CHIP FORMATION IN THE MACHINING OF SiC-PARTICLE-REINFORCED ALUMINIUM-MATRIX COMPOSITES

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(Received 11 April 1996; revised 2 December 1996; accepted 7 July 1997)

Abstract
As a consequence of the widening range of applications of metal-matrix composites (MMCs), the machining of these materials has become a very important subject for research. Aluminium-matrix composites are widely used for their favourable specific strength/stiffness and corrosion resistance properties. This paper describes a study of chip formation during the machining of a DURALCAN® aluminium-matrix composite (A359/SiC/20p). For good machinability, it is desirable to have continuous chips in short segments without the use of a chip breaker. The chip-formation mechanism in machining this silicon-carbide-particle-reinforced aluminium composite at three different cutting speeds has therefore been investigated by using an explosive charged quick-stop device. An improved quick-stop device has enabled research to be carried out more easily on the mechanism of chip formation by achieving better chip control during machining. During the chip-breaking process, the primary chip-forming mechanism involves the initiation of cracks from the outer free surface of the chip due to the high shear stress. Meanwhile, some small voids are formed by the separation of particles and the matrix material within the chip because of the stress concentration at the edges of the particles. The crack propagation is enhanced through the coalescence of these voids along the shear plane. The fracture and sliding of material then follow to form semi-continuous 'saw-toothed' chips. 

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Keywords: A. metal-matrix composites, chip formation, quick-stop device, saw-toothed, shear angle

1 INTRODUCTION

With the increasing use of metal-matrix composites in various applications such as the aerospace industry, the automotive industry and in sports equipment, the machining of such materials has become a very important subject for study. Owing to the addition of reinforcing materials which are normally harder and stiffer than the matrix, machining becomes significantly more difficult than is the case for conventional materials, as reported in earlier publications.1-3 It has been shown5 that while machining the DURALCAN® aluminium-matrix composite A359/SiC/20p, short chips formed without a chip breaker are desirable for a continuous machining operation. This not only improves the machinability of this composite, but also enhances its applicability in various industries. On the other hand, the importance of chip formation has been well recognised and studied by other researchers.6 Problems with surface finish, workpiece accuracy and tool life can be caused even by minor changes in the chip-formation process. Hence, it is necessary to understand the chip-forming mechanism for this material through further investigation. This will render the material more suitable for advanced applications and more efficient chip control in machining can also be achieved.

Basically, chip formation is a shear process involving plastic deformation within the shear zone. While studying the nature of the shear zone in metal cutting, conflicting evidence has led to two basic schools of thought with regard to analysis of the deformation zone, namely the thin-plane (or thin-zone) model as shown in Fig. 1(a) and the thick-zone model, Fig. 1(b). The available experimental evidence indicates that at higher speeds a thin shear plane is approached.7 Thus it seems that the thin-zone model is likely to be the most useful for practical cutting conditions since the shear angle can be more easily identified.

However, the types of chip formed are not only related to the nature of the shear zone but are also influenced by material properties such as ductility, thermal conductivity and microstructure. Furthermore, physical phenomena such as instability in the cutting process can change the chip-formation mechanism.8-11

The research into chip-formation mechanisms has been facilitated significantly by the employment of the quick-stop device,12,13 which provides a suitable method of 'freezing' the chips on the workpiece for an in situ
study of the microstructure while the chip is being formed. The use of an explosive charge on the quick-stop device gives the tool a very high acceleration to retract from the seat of cutting in an extremely short time (within a few nanoseconds), thus permitting the examination of chip formation in the steady-state condition even at relatively high cutting speeds. The present paper describes a study on the effects of SiC particles on the chip-formation process by the use of a quick-stop device on a lathe while machining the aluminium MMC under various cutting conditions. The effect of cutting speed on changing the shear angle during the chip-forming process is also elucidated.

2 EXPERIMENTAL PROCEDURE

The type of DURALCAN® metal-matrix composite used in this study is 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% of silicon carbide (SiC) particles having a mean diameter of 12.8 μm. In this study, the MMC bars were machined with slightly worn polycrystalline diamond (PCD) inserts because cutting with a blunt tool can easily produce the short type of chips as indicated in earlier research. They were machined with 1.5 mm depth of cut and 0.4 mm rev⁻¹ feed rate at three different cutting speeds: 300, 500 and 700 m min⁻¹. Table 1 summarises the details of the experimental conditions. The reason for the high feed rate and deep cut is to produce a robust chip which would be able to stick to the workpiece when the quick-stop device is in action.

