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Case Study

Machinability of a silicon carbide reinforced aluminium metal matrix composite

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Abstract

The machinability of a *DURALCAN®* aluminium metal matrix composite (A359/SiC/20p) has been studied in this paper. Continuous turning of round composite bars using tools with 25 mm polycrystalline diamond (PCD) inserts has been selected as the test method. The matrix of test conditions included cutting speeds of 300, 500 and 700 m min^{-1} and feed rates of 0.1, 0.2 and 0.4 mm rev^{-1} while the depth of cut has been kept constant at 0.5 mm.

The performance of the tools is based on development of 0.25 mm maximum flank wear, which has been monitored by optical and scanning electron microscopy. The tool life data have been analyzed using regression techniques and a general form of the Taylor equation has been developed to describe the tool performance on this composite. The time required to reach the tool wear limit decreased with increases of speed and feed. However, the volume of material removed before reaching the wear limit actually increases with the higher feed rate. These phenomena have been reconciled by rewriting the Taylor equation in a modified form. Practical implications of this deviation are discussed and comments are made on the effects of cutting parameters on surface finish and chip formation.

Keywords: Machinability; Metal matrix composites; Tool wear; Taylor equation; Material removal

1. Introduction

Increasing quantities of metal matrix composites (MMCs) are being used to replace conventional materials in many applications, especially in the automobile and recreational industries, owing to increasing performance requirements. The most popular types of MMCs are aluminium alloys reinforced with ceramic particles. These low cost composites provide higher strength, stiffness and fatigue resistance [1,2], with a minimal increase in density over the base alloy. The superior mechanical properties achieved by the reinforcements in MMCs, on the other hand, significantly influence their "machinability". This term which describes the operational characteristics of a cutting tool in machining a material is rather ill-defined and is normally judged in terms of tool life, surface finish and power required for material removal [3].

The type of MMC studied in this paper for its machinability is a *DURALCAN®* composite – an aluminium alloy processed by ingot metallurgy with the ceramic particles stirred into the melt. Specifically this MMC consists of A359 aluminium reinforced with 20 vol.% silicon carbide (SiC) particles having a mean diameter of 12.8 mm [4]. A typical microstructure of this material is shown in Fig. 1.

Although some preliminary studies have been carried out [4–6], insufficient data exist to propose a generalised model of tool wear rate as a function of cutting parameters over a wide range of practical use. In the present study the criteria for determining machinability are based on tool wear, surface finish and chip formation. It is well known that tool life varies significantly as a function of speed, feed and depth of cut, and it can be expressed by the Taylor equation for a constant depth of cut as

$$T=K/V^{n_1}f^{n_2} \tag{1}$$

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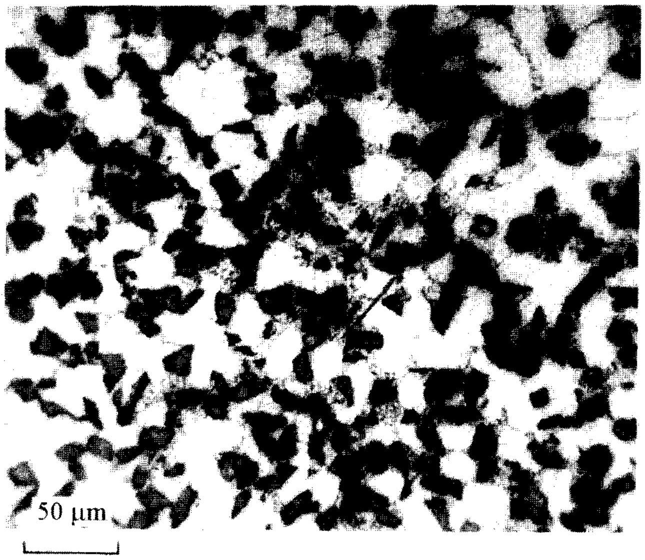

Fig. 1. Microstructure of *DURALCAN®* material.

