 200 billets;

(c) 400 billets, and

(d) 600 billets,

on Electem dies.

Because of the unexpected and peculiar shapes of the wear traces obtained after 50, 100 and 200 forging operations, the test was extended to three more runs up to 600 forgings. The die surfaces, represented by the wear traces, were quite rough with possible metal build-up all over the wear area. The traces are protruding over the horizontal surface line with peaks at some locations. The bulging-out profile of the central die area suggests metal pick-up or an irregular distribution of surface distortion. This feature disappeared with the increase of the forging operations. The progress in changes in profile shown in Figures 14c, d indicates that metal was pushed sideways by the metal flow of the forged billet and it seems to gather along crack locations. Apart from the two ridges appearing to be at crack sites along the wear ring edges, the profile shows no sign of wear.

Figure 15 shows Talylin traces of H.13 dies after forging 50, 100 and 200 billets. They are almost similar in shape. The trace after two hundred forgings shows a slightly rougher profile. In the three cases there are convex shapes characterising the traces, c having the highest level of curvature and b having the semi-flat profile. This indicates that the forged metal might adhere and abrade alternately during forging. No surface damage and no cracks were detected; the wear volume measurement was not possible since there were no recesses in the traces produced.

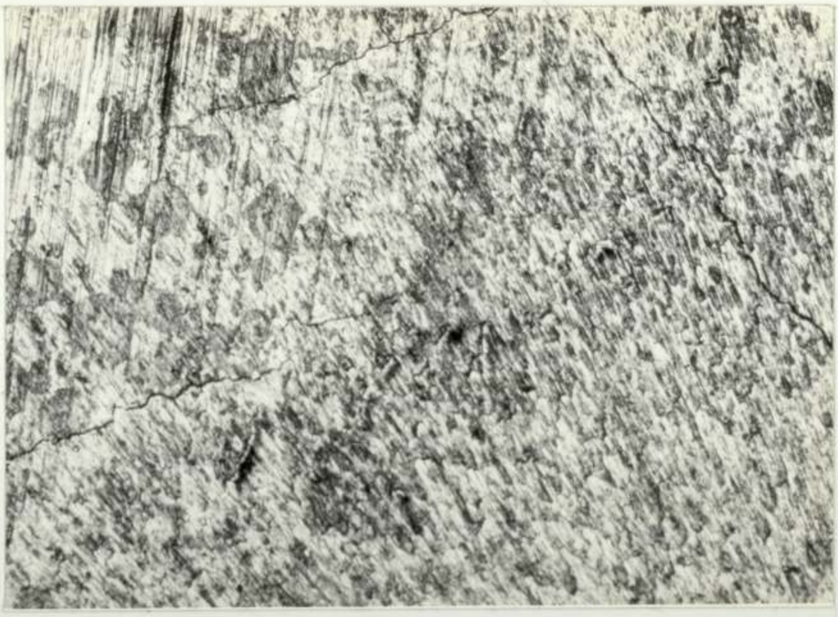
4.2 Surface Studies

The results obtained for the uncoated dies examined under the optical microscope have been presented in this section to give a general idea about the surface wear behaviour of the two steels used as die substrates in this work. The wear mechanisms associated with these steels during hot forging in the hardened and tempered condition have been investigated previously [2,29]. The main emphasis in surface and sub-surface studies will be given to the failure mechanisms of the two wear-resistant coatings employed in the research.

4.2.1 Uncoated Dies

Figures 19a, b show an uncoated Electem pair of dies after forging 200 billets. They illustrate tracks of abrasion and cracking of the wear region. Figure 19a shows small multi-cracks in the outer edge of the wear region of the bottom die, while Fig. 19b shows a long crack extending from the central plateau region of the top die and crossing the wear ring where it becomes finer.

The micrographs in Figs. 20a, b show H.13 worn dies after forging 200 billets. There are almost no cracks observed in these dies, but the wear ring of the bottom die (Fig. 20a) was highly polished. Figure 20b shows the top die gouging abrasion marks in the wear ring, while the central plateau (bottom left) keeps its original grinding tracks. Figures 21a, b show the failure of an uncoated Electem die after forging 1000 billets. Figure 21a shows the unworn central plateau. A group of cracks initiated and propagated



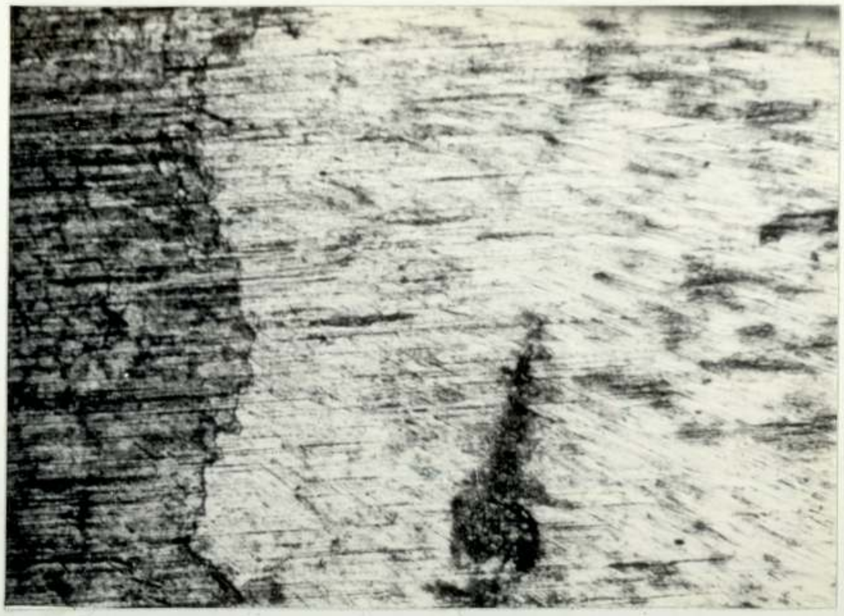
a

Central
Plateau

b

FIGURE 19: Optical micrograph of uncoated Electem die surface after forging 200 billets showing the wear region cracks and abrasion marks, x325
a) multi-cracked bottom die;
b) single deep crack across the top die wear ring

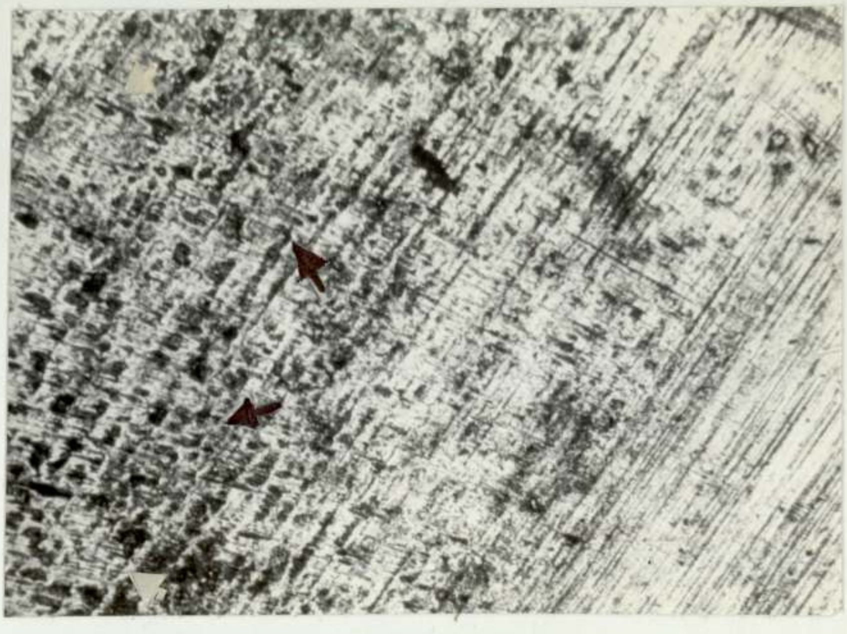
Central Plateau



Wear ring

a

Wear ring



Central Plateau

b

FIGURE 20: Optical micrographs of uncoated H.13 die surface after forging 200 billets showing the abraded, eroded and uncracked wear ring, x325
a) central plateau/wear ring of bottom die
b) gouging of the top die

N.B. Gouging abrasion marks are indicated by arrows

a

b

FIGURE 21: Optical micrograph of uncoated Electem die surface after forging 1000 billets, x325

a) Unworn central plateau with its original grinding marks. Cracks initiated and propagated around a surface inclusion

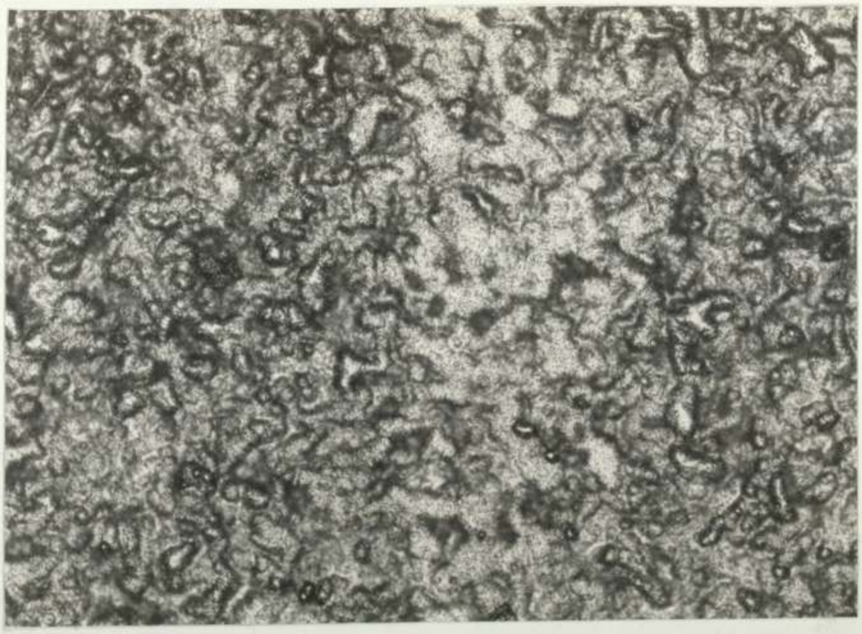
b) Abrasion in the low wear region and erosion in the heavy wear region with a crack linking the central plateau and the wear ring around a surface inclusion. Figure 21b illustrates a heavily abraded and eroded region in the wear ring with a deep crack extending from the central plateau to the wear ring where it disappears gradually.

