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Research Article

Surface Integrity of Newly Developed of Alsi/AlN Metal Matrix Composite during End Milling Under Dry Cutting Conditions

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Abstract: The investigation on surface integrity (surface roughness, microstructure and microhardness) were carried out in order to analyze the cutting parameters affected the surface integrity for better machinability of AlSi/AlN MMC. Five cutting parameters (cutting speed, feed rate, depth of cut, volume fraction of particles reinforcement and type of coated insert) were performed. Two types of coating (TiB_2 and TiN/TiCN/TiN) of carbide cutting tools were employed to machine various volume fractions of AlN particles (5%, 7% and 10%) reinforced to AlSi Alloy MMC under dry cutting condition. The results shows that the optimum levels for minimum surface roughness are; A_1 (single coating of insert), B_3 (cutting speed: 250 m/min), C_2 (feed rate: 0.75 mm/tooth), D_1 (axial depth: 0.6 mm) and E_1 (5% reinforcement). Surface roughness value increases along with increase in volume fraction of reinforcement. Depth of cut is more significant than feed rate and cutting speed in obtaining lower surface roughness. This could be due to the formation of BUE on the rake face of cutting tool at higher Depth Of Cut (DOC). The increases of volume fraction of AlN particles, from 5 to 10% give contribution to the changes of hardness. A surface dislocation is occurred at the highest speed and feed; 250 m/min and 0.9 mm/tooth. This phenomenon happens at high cutting condition due to the highly heat generation which softens the machined surface.

Keywords: AlSi/AlN Metal matrix composite, coated carbide, end milling, surface integrity

INTRODUCTION

Metal Matrix Composite (MMC), a lightweight materials, have a good potential for application in the automotive and aerospace industries (Kennedy *et al*., 1997; Ravikiran and Surappa, 1997; Allision and Gole, 1993). These materials are new generation of composite materials, which combines the tough metallic matrix with a hard ceramic reinforcement. The combinations resulting high strength, hardness, wear resistance and strength to weight ratio (Muthukrishnan *et al*., 2008a, b; Barnes *et al*., 1999). Due to its greater mechanical properties, MMC being used as a replacement material in various engineering applications such as for cylinder block liners, vehicle drive shafts, automotive pistons, bicycle frames and etc (Gallab and Sklad, 1998).

The type and properties of the matrix, reinforcement and interface will affect the structure and properties of MMCs. Aluminium, titanium and magnesium are the various types of materials commonly used as matrix phase and the most popular of reinforcements are silicon carbide and aluminium oxide (Seeman *et al*., 2010; Sornakumar and Kathiresan, 2010). Particulate Metal Matrix Composites (PMMCs) are more attractive than continuous fiber reinforced MMCs due to the higher ductility and lower anisotropy. Moreover, they are much cheaper and need simpler processing methods (Karl, 2006). Mostly MMCs are manufactured by near net shape manufacturing technique. However, secondary processes by conventional turning or milling is always necessary (Gallab and Sklad, 1998). As example, Toyota has developed a 5% Al2O3 short fiber reinforced Al alloy diesel engine piston and continued the process to the secondary machining operations (Altunpak and Akbulut, 2009).

One of the main concerns in machining of MMC is the surface integrity of the finished part or components in order to achieve better quality to the greater extent. Therefore the assessment of surface integrity (surface roughness, microstructure and microhardness) will provide contributions for better machining process of AlSi/AlN MMC. Reddy *et al*. (2008) in their research had mentioned about the high heat generation in the

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machining zone. During the machining process, workpiece will receive a large amount of heat, expands leading to dimensional inaccuracies. The larger thermal load happened when the tool approached the workpiece which can result in higher levels of diffusion, oxidation, etc., leading to high tool wear. They used TiAlN coated tools in their experimental study and found that the tools could withstand the heat generated under the predetermined operating conditions. The improved machining performance was due to the coating material which is able to maintain high hardness and resistance to oxidation at high operating temperatures.

Gallab and Sklad (1998) in their experimental study in surface integrity, found that the reinforcing SiC particles become pulled-out of the surface, while others become fractured when machining of Al/20% SiC PMMC and it is due to plastic deformation in the matrix material. They concluded that by increasing the feed rate and depth of cut, the voids surrounding the particles join up and cause chip segmentation. Also, by increasing the cutting speed only, i.e., keeping the low feed rate and depth of cut, leads to ductile tearing of the chips.

