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Full Length Research Paper

Analysis of chip formation in machining aluminium hybrid composites

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Aluminium metal matrix composites are considered to be one of the most difficult to machine materials, because of the presence of reinforcements which are much harder than the parent matrix. This paper focuses on the study of chip formation during the turning of aluminium/alumina/graphite hybrid metal matrix composites and to study the influence of machining conditions, surface roughness and tool wear on the chip geometry. The cutting tool used in the present study was uncoated carbide tip insert. The surface roughness was measured and the results were observed for different machining conditions. Based on the surface roughness value, chips were classified as favorable and unfavorable chips.

Keywords: Hybrid metal matrix composite, machining, surface roughness, chip formation

INTRODUCTION

Particulate reinforced aluminium metal matrix composites are considered to be one of the 'difficult to machine' materials. Due to the addition of reinforcements like Silicon Carbide (SiC), alumina which are normally harder and stiffer than the matrix, machining become significantly more difficult when compared to normal conventional materials. Many authors have derived their excellent mechanical properties from the combination of reinforcement like SiC and a ductile matrix material such as Magnesium. The properties of Metal Matrix Composites (MMCs) are influenced by their matrix, reinforcement, and interface properties. Matrix materials are usually lightweight materials, and especially ceramic reinforcements are added to get high specific strength (Joshi et al., 1999; Caroline et al., 2000). Reinforcements have been used in the form of particulates, whiskers, or continuous fibers. Currently, most of the processes employed in the synthesis of MMCs involve the incorporation of ceramic particles such as carbides and borides into the matrices (Lin et al., 1997). Reinforcements like alumina have high yield strength and high modulus of elasticity. It also improves the hardness of the composite. The addition of graphite makes it act like a self-lubricant preventing the need of supplying separate lubricants while machining.

The importance of chip formation has been well recognized and studied by other researchers. Problems with surface finish, work piece 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. The theory of metal cutting regards the study of chip formation as the cheapest and most effective way of understanding the machining characteristics of a material (Joshi et al., 1999).

Based on the available literature, it is clear that various factors like cutting speed, feed rate, rake angle and volume of reinforcement greatly influences on the chip formation mechanism. Joshi et al. (1999) observed that the chips produced while machining the composite

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Table 1. Process parameters and its levels

Process parameters	Level		
	1	2	3
Cutting speed(m/min)	200	250	300
Feed rate(mm/rev)	0.1	0.15	0.2
Depth of cut(mm)	0.5	1	1.5

showed a systematic breaking pattern depending on the volume of reinforcement in the composite material and found that the chip breaking can be related to mechanical properties by a chip breaking criterion. They also observed that at negative rake angles, the length of contact of chip on the tool face is higher; hence the chips could be flatter and hence comparatively larger in diameter. Besides that they also found that, if the cutting speed is low, the shear strength of a work hardening material is high resulting in an early breakage of chips. Thus, the phenomenon also decreased the number of circles (or the length of chip) through which a chip curls.

According to Raviraj et al. (2008), chips of discontinuously reinforced aluminium composites curl through circles of wider and larger diameter as the cutting speed increases; this may be due to adhering of work piece material on the tool face. The initial radius decreases with decrease in cutting speed. This could be due to changes in the length of contact on to tool face. Further studies reveal that the chip formation mechanism, during the machining of composites is mainly influenced by cutting speed. Increase in cutting speed results in the decrease in saw toothed chip.

Studies by Uday and Suhas (2009) also have concluded that feed rate is also a major factor in chip formation mechanism. At higher feed rates, the number of chip curls found is more than for a lower feed. This may be attributed to the increased deformation volume and tool-chip contact length. It increases the machining temperature and thereby the ductility and increases the number of chip curls. However, at lower feed rate, the chip cross-sectional area is very small due to which flake, needle type segmented and small radii curled chips are generated.

The aim of the paper is to present the mechanism of the chip formation while machining aluminium metal matrix composites. The mechanism of the chip formation was studied for various values of cutting parameters and tool conditions.

