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Surface damage in machining titanium 6Al–2Sn–4Zr–2Mo alloy

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An experimental investigation was conducted to study the effect of cutting speed and tool wear and length on the surface damage produced during orthogonal machining of titanium 6Al–2Sn–4Zr–2Mo alloy under dry unlubricated and lubricated conditions. Cutting speeds ranging from 20 to 160 ft min^{-1} (10 to 80 cm sec^{-1}) lengths ranging from 0.000 to 0.02 in (0.051 cm) were used. Key-cut-keystone which is a highly chlorinated water-soluble oil was used as the lubricant. The results of the investigation show that the damage in the surface due to machining consists of a wide variety of defects such as chatter marks, long straight grooves, cavities, macro- and microcracks, and severe plastic deformation, etc. The severity of the damage decreases with an increase in the cutting speed and tool wearland length. The presence of lubricant in the cutting region resulted in a surface of extremely high integrity.

1. Introduction

It is well understood that in the machining of metals the quality of surface generated depends on cutting parameters such as cutting speed, feed, work and tool materials, tool geometry, and presence or absence of lubricant in the cutting region, etc. [1]. Previous investigations have shown that in the machining of metals a damaged surface region is produced that is different from the bulk of the material [2–8]. The damage in the surface region consists of plastic deformation, which is a result of the interaction between the nose region of the tool and the machined surface of the workpiece. The nose region includes the cutting edge and the land and rake face of the tool. The machined surface of the material contains residual stress, the magnitude and nature of which depends on the parameters mentioned above. The geometric defects in the surface consist of grooves parallel to the direction of relative tool motion, fine scale chatter marks, cavities, surface roughness and other stress risers. The presence of a lubricant in the cutting region usually results in a considerable reduction in the surface and subsurface damage [9, 10].

The failure of machined parts in service is invariably due to creep, fatigue and stress corrosion. Such failures start as a small crack at the surface of a component which propagates to the core and leads to sudden failure. These failures depend very sensitively on the quality of the surface [10–13]. Therefore, it is important that the impact of machining on the condition of the surface generated be understood so that remedial manufacturing procedures can be introduced to reduce such failures.

The object of the present investigation was to determine the effect of cutting speed and tool wearland length on the nature of the surface generated for titanium 6242 alloy when machined orthogonally under dry unlubricated and lubricated conditions using optical and scanning electron microscopy.

2. Experimental work

2.1. Cutting conditions

In the traditional machining of metals there is a

TABLE I Summary of test conditions*

Rake angle (deg)	Combinations tested for the following cutting speeds ($ft\,min^{-1}$) S.I. values given in parentheses ($cm\,sec^{-1}$)				Tool wearland (in) S.I. values in parentheses (cm)
	20(10)	40(20)	80(40)	160(80)	
10	●	●	●	●	0.000
	●	●	●	●	0.005(0.013)
	●	●	●	●	0.010(0.025)
	●	●	●	●	0.020(0.050)

*●, combinations tested; material, 6242 titanium alloy; feed, 0.010 in rev^{-1} (0.025 cm rev^{-1}); width of cut, 0.125 in (0.32 cm); tool material, tungsten carbide grade C3; clearance angle, 5°; heat treatment, double annealed to a hardness of 39 HRC; lubricant, oil.

very wide variety in the type of operations employed and selection of the most appropriate one for research investigation is difficult. It was therefore decided to select a process which was perhaps typical of all chip removal processes, namely orthogonal machining. In orthogonal machining, the cutting edge of the tool is perpendicular to the direction of relative work tool motion. From an industrial viewpoint it could be argued that a process such as end milling or shaping has greater utility than orthogonal machining. However, it was believed that in a complex process such as machining the number of independent variables should be kept as small as possible and the simpler orthogonal process was preferred. In orthogonal machining, factors such as tool forces, the type of chip produced, and the temperatures generated can be determined readily. Moreover, conditions of plane strain deformation can be maintained. In other types of machining (end milling, turning, etc.) such determinations are difficult if not impossible to carry out.

