JOURNAL OF MATERIALS SCIENCE 21 (1986) 155–160

Dependence of fatigue life on the surface integrity in the machining of 2024–T351 aluminium alloy – unlubricated conditions

S. JEELANI, M. MUSIAL
School of Engineering and Architecture, Tuskegee Institute, Tuskegee, Alabama 36088, USA

An experimental investigation was conducted to study the dependence of fatigue life on the surface integrity in the machining of 2024–T351 aluminium alloy under dry unlubricated conditions. Cutting speeds ranging from 100 to 250 ft min^{-1} (30.48 to 76.2 m min^{-1}) and tool rake angles ranging from 10 to 30° were used. The results of the investigation show that the damage in the surface due to machining consists of a wide variety of defects such as cracks, long straight grooves, cavities, microcracks and macrocracks, and severe plastic deformation, etc. The severity of the damage decreases with an increase in the cutting speed and tool rake angle. An increase in the cutting speed or tool rake angle resulted in an increase in the fatigue life of the specimen.

1. Introduction

Many technological advances have taken place in recent years in the development of new and improved production techniques, but the metal machining process continues to play an important role in the manufacture of most metal items used today. Machining consists of the removal of layers of the material from the workpiece in the form of chips by the action of a wedge-shaped cutting tool. The chips are formed as the material is sheared in the deformation zone [1]. The type of chip produced has a controlling influence on the condition of the surface generated. The discontinuous formation of a chip, for example, results in a machined surface which contains severely deformed areas, microcracks and macrocracks, cavities, etc. Continuous chip formation, on the other hand, produces a smooth surface.

The type of surface generated in machining depends on several variables; the work and tool materials, tool geometry, cutting speed, feed, the presence or absence of a lubricant in the cutting region, etc. 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 depend on the parameters mentioned above. The geometric defects in the surface consist of grooves parallel to the direction of relative tool motion, microcracks and macrocracks perpendicular to the direction of the 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 [11–13]. 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 service failures.

The objective of the present investigation was to determine the effect of cutting speed and tool rake angle on the nature of the surface generated for 2024–T351 aluminium alloy when machined orthogonally under dry unlubricated conditions, using optical and scanning electron microscopy and to show the dependence of fatigue life on the surface integrity in machining.

2. Experimental work

2.1. Workpiece and tool

In this investigation aluminium alloy 2024–T351 was used as the work material. The chemical composition and mechanical properties of this alloy are given elsewhere [14]. This material was selected because of its wide application in industry. It has high strength and good strength-to-weight ratio, and is therefore extensively used in weight-sensitive situations, especially in modern aircraft and ship components, and is widely accepted as an engineering structural material in industry.

The design of the workpiece is shown in Fig. 1. The ring-shape design was preferred over the usual disc or tube-type workpiece because it is convenient to test a

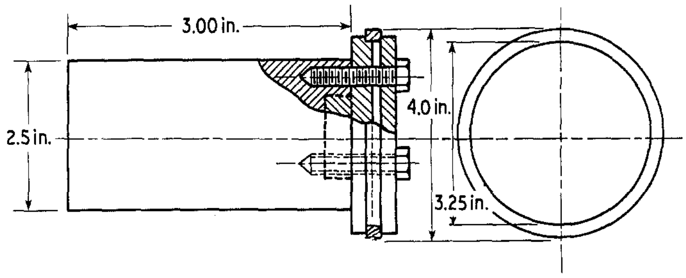


Figure 1 Workpiece and mandrel.

ring or its segment in fatigue. The rings were cut from an extruded seamless tube. The workpiece was held in a mandrel, as shown in Fig. 1, while machining.

High-speed steel containing cobalt has been used as a tool material. The addition of cobalt provides greater hardness and wear resistance, however, it results in lower toughness. The selection of cutting tools is based on characteristics such as high strength and rigidity combined with dimensional stability [15].

