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High Speed Milling of Al_2O_3 Particles Reinforced Aluminum MMC

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Abstract: High speed milling of various proportions Al_2O_3 particles reinforced aluminum-based Metal Matrix Composites (MMC) by coated carbide tools under different cutting fluid application conditions is presented in this paper. It is found that Built-Up Edge (BUE) formed easily in high speed dry milling of 10 wt% Al_2O_3 aluminum MMCs. The chip welding is significantly reduced and a better workpiece surface finish and lowering cutting force is achieved together with negligibly small tool wear under wet cutting and MQL (minimum quantity lubrication). Hence a very high cutting speed together with MQL is recommended to cut this type of MMCs. High speed dry milling of 15 wt% Al_2O_3 aluminum MMCs generates few BUE but accompanied with serious wear of the tool by abrasion. A better machined surface finish and an increased tool life than those under dry cutting and wet cutting are resulted when MQL is applied. Permeation of the oil mist to wet tool-chip interface is responsible for these advantageous effects. On the contrary, the wear due to the increasing amount of Al_2O_3 reinforced particles is so serious that there is little improvement in tool wear and workpiece surface finish in the machining of 20 wt% Al_2O_3 aluminum MMCs under MQL condition. In summary, high cutting speed with the aid of MQL is appropriate in machining aluminum MMCs containing fewer reinforced particles. Aluminum MMCs with reinforced particles content higher than 20 wt% should be cut at a lower cutting speed.

Keywords: Flank wear, high speed machining, metal matrix composites, minimum quantity lubrication, surface roughness

INTRODUCTION

Metal Matrix Composites (MMCs), a combination of two or more materials to achieve better mechanical, chemical and physical properties, were developed in late 1960s. Currently, aluminum-, copper- and magnesium-based MMCs have been widely applied in the defense, aerospace, automotive and electronic industries. In general, machining procedures are usually needed to obtain the desired dimensional accuracy and surface finish. However, various studies have indicated that the machinability of aluminum MMCs is very limited due to severe tool wear. Many reports have shown that reinforced particles are the main reason leading to the flank face tool wear (Quan and Zhou, 1998; Quan and Ye, 2001). Sahin and Sur (2004) found that the higher content of reinforced particles in MMCs would result in more serious wear of the tool and hence concluded that the abrasive wear caused by the reinforced particles was the main mechanism. Other studies claimed that cutting speed was also important in machining of aluminum MMCs. Kılıçkap *et al*. (2005) carried out an investigation on turning of 5% SiC particle reinforced aluminum MMCs with different cutting speeds and feed rates. According to their observations, the accelerated flank wear occurred at higher speed. This implies that cutting speed is one of the most influential parameter on tool wear. Besides, some literatures concentrated on the built-up edge (BUE) that influent the machined surface finish of aluminum MMCs (Looney *et al*., 1992; Barnes and Pashby, 2000). BUE is apt to form in machining aluminum base materials and leads to a degradation of the machined surface finish. Manna and Bhattacharayya (2003) found that no BUE formed at high speed and low depth of cut in machining of SiC particle reinforced aluminum MMCs. It is therefore suggested that high cutting speed can be selected to achieve better surface finish. However, the reduction of BUE is accompanied with increasing tool wear at high cutting speed.

In summary, there have been various studies on tool wear characteristics in machining of aluminum MMCs, but the approaches to achieve better machinability such as machined surface roughness and tool wear are still limited. High speed machining is an ideal manufacturing technique for higher productivity, fewer BUE and better surface finish. But the high temperature will result in serious tool wear. In general, cutting fluid is often applied in the machining process for preventing BUE formation and reducing tool wear, but it causes an increase in cost as well as waste disposal problems. Recently, the Minimum Quantity Lubrication (MQL) technique has been developed which uses the high pressure air together with