All cutting tests were carried out on a Cincinnati 17 in hydrashift lathe equipped with a tachometer generator and a variable speed adjuster. A wide range of spindle speeds from 5 to 1500 rev min^{-1} and feeds in the range from 0.001 to 0.060 in rev^{-1} (0.03 to 0.15 cm rev^{-1}) can be obtained. The tests were conducted for both lubricated and unlubricated conditions. A highly chlorinated water-soluble oil (key-cut-keystone) was used as the cutting fluid. A constant feed rate of 0.010 in rev^{-1} (0.025 cm rev^{-1}) was used. This feed rate gave a ratio of the width to the depth of cut of 12:1, which was sufficient to ensure plane strain deformation.

Table I shows a summary of the cutting conditions used during the investigation.

2.2. Design of the workpiece

A workpiece of titanium 6242 alloy was used in this investigation. Table II shows the chemical composition of the alloy. This material was selected because it was expected to suffer surface and subsurface damage and a deterioration in surface sensitive mechanical properties as a consequence of the impact of the machining process. In addition, 6242 titanium alloy is industrially important, possessing a high strength and a high strength-to-weight ratio. At present it is used extensively for critical weight sensitive components.

The work material of titanium 6242 alloy, which was received in the form of solid bar, was cut into small discs and machined into disc-shaped specimens of 3 in diameter and 0.063 in width with a central hub on one side and a shallow recess on the opposite side. The work-piece geometry is shown in Fig. 1. The work material was double annealed in a nitrogen atmosphere. The discs were heated to 1650° F, held for 1 h and air cooled to room temperature, then heated again to 1100° F, held for 8 h and air cooled to room temperature.

TABLE II Chemical composition of titanium 6242 alloy

Element	wt %	Element	wt %
Aluminium	5.5–6.5	Nitrogen	0.5 max
Tin	1.8–2.2	Oxygen	0.12 max
Zirconium	3.6–4.4	Hydrogen	0.125 max
Molybdenum	1.8–2.2	Any other element	0.10 max
Iron	0.25 max	Total other element	0.30 max
Carbon	0.05 max	Titanium	Balance

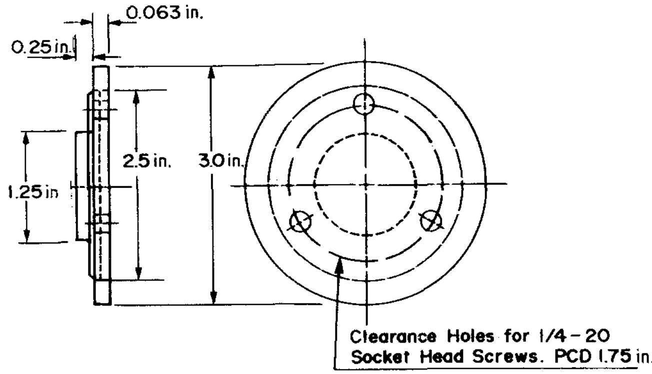

Figure 1 The workpiece geometry.

2.3. Cutting tool

The tool material as recommended by Metcut Research Associated [14] and the American Society for Metals for machining 6242 titanium alloy was tungsten carbide grade C3 (Kennametal K8). High strength and rigidity combined with dimensional stability and high resistance to impact, corrosion, wear and softening at high temperatures are the characteristics which make Kennametal K8 a unique tool material for machining maraging steels.

Tungsten carbide inserts were brazed to preformed steel shanks using silvalloy polymetal 5031 brazing alloy. The tool tips were ground to a rake angle of 10° and a clearance angle of 5°. Artificial wear lands of 0.005, 0.01 and 0.02 in (0.013, 0.025 and 0.050 cm) were ground on the flank of the tools. Tools with zero wearland were also used.

A special tool fixture was used to hold the cutting tools during grinding in order to have all tools with the same rake and clearance angles. A Rockwell Delta surface grinder was used for preparing the tools. The tool tips were first rough ground with a 60 grit silicon carbide wheel at a downward feed of 0.0025 in (0.0064 cm) per pass and a cross-feed of 0.010 in (0.025 cm) per pass. A 120 grit silicon carbide grinding wheel was used to achieve a fine surface on the rake and flank faces at a downward feed of 0.005 in (0.013 cm) per pass and a cross-feed of 0.010 in (0.025 cm) per pass. A two-phase air and soluble oil lubricant was used in grinding the tool faces.