4.2.2 Titanium Nitride Coated Dies - C.V.D.

The TiN coating structures are shown by Figs. 22a, b. Figure 22a illustrates the compact small topographical features of the Electem die surface, coated with TiN while Fig. 22b shows the larger features typical of H.13 die surfaces. The dark spots on the H.13 die surface suggest slight oxidation occurrence during heat treatment. After heat treatment and prior to forging the Electem dies appeared to retain their colour more than H.13 dies on which some areas of the surface had turned to greenish-yellow instead of the original bright yellow. This is because slight oxidation had occurred during tempering.

Figures 23a, b show scanning electron micro-graphs of TiN coated Electem dies after forging 100 billets. Fine cracks are initiated at the nodule boundaries in the wear region (Fig. 23a), and along the ridge of a pit (Fig. 23b). An isolated inclusion and scattered tiny wear debris can be observed in and outside the pit.

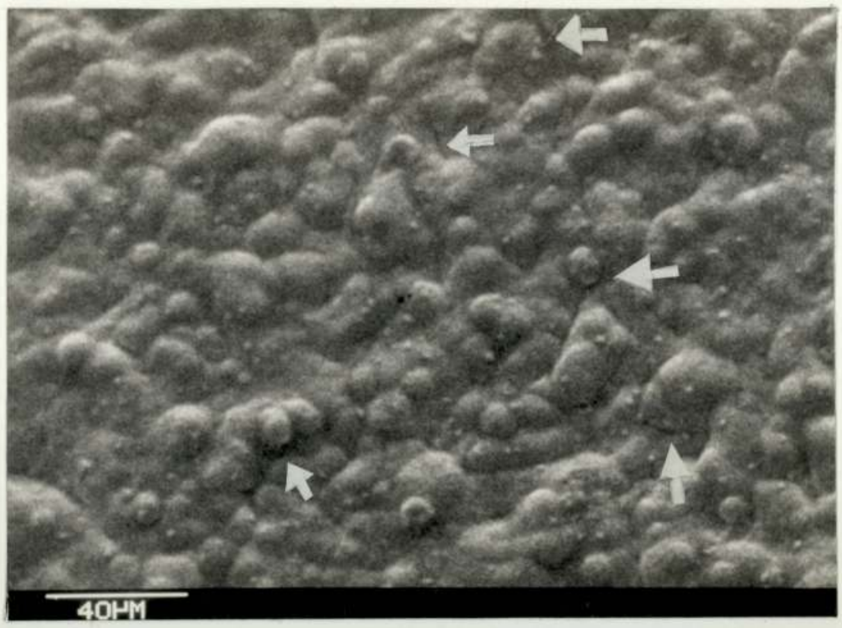
Figures 24a, b show the extent of void and crack formation on the surface of TiN coated H.13 die after forging 100 billets. The large nodules were partially polished, while separate voids were formed (Fig. 24a). Figure 24b shows different sizes of cracks joining the voids and propagating longitudinally through the surface.



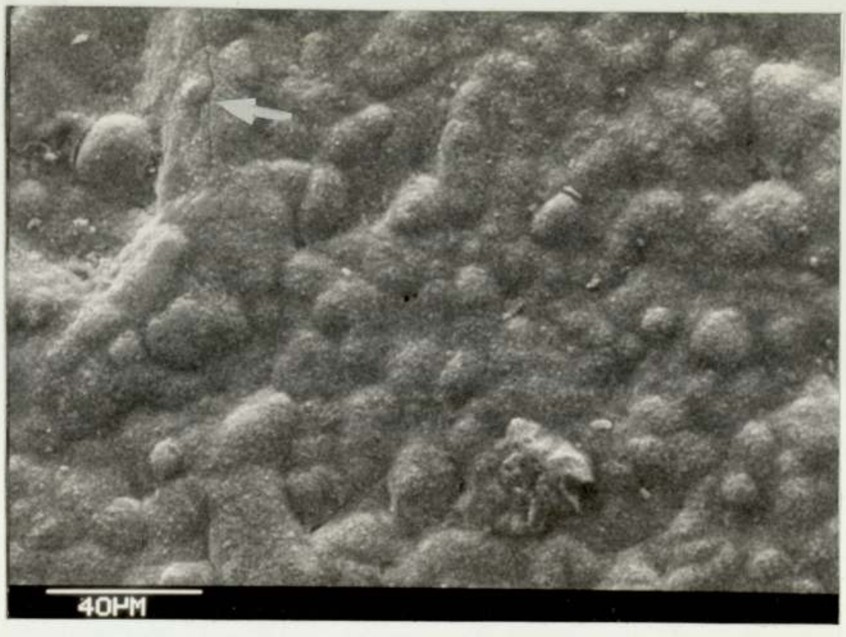
a

b

FIGURE 22: Optical micrographs of TiN coated dies showing the coating structure and the nodules distribution on the surface, x 200
a) Electem die surface
b) H.13 die surface



a



b

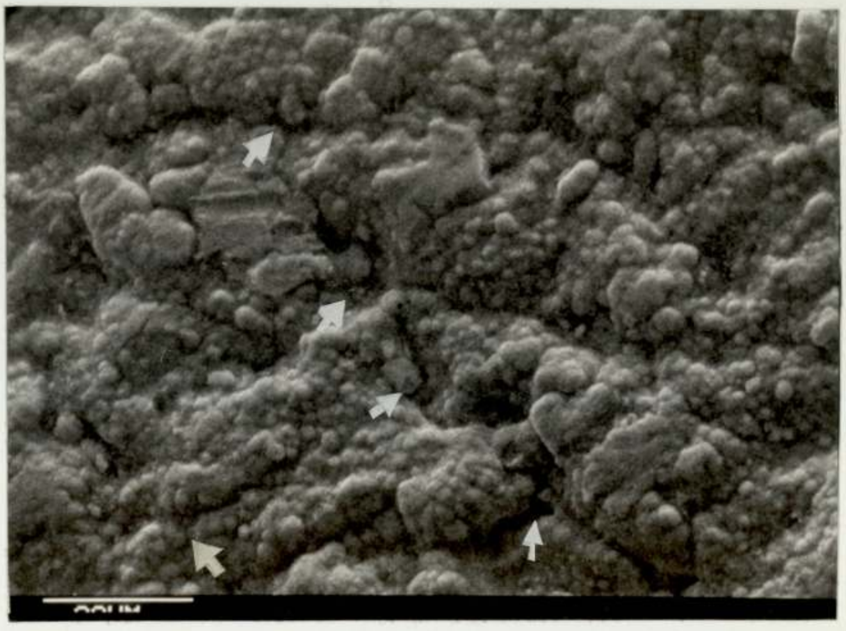
FIGURE 23: S.E.M. micrographs of TiN coated Electem die after forging 100 billets showing the wear region surface, x 500

a) fine cracks initiated at nodule boundaries

b) fine cracks on a pit ridge, an isolated inclusion and scattered tiny wear debris

N.B.)cracks are indicated by arrows)

a



b

FIGURE 24: S.E.M. micrographs of TiN coated H.13 dies after forging 100 billets showing the wear region surface
a) void formation around the polished large nodules, x 500
b) different sizes of cracks joining the surface voids, x 1000

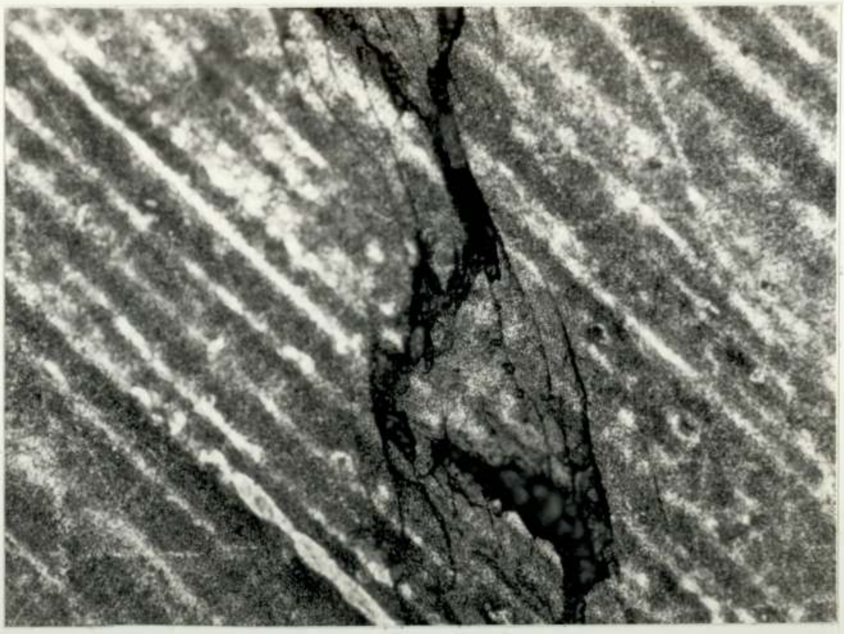
N.B. voids and cracks are indicated by arrows

The continuation of void and crack formation with plastic deformation is shown by the newly formed cracks and micro-voids. These intergranular cracks occurred as a result of dislocation of the surface grains.