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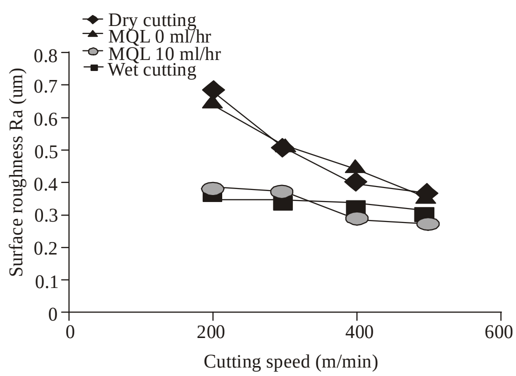
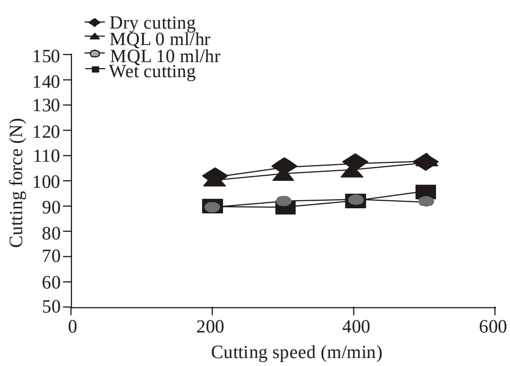
the minimum amount of cutting oil (<50 mL/h) and has found wide applications in practice. In this study experiments in milling aluminum MMCs at relatively high cutting speed under different cutting fluid applications (dry cutting, wet cutting and MQL) were conducted and the mechanisms of tool wear and the machined surface roughness were investigated.

EXPERIMENT

A CNC milling machine was applied to machine different proportioned (10, 15 and 20 wt% Al_2O_3, respectively) aluminum MMCs in this study. The 12 mm diameter Sandvik R390-012A-11L (inclination angle 8º and top rake angle 20º) one tooth milling cutter was used. The insert was TiAlN+TiN coated carbide of Sandvik R390-11 T3 04E-PL 1025. In the experiment, the depth of cut and feed were kept constant at 0.5 mm and 1 mm/tooth. The cutting speed ranging from 200 to 500 m/min was selected. The total distance of cut for each test was 456 mm. The experiments were conducted under dry cutting, wet cutting and MQL conditions. USA water miscible sulfonated castor oil was used in wet cutting and MQL. The MQL was accomplished by Steidle's Lubrimat^{Ò} L50. The tool wear, cutting force (along three directions Fx, Fy and Fz) and surface roughness were measured in order to get more insight of the effects of various cutting fluids and application methods. Tool wear on the flank (V_b) was measured under the Nikon MM40 toolmaker microscope. The cutting forces were measured by the Kistler's Type 9257BA Dynamometer. The roughness of machined surface in terms of arithmetic average surface roughness (Ra) was measured by Taylor Hobson Sur-Tronic 3+ surface roughness measuring instrument with a cut-off and evaluation length of 0.8 and 4 mm, respectively.



(a)



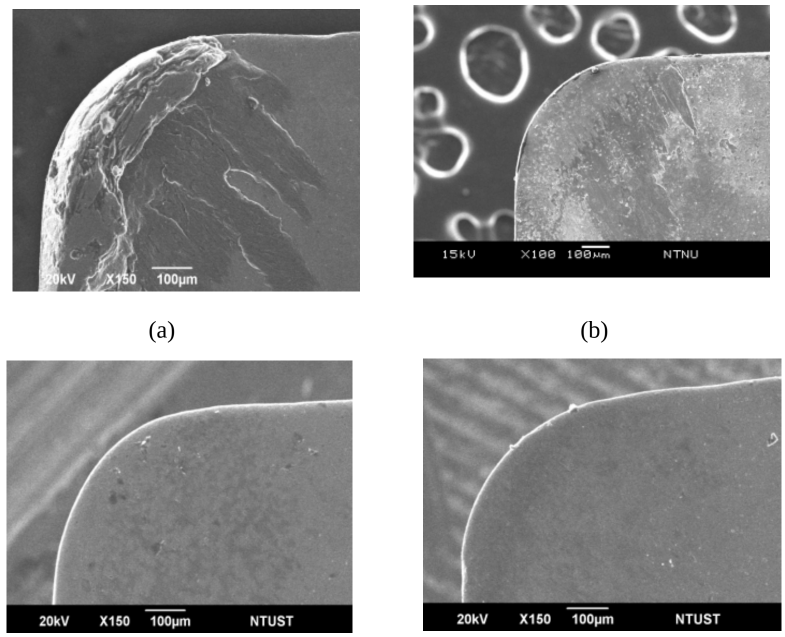
(b)