Figure 2 shows the constructional details of the explosive quick-stop device used in this study. During machining, the PCD insert (G) was fixed by tool clamp (F) on a swivelling tool holder (H), which was supported by a double-necked cast iron shear pin (I) to perform normal cutting action. In addition, the tool holder was held by the fixing screws (A) to prevent it from moving freely during machining. Because of the brittleness of the cast iron and the pre-positioned necks, once the gun was triggered, the explosive force pushed the piston (C) with the impacting head (D) to strike the swivelling tool holder on the impact pad (E). This impact led to breakage of the cast iron shear pin and instantaneous detachment of the tool from the machined surface followed. The tool holder with insert was then caught by a plasticine buffer (J) to prevent it from sustaining damage caused by the rapidly falling tool holder on the bed of the device.

After the detachment, an unbroken chip, which stayed on the workpiece surface, was carefully cut from the workpiece and mounted in epoxy resin for further metallurgical preparation. The specimens were then ground sequentially with #120, #250, #500 and #1200 SiC papers and polished with 15, 6, 3 and 1 μm diamond suspensions to reveal the silicon carbide reinforcement, and finally polished with 0.4 μm silica solution to reveal the aluminium matrix. An Olympus optical microscope and a scanning electron microscope (SEM) were used to take micrographs and photographs of the specimens at different magnifications to study the microstructure and the morphology of the chips formed.

3 RESULTS AND DISCUSSION

3.1 Chip formation

Microphotos of the chips formed in machining this aluminium MMC are shown in Fig. 3(a) and (b). From the shape of the cross-section, the chips can be categorised...
as 'saw-toothed' chips. The chip formation during machining is accompanied by very severe plastic deformation at the shear zone, as shown in Fig. 4(a), and owing to the lack of sufficient ductility of the work-material, the deformation is limited by the crack initiation at the surface where no hydrostatic pressure exists, Fig. 4(b). This type of chip is similar, in terms of the cross-sectional shape, to the 'segmental' chips obtained during cutting of titanium. The chip formation in titanium has been attributed to adiabatic shear in high-speed machining because of its poor thermal conductivity. It is also very similar to the type of chip formed in low-speed cutting of titanium, where the periodic fracture and gross sliding of the material can be clearly observed. The 'saw-toothed' and 'segmental' types of chip, together with the 'wavy (or shear type) chip', may be collectively called 'semi-continuous chips'. The addition of SiC particle reinforcement into the aluminium matrix has caused a reduction in its ductility and makes the material ideal for producing such semi-continuous chips, Fig. 5, which can be easily discarded after machining. This could be beneficial to the machinability aspects; however, it creates some fluctuation in the force measurements as discussed later.

It appears from the microstructure of the chips, Fig. 6, that the distribution of the SiC particles is generally quite uniform but some small clusters of particles, which can act as stress raisers to facilitate crack propagation and eventually lead to fracture of the material, can be observed. When the material underwent shear by the movement of the cutting tool during the chip-forming process, cracks were initiated from the outside free surface of the chip and some small voids were formed by

Fig. 2. Constructional details of the explosive quick-stop device.

Fig. 3. Photographs of the chips formed during machining at (a) 300 m min⁻¹ and (b) 700 m min⁻¹.
the separation of particles and matrix material within the chip as a consequence of the stress concentration at the edge of the particles, Fig. 7. Once the material was sheared further, the coalescence of the voids caused the crack to grow and propagate in a zigzag manner along the shear plane through the thickness of the chip. The resulting fracture and sliding of material formed the 'saw-toothed' chips, Fig. 8. Further evidence could be gathered from Fig. 9, where the photographs were taken from the short chip formed during machining. The extent of crack growth is variable with some cracks completely traversing the chip, others almost traversing the chip, and yet others traversing only about 50% of the chip. During machining, the propagation of the crack is accelerated by the upward and side-curling action of the chip which, from time to time, helps break a long chip into smaller pieces. The crack path through the material seems to follow the boundary of the SiC particles. The SiC/Al interface seems to be a plane of weakness with the particle/matrix bond being weak. Thus the crack propagates from particle to particle through some ductile fracture process following particle/matrix decohesion.