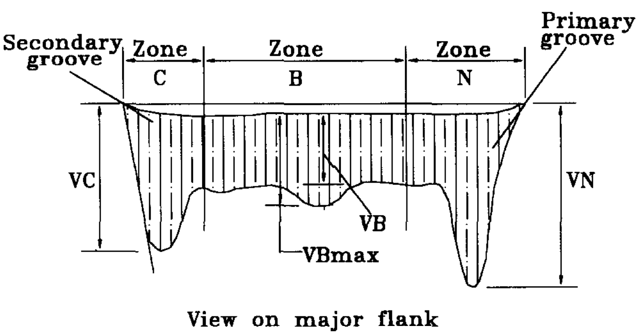

Fig. 2. Criteria based on features of tool flank wear [6].

where K, n_1 and n_2 are constants for given workpiece and tool materials, requiring $n_1 > n_2$. T, V and f are the tool life (min), cutting speed (m min^{-1}), and feed rate (mm rev^{-1}) respectively.

2. Experimental procedure

The prepared bars were machined with polycrystalline diamond (PCD) inserts at three different speeds (300–700 m min^{-1}) with three different feed rates (0.1–0.4 mm rev^{-1}) and a constant depth of cut of 0.5 mm. Table 1 summaries the details of the experimental conditions. The use of PCD inserts in this study is due to its excellent performance compared with ceramic tools when machining aluminium MMCs [4,6,7].

The tool wear and the surface roughness were measured at predetermined intervals. A record on the nature of chips formed at every pass was also maintained. The tool performance was judged primarily by the flank wear growth and the workpiece surface finish. The maximum flank wear of 0.25 mm was chosen as the tool life limit for consistency and to facilitate tool resharpening.

An Olympus optical microscope with measuring grids on the eye-piece was used to measure the maximum flank wear on the tool tip, VB_{max} as shown in Fig. 2. Occasionally a scanning electron microscope (SEM), Philips 505, was also used to study the wear land of the worn PCD tool. Surface finish in the direction of tool movement was measured using a surface roughness measurer, Surtronic-3, with cut-off and traverse lengths of 0.8 mm and 5 mm respectively. The cutting and feed forces were also monitored at every pass by using the Kistler 3-D force dynamometer (type 9441) to record the force changing data.

3. Results and discussion

3.1. Tool wear and Taylor equation

Although various types of wear can influence the tool life [8] under the conditions used in this study, the flank wear was the dominant type of wear mode, Fig. 3(a). By examining the wear land on the tool tip, Fig. 3(b), scratched grooves can be easily found parallel to the directions of chip flow and workpiece material movement. Those grooves were formed by the mixture of two-body and three-body abrasion between the workpiece material and the tool due to the irregular shape of the particulate SiC reinforcement and the loose particles found during machining. (Two body abrasive wear is where a hard, rough surface slides against a softer surface, digs into it and ploughs a series of grooves; three-body abrasive wear is where hard abrasive particles are introduced between sliding surfaces and abrade material off each [9].) This confirms that the primary wear mechanism in machining particulate reinforced MMC is abrasion by the reinforcement particles [4].

Fig. 4(a) shows typical curves of wear growth on the tool tip vs. time when the material was machined at a constant feed rate with three different cutting speeds. As expected from traditional Taylor model, wear growth increased faster with the increase of cutting speed, resulting in shorter cutting time. Likewise, Fig. 4(b) shows the typical wear growth on the tool tip vs. time when the material was machined at a constant speed with three different feed rates. Here also, the wear growth has increased more rapidly with increasing feed rate. This trend can be explained by the increased tool temperature at higher speeds and feed rates. Softening of tool material and diffusion wear caused by the thermal effects along with the impact by reinforced SiC particles of higher kinetic energy accelerate the tool wear process [4].

It is an established practice to use linear regression analysis to obtain tool-life exponents [10]. Therefore, a similar method has been used for deriving the final

Table 1
Experimental details

Workpiece material	Direct-chill cast A359/SiC/20p (175 mm×400 mm long diameter billets)
Machine	Dean Smith & Grace 1609 centre lathe
Tool insert	TPG322 COMPAX 1500 (PCD)
Tool holder	TARP-16-3hR175.2-2525-16 (Sandvik Coromat)
Cutting parameters	Cutting speed, 300, 500 and 700 m min^{-1} Feed rate, 0.1, 0.2 and 0.4 mm rev^{-1} Depth of cut, 0.5 mm Side cutting edge angle, 0°
Tool dynamometer	Kistler 3-D force dynamometer (type 9441)
Surface texture-instrument	Surtronic-3 surface roughness measurer