3. Experimental procedure

The workpieces were bolted to a specially made mandrel which was held in the chuck of the lathe. The tool was held in a dynamometer such that the cutting edge of the tool was parallel to the axis of the lathe. The direction of the tool motion (feed) was perpendicular to the axis of rotation of the workpiece. Fig. 2 shows the workpiece and the tool during the cutting action. The cutting was continued until the steady state was reached. The cutting action was then suddenly stopped, leaving the chip attached to the workpiece. Small pieces measuring approximately 1 in (2.5 cm) long along the surface of the workpiece and $\frac{1}{8}$ in (0.3 cm) along the direction perpendicular to the machined surface were cut from the machine workpiece. The surfaces were prepared for examination under the optical and scanning electron microscopes.

4. Results and discussion

Figs. 3 and 4 show optical micrographs of the surfaces generated when machining the work material with a sharp tool having no wearland under dry unlubricated conditions at cutting speeds of 40 and 160 ft min^{-1} (20 to 180 cm sec^{-1}), respectively. Figs. 5 and 6 show the surfaces generated when the work material

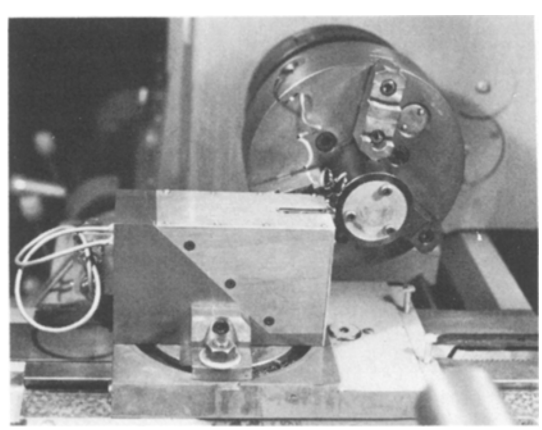

Figure 2 Cutting action.

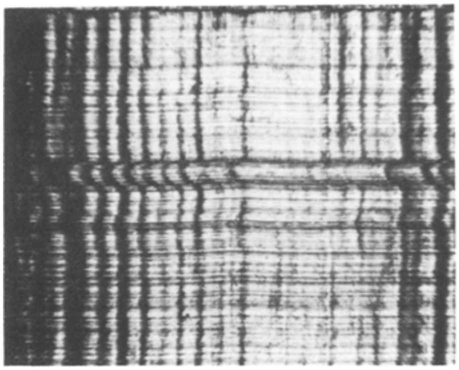

Figure 3 Optical macrograph of machined surface of titanium alloy. Dry cutting. Cutting speed 40 ft min^{-1} (20 cm sec^{-1}), wearland length 0.000 in ×20.

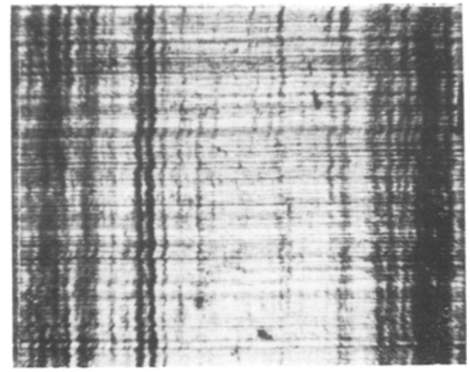

Figure 5 Optical macrograph of machined surface of titanium alloy. Dry cutting. Cutting speed 40 ft min^{-1} (20 cm sec^{-1}), wearland length 0.010 in (0.025 cm) ×20.

was machined at cutting speeds of 40 and 160 ft min^{-1}, respectively, with a tool having an artifically ground wearland of 0.01 in (0.025 cm) length under dry unlubricated conditions. It can be seen that the surfaces contain chatter marks perpendicular to the direction of relative work tool motion, long straight grooves parallel to the direction of relative work tool motion, and regions of coarse and fine scale damage. The intensity of the chatter marks is high at low cutting speed (Fig. 3), and decreases as the cutting speed of tool wearland is increased (Fig. 6).