2.2. Cutting conditions

In the traditional machining of metals there is a very wide variety in the types of operations employed and selection of the most appropriate one for research investigations 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 operation (end milling, turning, etc.) such determinations are difficult if not impossible to carry out. The orthogonal cutting process is shown in Fig. 2.

The tests were conducted over a wide range of cutting speed and tool rake angle under unlubricated conditions. A constant feed rate of 0.010 in. (0.0254 cm) per revolution was used throughout the work. A summary of the cutting conditions is given in Table I.

2.3. Test procedures

Two sets of specimens were used in this investigation. One set of approximately 50 specimens was used to generate the $S-N$ diagram, while the other set of approximately 200 specimens was used for cutting and fatigue tests.

All the surfaces of the specimens used to generate the $S-N$ diagram were polished to remove tool marks, scratches, and other stress risers. A direct stress tension–compression fatigue machine DS-600 HLM, manufactured by Fatigue Dynamics Inc. (Dearborn, Michigan, USA) was used to conduct all the tests. The machine is equipped with an automatic hydraulic load maintainer which adjusts the preload continuously to a present value without affecting the cyclical load. The cyclical load can be adjusted manually up to ± 600 lb (~ 272 kg). The test frequency of the machine ranges from 600 to 2200 cycles per minute. A load cell is provided to read the direct tensile or compressive load on the specimen. The load cell is connected to a strain indicator which is calibrated to read the maximum stress in the specimen directly. Special specimen grips were designed to hold the ring shaped specimen while being tested in fatigue. All the fatigue tests were conducted in tension only, using a stress ratio of $R = 0$.

The specimens used for the cutting tests were polished on the side and inner surfaces. The dimensions of the specimens were measured before and after

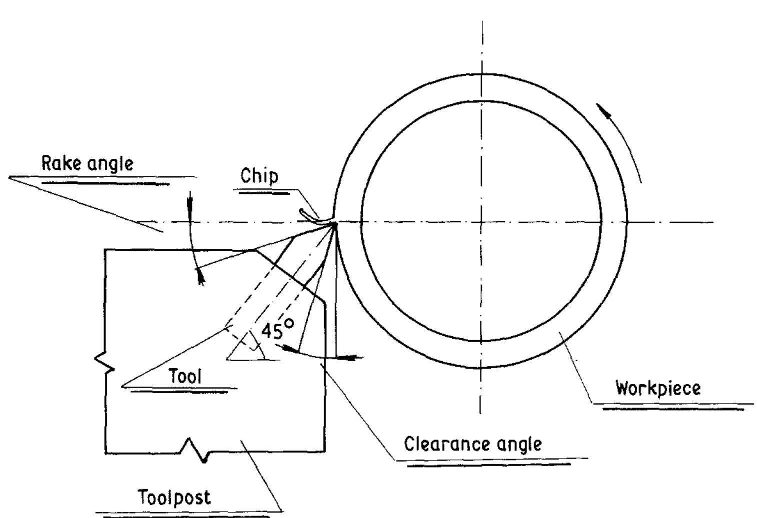


Figure 2 Cutting action.

TABLE I Summary of cutting conditions

Cutting speed (ft min^{-1})	100, 150, 200, 250
Feed (in./rev)	0.010
Rake angle (deg.)	10, 15, 20, 25, 30
Clearance angle (deg.)	5
Width of cut (in.)	0.250
Tool-wear land (in.)	0.000
Lubricant	None
Tool material	High speed steel

each test. The cutting tests were performed on a lathe equipped with a quick stop device. Approximately ten specimens were tested at each cutting speed and rake angle shown in Table I. Before testing the machined rings in fatigue, the machined surfaces were examined using optical and scanning electron microscopes. The roughness of the surfaces was also measured. To study the dependence of surface integrity on the fatigue life of the specimens, all the machined rings were fatgued at the same maximum stress of 60 000 psi ($\sim$413 N min^{-2}), and a stress ratio of $R = 0$.