Insufficient investigations have been done to find out the effect of cutting parameters on surface integrity during machining of MMC. It is known that the study of surface integrity is the most effective way of understanding machining characteristics of a material. The study would be helpful for the efficient and economic machining so that these materials will have large applications in a near future. Therefore, the objective of this paper is to study the surface integrity of AlSi/AlN MMC using single and triple coated carbide tool during end milling operation under dry cutting condition. Investigations to see the effect of cutting parameters on surface quality of machined AlSi/AlN MMC were carried out. The comparison in terms of surface integrity (roughness, microstructure and microhardness) was analyzed in order to know the machinability of these materials.

WORKPIECE MATERIALS

The experimental study was carried out using Alumunium Nitride (AlN) particles reinforced aluminium alloy composites. The different wt% of AlN particles; 5, 7 and 10 wt% (Wahab *et al*., 2009) were used with mean size of the reinforcement particles is <10 µm and the purity >98%. The chemical composition of AlSi alloy was determined by a glow discharge profiler (Model-Horiba Jobin Yyon). Table 1 shows the chemical composition of AlSi alloy. The AlSi/AlN MMC was fabricated by the stir casting method. Firstly, AlSi alloy ingot was heated in a graphite crucible at 750 ^{0}C and held for 30 min until the material melted completely. The preheated AlN particles were added to the molten metal and stirred for 5 min (Fig. 1), then immediately cast into a permanent mould by the bottom pour technique. The solidified AlSi/AlN metal matrix composite passed through a heat treatment process to increase the mechanical properties; strength and hardness.

Table 1: Chemical composition of AlSi alloy

Elements	Fe	Si	Zn	Mg	Cu	Ni
Wt%	0.42	11.1	0.02	0.01	0.02	0.001
Elements	Sn	Co	Ti	Cr	Al	
Wt%	0.016	0.004	0.009	0.008	Balance	

Table 2: Cutting parameters and levels

		Levels		
Parameters	Factors	1	2	3
Type of coating	A	Single	Triple	
Cutting speed (m/min)	B	150	200	250
Feed rate (mm/tooth)	C	0.6	0.75	0.9
Axial depth of cut (mm)	D	0.6	0.75	0.9
% of reinforcement	E	5	7	10

Fig. 1: Stir casting process

Cutting conditions: The end milling process was used in this experimental study. A high precision CNC milling machine, DMC635V eco DMGECOLINE vertical milling machine was fitted with a KISTLER dynamometer. The cutting factors considered for the study were cutting speed, feed, depth of cut, wt% of AlN, with two types of cutting tools. Effects of parameters on surface integrity were studied by conducting a set of experiments, Taguchi method (Ghani *et al*., 2004) under dry cutting condition. The cutting parameters and its levels are shown in Table 2. The cutting inserts were PVD TiB2 coated and PVD TiN/TiCN/TiN coated. Cutting inserts were attached in the tool body with diameter ∅12 mm. Eighteen experiments were done to determine the surface integrity (surface roughness, microstructure and microhardness). Microstructure of machined material on a section perpendicular to the surface of workpiece was analyzed using optic microscope (Olympus Optical Microscope). The surface roughness of the machined surface was observed using a roughness tester Mpi mahr perthometer and the microhardness measurement was carried out using a Vickers microhardness tester.

RESULTS AND DISCUSSION

Surface roughness: The roughness of the machined surface was measured using a roughness tester Mpi mahr perthometer. Table 3 shows the summarized data

Table 3: Surface roughness, Ra and S/N ratio for L18 standard orthogonal array

Exp no.	A	B	C	D	E	Ra (μm)	S/N ratio (db)
1	1	1	1	1	1	0.270	11.373
2	1	1	2	2	2	0.443	7.072
3	1	1	3	3	3	0.559	5.052
4	1	2	1	1	2	0.449	6.955
5	1	2	2	2	3	0.572	4.852
6	1	2	3	3	1	0.439	7.151
7	1	3	1	2	1	0.373	8.566
8	1	3	2	3	2	0.408	7.787
9	1	3	3	1	3	0.475	6.466
10	2	1	1	3	3	0.626	4.069
11	2	1	2	1	1	0.357	8.947
12	2	1	3	2	2	0.655	3.675
13	2	2	1	2	3	0.585	4.657
14	2	2	2	3	1	0.464	6.670
15	2	2	3	1	2	0.593	4.539
16	2	3	1	3	2	0.668	3.504
17	2	3	2	1	3	0.424	7.453
18	2	3	3	2	1	0.411	7.723