4.2.3 Vanadium Carbide Coated Dies - T.D.

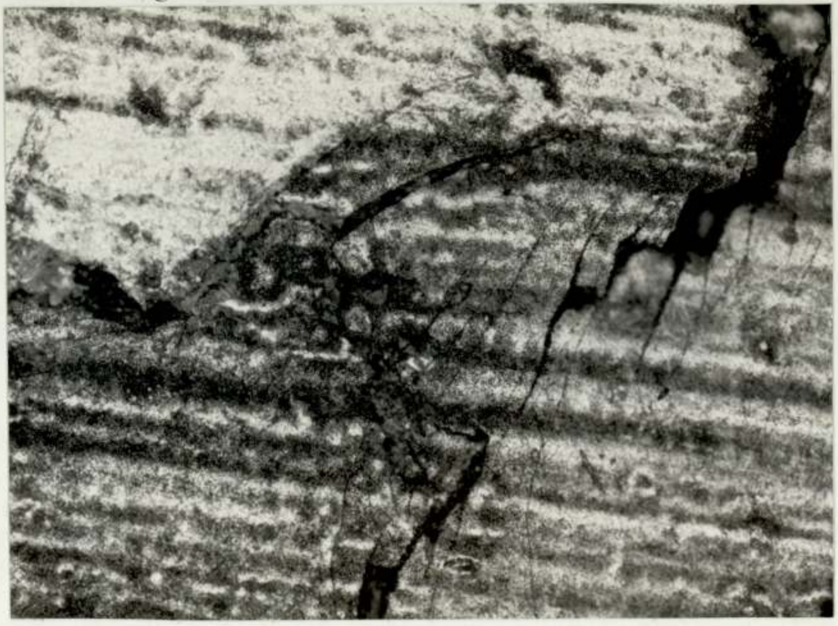
The surface examination of V.C. coated Electem dies showed evidence of cracking after forging 50 billets (Fig. 25a). These cracks occurred in the wear ring region, but after 200 forgings this region appeared to be highly polished and the surface cracks remained only in the central plateau edge close to the wear ring (Fig. 25b). The cracks in the wear ring region were polished away leaving the shiny surface and very light tracks of the abraded shallow cracks. Figures 26a, b show scanning electron micro-graphs of other worn areas of the previous Electem die. Figure 26a shows a micro-pitted and eroded area, while Fig. 26b shows the ploughing abrasion marks with the ridged coating ready to be worn in the subsequent cutting abrasion.

Figure 27 shows a surface view of a sector in the wear scar of V.C. coated H.13 die after forging 100 billets. The forged metal tracks were observed in the wear ring region where abrasive wear took place rubbing away the grinding marks which were quite clear in the dark central plateau. Figure 28 illustrates the extent of surface cracking after increasing the number of forgings to 200 billets. The multi-cracks formed were very fine spreading all over the wear ring/central plateau edge.



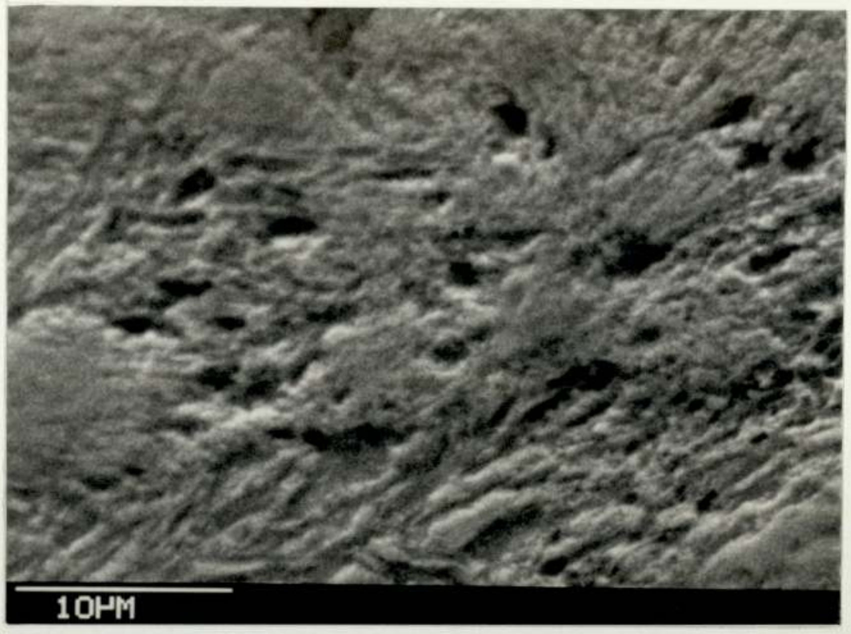
a

Wear ring



b Central plateau

FIGURE 25: Optical micrographs of VC coated Electem die surface showing the cleavage cracks increasing with the increase of the number of forgings
a) the wear region after 50 billets forged, x 200
b) cracks propagation after 200 billets forged, x 160



a

b

FIGURE 26: S.E.M. micrographs of VC coated Electem die surface after forging 50 billets, x 2000
a) micropitted and eroded area in the wear ring region close to the central plateau edge.
b) ploughing abrasion track with ridged coating ready for subsequent cutting action inside the wear ring region

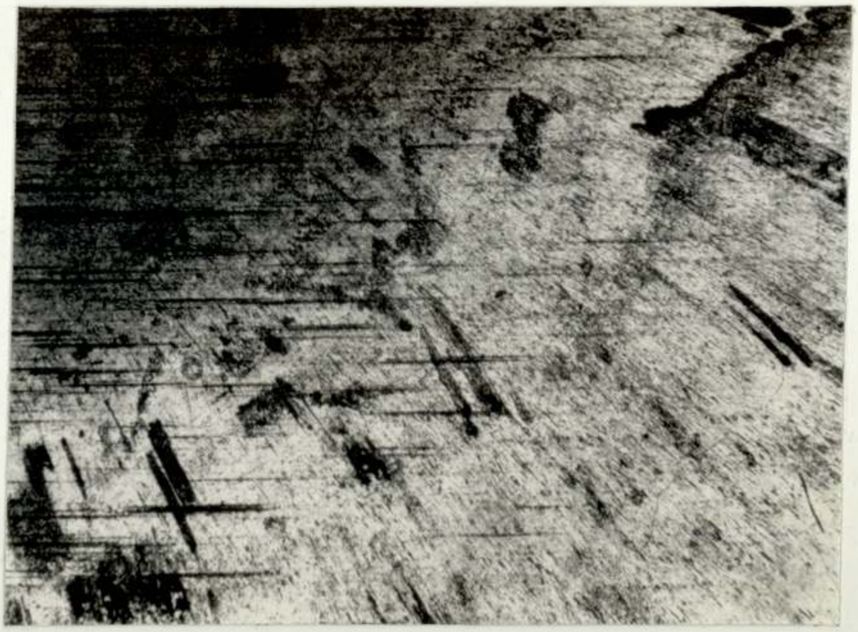
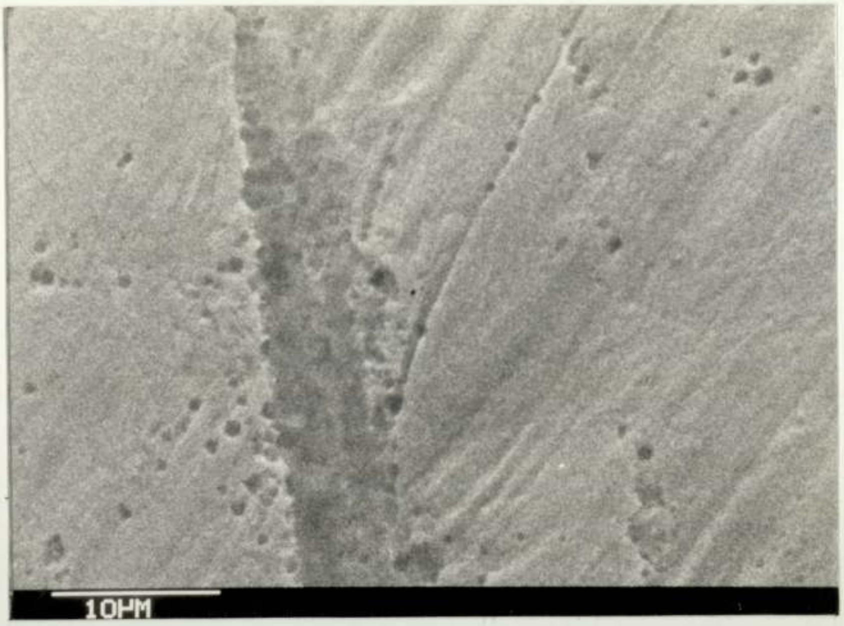
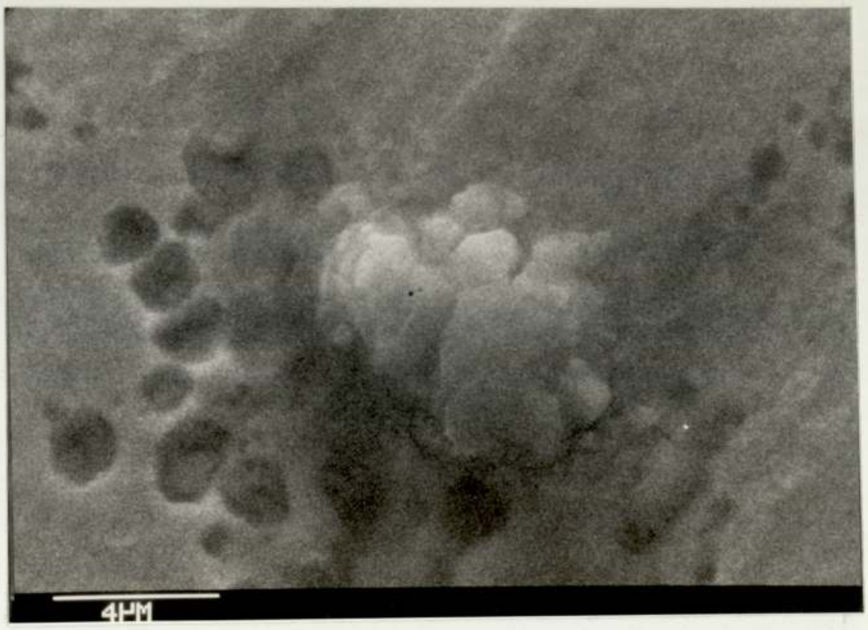