EXPERIMENTAL DESIGN

The main objective of the paper is to present the mechanism of the chip formation and study the effects of various cutting conditions on chip formation while machining aluminium metal matrix composites. Accordingly experiments were conducted under varying machining conditions (speed, feedrate, and depth of cut) and tool conditions (new, worn-out).

Plan of experiments

Three independent variables such as speed, feed rate and depth of cut are used in this work. Based on the preliminary set of experiments performed on the machining of aluminium composite three levels of each independent variables has been selected (Table1). A total of 27 experiments were carried out on the composite.

Cutting tool life is one of the most important considerations in metal cutting.The major parameters which affect the tool life are the tool angle (rake angle), cutting speed and the feed rates.The use of very low speed and feed to give maximum tool life is uneconomical because of the low production rates. Tool rake angles can be positive or negative, the latter increases the number of usable cutting edges by allowing the insert to be inverted to utilize the edges on the lower insert face; but on the other hand produces thicker chips resulting in higher cutting forces. An increase in the rake generally tends to improve the cutting conditions leading to longer tool life. However it is evident that the usage of larger rake angles makes the cutting edges mechanically weak; this results in higher wear rates and shorter tool life. Hence an uncoated carbide insert ML K10 with front rake angle of 12^0 and nose radius of 0.4mm was chosen for the present work.

Experimental Setup

The type of hybrid metal matrix composites studied in this paper consists of LM9 aluminium(Al_2O_3) alloy reinforced with 9% by weight of alumina particles of 23µ mean diameter and 3% by weight of 45µ graphite particles. Chemical composition of matrix alloy is given in Table 2.

Ten cylindrical bars were manufactured using stir casting process. LM9 was heated to a temperature of 750 ˚C in a graphite coated crucible. 9% by weight of Al_2O_3 and 3% by weight of graphite particles were pre heated to 320 ˚C on a flame heater. The pre heated mixture was then added to the melt and mixed thoroughly.

Table 2. Chemical composition of the matrix alloy

Chemical Composition	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
%	0.1 max	0.2-0.6	10.0-13.0	0.6 max	0.3-0.7	0.1 max	0.1 max	0.1 max	0.05 max	0.2 max	Balance

1% by weight of magnesium in the form of ribbons was added to improve wettability of the melt. The mixture was stirred using a standard drill fixed with a stirrer at 200 rpm for three minutes.

The green sand mould which was prepared for the preferred dimension and tolerance was pre heated using a flame heater for 2 min to remove moisture. The melt was then poured into the mould using a ladle and allowed to solidify. The work pieces were then cooled in air for three hours after solidification and removed from the mould.

The turning operation on aluminium MMCs of length 308mm and 32mm diameter using carbide coated ML K10 insert for TNMG type tool holder was performed in an industry standard CNClathe(LMWLL20T L5) under dry machining conditions. Large numbers of chips were collected for various experiments. The surface roughnesses of work pieces were taken after each experiment using TESA surf tester with sample length and cutoff length being 8mm and 4mm respectively. The surface roughness of the work piece after each experiment was recorded. Theimages of the chips were captured using a digital camera and inspected. The observations made on them were used to classify according to their physical structure and appearance.

RESULTS AND OBSERVATIONS

Based on the nature of chips, chips were classified as continuous chips and discontinuous chips.

Continuous chips: The cutting of alumina reinforced aluminium composites results in various types of chip formation. When the tool edge cuts only the matrix and not the reinforcement, plastic deformation takes place. If this is hindered by reinforcing particles, squeeze-break and collapse cutting will occur (Kannan et al., 2006). Continuous chips are produced normally when ductile materials like aluminium, copper, wrought iron and copper are machined at very high speeds. The formation of chips depends on the type of work piece material, geometry and material of cutting tool, and machining conditions such as speed, feed and depth of cut (Lin et al., 1997). Machining using worn-out tool will also result in the formation of long continuous chips without saw toothed tip. The cutting operation involves shearing of the work piece material and sliding of the chips along the face of the cutting tool. The chip remains in contact with the tool face for a short distance before curling away from work piece.