3. Results and discussion

A considerable amount of data was generated on the surface damage in aluminium 2024–T351 alloy that was machined orthogonally over a wide range of cutting conditions. In the following, only selected data representative of the results in general are presented.

Figs. 3 to 6 show scanning electron micrographs of selected surfaces generated when machining the material with a sharp tool having a rake angle of 10° at cutting speeds ranging from 100 to 250 ft min^{-1} (30.48 to 76.2 m min^{-1}) under dry, unlubricated conditions.

It can be seen that the 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 (mi) 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 smooth; however, fine scale damage in isolated areas can be seen at higher magnification. From Fig. 3 it can be seen that in addition to grooves and cavities, the surface consists of fine scale cracks (t) perpendicular to the direction of relative work-tool motion. At higher magnification it can be seen that in several locations the surface has been plastically deformed (Pd). Evidence of fibrous fracture of the material (f) may also be seen in several places. Fibrous fracture of the material in the surface region is due to the fragmentation of the chip at the root.

Figs. 4 and 5 show that as the cutting speed is increased the cavities, grooves and other forms of surface damage decrease in size and intensity. Fine grooves left in the surface due to the formation of microchips (mi) are discontinuous and poorly defined. Fig. 6, which shows the surface generated at the highest cutting speed used in this investigation, reveals that the surface is very smooth with small and shallow grooves and cavities that exist only in isolated areas. At higher magnification it can be seen that tiny fragments of the tool material or the built-up edge (b) are deposited at the surface.

Figs. 6 and 7 show the effect of the increase in the tool rake angle on the surface produced in machining. It can be seen that an increase in the rake angle produces a decrease in the surface damage. The surface seems to be dimpled with some fine scale cracks in isolated areas. Fig. 7c shows an enlarged view of a microcrack (cr). It can be seen that the material is essentially torn off, leaving signs of plastic deformation and fibrous fracture during the formation of the crack.

Machining metal consists of the removal of layers of the material from the workpiece in the form of chips