Several cutting tests were conducted in the presence of the lubricant in the cutting region. The presence of lubricant has resulted in a machined surface of practically no chatter marks. Fig. 7 shows such a surface produced when machining the work material at a cutting speed of 40 ft min^{-1} (20 cm sec^{-1}) with a sharp tool having no wearland. Comparison of this figure with Fig. 3 reveals that the former is far superior in quality. The fine scale grooves parallel to the direction of relative work tool motion appear to be due to the profile of the cutting edge of the tool.

The examination of machined surfaces with an optical microscope does not enable the study to be as detailed as is possible with the use of a scanning electron microscope because of high resolution and large depth of field obtainable. The machined surfaces were, therefore, examined under a scanning electron microscope over a wide range of magnification to determine the details of variation in the structure of the surface produced by changes in the cutting speed and tool wearland length.

Figs. 8 and 9 show a selection of surfaces generated when machining with a sharp cutting tool having no wearland at cutting speeds of 40 and 160 ft min^{-1}, respectively, under

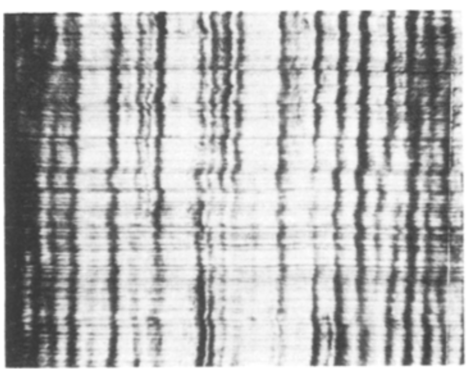

Figure 4 Optical macrograph of machined surface of titanium alloy. Dry cutting. Cutting speed 160 ft min^{-1} (80 cm sec^{-1}), wearland length 0.000 in ×20.

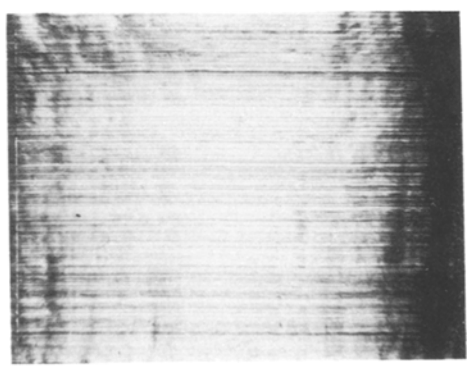

Figure 6 Optical macrograph of machined surface of titanium alloy. Dry cutting. Cutting speed 160 ft min^{-1} (80 cm sec^{-1}), wearland length 0.010 in (0.025 cm) ×20.

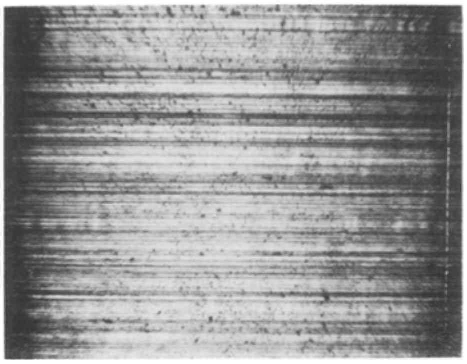

Figure 7 Optical macrograph of machined surface of titanium alloy. Dry cutting. Cutting speed 40 ft min^{-1} (20 cm sec^{-1}), wearland length 0.000 in ×20.