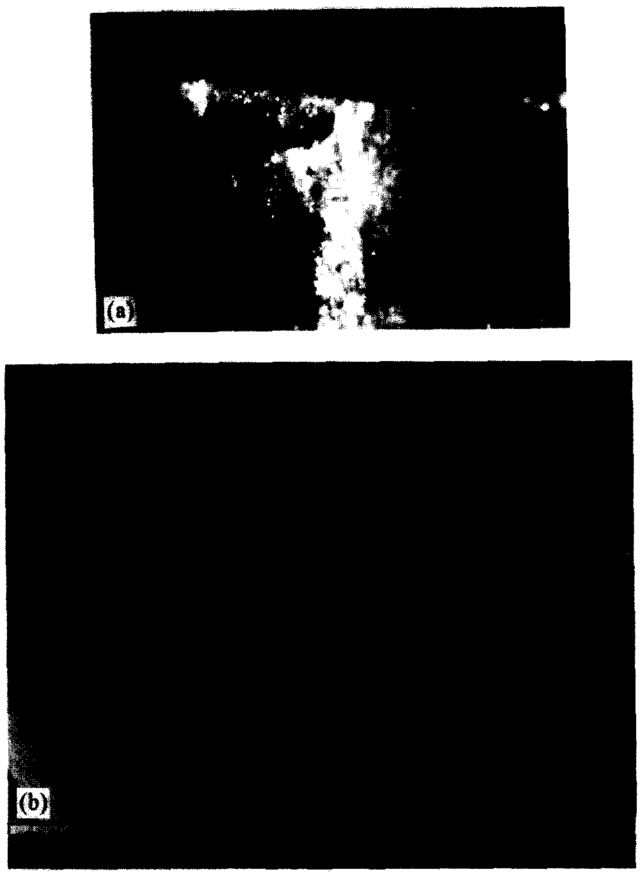

Fig. 3. The wear land on the tip of PCD tool, (a) from an optica microscope and (b) an SEM picture. (Arrows indicate the direction: of movement of the workpiece material relative to the tool surfaces.)

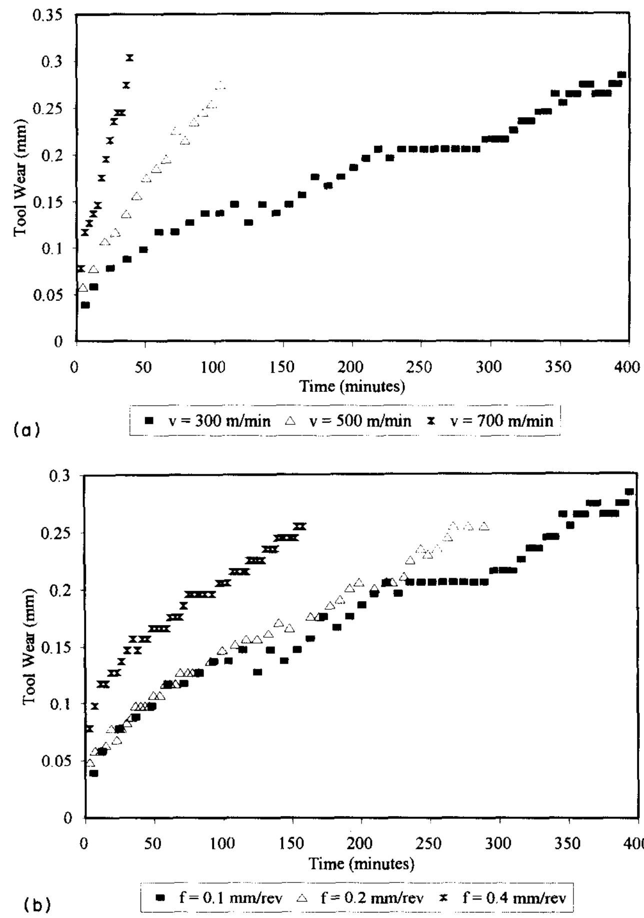

Fig. 4. Tool wear against time in machining *DURALCAN®* at (a) 0.1 mm rev^{-1} feed rate with different cutting speeds (b) 300 m min^{-1} cutting speed with different feed rates.

form of Taylor equation with two independent variables, V and f, and one dependent variable, tool life T. A best fit Taylor equation that can be obtained from experimental data is shown as $T=4.82\times10^8 V^{-2.733}F^{-0.637}$. The percentage errors calculated for tool lives compared with those obtained from experiments lie mostly well within ±4% (The R^2 value for this regression result is 0.998). The obtained speed exponent (n_1) has a higher value of 2.73 compared to that of 1.64 based on the n-value obtained by Tomac and Tønnessen [6], who developed the Taylor equation for a similar material using cutting speed as the only independent variable. Furthermore, their SiC content was less (14 vol.%) and their experiments were conducted in a much lower speed range (20–120 m min^{-1}). However, it must be noted that for practical applications using PCD inserts, the cutting speeds have normally much higher magnitudes, similar to those reported in this paper. On the other hand, the influence of the feed rate on Taylor equation, though a less affecting factor, is as important as the cutting speed when assessing tool life and cannot be neglected, especially when material removal is concerned as explained in the following section.