Discontinuous chips: Discontinuous chips are formed while machining brittle materials or ductile materials under high feed and low cutting speed condition. The chip formation mechanism in this case is quite different from that in the case of ductile materials (Lal, 2007). Even a slight plastic deformation produced by a small advance of the cutting edge into the job leads to a crack formation in the deforming zone. With further advance of the cutting tool, the crack travels and a small lump of material starts moving up the rake face. The force and constraints in the motion acting on the lump make the crack propagate towards the surface, and thus a small fragment of the chip gets detached. As the tool moves further, this sequence is repeated .When the work material is brittle, fracture occurs in the primary deformation zone. This occurs when the chip is only partly formed. Under these conditions chips break in small segments in a cyclic manner leading to the formation of discontinuous chips. The major parameters affecting the chip geometry were cutting speed and feed (Lin et al., 1997).

Effect of cutting speed and feed rate

At high cutting speeds (300m/min and 0.1mm/rev with 1mm depth of cut) the chips formed were very long, formed in curls(Figure1a). The diameter of the curl was found to increase with the feed rate (Figure 3). As the cutting edge of the tool approaches the work piece material, it gets compressed because of the relative motion of the tool and work piece and reaches a plastic state. This initiates the chip formation along the rake face of the tool. Thus a finite thickness of the work piece gets sheared across the shear plane in a continuous manner resulting in the formation of lengthy chips(Uday and Suhas, 2009; Kilickap et al., 2005). The change in form of chips as the cutting speed increases is due to increased ductility of the work material because of the high machining temperature at higher cutting speeds (Figure1a).

For lower cutting speeds segmented chips were obtained (Figure1b). When the cutting edge of the tool approaches the work piece, the work piece material gets severely compressed resulting in high strain. Because of this strain hardening and the fact that the material