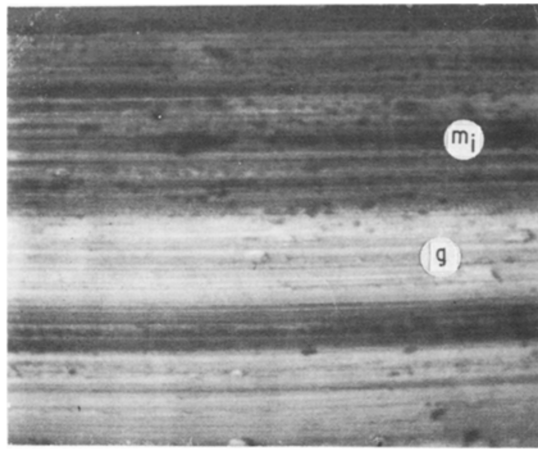

Figure 9 Scanning electron micrograph of machined surface of titanium alloy. Dry cutting. Cutting speed 160 ft min^{-1} (80 cm sec^{-1}), wearland length 0.000 in ×246.

unlubricated conditions. It can be seen that surfaces consist of a wide variety of damage including long, straight grooves (g) parallel to the direction of relative work tool motion, cavities (c) spaced widely in isolated areas, and fine scale damage in between cavities. Straight grooves left in the surfaces due to the formation of microchips (m_i) may also be seen in the micrographs. An increase in the cutting speed results in a decrease in the surface damage. The formation of cavities at low cutting speed is due to the fragmentation of the chip at the surface. At high cutting speed the surface appears to be smooth, however, certain areas of the surface are dimpled (Fig. 9) indicating the evidence of severe plastic deformation.

Figs. 10a and b show the surface generated at a cutting speed of 40 ft min^{-1} (20 cm sec^{-1}) with a sharp tool having a wearland 0.01 in (0.025 cm) long under unlubricated conditions. Comparison of Figs. 8 and 10a reveals that an increase in the tool wearland length results in the formation of smooth surfaces with the grooves parallel to the direction of relative work tool motion discontinuous and poorly defined. The micrograph shown in Fig. 10a was obtained at a magnification in excess of three times that shown in Fig. 8. It is evident that the cavities still exist in the surface produced with a tool of large wearland, but with a lesser degree of intensity. Fig. 10b is the enlargement of the cavity enclosed by the dotted rectangle in Fig. 10a. Grooves parallel to the direction of relative work tool motion may still be seen. But they are very shallow, discontinuous and poorly defined. The cavity is formed due to fracture of the chip at the workpiece surface. It can be seen that the material has been removed from below the surface level causing severe plastic deformation (p) and fracture. The dimpled (d) area in the cavity indicates that the material was essentially pulled during the fracture of the chip.

Figs. 11a and b show the scanning electron micrographs of the surface generated when machining the workpiece at a cutting speed of 160 ft min^{-1} (80 cm sec^{-1}) with a sharp tool having an artificially ground wearland of 0.010 in (0.025 cm) in length, under dry unlubricated conditions. Comparision of these micrographs with those shown in Fig. 10 reveals that

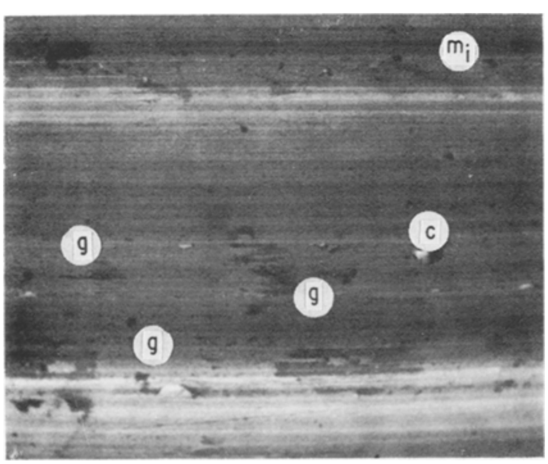

Figure 8 Scanning electron micrograph of machined surface of titanium alloy. Dry cutting. Cutting speed 40 ft min^{-1} (20 cm sec^{-1}), wearland length 0.000 in ×246.