3.2. Material removal

It is most interesting to note that if the tool life is considered in terms of workpiece material removed, a different picture emerges, Figs. 5 and 6. For the same cutting speed, the tool life increases with an increasing feed rate. This apparent contradiction might cause confusion to the consumers and clearly warrants an explanation, which can be obtained by rewriting the Taylor equation in the following manner. The volume of workpiece material removed (cc),

$$WR = T \times V \times f \times d \tag{2}$$

where T is machining time (min), V is cutting speed (m min^{-1}), f is feed rate (mm rev^{-1}) and d is depth

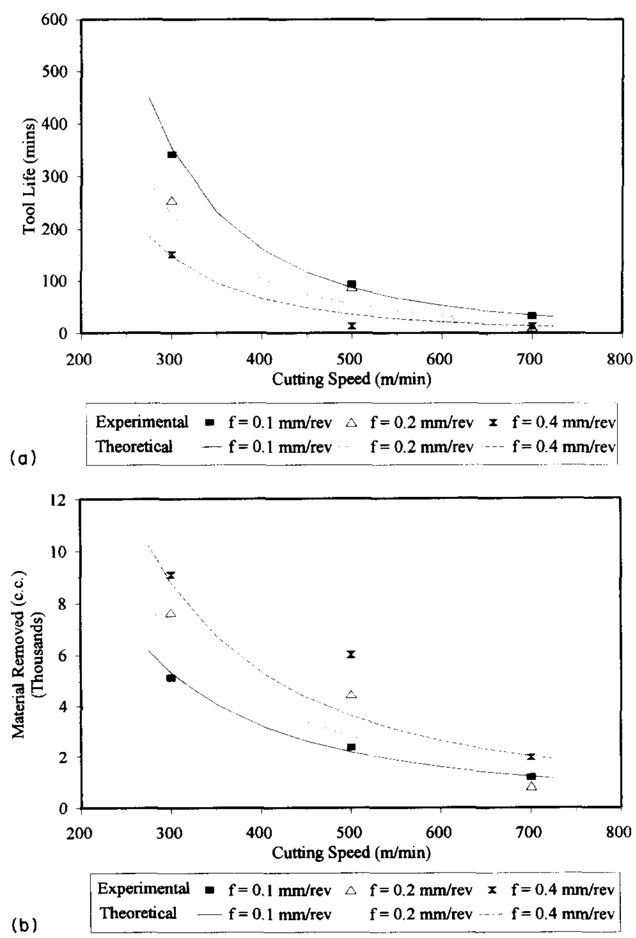

Fig. 5. The comparison of experimental tool life with the value from the Taylor equation for increasing cutting speed, in terms of (a) time, (b) volume removal.