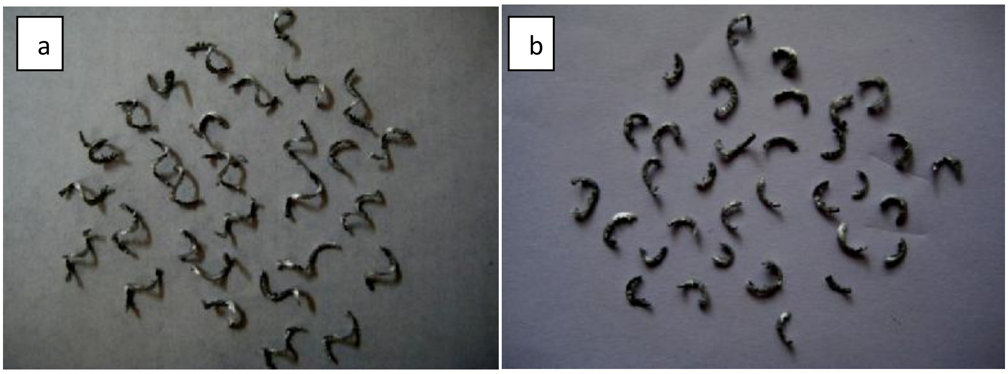

Figure 1 (a). High Speed condition **(b).** Low Speed condition

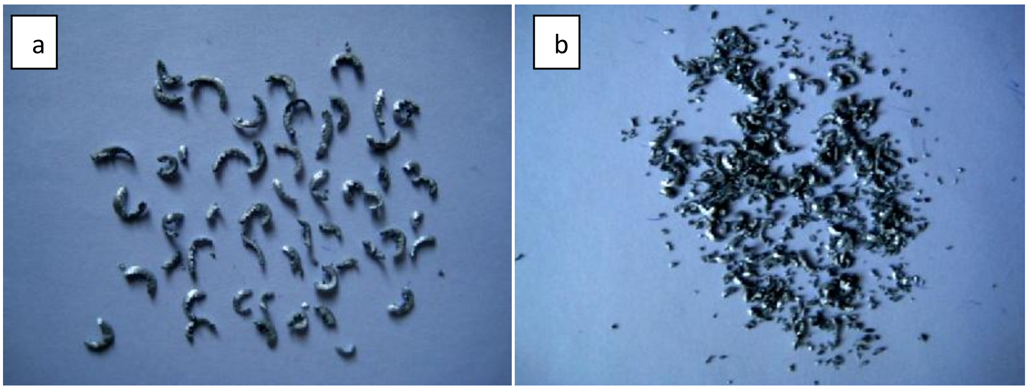

Figure 2 (a). High Feed condition **(b).** Low feed condition

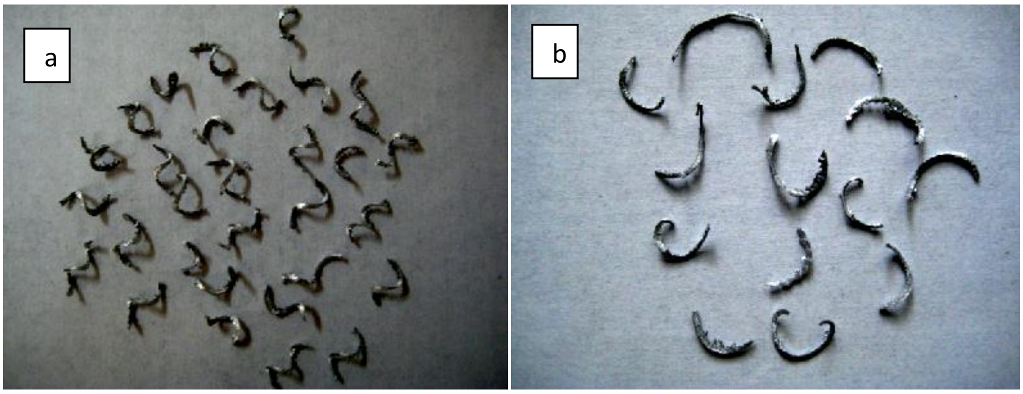

Figure 3 **(a).** Lowfeed (high speeds condition) **(b).** High feed (high speeds condition)

deforms plastically beyond a critical stated is continuous segmented chips were formed (Raviraj et al., 2008).The material behaves like a brittle material when machining at lower cutting speeds. More over brittle type of failure was more predominant (because of very less displacement of alumina particles) which is the main reason for the formation of segmented chips.

At higher feed rates (Figure 2a) the number of curls in the chips formed was more when compared to those formed at lower feed rates (Figure 2b).