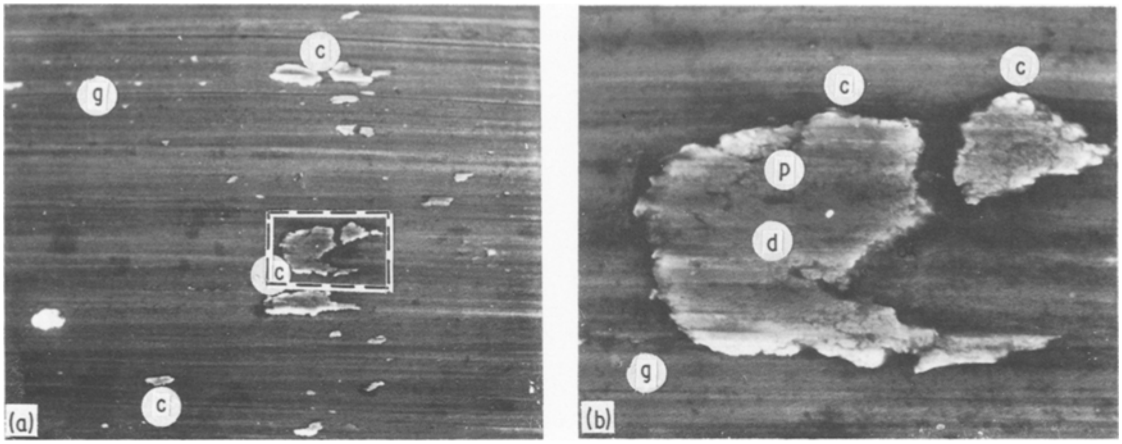

Figure 10 Scanning electron micrographs of machined surface of titanium alloy. Dry cutting. Cutting speed 40 ft min^{-1} (20 cm sec^{-1}), wearland length 0.010 in (0.025 cm) (a) ×820; (b) ×2460.

when the work material is machined with a tool of constant wearland length, the damage in the surface decreases with an increase in the cutting speed. While some cavities may be seen in some isolated areas, the overall surface is very smooth and free of deep grooves and other stress risers that tends to reduce the life of a machined component.

Cutting tests were conducted using a lubricant in the cutting region over the entire range of the conditions shown in Table I. Fig. 12 shows the scanning electron micrograph of a surface produced when machining the workpiece with a sharp tool having a wearland of 0.01 in (0.025 cm) in length at a cutting speed of 40 ft min^{-1} (20 cm sec^{-1}). The surfaces produced using the lubricant are generally superior to the corresponding surfaces generated under dry unlubricated cutting. Microchip grooves, cavities, and regions of fine scale surface damage may still be seen.

Machining metals consists of the removal of layers of the material from the workpiece in the form of chips by the action of the cutting tool. The chips are formed as the material is sheared in the primary deformation zone. The type of chip produced has a controlling influence on the type of machined surface produced.

At low cutting speed the cutting temperature is low and the tool forces are high. The chip formation process is discontinuous or partially discontinuous. The surface produced under this condition consists of cavities and coarse scale damage in the surface. Several mechanisms of

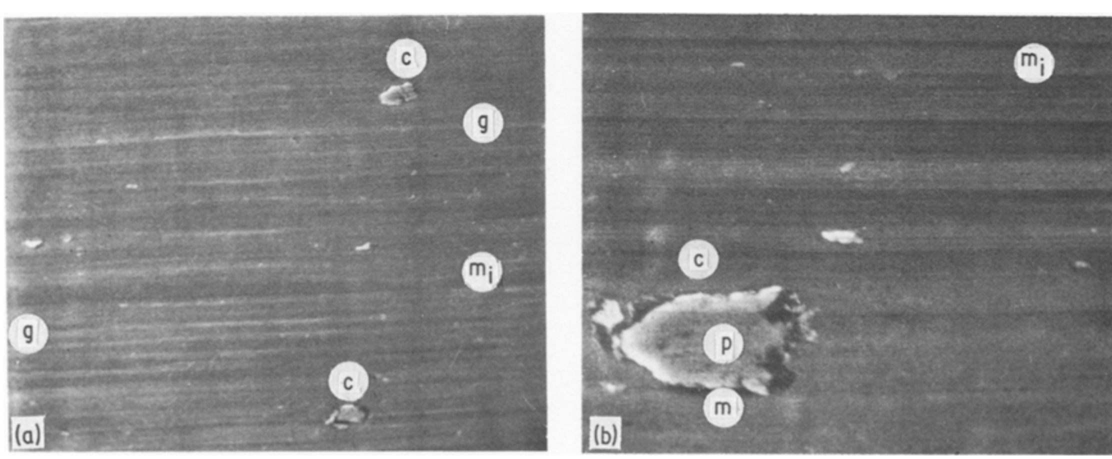

Figure 11 Scanning electron micrographs of machined surface of titanium alloy. Dry cutting. Cutting speed 160 ft min^{-1} (80 cm sec^{-1}), wearland length 0.010 in (0.025 cm) (a) ×820; (b) ×2460.