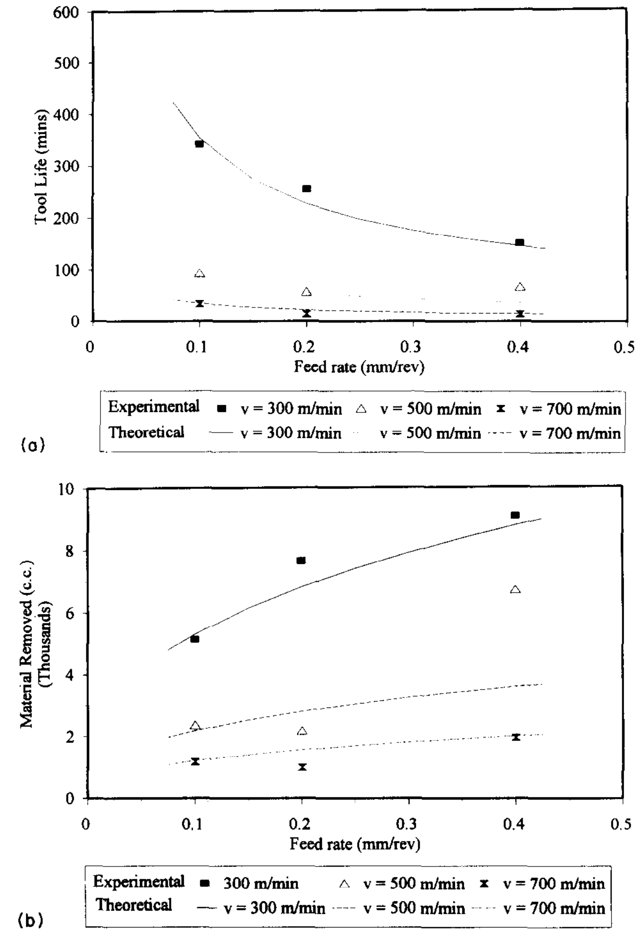

Fig. 6. The comparison of experimental tool life with the value from the Taylor equation for increasing feed rate, in terms of (a) time, (b) volume removal.

of cut which was constant (0.5 mm) in this study. Substituting Eq. (1) in Eq. (2), the workpiece material removed can be expressed as,

$$WR = KV^{(1-n_1)}f^{(1-n_2)} \tag{3}$$

It is evident from Eq. (3) that if both n_1 and n_2 are greater than 1, the increasing speed and feed rate will have a similar effect on T and WR. However, if $n_1 > 1$ and $n_2 < 1$, then these effects are opposite in nature. The form of the Taylor equation for this study comes under the second category giving

$$WR = 2.41 \times 10^8 f^{0.36}/V^{1.73} \tag{4}$$

This equation clearly shows that the cutting speed has a more dominant influence on the volume of workpiece material removal. Consequently, the tool life (cutting time for reaching a particular flank wear limit) and workpiece material removal show different trends. Therefore, if maximum cutting time between tool changes is needed, a lower feed rate is preferable. A better surface finish can also be obtained under these conditions. On the other hand, if the greatest amount of workpiece material removal per insert is desired, then the largest possible feed rate should be chosen after giving proper consideration towards the surface finish. This is in agreement with the practice commonly followed in the selection of cutting parameters based on optimising the balance between workpiece requirements, cycle time, and insert cost [11].

3.3. Surface finish

Fig. 7(a) shows the average roughness (R_a) of the workpiece surface vs. time when the material was machined at one constant feed rate (0.4 mm rev^{-1}) with three different cutting speeds. The surface finish obtained did not change significantly with speed within the experimental range. Theoretically, the ideal value of surface finish [10] for a given feed rate can be calculated by using the equation:

$$R_a = f^2/18\sqrt{3}R \qquad (5)$$

where R is the nose radius of the tool, which in this study was about 0.8 mm, and f is the feed rate. Therefore, the ideal values of surface finish for 0.1, 0.2 and 0.4 mm rev^{-1} feed rates are 0.4, 1.6 and 6.4 mm respectively. Since Eq. (5) is just a simple method of assessing the influence of feed rate on surface roughness by considering tool geometry, the reason for the deviation of experimental data can be attributed to the fact that the influence of the secondary factors, such as cutting speed, depth of cut, rake angle, load, etc., and their interactions can shift the curves. However, the effects are too complex to be easily modelled. Generally, the surface finish is improved with the increasing cutting speed at the same feed rate, eventually reaching the ideal surface finish. It is interesting to note that the best surface finish is obtained with a slightly worn tool; this is likely due to the stabilisation of the nose and cutting edge radii. This observation is supported by Lane [4] who has found that in order to maintain a consistent wear rate with the accompanying dimensional tolerances and surface finish, a slightly honed cutting edge is often preferable. Fig. 7(b) shows the surface roughness on the machined surface vs. time when the material was machined at a constant cutting speed with three different feed rates. The surface finish has expectedly deteriorated with the increase in feed rate, but at lower feed rates, little difference exists.