FIGURE 27: Surface view of a sector in the wear scar of VC coated H.13 die after forging 100 billets showing the abraded region and the central plateau region with its original polishing marks, x 20

FIGURE 28: Optical micrograph of VC coated H.13 die surface after forging 200 billets showing the central plateau/wear ring edge multi-cracks. The cracks in the wear region (top left) are very fine and shallow, x 100



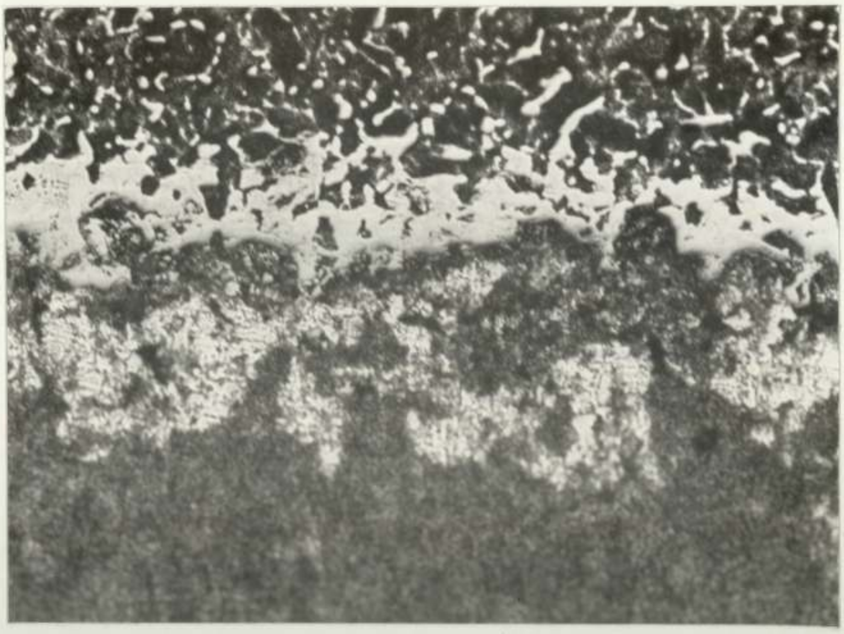
a



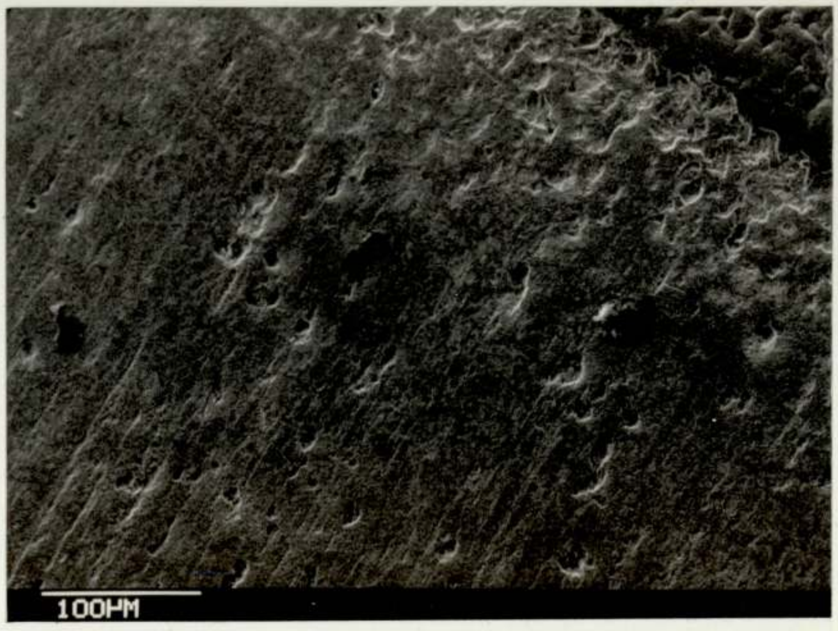
b

FIGURE 29: S.E.M. micrographs of VC coated H.13 die surface after forging 100 billets
a) erosion and void concentration area, x 2000
b) Localised micropits and accumulated wear platelets, x 5000

Figures 29a, b show the type of localised failure initiated in the surface of H.13 die after forging 100 billets. Erosion in the void concentration zone had taken place (Fig. 29a). Micro-pitting of the V.C. coating occurred where the stripped-off platelets accumulated to form a fragment of larger size (Fig. 29b).



a



b

FIGURE 30: Taper sections of TiN coated Electem dies after forging 100 billets showing the subsurface voids, x 200
a) optical micrograph
b) S.E.M. micrograph

4.3 Sub-Surface Studies

4.3.1 Titanium Nitride Coated Dies - C.V.D.

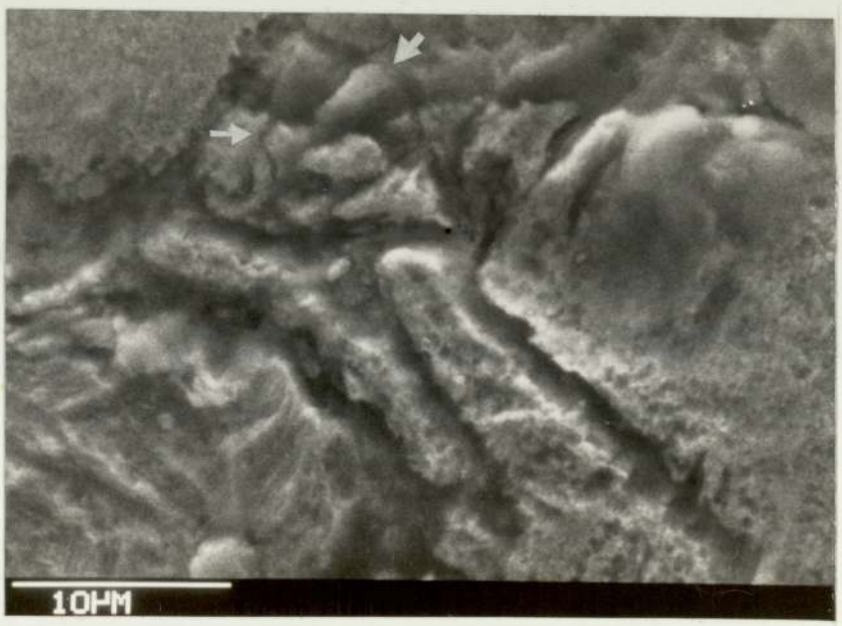
Figures 30a, b show two views of a taper section taken from a TiN coated die after forging 100 billets. Figure 30a is an optical micro-graph showing the two layer coating. No sign of wear was detectable in the compact top layer of TiN but the TiC layer showed irregularity and gaps within the sub-surface. The void formation is illustrated by the scanning electron micro-graph (Fig. 30b). Apart from these few voids no other signs of sub-surface failure could be revealed by the optical microscope or the S.E.M.

4.3.2 Vanadium Carbide Coated Dies - T.D.

Figure 31a is an optical micrograph of a taper section of V.C. coated Electem die after forging 100 billets. It shows a single crack penetrating the coating. The surface (top) shows the grinding marks which were quite shallow. The sub-surface shows no sign of wear and the good performance may be enhanced by the lamellar structure of the coating and the good adhesion indicated by the keying of the coating to the substrate.