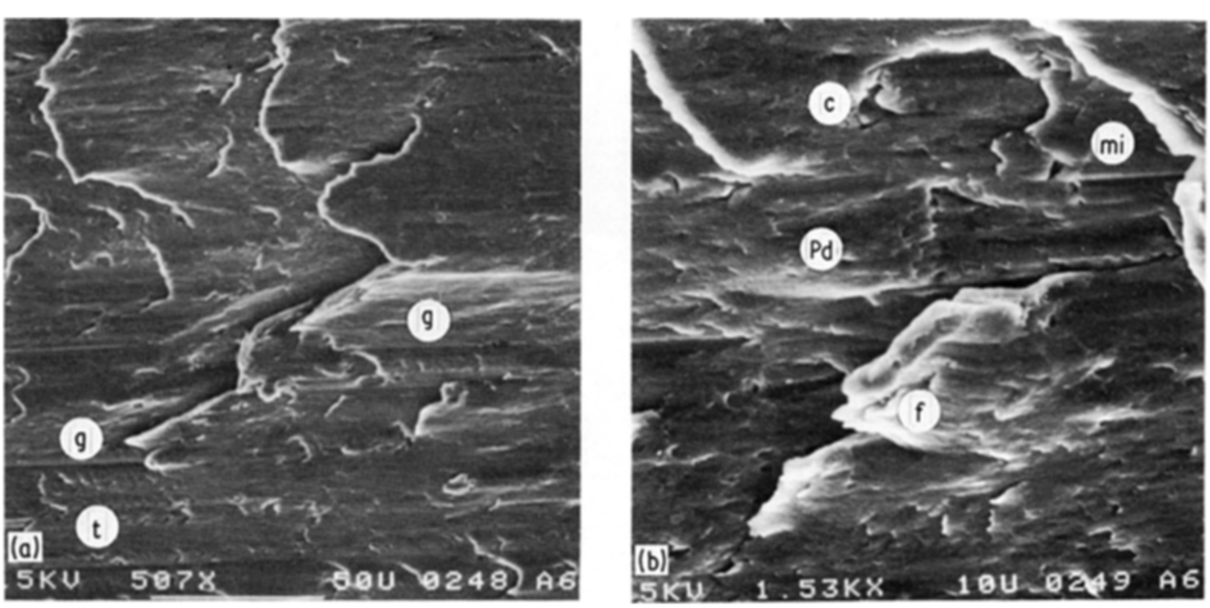


Figure 3 Scanning electron micrographs of the surface generated at cutting speed of 100 ft min^{-1} (30.48 m min^{-1}) with a tool having a rake angle of 10°, dry cutting. (a) × 400, (b) × 1200.

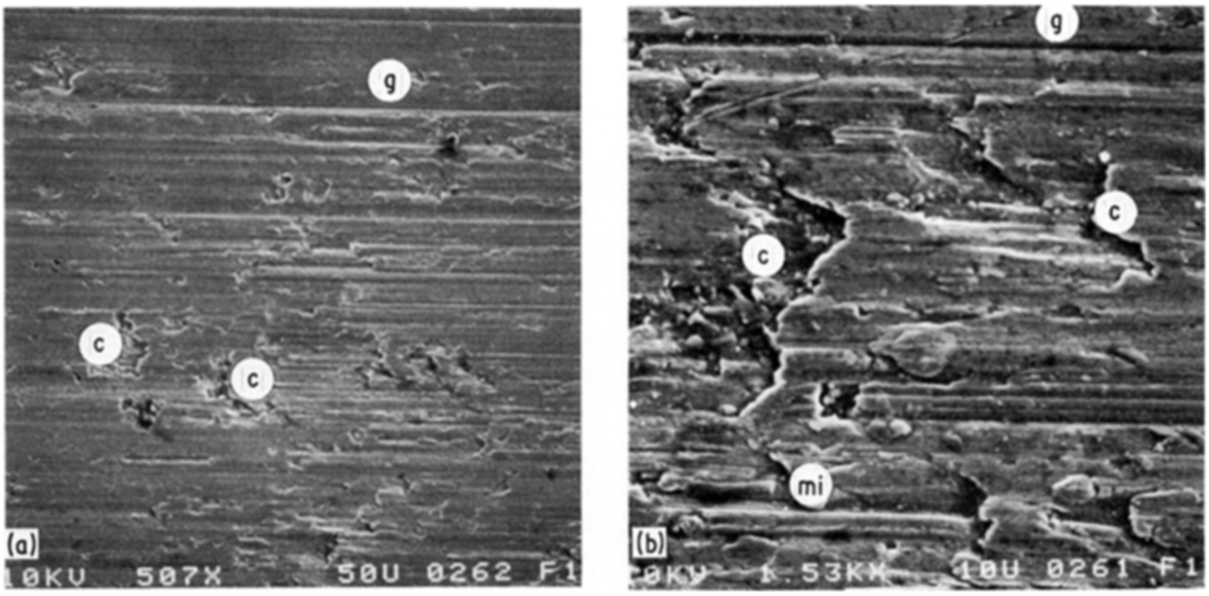


Figure 4 Scanning electron micrographs of the surface generated at cutting speed of 150 ft min^{-1} (45.72 m min^{-1}) with a tool having a rake angle of 10°, dry cutting. (a) × 400, (b) × 1200.

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 cavity and crack formation have been presented in earlier papers [16, 17]. 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 produce 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. 5 and 6). The continuous chip formation results in a reduction in the fluctuation in tool forces which in turn yields surfaces free of microcracks perpendicular to the direction of relative work-tool motion, cavities, and grooves (Fig. 6).