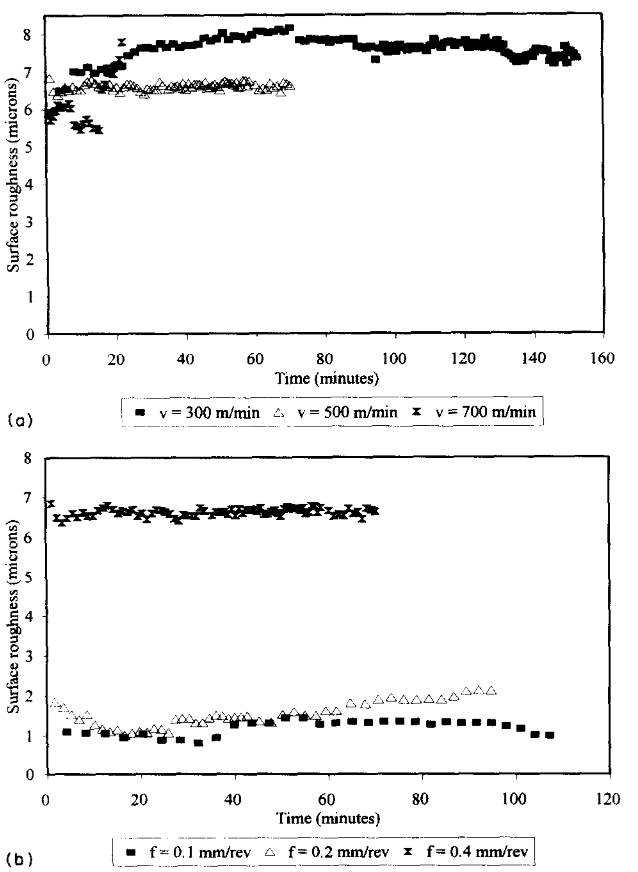

Fig. 7. Surface roughness against time in machining *DURALCAN* at (a) 0.4 mm rev^{-1} feed rate with different cutting speeds and (b) 500 m min^{-1} cutting speed with different feed rates.

3.4. Nature of chip formation

In this study, the nature of chips formed during machining *DURALCAN®* changed with the extent of tool wear. When the tool is sharp, long washer type helical chips (type 4.1 ISO 3685) are mainly formed, sometimes accompanied by small amount of snarled washer helical chips (type 4.3) which was owing to the constraint on chip flow by the tool holder. Once the tool started getting blunt, the chip type changed into short washer helical chips (type 4.2) with some loose arch (type 6.2). The blunter the tool was , the more loose arch chips are produced. The reasons for such short chips being formed during machining are twofold. First, the reduction in ductility of aluminium material by addition of ceramic reinforcement induces fracture in the shear zone. Second, the unstable built-up edge on the tool tip operates as a chip breaker. From machinability point of view, since short chips can easily detach themselves from workpiece and prevent the tool and workpiece damage caused by recutting, this type of chip is more desirable if the surface finish stays within the limit. A more detailed study on the chip formation of this material will be described in a forthcoming paper [12].

3.5. Machining forces

Both cutting and feed forces were monitored regularly and seemed to steadily increase up to the maximum value of 185 N and 90 N respectively during machining as the tool wear increased. (Detailed results are not reported in this paper.) At the same cutting speed, both cutting and feed forces increased as increasing feed rate. However, at the same feed rate, as the cutting speed increased, the changes in both feed and the cutting were minimal.

4. Conclusions

The following conclusions can be drawn from the results of this study:

1. The main types of tool wear during machining *DURALCAN®* aluminium composite take place on flank and rake surfaces, with flank wear being dominant in the quoted speed–feed range. The primary mechanism of wear formation is believed to be the abrasion between reinforcement particles and cutting tool material.
2. As expected, the cutting time decreases with increasing cutting speeds and feed rates. However, the total volume of workpiece material removed increases with increasing feed rates giving an anomalous picture to the users. This interesting phenomenon has been explained by modifying the Taylor equation to incorporate the workpiece volume removal. Proper operating conditions should be chosen according to the requirement of practical applications.
3. The surface finish of the machined samples deteriorates with increasing feed rates at a constant cutting speed, but does not change significantly with the change of cutting speed. The best surface finish is achieved when the tool is slightly worn rather than when it is fully sharp. However, within the range of this study, the surface finish eventually approaches a constant value due to the stabilisation of tool nose and cutting edge radii.
4. By using regression analysis on the experimental results, the general form of Taylor equation is obtained as $t=4.82\times10^8\ V^{-2.733}f^{-0.637}$, or $WR=2.41\times10^8\ V^{-1.733}f^{0.363}$. ($T$ is the cutting time for reaching 0.25 mm flank wear; WR is the volume of workpiece material removal.)
5. The short type of chips produced without chip breaker in machining *DURALCAN®* aluminium metal matrix composite renders this material well-suited for continuous operation.

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