After 100 forgings localised deformation may occur at sites of sub-surface discontinuity (Fig. 31b), where a few polygonal cracks and small metal islands were formed and some separated as loosely attached thin flakes, resting on crack edges. However, the crack formation increased with the increase of number of billets forged. The extent of cracking after 200 forgings is illustrated by the optical micro-graph (Fig. 32a) and the SEM micro-graph (Fig. 32b). Cleavage cracks and delaminated coating sheets were shown. The surface cracks

a



b

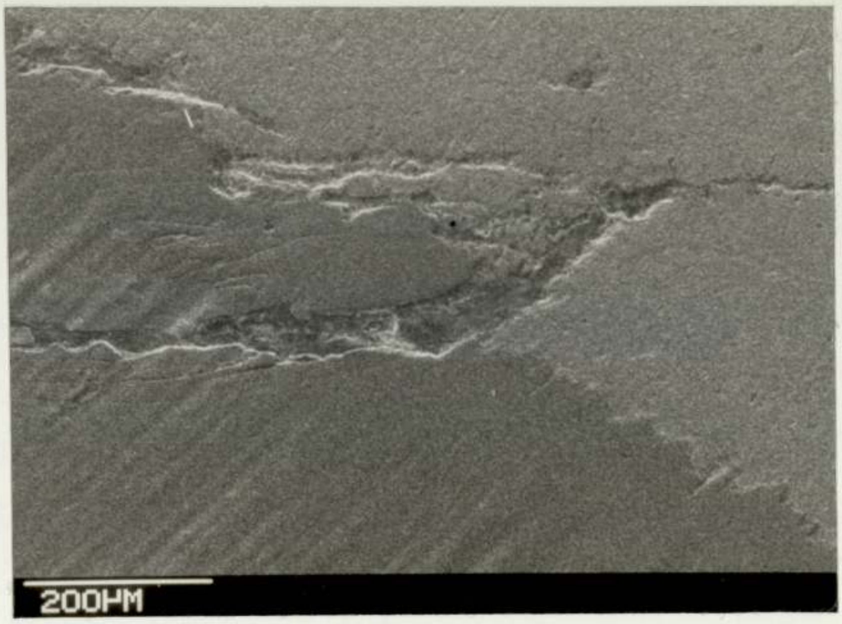
FIGURE 31: Taper section of VC coated Electem die after forging 100 billets
a) optical micrograph showing the lamellar structure of the coating and a penetrating crack, x 200
b) S.E.M. micrograph showing a localised deformation forming polygonal cracks, metal islands and thin flakes loosely attached (indicated by arrows), x 2000

Coating surface

Coating sub-surface

substrate

a



Coating

substrate

b

FIGURE 32: Taper section of VC coated Electem die after forging 200 billets
a) optical micrograph showing cleavage cracks and delaminated coating sheets (indicated by arrows), x 200
b) S.E.M. micrograph showing an extended crack across the coating (top right), branching at the interface and propagating in the substrate, x 100

penetrated the coating at void sites, branched at the interface and propagated in the substrate where deformation appeared to be more severe than in the coating layer (Fig. 32b).

4.4 Extended Surface and Sub-Surface Studies

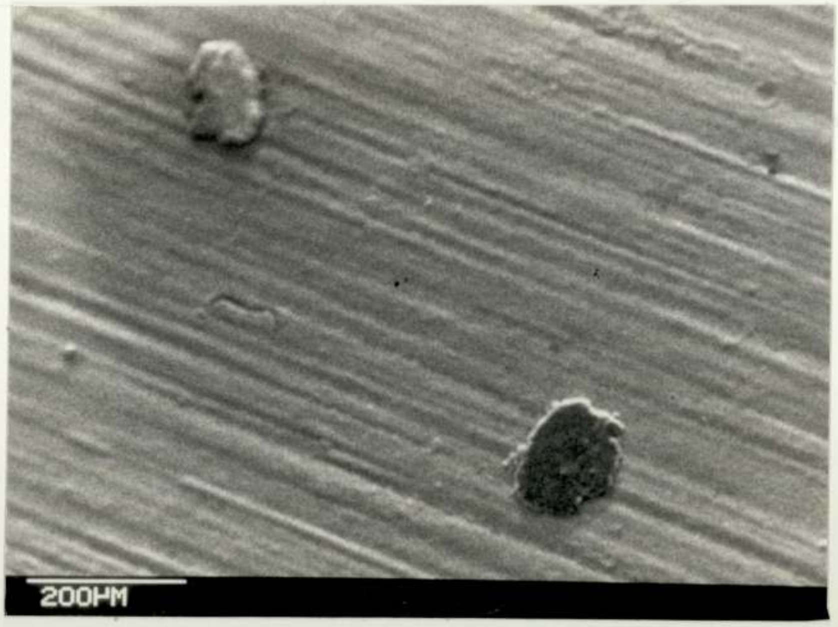
The experimental work in this study was originally designed to carry out 50, 100 and 200 forging operations. At this stage wear resistant coatings are expected to perform satisfactorily under hot forging conditions. However, after wear evaluation in the first phase of this investigation it was decided to increase the number of forging operations on dies coated by one of the two types of coating employed in order to obtain quantified wear data on the die surface. Additional forging of 300, 400 and 600 billets was carried out on vanadium carbide coated Electem. It was found that wear could still not be quantified, but the microscopic examination revealed interesting surface and sub-surface wear features.

4.4.1 Surface Examination

Figures 33a, b show SEM micro-graphs of a V.C. coated Electem die surface. After 400 forgings separated fragments of surface scale were shown adhering to the wear region (Fig. 33a). These fragments could move with the flowing forged metal in subsequent forging leading to severe abrasion of the surface. Figure 33b shows another worn area where abrasion grooves occurred with a long crossing crack joining surface voids.

4.4.2 Sub-Surface Examination

Figure 34 demonstrates the difference between the original unworn V.C. coating and the worn coating after forging 400 billets. Figure 34a shows the regular and uniform V.C. layer outside the wear ring, while Fig. 34b shows the



a

b

FIGURE 33: S.E.M. micrographs of VC coated Electem die surface after forging 400 billets
a) scale fragments in the wear region, x 100
b) voids joined by a crack across abrasion grooves in the wear region, x 50

a

b

FIGURE 34: Vertical sections of VC coated Electem die after forging 400 billets, x 200
a) the unworn and uniform coating outside the wear ring
b) deformation and penetrating cracks in the wear region

deformation and cracking that occurred in the wear ring region.

Heavy cracking occurred after increasing the number of forgings to 600 billets. This is illustrated by the optical micro-graph of the vertical section shown in Fig. 35. The cracks formed in thesurface propagated to the sub-surface and substrate where they formed a network of branched cracks and different sizes of metal islands.

Figure 36 shows the developments of void formation in the coating sub-surface. The SEM micrograph for a region in the central plateau edge close to the wear ring shows the voids formed near the coating/substrate interface, and oriented in a longitudinal pattern within the coating.

Figure 37 shows SEM micrograph of a vertical section through the wear ring region of the same die as that illustrated in Fig. 36. Continuous formation of voids in the sub-surface at the wear region had weakened the coating layer where the voids joined by cracks which propagated and formed delamination wear platelets. The micrograph illustrates the severe cracking and the delamination that occurred in the high wear region sub-surface and coating/substrate interface after forging 600 billets.

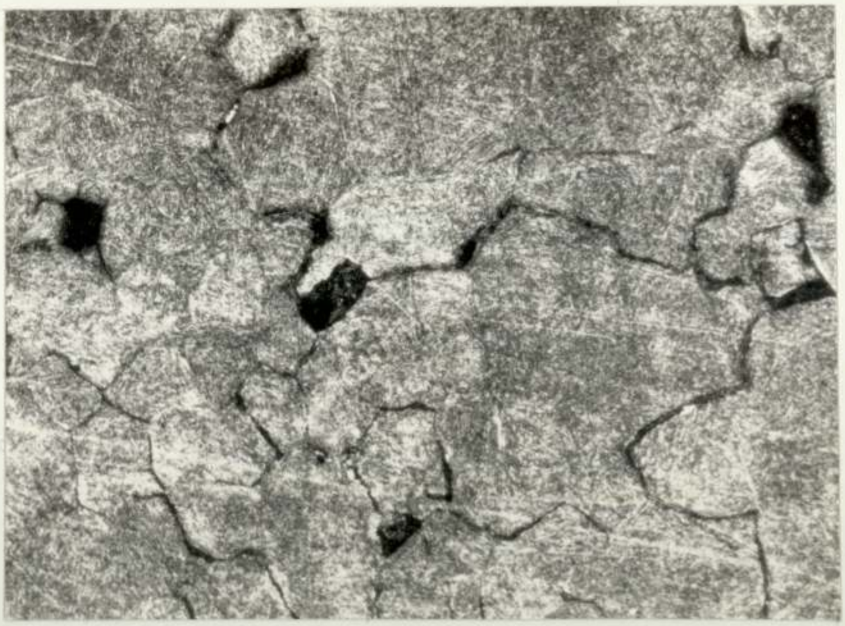


FIGURE 35: Optical micrograph of a vertical section at the central plateau/wear ring edge of a VC coated Electem die after forging 600 billets illustrating the formation and propagation of cracks in the substrate. Magnification x 100

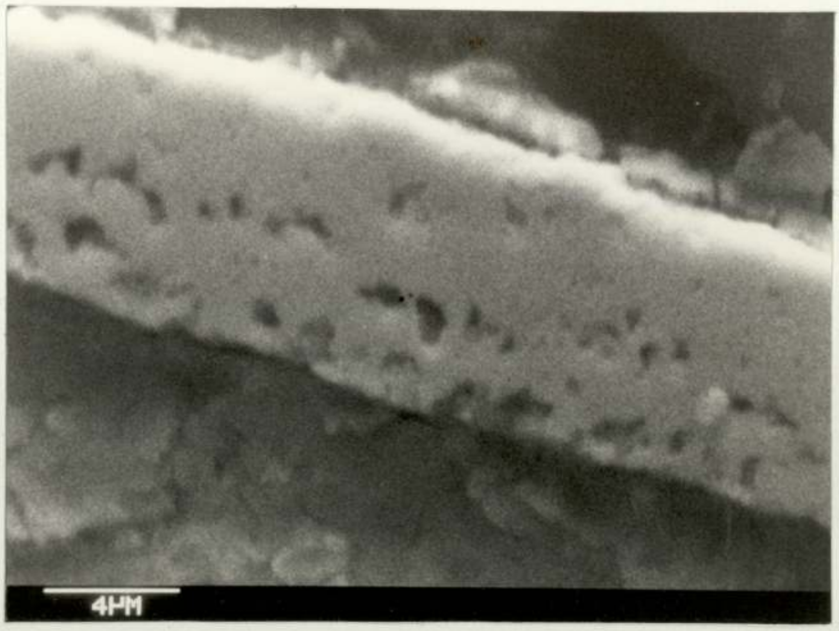


FIGURE 36: S.E.M. micrograph of a VC-coated Electem die vertical section after forging 600 billets. It illustrates the void formation within the coating near the substrate in the central plateau edge close to the wear ring region, x 5000