An increase in the tool rake angle results in a decrease in the cutting and thrust components of tool forces, which in turn reduces the damage in the surface region (Fig. 7).

Figure 8 shows the effect of changes in the cutting speed and tool rake angle on the fatigue life of 2024–T351 aluminium alloy [18]. The fatigue life of polished (virgin) specimens is also shown by a dashed line in this figure. It can be seen that a substantial

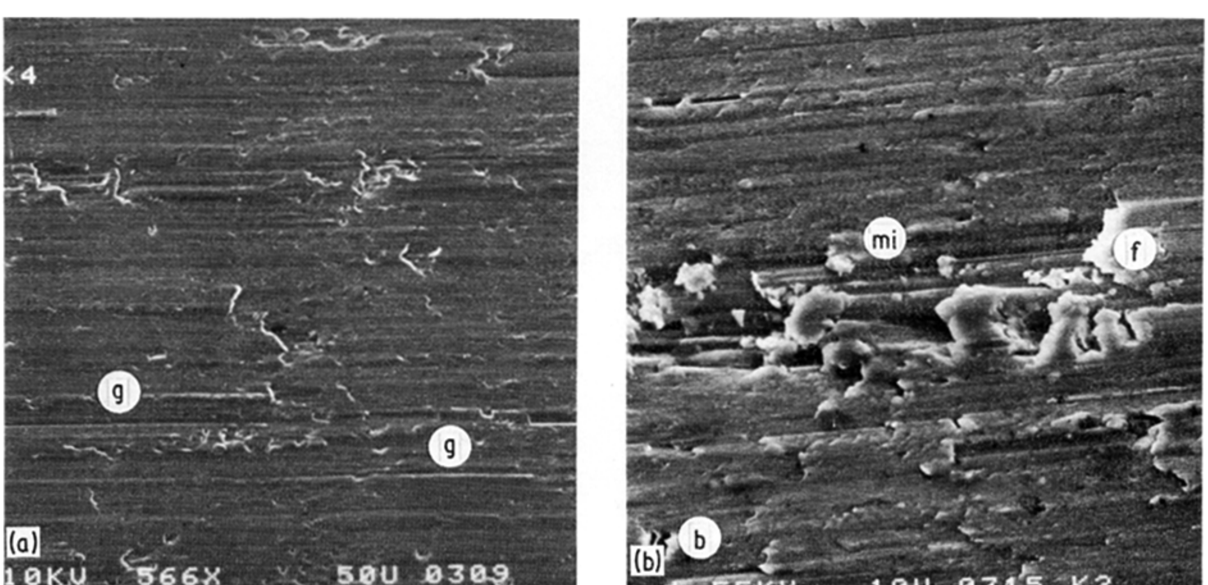


Figure 5 Scanning electron micrographs of the surfaces generated at cutting speed of 200 ft min^{-1} (60.96 m min^{-1}) with a tool having a rake angle of 10°, dry cutting. (a) × 400, (b) × 1200.