The side curling of chips during turning is attributed mostly to the gradient of chip length ratio over cutting edge. Because of the 0° side cutting edge angle used in this study, the severe side flow of the material at the free edge of chip makes this side of the chip shorter than the other and causes the side curling. The chip becomes a helical type of chip by the combined action of up and side curling. Close examination of the chip, Fig. 10, shows the morphology of the side-flow material. The side flow which occurs during the chip-forming process gives the chip its saw-tooth shape. The pitch of chip formation becomes irregular at times and this may be attributed to the distribution of the SiC particles, which

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Fig. 4. Models of chip formation. 

Fig. 5. The semi-continuous type of chips formed during machining.

Fig. 6. The microstructure of the chip root.

Fig. 7. The separation of particles and the matrix material within the chip.
makes the initiation of cracks from the outside free surface irregular.

Another feature of this type of chip formation is the 'stick–slip' friction of the chip segment on the tool face. As shown in Fig. 11, the periodic adhesion patches and sliding regions suggest that the formation of each tooth segment decelerates during the build-up stage and accelerates during the second stage of chip segmentation, which is the finish of a segment and the start of the following segment build-up. This type of friction causes fluctuation of the cutting forces, as shown in Fig. 12, and also slightly influences the mechanism of tool wear. However, the reduction of the ductility of the material, caused by the addition of SiC particles, makes the 'stick' portion of friction much less than that of the 'slipping' portion during the chip-forming process. Meanwhile, it also causes more serious abrasive wear than adhesive wear on the tool surface.

3.2 Shear angle

Although Komanduri and Von Turkovich suggested that use of the term 'shear angle' is inappropriate for serrated chip formation, the shear angle is still a significant parameter for analysing the chip-formation mechanism in metal-cutting processes. However, during this type of cyclic chip-forming process, the shear angle is not simply a constant value, but changes cyclically as the cyclic chip formation takes place. Referring to Fig. 3, the shear zones of the chip formation cannot be clearly identified for the three cutting speeds even after the specimens have been etched. This can be explained by the following phenomena. First, the reduction in ductility by adding SiC particle reinforcement and their random distribution in the matrix make the material flow less obvious. Second, employment of the explosive

![Fig. 8.](image1) ![Fig. 9.](image2)

Fig. 8. (a) Shear fracture of the chip formed. (b) Higher magnification of (a) to show the shear marks of the fractured material.

Fig. 9. Different stages of crack propagation.
charge quick-stop device shortened the retraction time which reduced the chance of the shear zone being additionally strained by the change in rake angle accompanying the rotation of the tool during retraction.\textsuperscript{12}

3.3 Built-up edge of the chip formation
Figure 13 shows a case where, at the vicinity of the chip root, a small cavity is formed. The size of the cavity decreases with increasing cutting speed which confirms the existence of a built up edge (BUE) forming during machining of this material. Once the tool is detached from the chip root, some built-up material on the tool rake surface is taken away with the tool to form a small cavity. The decreasing size of the cavity is primarily due to the increasing cutting speed which makes the BUE more difficult to grow, and it is more easily carried away with the chip flow as the machining continues.

Furthermore, the particles seem to plough through the tool surface to form wear grooves and some loose debris. Those debris containing SiC particles are squeezed through the material tool contacting surface to intensify the abrasive tool wear. As mentioned in the earlier study,\textsuperscript{5} this is the major tool wear mechanism while machining this MMC.

Fig. 10. The morphology of the side-flow material.

Fig. 11. The 'stick–slip' marks on the smooth side of a chip.

Fig. 12. The fluctuation of the forces measured during machining (100 N per division for force axis and 1 s per division for time axis).

Fig. 13. The microstructure at the vicinity of the chip root.
4 CONCLUDING REMARKS

By using the explosive charge quick-stop device to study the chip-formation mechanism during machining of SiC-particle-reinforced aluminium MMC, the following remarks can be made.

1. The reduction in ductility of the aluminium alloy by the addition of SiC particles helps to produce a semi-continuous type of chip during machining this MMC. This not only reinforces the material to give superior performance, but also achieves better chip control to render the material very suitable for machining.

2. The chip-forming mechanism involves the cracks initiating from the outside free surface of the chip because of the stress shear applied by the tool rake surface; some small voids are also formed by the separation of particles and matrix material within the chip caused by the stress concentration at the edge of the particles. Once the material is further sheared, the coalescence of the voids accelerates the crack growth and propagation along the shear plane, and fracture and sliding of the material follow to finish forming the semi-continuous 'saw-toothed' chips.

REFERENCES