Interface

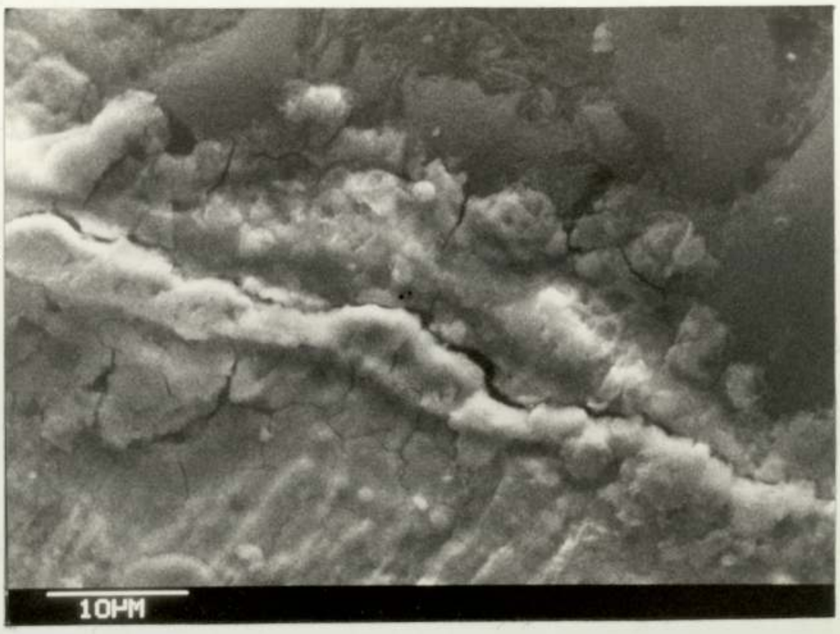


FIGURE 37: S.E.M. micrograph of a vertical section in the same die of Figure 36 inside the wear ring. It shows the propagation of sub-surface and interface cracks, and the delamination wear, x 2000

5. DISCUSSION

5.1 Wear Volume Measurement Studies

Hot forging dies are one of the major types of metal-working tools that are usually subjected to arduous service conditions leading to excessive wear. Poor die performance or complete failure is a major threat to productivity, hence looking for means to improve the producitivity through improving die performance or extension of die-life is a common issue attracting the interest of the forging department staff at every level of responsibility. Several means to enhance the wear resistance of forging dies could be followed such as the modification of die design or the choice of an alternative die steel. However, the rapid development in metal surface technology has changed the trend towards the use of wear resistant coatings to achieve the required properties and cut the high costs associated with the use of highly alloyed steels.

Coatings are required to prevent or reduce the dominant modes of failure associated with the particular application of tools. The main modes of failure experienced in hot forging dies are the cracking due to thermal and mechanical shocks, abrasion, erosion and deformation resulting from the flow of forged metal over the die surface, and the phenomenon of surface and sub-surface delamination. However, these wear mechanisms may act separately or together during forging.

The wear volume results obtained in this work showed that on comparing the performance of the uncoated Electem No. 5

dies with the uncoated H.13 dies, the latter were found to exhibit more wear resistance than the former. These results were expected since H.13 is harder than Electem No. 5 die steel and more highly alloyed. However, at this low number of forging operations, the slightly better performance of the more expensive H.13 does not justify its use as a substitute for Electem No. 5 die steel. The detailed results show that the uncoated Electem bottom dies were worn more than the top dies. This agrees with the findings of previous investigators [2,3] and follows the general features accompanying the upsetting processes where the time of contact between the hot slug and the bottom die surface is relatively longer than that with the top die [41]. In the case of H.13 dies the top dies showed more wear than the bottom dies. This might indicate that the slug's high temperature does not affect the bottom die surface, which may be acceptable when considering the good hot working property of H.13 steel, but there is no reason for the occurrence of the unexpected higher wear of the top die. The results for coated dies showed varying behaviour with regard to the wear of the top and bottom dies made from this type of steel.

The wear volume assessment of the chemical vapour deposited coating of titanium nitride was carried out on two batches of dies, each batch receiving a different post-coating heat treatment procedure as described in section 3.1.3. The results reflected the significance of post-coating heat treatment associated with the chemical vapour deposition coatings. The high temperature of the process is essential for the chemical reaction and coating to take place, but this high temperature usually softens the steel and heat treatment is required to reharden the tool. This heat treatment should be carried out under controlled conditions, since titanium nitride is very susceptible to oxidation. A slight oxidation will discolour the surface and an excessive oxidation will destroy the coating [88]. The critical effect of heat treatment procedure on wear was demonstrated by the vast difference between results of the first and second batches of chemical vapour deposited coatings. Oxidation had occurred in the first case and some change in the coating colour was observed. Despite this uncontrolled procedure, the wear volume results showed a clear improvement in coated die performance for both types of steel over the uncoated dies. This improvement was far less than that obtained by the second batch, but still some comparative relationships could be drawn. However, the quantitative wear of the first batch does not represent the actual performance of this coating. The wear behaviour of coated dies followed the same pattern as the uncoated dies, with H.13 showing the lower wear volumes at the early stages of forging. With the increase in the number of forgings the Electem dies showed remarkable improvement and at 200 forgings it performed even better than the H.13 dies. Although H.13 steel is one of the most widely used hot work tool steels, it is more likely to be recommended for use as hardened and tempered more than in the coated condition. However, it might be more successful with certain coatings than others. H.13 dies might be used when low numbers of forging operations are required. Electem No. 5 die steel, both uncoated and coated exhibited more wear of the bottom die than the top for the reason mentioned earlier. Coated H.13 dies, like the uncoated, started with a reverse condition but after more forgings the bottom dies showed a sudden change by wearing very much more than the top dies. The extent of scale formation on the die surface during forging may play some part in the fluctuating values of bottom and top die wear. Moreover, the susceptibility of titanium nitride coatings to oxidation might lead to oxide layer formation on the bottom die surface while in contact with the hot slugs. The oxide layer may delay wear occurrence for some time, then on breaking of this layer wear progressively takes place as a result of die surface exposure and formation of abrasive oxide particles.

Whilst wear of the uncoated Electem and H.13 dies started after forging a few billets, the TiN and the VC coated dies of the same steels showed almost no wear up to 200 forgings. The assessment that was carried out through wear volume evaluation methods demonstrated the effectiveness of TiN and VC as extremely wear resistant coatings for hot forging applications. However, this high wear resistance is a function of the deposition processes as well as the coating properties. Furthermore, the post-coating heat treatment procedure has already proved its critical effect on die performance.

Visual observation on the dies after forging revealed the occurrence of surface cracking associated with vanadium carbide coatings particularly on Electem No. 5 dies. This encouraged the extension of the die testing programme to include tests using up to 600 billets. However, the amount of wear was still too small to evaluate. The surface and sub-surface studies carried out on the optical microscope and the scanning electron microscope, SEM, proved successful in revealing the acting modes of failure associated with these coatings.

5.2 Surface and Sub-Surface Studies

The modes of failure and wear mechanisms involved in hot forging using Electem No. 5 die steel and H.13 steel dies in their uncoated condition were well established after comprehensive previous work [1,2,28,29,49-53]. Failure of dies most likely occurs as a result of interaction between two or more mechanisms with varying degrees. However the main modes of failure experienced in hot forging have been mentioned at the start of this discussion, and the coating systems investigated in this work have already shown their effectiveness in resisting these mechanisms on both types of steel used. This has been demonstrated by the inability to measure the small wear volumes by the Talylin trace method. It is known that die failure usually does not occur suddenly, in fact the loss of volume from die surfaces represents a late stage of wear, and earlier stages of failure can be identified more easily by microscopic examination. However results obtained using the optical microscope and the scanning electron microscope to examine the surfaces and sub-surfaces of the coated dies, exhibited remarkable improvement over the uncoated die results.

The mechanical and thermal fatigue cracking, erosion and abrasion marks observed on the uncoated dies after a few forgings were almost absent on the coated tools. The multi-cracks in the uncoated dies appear after a very low number of forging operations (2-5) [29]. After 200 forgings, cracks were observed in both the central plateau and the wear ring regions. They were very deep and sometimes develop to bring about serious localized deformation, especially after many forging operations. Both the top and bottom Electem dies showed severe cracking and gouging abrasion while the H.13 dies were better in respect of crack formation but they were heavily abraded and eroded. Sometimes abrasion follows preliminary micro-crack formation which is later polished away by abrasion. The very fine longitudinal cracks observed on the titanium nitride coatings were shallow cleavage cracks that occurred in the thin oxide layer and brought no serious damage to the coating structure. The slight oxidation of the surface is an expected phenomenon of titanium nitride coatings which are very susceptible to oxidation. The slight discolouring of the surface after tempering is an indication of this oxidation. Slight oxidation occurred on the H.13 dies with the development of a greenish colour on some parts.