Fig. 1: (a) Machined surface roughness and (b) cutting force in cutting of 10 wt.% Al_2O_3 MMCs under dry cutting and various cutting fluid application conditions (depth of cut=0.5 mm, feed =0.1 mm/t)

RESULTS AND DISCUSSION

The machined surface roughness and cutting force in cutting of 10 wt% Al_2O3 aluminum MMCs at various cutting speeds under various cutting fluid application methods are shown in Fig. 1a and b, respectively. In MQL besides the use of 10 mL/h cutting fluid, 0 mL/h or pressurized air only was also tested for comparison purpose. It can be seen from these two figures that the machined surface roughness is decreased while the cutting force is increased with the increase of cutting speed under all cases. It is also noted that surface roughness (also cutting force) with respect to cutting speed under dry cutting and MQL with 0 mL/h cutting fluid condition is almost the same. Similar results are observed under wet cutting and MQL with 10 mL/h cutting fluid condition. The SEM microphotographs of the tool face in dry cutting at the cutting speed of 200 and 500 m/min are given in Fig. 2a and b, respectively. It is clear from these two figures that there is less amount of BUE at higher cutting speed (i.e., 500 m/min in this case) since the temperature is higher. Looking at the recorded cutting forces with time under these two cutting conditions as depicted in Fig. 3a and b, it is noticed that the variation of cutting force at cutting speed 500 m/min is smaller than that at 200 m/min. This indicates that the machining process becomes more stable as the cutting speed is increased. Apparently, less amount of BUE together with more stable machining process contribute better surface finish at higher cutting speeds. On the other hand, the surface finish will be deteriorated with the increase of the tool wear; a fact generally takes place at higher cutting speed. However it is found that there is nearly no wear on the tool flank even at the higher cutting speed of 500 m/min and hence the negative effect due to tool wear with the increase of cutting speed can be neglected in this case. Since the tool wear is negligible, the increase of cutting force with respect to cutting speed may be the result of the increase of rake angle owing to the reduction of the amount of BUE as cutting speed is increased.

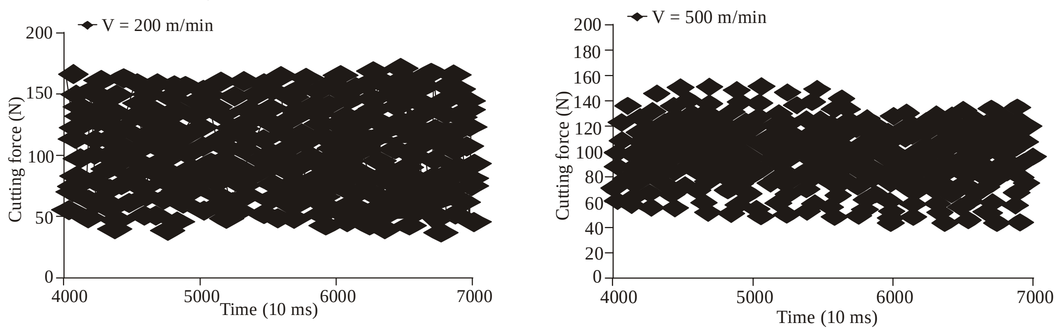
The SEM microphotographs of the tool face under wet cutting and MQL with 10 mL/h cutting fluid



(a) (b)

(c) (d)

Fig. 2: SEM microphotographs of tool face in cutting 10 wt.% Al_2O_3MMCs under (a) dry cutting at V = 200 m/min, (b) dry cutting at V = 500 m/min, (c) wet cutting at V = 200 m/min (d) MQL with 10 mL/h cutting fluid at V = 200 m/min (depth of cut = 0.5 mm, feed = 0.1 mm/t)