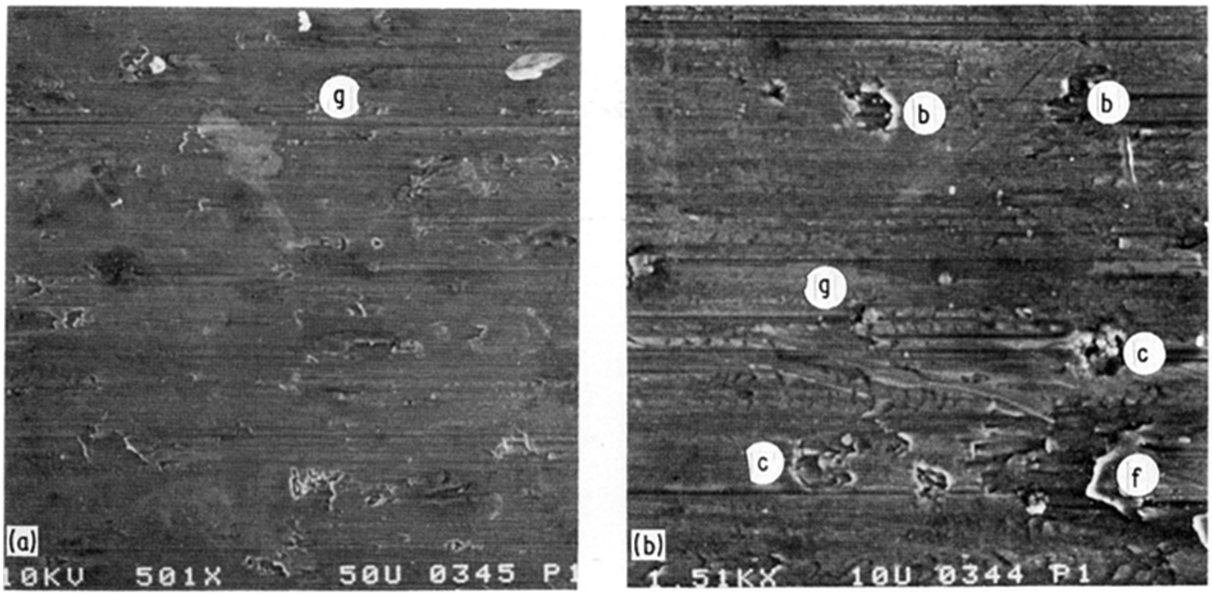
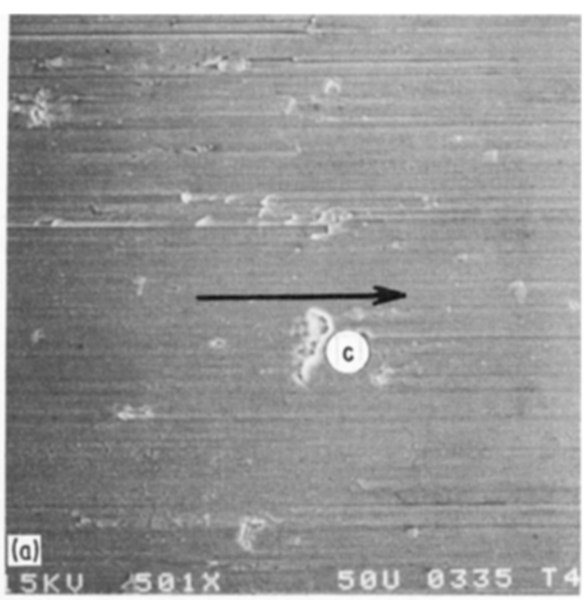


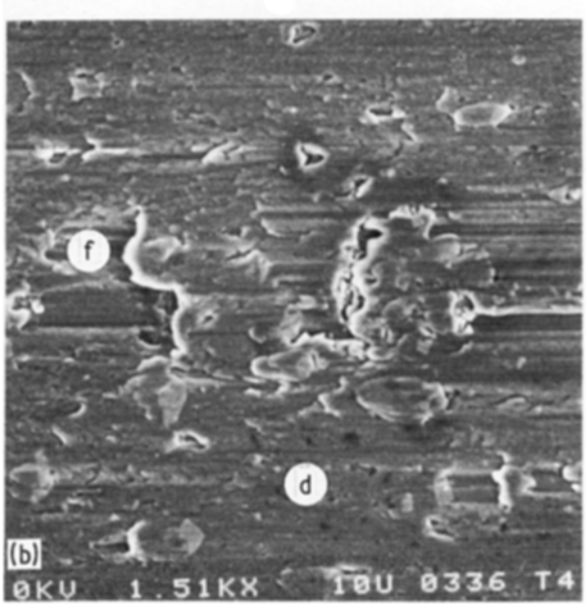
Figure 6 Scanning electron micrographs of the surfaces generated at cutting speed of 250 ft min^{-1} (76.2 m min^{-1}) with a tool having a rake angle of 10°, dry cutting. (a) × 400, (b) × 1200.