Table 4: Mean values of S/N ratio for surface roughness

Main effect for S/N ratio					
Levels	A	B	C	D	E
1	7.253	6.698	6.521	7.622	8.405
2	5.693	5.804	7.130	6.091	5.589
3		6.917	5.768	5.705	5.425
diff Δ	1.560	0.894	1.362	1.917	2.980

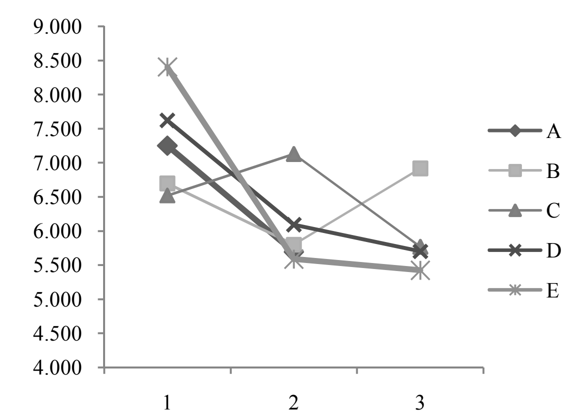


Fig. 2: Effect of cutting parameters on mean value S/N ratio for surface roughness

for surface roughness, Ra and S/N ratio. The S/N ratio was calculated using the condition smaller-the-better as shown in Eq. (1).

Smaller-the-better S/N (Reddy *et al*., 2008):

$$\eta = -10\log_{10}\left(\left(\frac{1}{n}\sum_{n=1}^{n} y_i^2\right)\right) \quad (1)$$

Due to the orthogonal experimental design, the effects of each parameter were separated at different levels. For example, the mean S/N ratio for the cutting speed at level 1 was calculated by averaging the S/N ratios for the experiments 1-3 and 10-12. Mean S/N ratio at level 2 were calculated by averaging the S/N ratios for the experiments 4-6 and 13-15. While, for level 3 were calculated by averaging the S/N ratios for the experiments 7-9 and 16-18. The mean values of the S/N ratio for each cutting parameter were calculated and summarized in Table 4. Also, the main effects for surface roughness, S/N ratio of the five control factors at each level are shown in Fig. 2.

The highest mean value of the S/N ratio for each parameter was chosen, representing the optimum condition. It can be seen from Fig. 2 that the optimum levels for minimum surface roughness were; A_1 (single coating of insert), B_3 (cutting speed: 250 m/min), C_2 (feed rate: 0.75 mm/tooth), D_1 (axial depth: 0.6 mm) and E_1 (5% reinforcement).

Pareto ANOVA (Ghani *et al*., 2004) was also performed to study the relative significance of the cutting parameters. The percentage of factor contribution was defined as the significance rate of the cutting parameters on the surface roughness. Table 5 shows that the percentage of reinforcement (E), axial depth of cut (D), feed rate (C), type of coating (A) and cutting speed (B) affect surface roughness of the surface of AlSi/AlN metal matrix composite by 56, 20, 9, 8 and 7%, respectively. From the experiment, it has been observed that the percentage of reinforcement and depth of cut are the most significant factors contributing to the minimum surface roughness. Surface roughness value increases along with increase in percentage of reinforcement (Sahin *et al*., 2002). Furthermore, the depth of cut is more significant than feed rate and cutting speed (Oktem *et al*., 2006; Ramanujam *et al*., 2011) in obtaining lower surface roughness. This could be due to the formation of BUE on the rake face of cutting tool at higher Depth Of Cut (DOC). The increase in DOC results in high normal pressure and seizure on the rake face and promotes the BUE formation, which caused the increasing of roughness value when the DOC is increased (Seeman *et al*., 2010; Palanikumar and Karthikeyan, 2007).