(a) (b)

Fig. 3: The relationship between cutting force and cutting time in cutting of 10 wt.% Al_2O_3MMCs under dry cutting condition at (a) V = 200 m/min and (b) V = 500 m/min (depth of cut = 0.5 mm, feed = 0.1 mm/t)

condition at the cutting speed of 200 m/min are shown in Fig. 2c and d, respectively. Comparing to that shown in Fig. 2a it can be clearly seen that the amount of BUE is greatly reduced and there is practically no difference in the SEM microphotograph of tool face under wet cutting and MQL with 10 mL/h cutting fluid condition. This may explain the reason why the improvements of surface finish under both conditions with respect to cutting speed over dry cutting

As that shown in Fig. 1a is almost the same. The very little difference in surface roughness and cutting force obtained in dry cutting and under MQL with 0 mL/h cutting fluid (pressurized air) condition implies that cooling effect plays very minor role in high speed cutting of 10 wt% Al_2O_3MMCs. On the contrary, the reduction of BUE under wet cutting and MQL with 10 mL/h cutting fluid condition suggests that the effect of lubrication is important. It is responsible for the apparent improvement of surface finish Fig. 1a and the decrease of cutting force Fig. 1b under wet cutting and MQL with 10 mL/h cutting fluid condition. Since there is nearly no wear of the tool in high speed cutting of 10 wt% Al_2O_3 MMCs and because the lubrication effect is essential to reduce BUE, it is concluded that very high speed even higher

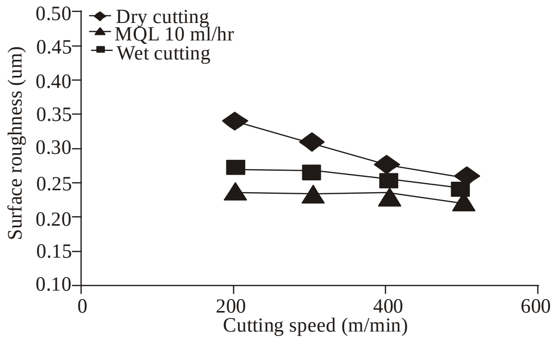
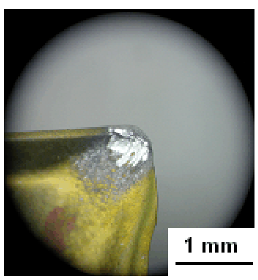


Fig. 4: Machined surface roughness in cutting of 15 wt.% Al_2O_3 MMCs under dry cutting and various cutting fluid application conditions (depth of cut = 0.5 mm, feed = 0.1 mm/t)



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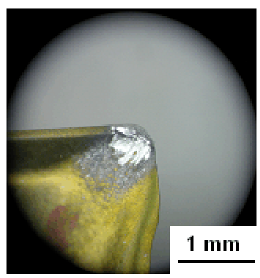

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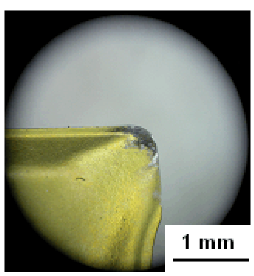
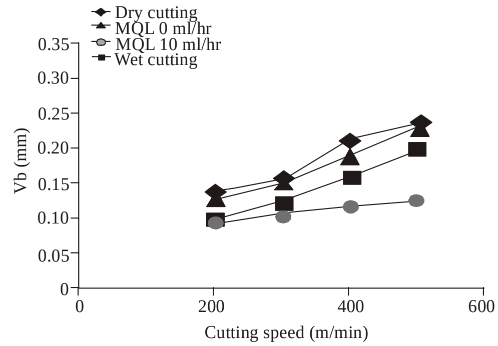


(c)

Fig. 5: Photographs of tool face in cutting (a) 10 wt.% Al_2O_3 MMC, (b) 15 wt.% Al_2O_3 MMCs and (c) 20 wt.% Al_2O_3 MMCs under dry cutting condition at V = 200 m/min. (depth of cut = 0.5 mm, feed = 0.1 mm/t)

than of 500 m/min together with the application of MQL with 10 mL/h cutting fluid is appropriate to machine 10 wt% Al_2O_3 MMCs.