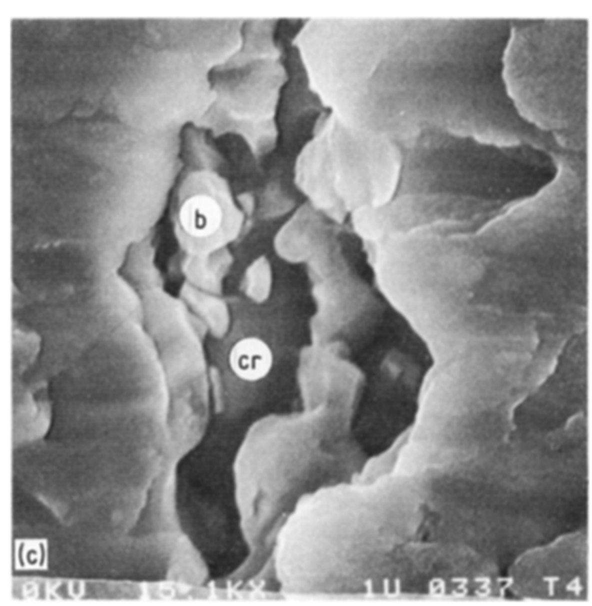


increase in the fatigue life can be obtained by increasing the cutting speed. At low cutting speeds the damage in the machined surface is very high, consequently the fatigue life is low. As the cutting speed is increased the damage in the surface region decreases resulting in an increase in the fatigue life. An increase in the tool rake angle results in a decrease to the damage in the surface and subsurface of the material. Therefore, the increase in the fatigue life with an increase in the rake angle can be understood.

An interesting observation that can be made from Fig. 8 is that the fatigue life of the machined specimens is higher than that of the virgin material tested at the same maximum stress for cutting speeds other than

Figure 7 Scanning electron micrographs of the surfaces generated at cutting speed of 250 ft min^{-1} (76.2 m min^{-1}) with a tool having a rake angle of 30°, dry cutting. (a) × 400, (b) × 1200, (c) × 12 000.





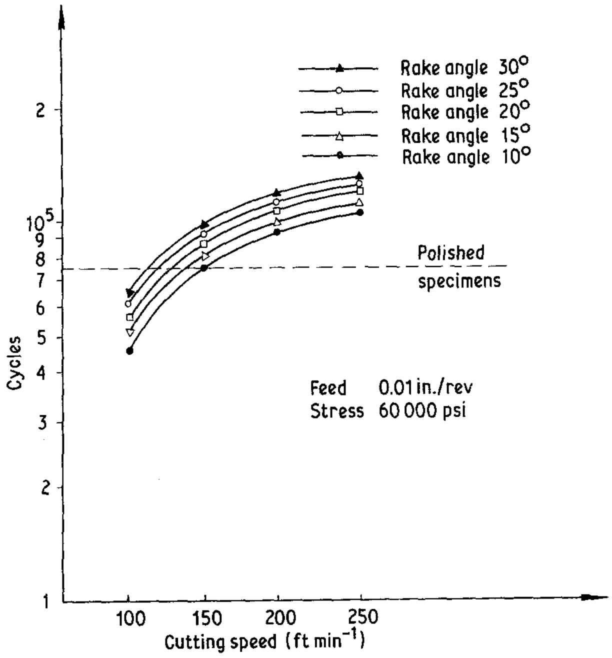


Figure 8 Fatigue life of 2024–T351 aluminium alloy specimens machined at various cutting speeds and rake angles.

those between 100 and 150 ft min^{-1} (30.48 and 45.72 m min^{-1}). This phenomenon may be explained in the light of the work by Natarajan *et al.* [19] on the measurement of residual stresses in 2024–T351 aluminium alloy. It has been found that the residual stresses in the surface layers of this alloy due to machining are compressive for the cutting conditions used in this investigation. The presence of compressive residual stress in the surface region tends to increase the fatigue life of the material. In the range of the cutting speeds between 100 and 150 ft min^{-1} (30.48 and 45.72 m min^{-1}), however, the surface roughness and lack of surface integrity are so high that, in spite of the presence of compressive residual stresses, the fatigue life of the specimens is less than that of the virgin material.