By employing the scanning electron microscope it was possible to locate some signs of failure at high magnification. Spots of adhering scale were observed on the Electem dies. Although these scales were very small, they can break into smaller particles and move on the die surface with the forged metal causing abrasion scratches and grooves depending on the particle size and shape. It is possible that the thin oxide film formed on the surface can break and tear so that some particles accumulate in certain locations and are shown as spots of thick scale under the SEM. The Electem dies also showed very fine cracks at nodule boundaries after forging 100 billets. Repeated plastic deformation under impact followed by shearing forces exerted by the flowing of metal nucleate fine cracks and small voids in the wear ring region. Under further forging the voids elongate forming weak sites where stress concentrations occur and new cracks may be initiated to join former cracks and voids which result in delamination wear. No clear cracking of the central plateau surface was detected but surface defects such as inclusions and pits were observed. Fine cracks were formed on the pit's ridge while the inclusion may stay for some time during forging to form a new cracking site, or it may be separated and act as an abrasive fragment. The titanium nitride coated H.13 dies suffered void formation and crack propagation more than the Electem dies. This mechanism resulted in weakening of the coating/substrate bond, and some loose particles were observed besides the scattered platelets with their polished and smooth surface. The extent of this failure showed the lower wear resistance of H.13 dies in comparison with the high wear resistance of Electem No. 5 dies with the same coating of TiN and after the same number of forgings. This may be due to the effect of the thin oxide layer formed on the H.13 die surface during heat treatment, or may be related to the coating/substrate interface behaviour.

The superiority of TiN coated Electem No. 5 die steel may be due to the Electem's relatively high carbon content (0.55%) compared with 0.37% in H.13 tool steel. In the presence of a decarburised layer the coating looses its support and the thin brittle layer reduced the coating adhesion to the substrate. Accordingly when impact occurs during the forging stroke, the plastic deformation of the surface and the shearing stress of the forged metal create dislocations in the die surface and sub-surface. The underlying soft layer may accelerate void formation and crack initiation and propagation.

Surface examination results for the vanadium carbide coated dies revealed cleavage cracks and tears identical to those that occurred on the titanium nitride coatings but in the VC coated dies the failure appears after only 50 forgings. Heavy cracking was detected on the central plateau/wear ring edge, beyond which high polishing of the wear region was evident. These fracture cracks are most likely to occur at certain regions due to defects originally found in the surface such as inclusions or voids formed during forging. In fact the presence of some faint scratches in the polished wear region suggests that these cracks may be formed in the wear ring region during early forging operations but then are polished out due to abrasive action. The scanning electron microscope revealed micro-pitting and abrasion marks after 50 forgings on Electem dies. The tiny cracks initiated in a few VC-coated H.13 die surfaces indicated that this coating is more successful on H.13 than on No. 5 die steel. The coating minimized crack formation and abrasion but there was considerable scale formation on the central plateau, particularly at the edges. The presence of adherent scale and oxide was detected by the Talylin surface analyser which showed convex shapes above the surface horizontal profile. No failure was detected under the SEM except very limited and localized micro-pits observed by high magnification.

The information collected from the surface examination of TiN and VC coatings after forging 50, 100 and 200 billets indicated similar performance of both coatings and steels with slight differences which do not represent a strong basis for definite conclusions. There is an indication that a TiN coating might perform slightly better on Electem than on H.13 while VC coating on H.13 showed less cracking and abrasion than on Electem No. 5 die steel. However, it is quite evident that appreciable improvement in wear resistance has been achieved after using both types of coatings.

The results obtained after sub-surface examination showed more and new features of failure. Both the taper sectioning and the vertical sectioning revealed the initial stages of certain failure mechanisms. It has been suggested previously [29,92] that wear of the sub-surface and the near surface of hot forging dies occurs according to the delamination theory originally proposed for sliding wear [35].

At low magnifications it was only possible to notice the difference in the coating layer thickness in the wear ring region and outside the wear region of a TiN coated die. However, the high magnification showed the smooth structure and uniformity of the TiN layer in comparison with the micro-cracked underlying layer of TiC. Voids were nucleated within the carbide layer mainly near its interface with the TiN top layer. These voids represent the early signs of sub-surface deformation wear. However, the voids exposed by the SEM micrographs suggested that void formation during forging could concentrate in the coating sub-surface as well as in the substrate. After more deformation these voids were joined by cracks which appeared to propagate laterally along the sub-surface, and can lead to delamination after subsequent deformation. Deformation of TiN coated dies is most likely to occur beneath the coating layers, but up to 100 forgings no sign of surface or sub-surface failure was detected, apart from the small number of voids mentioned above.

The extent of failure in VC coated dies was studied by the taper section technique. This type of coating was observed to be less wear resistant than the CVD coatings. However, both of the coatings have already proved their success in delaying wear of forging dies.

The superiority of the C.V.D. coatings is evident after the number of billets forged. Taper sectioning illustrated certain degrees of sub-surface deformation, some of which was linked with surface wear and some occurred at the inner layers of coating and substrate. Slight erosion and penetration of fatigue cracks has been highlighted as well as heavy sub-surface deformation and propagation of cracks. The void concenteation under the coating had weakened the region and the carbide layer lost its support from underneath leading to cracking and heavy deformation. Some localized deformation could be initiated around sub-surface inclusions and micro-voids. Early signs of the delamination mechanism occurrence were detected where voids were initiated and joined by cracks which propagated and intersected forming polygonal metal islands and loosely attached fragments. Thermal fatigue cracks branched near the interface before forming localized deformation at the 'delta'-shaped branches. However, most of the surface and sub-surface cracking that occurred was on the Electem dies. VC coatings were more successful on H.13 dies than on Electem dies which was in agreement with the information derived from the surface examination results. In theory the formation of carbide layers deposited by the T.D. process depends largely on the carbon content in the substrate steel as the carbon needed to form the coating layer is extracted from the steel. However, good performance is not only a function of the percentage of carbon in the substrate steel, which is higher in Electem than in H.13, but it is due to the optimum thickness of the coating formed as well as to factors such as good adhesion and behaviour of the alloying elements in the substrate.

5.3 Extended Surface and Sub-Surface Studies

The results discussed up to this stage have shown the elimination or reduction of the conventional wear mechanisms associated with hot forging. However, most of the early signs of failure detected in the surface and the sub-surface of the coated dies produced a clear identification of the wear mechanism expected to dominate after further forging operations. The void nucleation, crack initiation and propagation and the formation of polygonal islands of metals have encouraged further surface and sub-surface examination after performing additional forging operations. This was carried out on the VC coated Electem, the least wear resistant coating (Table 7). The study was done after 400 and 600 forgings. The surface examination showed highly polished tracks in the wear ring region and revealed evidence of erosion and abrasion grooves across cracks joining deep voids in the same zone. No sign of failure was detected on the surface of the central plateau, but scattered scale fragments were observed adhering to the central plateau/wear ring edge. The micrographs produced for the vertical section illustrated unworn and worn regions demonstrating the extent of wear that occurred during forging. The coating surface deformation and fatigue cracks penetrated the coating causing heavy substrate cracking. Crack formation and propagation increased significantly with the increase of the number of forging operations. This delamination feature occurred in the coating as well as in the substrate after forging 600 billets.

During forging repeated plastic deformation of the die surface occurred forming sub-surface voids. This interesting

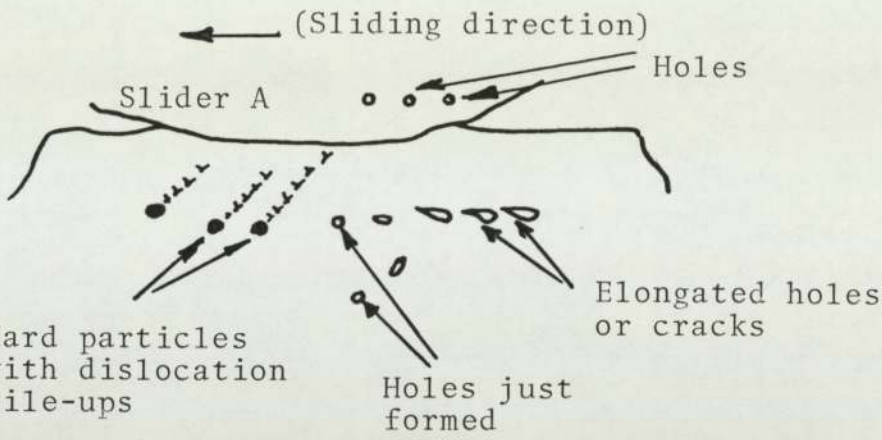
TABLE 7

WEAR PERFORMANCE OF COATED DIES AFTER FORGING 200 BILLETS

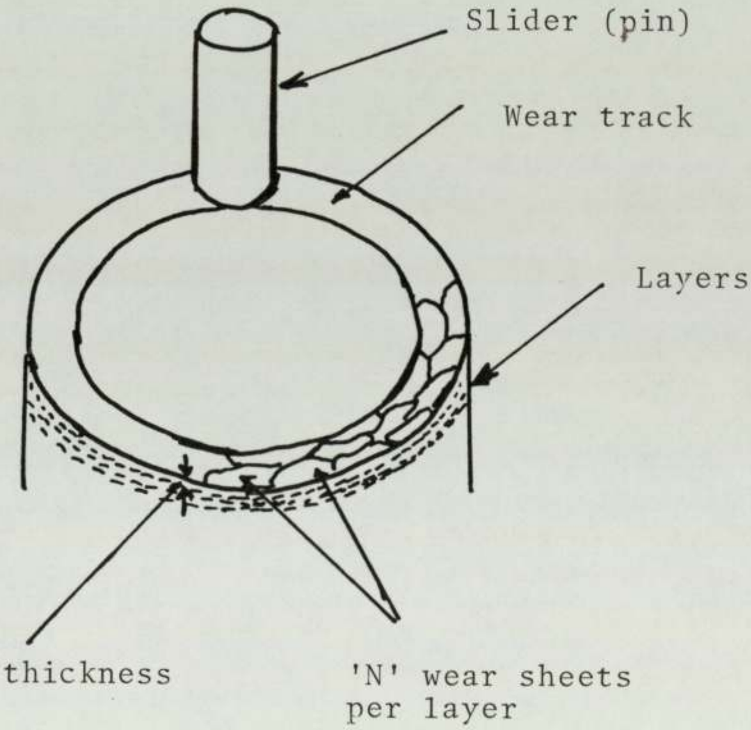
Order of Merit	Surface Treatment and Coating	Die-Steel
1	CVD - (TiN)	Electem
2	CVD - (TiN)	H.13
3	TD - (VC)	H.13
4	TD - (VC)	Electem

feature of die failure was demonstrated by the scanning electron microscope, where the weak regions in the coating and the sub-surface void sites were quite clear. Using high magnifications it was possible to expose the development of the delamination mechanism stages. The sub-surface void concentration was observed in vertical sections near the wear ring region. Across the wear ring the voids were replaced by a network of cracks propagating within the coating and parallel to the die surface. In the high wear region the cracks intersected and formed thin platelets, some of which had already delaminated leaving the cracks underneath ready for further flake formation under continuous sub-surface deformation and additional forged metal flow. The horizontal orientation of the sub-surface voids formed during early stages of plastic flow and dislocations progressed to micro-cracks which were responsible for further propagation of long cracks in the sub-surface leading to delamination of the coating.