Figure 4 presents the results of machined surface roughness with respect to cutting speed under various cutting fluid application methods in machining of 15 wt% Al_2O_3 MMCs. It can be seen that the surface roughness decreases with the increase of cutting speed; similar to the cutting of 10 wt% Al_2O_3 MMCs. But a better surface roughness can be obtained in machining of 15 wt% Al_2O_3 MMCs as comparing to that in machining of 10 wt%



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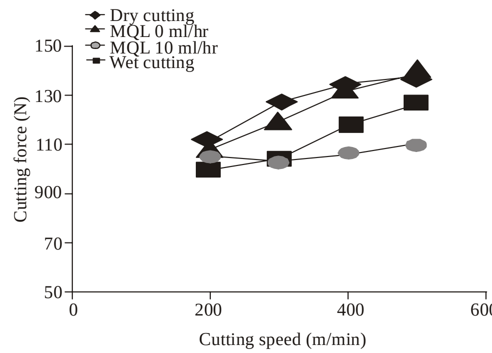
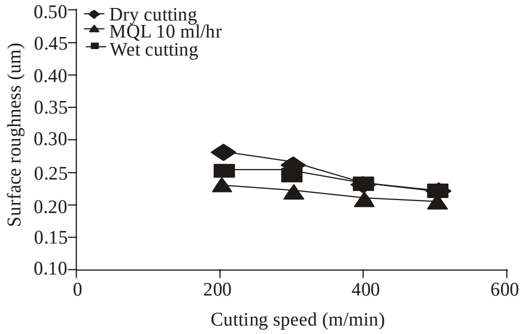


(b)

Fig. 6: (a) Flank wear and (b) cutting force in cutting 15 wt.% Al_2O_3 MMCs under dry cutting and various cutting fluid application conditions (depth of cut = 0.5 mm, feed = 0.1 mm/t)

Al_2O_3 MMCs Fig. 1a. The surface roughness in terms of Ra is about 0.7 μm in dry cutting of 10 wt% Al_2O_3 MMCs at cutting speed 200 m/min while it is about 0.34 μm for 15 wt% Al_2O_3 MMCs. The tool faces in dry cutting of 10, 15 and 20wt% Al_2O_3 MMCs, respectively at the cutting speed of 200 m/min are shown in Fig. 5a to c. The amount of BUE is reduced with increasing amount of Al_2O_3 reinforced particles because plastic deformation of the aluminum MMCs becomes more difficult. Hence it can be readily concluded that the improvement in surface finish in cutting a higher content reinforced particles is due to less amount of BUE formed on the tool face. Similar to the cutting of 10 wt% Al_2O_3 MMCs, the cutting process becomes more stable in cutting 15 wt% Al_2O_3 MMCs under a higher cutting speed condition. But as shown in Fig. 6a the flank wear which will deteriorate machined surface is more severe with the increase of cutting speed. Even with this negative effect, as discussed above the surface finish is still improved with the increase of cutting speed. Hence it is concluded that BUE is still the most influential factor that affect the machined surface finish in machining 15 wt% Al_2O_3 MMCs.