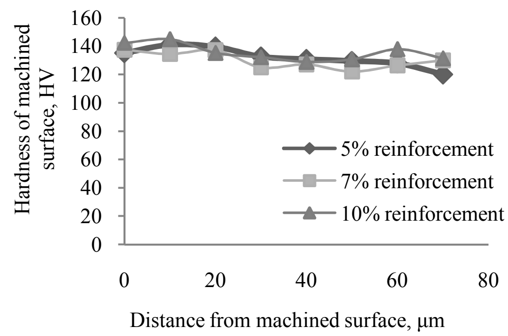
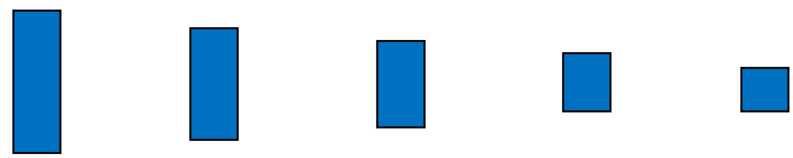


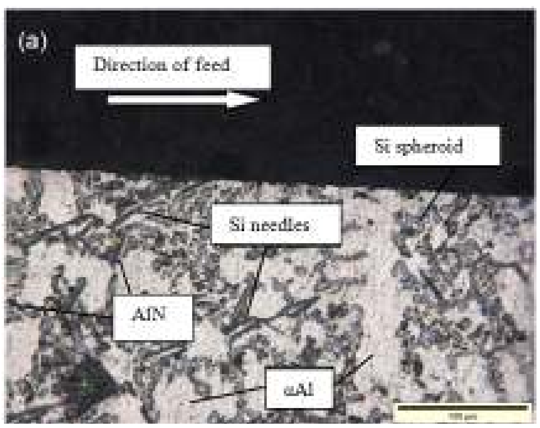
Fig. 3: Effect of percentage of reinforcement on microhardness variations for AlSi/AlN MMC

MICROHARDNESS

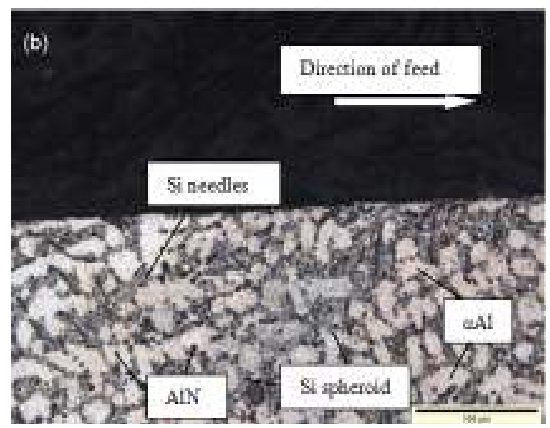
The microhardness data was taken at the different wt% of reinforcement. The depth of plastically

Table 5: Pareto ANOVA analysis for surface roughness

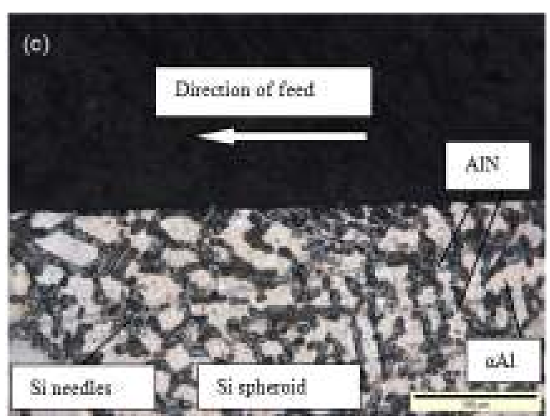
Sum at level/factor		A	B	C	D	E
	1	7.253	6.698	6.521	7.622	8.405
	2	5.693	5.804	7.130	6.091	5.589
	3		6.917	5.768	5.705	5.425
Sum of squares of differences (S)		2.433	2.085	2.794	6.167	16.838
Contribution ratio (%)		8.024	6.877	9.217	20.342	55.541
Pareto diagram						
Significant factor		E	D	C	A	B
Factor contribution		56%	20%	9%	8%	7%
Commulative contribution		56%	76%	85%	93%	100%
Combination of significant factor level		E1D1C2A1B3				