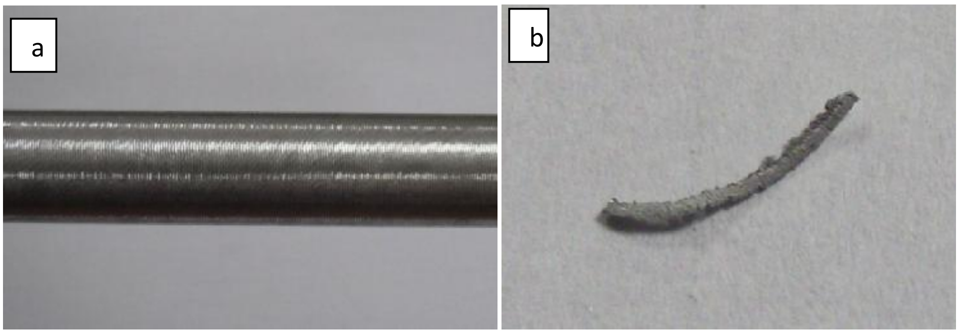

Figure 4 (a). Poor surface finish **(b).** Profile of unfavourable chip

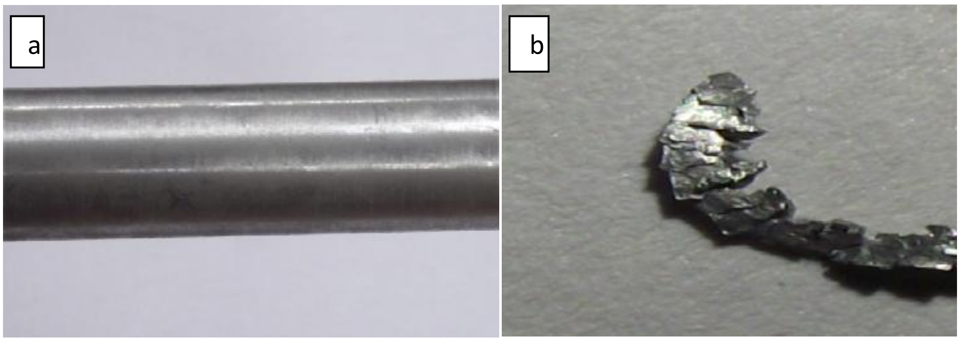

Figure 5 (a). Optimum surface finish **(b).** Profile of Saw toothed chip

This can be attributed to the increased deformation volume and the tool-chip contact length while machining. This increases the machining temperature which increases the ductility in the case of reinforcements like alumina. At lower feed rates the chip cross-sectional area is comparatively low .This is the main reason for the formation of segmented chips with low curl radii (Figure 2b).When the cutting speed is lowered (Figure 2b), for the low feed condition almost powder like chips were formed and the length of the chips begins to increase as the feed rate is gradually increased from 0.1mm/rev to 0.2mm/rev (Figure 2a).This can be attributed to very low chip cross sectional area and increase in the number of brittle failures, leading to the formation of segmented or almost powder like chips at lower feed rates.

Effect of Chip formation on tool wear

A tool flank wear of 0.2 mm and 0.4mm were intentionally made on the cutting tool using controlled grinding operation. The aluminium composite is then machined using this tool and large numbers of chips collected were analyzed. The chips formed for this condition (speed=300 m/min, feed rate = 0.1mm/rev, depth of cut= 0.5mm) were very long and continuous with curls of small radii. The saw tooth shape was not found in these chips (Figure 4b). The addition of alumina particles reinforcement into the aluminium matrix reduces the ductility and makes the material ideal for producing saw-toothed and segmental type chips during machining (Manna and Bhattacharya, 2003).During machining, the material undergoes shear by the movement of the cutting tool. These initiates the cracks from the outer free surface of the chip .Voids were formed due to the separation of the reinforcement and the parent matrix (Manna and Bhattacharya, 2003).Further shearing of the material causes the coalescence of the voids leading to crack propagation and growth in a zigzag manner along the shear plane. As a consequence of this fracture and sliding of materials saw toothed chips were formed. In the case of worn out tool, the movement of the cutting tool over the material was not uniform because of the wear (tool damage) present in the cutting edges. Hence saw tooth shape was not found in these chips.

Effect of Chip formation on Surface Roughness

The surface roughness obtained during a practical machining process may be considered as sum of two independent effects, one resulting from the geometry of the tool, feed or cutting speed and the other being natural surface roughness which being a result of irregularities in the cutting operation (Uday and Suhas, 2009). It was observed that for optimum surface finish(condition of minimum surface roughness, Figure 5a), saw-toothed chips were obtained as shown in Figure 5b and for poor

Table3. Surface Roughness values for experiments

Experiment No.	Feed (mm/rev)	Speed (m/min)	Depth of Cut (mm)	Flank Wear (mm)	Ra (μm)
1	0.1	200	0.5	0	1.255
2	0.1	200	1	0	1.322
3	0.1	200	1.5	0	1.412
4	0.1	250	0.5	0	1.432
5	0.1	250	1	0	2.632
6	0.1	250	1.5	0	1.183
7	0.1	300	0.5	0	1.048
8	0.1	300	1	0	1.08
9	0.1	300	1.5	0	1.177
10	0.15	200	0.5	0	3.132
11	0.15	200	1	0	3.362
12	0.15	200	1.5	0	2.542
13	0.15	250	0.5	0	2.048
14	0.15	250	1	0	2.155
15	0.15	250	1.5	0	1.977
16	0.15	300	0.5	0	1.923
17	0.15	300	1	0	1.897
18	0.15	300	1.5	0	2.655
19	0.2	200	0.5	0	2.11
20	0.2	200	1	0	2.53
21	0.2	200	1.5	0	3.06
22	0.2	250	0.5	0	1.911
23	0.2	250	1	0	2.116
24	0.2	250	1.5	0	2.965
25	0.2	300	0.5	0	2.355
26	0.2	300	1	0	2.688
27	0.2	300	1.5	0	1.988
28	0.1	300	0.5	0.2	2.55
29	0.1	300	0.5	0.4	3.125

surface finish due to tool wear are shown in Figure 4a.Unfavourable chips were formed due to tool wear and hence poor surface finish (Figure 4b).