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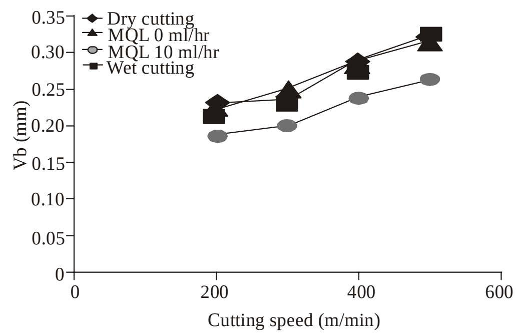

(b)

Fig. 7: (a) Flank wear and (b) machined surface roughness in cutting 20 wt.% Al_2O_3 MMCs under dry cutting and various cutting fluid application conditions (depth of cut = 0.5 mm, feed = 0.1 mm/t)

In comparing Fig. 1a and Fig. 4 it is noticed that there is less improvement of surface roughness by the application of cutting fluid in machining of 15 wt% Al_2O_3 MMCs than that in machining of 10 wt% Al_2O_3 MMCs. This is attributed to less amount of BUE formed on the tool face and the negative effect due to accelerated tool wear when there are more Al_2O_3 reinforced particles. From Fig. 4 it is also noted that the machined surface roughness under MQL with 10 mL/h cutting fluid condition is smaller than that under wet cutting condition. This may be attributed to the difference in the cutting fluid application. In MQL the pressurized air and cutting fluid mist is ejected toward cutting zone. This will result in a better permeation of cutting fluid to the chip-tool interface and leads to better lubrication effect as a result as compared to that of wet cutting.

The cutting forces in machining of 15 wt% Al_2O_3 aluminum MMCs under various cutting application methods are given in Fig. 6b. Similar to that in cutting 10 wt% Al_2O_3 aluminum MMCs the cutting force rises but to a larger extent with the increase of cutting speed. This is reasonable since there is less amount of BUE and tool wear is more serious in this case. The cutting force in dry cutting is larger than that under wet cutting and MQL with 10 mL/h cutting fluid condition, but it is very close to that under MQL with 0 mL/h cutting fluid condition. This result confirms again that the difference is originated from lubrication effect. The better lubrication under MQL condition discussed previously also leads to a lower cutting force and less flank wear Fig. 6b than that under wet cutting condition.

It can be summarized that MQL with 10 mL/h cutting fluid operated at the cutting speed of 200 to 500 m/min is recommended in cutting of 15 wt% Al_2O_3 aluminum MMCs.

The machined surface roughness and flank wear with respect to cutting speed in the cutting of 20 wt% Al_2O_3 aluminum MMCs under various cutting conditions are shown in Fig 7a and b, respectively. A better surface roughness than that in cutting 10 and 15 wt% Al_2O_3 aluminum MMCs is obtained since there is less amount of BUE (Fig. 5). It has been discussed previously that there nearly no tool wear taking place on flank face in cutting 10 wt% MMCs while there is obvious flank wear in cutting 10 wt% MMCs. This infers that abrasion by Al_2O_3 particles should be the main mechanism of flank wear. The hardness of Al_2O_3 particles and that for coated carbide tool are 2600 and 1650 Hv, respectively. Hence the most serious abrasive wear is observed in machining of 20 wt% Al_2O_3 aluminum MMCs, while the very few abrasive particles of 10 wt% Al_2O_3 aluminum MMCs causes little flank wear. It can be seen from Fig. 7b that tool wear is the least under MQL with 10 mL/h cutting fluid condition. Hence application of MQL with 10 mL/h cutting fluid is always recommended in cutting 20 wt% Al_2O_3 aluminum MMCs. But to alleviate the problem of serious tool wear, the use of lower cutting speed such as 200 m/min can be considered.

CONCLUSION

The performances of different cutting fluids and application methods in high speed milling of aluminum MMCs are studied in this paper. Based on the experimental results the following conclusions are obtained:

- The increased content of reinforced Al_2O_3 particles in aluminum MMCs leads to more flank wear of the cutting tool and less amount of BUE during the high speed milling process.
- MQL application in high speed machining of aluminum MMCs with coated carbide tool is a good choice in machining of 10 and 15 wt% Al_2O_3 MMCs. It results in satisfactory machined surface finish and small tool wear in addition to the benefits of environmental protection and cost savings.
- High speed milling is not suggested in the machining of aluminum MMCs with a higher content of Al_2O_3 particles such as 20 wt% Al_2O_3 MMCs. The serious

flank wear of the tool takes place easily during the machining process as the content of reinforced particles is increased.

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