(a) V = 200 m/min, f = 0.9 mm/tooth, 5wt% AlN



(b) V = 150 m/min, f = 0.9 mm/tooth, 7wt% AlN



(c) V = 250 m/min, f = 0.9 mm/tooth, 10wt% AlN

Fig. 4: Microstructure of AlSi/AlN MMC for different cutting condition

deformed zone is between 0 to 80 µm beneath the machined layer. Higher hardness value was detected at the machined surface. Moving beneath, the hardness decreases and reaches the hardness of the aluminium matrix of the bulk material.

The changes of material hardness are due to the plastic deformation and the changes of wt% reinforcement of MMC associated with thermal gradients during machining process. Cutting speed is one of the factors contributed to the changes of hardness. The increase in cutting speed will lead to the increase in strain, strain rate and temperature. At higher cutting speeds, the temperature and heat generated is higher. Lower mechanical stresses are imposed on the surface layer due to lower cutting forces generated. As a result, a portion of the heat generated gets dissipated into the matrix material that will be sufficient enough to penetrate and soften the material (Kannan and Kishawy, 2006). While decreasing the cutting speed decreases the temperature. Heat generated is lower and higher mechanical stress is imposed on the surface layer. This is due to the higher generation of cutting forces. Consequently, the effect of highly work hardening of the matrix causes the loss of strength due to thermal softening of the matrix material (Kannan and Kishawy, 2006).

The changes of wt% of reinforcement also contributing to the changes of hardness. The higher wt% reinforcement showed higher values of microhardness. With increasing the wt% reinforcement, the number of particles increases and spacing between particles decreases. It will resulting the higher hardness when the wt% of particles reinforcement is increased. Figure 3 shows the microhardness values for the different wt% reinforcement of MMC. However, there is no major changes in terms of hardnes. This could be due to the new cutting tool used in this experimental analysis. For the new cutting tool, the thermal gradients during machining process is lower compared to the tool which has been used for some period of time.

MICROSTRUCTURE

The samples of AlSi/AlN MMC were etched using the Keller Reagent before been observed under optical microscope (Olympus Optical microscope). The analysis was performed at different cutting speed and higher feed rate, 0.9 mm/tooth. Figure 4a to c shows the microstructure of 5, 7 and 10wt% of reinforcement. A surface dislocation is occurred at the highest speed and feed; 250 m/min and 0.9 mm/tooth. This phenomenon happens at high cutting condition due to the highly heat generation which softens the machined surface. It also happen when the cutting force induced the machined surface towards the cutting direction. Further beneath from the machined surface, the dislocation density is much lower. Matrix grains are much finer at machined surface compared to than those existing away from the machined surface. Strengthening by the AlN particles is another possible reason for the increase in hardness close to the machined surface of AlSi/AlN MMC.

CONCLUSION

In this study, the surface integrity of AlSi/AlN MMC was analyzed in order to understand the end milling machining process better; provide inputs that can ensure better machining of AlSi/AlN MMC. The following observations were made:

- The optimum levels for minimum surface roughness were; A_1 (single coating of insert), B_3 (cutting speed: 250 m/min), C_2 (feed rate: 0.75 mm/tooth), D_1 (axial depth: 0.6 mm) and E_1 (5% reinforcement). Surface roughness value increases along with increase in percentage of reinforcement. Furthermore, the depth of cut is more significant than feed rate and cutting speed in obtaining lower surface roughness. This could be due to the formation of BUE on the rake face of cutting tool at higher Depth Of Cut (DOC). The increase in DOC results in high normal pressure and seizure on the rake face and promotes the BUE formation, which caused the increasing of roughness value when the DOC is increase
- The changes of wt% of reinforcement also contributing to the changes of hardness. The higher wt% reinforcement showed higher values of microhardness. With increasing the wt% reinforcement, the number of particles increases and spacing between particles decreases. It will resulting the higher hardness when the wt% of particles reinforcement is increased
- A surface dislocation is occurred at the highest speed and feed; 250 m/min and 0.9 mm/tooth. This phenomenon happens at high cutting condition due to the highly heat generation which softens the machined surface.

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