The results attained after the surface and sub-surface studies throughout this work demonstrated the various progressive stages of failure identifying the delamination wear mechanism which was evident after forging 600 billets. The outcome agrees with the findings of previous investigators in their characterization of wear mechanisms. However, the delamination wear showed features similar to some other wear mechanisms such as erosive wear and fatigue wear. This indicated the possibility of interaction between more than one mechanism in some wear situations. Previous investigators agreed on the occurrence of fatigue cracks at the sub-surface. The maximum cyclic stress occurs in the sub-surface origin where cracks nucleate and then propagate to the surface [8]. Lancaster [10] considered the delamination theory an extension of localized fatigue failure. He pointed out that as a result of repeated contacts and sub-surface deformation, dislocations are generated beneath the surface and pile up around discontinuities such as impurity particles. The dislocations unite leading to voids, stress concentration and crack formation. The sub-surface layers weaken until fragments can be detached via adhesion or simple mechanical interlocking. This agrees with the development of void nucleation, crack formation and propagation on surface treated dies investigated in this work. However, these steps follow the original theory proposed by Suh [35] for sliding wear which suggested that the nucleated voids coalesce either by growth or shearing of the metal to form a crack parallel to the wear surface and when cracks reach critical lengths material between crack and surface shear yielding sheet-like particles (Fig. 38).



a) Void and crack formation



b) Metal removal layer by layer under circular wear track in a pin-on-disc wear test

FIGURE 38: Illustrations of delamination wear features (35)

6. CONCLUSIONS

A. Wear Volume Measurement

1. Post-coating heat treatment had a critical effect on CVD coating performance. The hardening should be carried out in a vacuum furnace, and during tempering the dies need to be isolated from air, otherwise oxidation will take place leading to discolouring of the coating and reduction of its wear resistance.

2. The uncoated H.13 dies showed less wear than the uncoated Electem dies, but the performance of the coated H.13 was better only at a low number of forgings. At higher numbers of forgings, coated Electem dies tended to be superior to the coated H.13 dies.

3. The wear performance of the top and bottom H.13 dies, uncoated and coated, was widely fluctuating and inconsistent.

4. Wear volume of uncoated and coated dies increased with the increase in number of forgings.

5. CVD coatings (TiN) and T.D. process coatings (VC) improved the wear resistance of hot forging dies significantly.

B. Surface and Sub-Surface Studies

1. CVD coatings (TiN) and T.D. process coatings (VC) reduced erosive wear, abrasive wear and the severe central plateau cracking of hot forging dies.

2. After 200 forgings the coated dies performed in the following order of merit:-

TiN-coated	Electem
TiN-coated	H.13
VC-coated	H.13
VC-coated	Electem

3. Coated die surfaces experienced fine cracking, but most of the cracks gathered around the central plateau/wear ring edge. The extension of these fine cracks in the wear ring region accelerated the abrasive wear.

4. During forging, void formation occurred in the coating sub-surface as well as around inclusions in the substrate.

5. On extended forging of 400 and 600 billets evidence of abrasive wear and slight localised erosion could be detected. The mechanism of failure which started as void nucleation and crack formation at early stages of forging, stepped up successively and led to delamination wear, which proved to be the most dominant mechanism of failure in the surface treated hot forging dies.

7. SUGGESTIONS FOR FUTURE WORK

The two coatings and the two surface treatment techniques investigated in this work have proved their potentiality in delaying wear of hot forging dies. However, the exact degree of improvement in wear resistance is yet to be found out. Since it is weel known that by increasing the number of forging operations wear of die surface will increase, there should be a certain number of forgings beyond which wear could be measured quantitatively. If a certain high number of forging operations is carried out on both uncoated and coated dies, the exact extent of die life improvement can be worked out. Forging 1000 billets on wear resistant coatings like TiN and VC probably may not bring about considerable amounts of wear, but this standard test if used may produce results comparable with the performance of previously tested coatings. Furthermore, if pairs of shaped (top) dies and flat (bottom) dies were used in the suggested standard test, results of the accelerated test could be achieved leading to better assessment.

Industrial trials are now required on dies subjected to these surface treatments so that consideration can be given to factors such as distortion of shaped tools and the use of lubricants during forging. Comparison could then be made with the experimental results reported.

Apart from hot forging dies which have been investigated in this work, probably the most interesting metal working tools that require study are the surface treated cutting tools. They have a wide scope of application where they face various aggressive service conditions. Their performance improvement may be reflected in different aspects such as feeds and cutting speeds.

As a continuation for the study of the wear resistance of surface treated metal working tools, the same coatings employed for this work could be used to investigate the performance of surface coated cutting tools.

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APPENDIX

1. MEASUREMENT OF WEAR AREA USING THE TALYLIN SURFACE ANALYSER AND THE PLANIMETER

Considering the Talylin traces obtained:-

The length scale used was x 10 'horizontal' and the graph magnification was 4 'vertical',

so, ordinate $1 \equiv 0.1$

abscissa $1 \equiv 0.0005$

$\therefore$ 1 sq. unit (on the graph) $\equiv 0.1 \times 0.0005$ sq. units $= K$

Considering the planimeter:-

Absolute vernier value $\nu = 10\ mm^2$

Length of tracer arm $L = 200$

(from table or calculated from $L = 20 \times \nu$)

The apparent area of wear trace F was found by making a full tracing of the bounded area and calculated from:-

$$F = N \times \nu \quad \text{sq. units} \qquad .....(1)$$

where N is the difference between the final and the initial vernier reading (in vernier units) and ν is the absolute vernier value.

The actual wear area Q was found from:-

$$Q = F \times K = N \times \nu \times K \qquad .....(2)$$

or $$Q = N \times V$$

where V is the relative vernier value ($V = \nu \times K$)

2. MEASUREMENT OF WEAR VOLUME

The wear volume was calculated by using the relationship:-

$$\text{Wear Volume} = \frac{\text{Wear Area}}{2} \times \text{Mean Wear Diameter} \times \pi$$

$$\text{Wear Volume} = \frac{\text{Wear Area}}{2}\left[\text{Int.dia.} + \left(\frac{\text{Ext.dia.} - \text{Int.dia}}{2}\right)\right] \times \pi$$

$$= \frac{Q}{2} \times \pi \left[\text{Int.dia.} + \left(\frac{\text{Ext.dia.} - \text{Int.dia}}{2}\right)\right] \quad .....(4)$$

Considering the scale used and the planimeter setting

$$\nu = 10 \text{ mm}^2$$

$$K = 0.1 \times 0.0005 = 5 \times 10^{-5}$$

$$\therefore \quad \nu \text{x} K = 10 \times 5 \times 10^{-5} \text{ mm}^2$$

$$= 0.5 \times 10^{-3} \text{ mm}^2$$

$$\therefore \quad \text{Wear Area } Q = 0.5 \times 10^{-3} \times N \text{ mm}^2$$

where N = final vernier reading - initial vernier reading.

Substituting for Q in equation (4)

$$\therefore \text{Wear Volume} = \frac{0.5\text{x}10^{-3}\text{x}N\text{x}\pi}{2}\left[\text{Int.dia.} + \left(\frac{\text{Ext.dia.} - \text{Int.dia.}}{2}\right)\right]$$

$$(\text{mm}^3) \quad .....(5)$$

To simplify this relationship:-

Let external wear diameter = A

internal wear diameter = B

initial vernier reading = C

final vernier reading = D

These are the variables in the wear volume formula No. (5), hence:

$$\text{Wear Volume } (mm^3) = \frac{0.5 \times 10^{-3} \times \pi}{2} (D-C)\left[B + \left(\frac{A-B}{2}\right)\right]$$

$$= \frac{0.5 \times 10^{-3} \times \pi}{2} (D-C)\left[\frac{2B+(A-B)}{2}\right]$$

$$= \frac{0.5 \times 10^{-3} \times \pi}{4} (D-C)\left[2B+A-B\right]$$

$$= \frac{0.5 \times 10^{-3} \times \pi}{4} (A+B)(D-C)$$

$\therefore$ Wear Volume = $0.39 \times 10^{-3} (A + B)(D - C)\ mm^3$

i.e. Wear Volume = $\left[0.39 \times 10^{-3}(A + B)(D - C)\right] \times 10^{-3}\ cm^3$