The index most commonly used to express the comparisons quantitatively is the arithmetic mean value (Ra). The Ra values obtained from TESA surf tester are shown in Table3.

Based on the obtained Ra values from the experiments, the chips were segregated as favorable chips and unfavorablechips. The maximum value of Ra was obtained for experiment number 11 (Table 3). The presence of graphitic film in the composite greatly influences the surface roughness while machining. The major reason for this is the reduction in coefficient of friction at the tool workpiece interface resulting in the easy cutting of material. Graphite particles being less dense and soft were easily smeared on the work piece surface. This results in the formation of pits and valleys which in turn leads to higher surface roughness values. Figure 6a and b show the effect of speed and feed rate on surface roughness. The graphs revealed that as cutting speed increases the surface roughness decreases and as feed increases the surface roughness increases. Table 4 shows the effect of chips on surface roughness.

CONCLUSION

At low cutting speed (200m/min), the chips formed were segmented and discontinuous. At higher cutting speeds (300m/min) semi continuous chips were formed with saw toothed tip found in the inner surface of the chip. As the feed rate is increased, keeping the other two parameters constant, the length of the chips increased. The number of curls was also found to increase. The surface roughness value (Ra value) was found minimum for semi continuous segmented chips. At lower cutting speeds and high feed rates the chips formed (discontinuous segmented chips) were found to be unfavorable as the

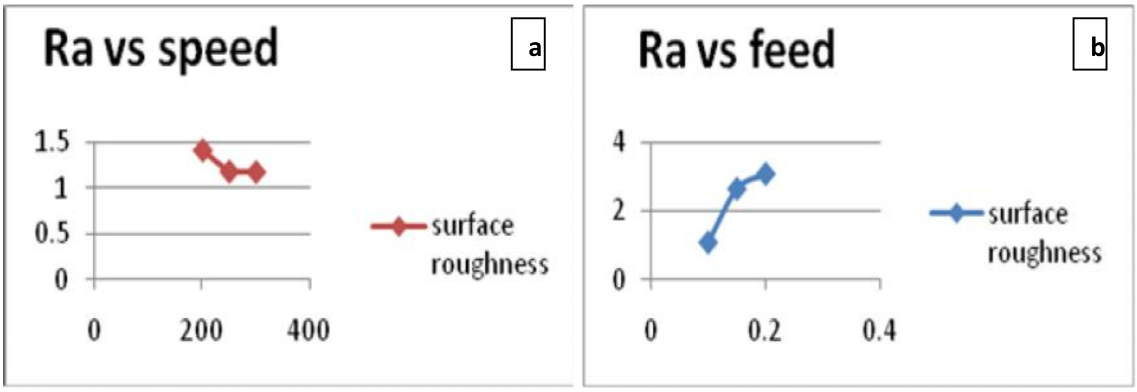

Figure 6 (a). Effect of speed **(b).** Effect of feed on Surface roughness

Table 4. Effect of chips on surface roughness

Chip condition	Experiment number	Feed	Speed	Ra
Favorable	6	0.1	250	1.183
	7		300	1.048
	8		300	1.08
	9		300	1.177
Unfavorable	11	0.15	200	
				3.362
	18	0.15	300	2.655
Unfavorable	21	0.2	200	
				3.06
	24	0.2	250	2.965
	26	0.2	300	2.688

surface roughness values were found to be larger. Saw toothed tip was not found in the chips classified under “unfavorable chips “indicating tool wear.

The fact that different kinds of chip formation can be observed for machining same material under different cutting conditions makes the analytical model of machining difficult because individual approaches tend to be aimed at one type of chip formation .Thus the prediction of when each type of chip formation will occur is a difficult complication to overcome. The experimental results can be validated by comparing it with the analytical results obtained through simulation of the metal turning operation using software’s like LS DYNA, DEFORM.

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