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Conventional Machining of Metal Matrix Composites : A Review

KEYWORDS: MMC, surface roughness, conventional machining, wear mechanism, tool life.

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ABSTRACT In recent years Metal Matrix Composites have gained interest in research world and in industries due to their specific characteristics like high specific strength, stiffness, and wear resistance. These properties associated with other properties like low density and ability to operate at higher temperature, have made these materials an excellent choice for different products from aerospace to sports industries. However, due to the abrasive nature of the reinforcements, MMC is considered as a difficult to cut material. The present paper focuses on the problems come across during high speed machining of Metal Matrix Composite. It also concentrated on tool life, surface quality, cutting force generated during different conventional processes.

I. INTRODUCTION

Conventional machining is considered for composites because their reinforcements are brittle and material separation is accomplished by brittle fracture rather than plastic deformation ahead of the tool. However, the cutting tool materials must be attentively chosen to minimize wear due to the hard abrasive constituents of the reinforcing phase in the composite representing the work material. Machining of a composite depends on the properties and relative content of the reinforcement and the matrix materials as well as on its response to the machining process.

MMCs can be classified into the following categories as per the types of reinforcements:

1. Particle reinforced MMCs;
2. Whiskers or short-fiber reinforced MMCs;
3. Long-fiber or continuous fiber reinforced MMCs

Types of MMCs	Reinforcements
Particle reinforced	Al_2O_3, SiC, WC, TiC, B_4C
Continuous fiber reinforcement	Al_2O_3, SiC, B, C, Al_2O_3 + SiO_2, Nb-Ti, Nb_2Sn, Si_2N_4
Whiskers or short fiber	Al_2O_3, B, C, Al_2O_3 + SiO_2, SiC, TiB_2

Table 1. different reinforcement used in different MMCs

Table 1. Shows typical types of reinforcement used in each category of MMC. Generally, these composites are fabricated by three techniques namely solid state, liquid state and powder metallurgy. Among them liquid state is the most widely used due to its low-cost and effortless production process. Some new methods like melt-stir casting, continuous casting, direct-chill casting etc., have been reported by several researchers [1–4] for fabrication of MMC. Conventional machining processes such as turning, drilling and milling are utilized for machining composite materials in which reinforcements are highly abrasive and hard; sometimes as hard as or even harder than the tool material.

II. TURNING OPERATION OF MMCs

In the recent research turning process has been mostly used for different studies like chip formation, tool life, tool wear mechanism, surface quality and for optimization of machining parameter for improving cutting tool performance.

A. WEAR MECHANISMS AND TOOL LIFE

The tool wear rate will depend on the mechanical properties of composites volume fraction, the reinforcement morphology, distribution and volume fraction, as well as the matrix properties, are all factors that affect the overall cutting process. Several researchers have also indicated that polycrystalline diamond (PCD) tools are the only tool material that is capable of providing a useful tool life during the machining of particulate light metal MMCs. PCD is sufficiently harder than most of the ceramic reinforcements and has no chemical tendency to react with the workpiece material. PCD tools contain larger grain structures that withstand more abrasion wear by micro-cutting compared to tools with a smaller grain structure Tomac and Tonnessen [6] investigated the machinability of Al-SiC MMCs using PCD, chemical vapor deposition (CVD), and coated tungsten carbide tools. The investigation revealed that abrasive wear is the main mode of tool failure. The PCD tools had over 30 times higher tool life than carbides they used under similar cutting conditions. Similar to the work of Tomac and Tonnessen [6], Hung et al. [7] carried out tests on turning of MMCs with CBN, PCD, WC and DCC (diamond-coated carbide) tools and compared the tool wear with different turning parameters. More recently Kishawy et al. [8] presented an analytical model for predicting tool flank wear progression during turning of particulate reinforced MMCs. Figure 1 shows a typical mode of tool wear when cutting MMC. The equation was developed to determine flank wear:

$$\frac{dV_B}{dt} = \frac{3K}{4RSin\left(\frac{\theta}{2}\right)V_B \tan\gamma}\left[\sqrt{\left(\frac{N\theta_c}{H_t}\right)^2 + \left(\frac{N\theta_c}{\pi H_t}\left(\frac{H_t}{H_a}\right)^1\left(\frac{D}{d}\right)\left(\frac{f_v}{\pi(1-f_v)}\right)\right)^2}\right] \quad (1)$$

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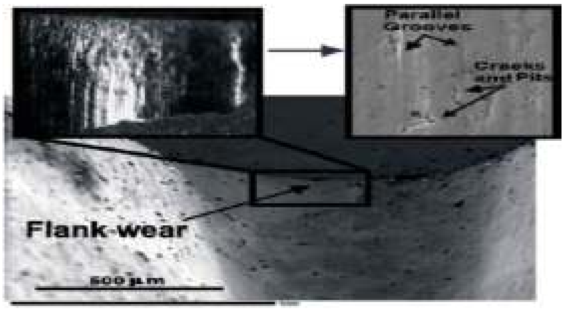