4. Conclusions

The following conclusions are drawn based on the results of the investigation of the effect of surface integrity on the fatigue life of 2024–T351 aluminium alloy machined orthogonally under dry, unlubricated 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 cracks perpendicular to the direction of relative work-tool motion, long straight, grooves parallel to the direction of relative work-tool motion, cracks, and cavities in the surface, microcracks and macrocracks 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 rake angle results in a decrease in the coarse and fine scale damage.
4. An increase in the cutting speed or tool rake angle results in an increase in the fatigue life of the specimen.
5. Owing to the presence of compressive residual stresses in the surface layers, the fatigue life of the specimens machined at higher cutting speeds is higher than that of the virgin material.
6. At low cutting speeds the surface damage is so severe that, in spite of the presence of compressive residual stresses in surface layers, the fatigue life of the machined specimens is lower than that of the virgin material.

Acknowledgements

The authors wish to express their appreciation to the School of Engineering and Architecture, Tuskegee Institute, Alabama, for providing assistance and facilities for this study. Gratitude is also expressed to the Department of the Navy, Naval Air Systems Command, Washington, DC for providing financial support for this research through contract no. N00019-82-C-0316.

References

1. S. JEELANI, PhD thesis, North Carolina State University (1975).
2. J. A. BAILEY and S. JEELANI, *Soc. Manuf. Eng. Trans.* (1974) 174.
3. *Idem, Wear* **36** (1976) 199.
4. J. A. BAILEY, S. JEELANI and S. E. BECKER, *ASME, J. Eng. Ind.* **98** (1976) 999.
5. J. A. BAILEY and S. JEELANI, *Wear* **72** (1981) 237.
6. S. JEELANI and K. RAMAKRISHNAN, *ibid.* **81** (1982) 263.
7. *Idem, ibid.* **82** (1982) 67.
8. *Idem, ibid.* **85** (1983) 121.
9. J. A. BAILEY, *ibid.* **42** (1977) 297.
10. *Idem, ibid.* **44** (1977) 371.
11. P. G. FLUCK, *Proc. Am. Soc. Testing Mater.* **51** (1951) 584.
12. W. P. KOSTER, L. J. FRITZ, and J. B. KOHLS, "Surface integrity in machining of AISI 4340 steel and Ti–6Al–4B alloy", SME Technical Paper no. IQ71-237 (1971).
13. W. P. KOSTER and L. J. FRITZ, "Surface integrity in conventional machining", ASME Paper no. 70-Gt 100 (1970).
14. M. MUSIAL, MS thesis, Department of Mechanical Engineering, Tuskegee Institute, Alabama.
15. "Machining Data Handbook" (Metcut Research Associates, Cincinnati, Ohio, 1966).
16. J. A. BAILEY, *Wear* **27** (1974) 161.
17. *Idem, ibid.* **42** (1977) 277.
18. S. JEELANI and M. MUSIAL, *Int. J. Fatigue* **6** (3) (1984) 169.
19. R. NATARAJAN, S. BISWAS and S. JEELANI, "Measurement of residual stress distribution due to machining in aluminium alloy 2024-T351, using finite element method", presented at the ASME International Conference on Computers in Mechanical Engineering, Las Vegas, Nevada, August (1984), "Computers in Engineering", Vol. 2 (American Society of Mechanical Engineers, 1984) pp. 773–7.

Received 30 January
and accepted 8 March 1985