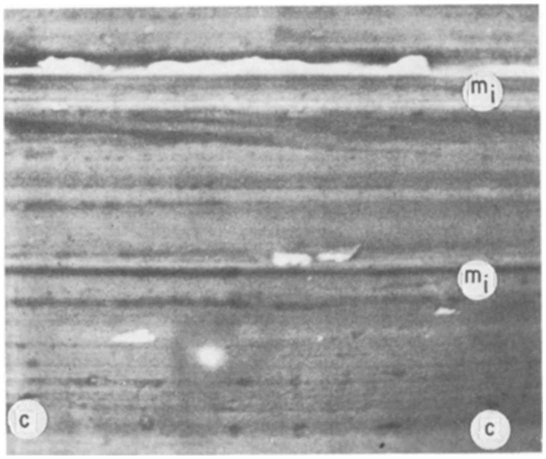

Figure 12 Scanning electron micrograph of machined surface of titanium alloy. Lubricated cutting. Cutting speed $40\,ft\,min^{-1}$ ($20\,cm\,sec^{-1}$), wearland length 0.010 in (0.025 cm) $\times 820$.

cavity and crack formation have been presented in earlier papers [15, 16]. The formation of discontinuous chips is responsible for the fluctuations in the forces on the cutting tool. It is suggested that the fluctuating tool forces yield a surface with chatter marks perpendicular to the direction of relative work tool motion (Fig. 3).

As the cutting speed is increased the temperature in the primary deformation zone increases and the formation of the chips changes from discontinuous and partially discontinuous to continuous. The surfaces produced under these conditions are smooth with only fine scale surface damage in isolated areas (Figs. 9 and 11). The continuous chip formation results in a reduction in the fluctuation in tool forces which in turn yields surfaces free of chatter marks perpendicular to the direction of relative work tool motion (Fig. 6).

An increase in the tool wearland results in an increase in the area of contact between freshly machined workpiece surface and the flank face of the tool. The friction force between the flank of the tool and workpiece surfaces increases resulting in an increase in the temperature on the flank face. The increase in temperature produces partial softening of the work material which results in the production of smooth surfaces with only fine scale damage (Fig. 11). In certain instances when the condition of sliding friction between the flank face of the tool and the workpiece surface changes to sticking friction, metal pieces are pulled from the workpiece surface leaving severely deformed cavities (Fig. 10). These metal pieces are sometimes deposited in other locations on the workpiece surface in the form of debris.

The presence of lubricant in the cutting region produced a condition of sliding friction on the rake and flank faces of the tool. The chip produced under the cutting conditions shown in Table I in the presence of lubricant were smooth and continuous. The surfaces produced were in general very smooth with a substantial decrease in the cavities and grooves parallel to the direction of relative work tool motion. The lubricant essentially washes away any metal debris formed in the cutting process.

5. Conclusions

The following conclusions are drawn based on the results of the investigation of the effect of cutting speed and tool wearland length on the surface produced in machining titanium 6Al–2Sn–4Zr–2Mo alloy orthogonally under dry unlubricated and lubricated conditions.

1. In the machining of metal under the cutting conditions used in the investigation a wide variety of surface defects were produced. The defects consist of chatter marks perpendicular to the direction of relative work tool motion, long, straight grooves parallel to the direction relative work tool motion, cracks and cavities in the surface, macro and microcracks and plastic deformation.

2. The damage in the surface is high at low cutting speeds and decreases as the cutting speed is increased.

3. An increase in the tool wearland length results in a decrease in the coarse and fine scale damage.

4. The presence of lubricant reduces the amount of surface damage in the workpiece at both low and high cutting speed in the presence or absence of the wearland in the cutting tool.

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