Figure 1. Flank wear when cutting under typical condition [8]

For finding out a better tool performance Chen [9] studied the performance of self-propelled rotary tools through turning trials on Al-SiC MMCs and compared the results with fixed tools. It was concluded that the rotary tool showed better tool life and wear resistance. Coelho et al. [10] proposed an empirical relationship between tool wear and milling speed and agreed with Chen's findings that the cutting speed had negligible effect on tool wear. several researchers have reported that the tool life decreases with increase in cutting speed. Lin et al. [11] reported a similar phenomenon as Sahin [12] when machining Al alloy with 20% reinforcement using PCD tools where the wear increased rapidly with the increase in cutting speed.

B. SURFACE ROUGHNESS

Number of researchers have investigated the relation between surface roughness and the cutting speed. Some of the obtained results were complementary while some showed a contradiction to the remaining available data. Tomac et al. [6] Excellent surface finish can be produced when machining with a PCD tool. Similar to those obtained by comparable grinding operations. The surface roughness deteriorates with increasing cutting speed due to the generation of narrow grooves on the specimen surfaces, caused by ploughing of the Sic panicles Manna and Bhattacharya [21], carried out turning of Al alloy with 15% SiC MMC using tungsten carbide tools. It was found that the surface roughness decreased by half with the increase in the cutting speed from 60 to 180 m/min. It is commonly believed that the feed rate has a negative effect on surface integrity, as shown in Fig. 2. The average roughness can be estimated with the following theoretical equation:

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

As noted by Tomac and Tonnessen [6], when feed rate is low, the theoretically calculated surface roughness (Ra) overestimates the real value measured from the experiments. This low roughness was attributed to the large nose radius when the tool wears. Similar results are reported by Manna and Bhattacharya [21] while machining Al-SiC MMC.

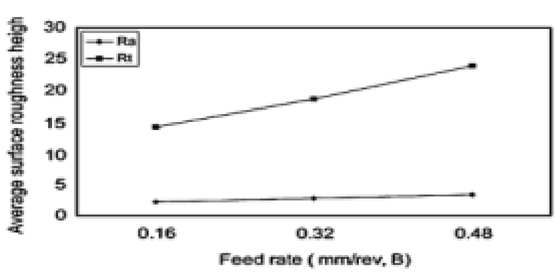

Figure 2 Average surface roughness Vs feed rate for different MMCs

Ciftci et al. [22] investigated the effect of particle size on surface roughness when turning Al/SiCp MMC with coated and uncoated tools. Based on the conducted study they concluded that roughness values (Ra and Rt) increased with the increase in particle size and the volume fraction of the reinforcement particles. Also, they observed better improvement of the surface finish at lower cutting speed when using un-coated carbide tool compared to cutting with coated tools (TiC, Al2O3). At higher cutting speeds a reversed trend was reported where the coated tools outperformed the uncoated ones. Songmene and Balazinski [23] studied the machinability of a new family of MMCs "GrA-Ni" consisting of an aluminum matrix reinforced with nickel coated graphite particles and SiC or Al2O3 particles. This generation of MMC is usually used for cylinder sleeves and brake drums. The researchers conducted turning tests using PCD and diamond-coated carbide tools.

C.CHIP FORMATION

The material ahead of the cutting tool edge is subjected to severe plastic deformation and subsequent shearing results in chip formation. Chip formation during turning of metal matrix composites differs slightly in some aspects. The reinforcement particles or fibers are distributed randomly at and about the tool movement/edge. The presence of hard reinforcements alters the plastic deformation characteristics of the soft matrix material compared to those of a conventional alloy. Thus, the change in mechanical properties coupled with reinforcement, configuration and distribution in the matrix determines the mechanism of chip formation (shearing, plowing, particle interface debonding, pull out and cracking) and hence the machinability of MMCs.

D. PROCESS OF MODELING

Most of the early studies were based either on experimental studies that compare the performance of different tools or on the empirical and numerical studies related to tool life. Very little research has been conducted to predict the cutting forces generated in MMC machining. Hoecheng et al. [25] carried out a thorough study on the effect of cutting conditions, such as cutting speed, depth of cut, rake angle and cutting fluid during machining MMCs. The volume fraction of reinforcing particles was responsible for the increased cutting force, while decreasing negative rake angle can lead to a reduction in cutting force. First analytical force model was developed by kishawy et al. [26] where the cutting force was estimated based on the energy consumed in the primary, secondary shear zone and reinforcement particle displacement and fracture. According to the model, total energy per unit volume of metal removed is:

$$e = E_p + E_s + E_d \qquad (3)$$

The chip formation force was obtained by using Merchant analysis but those due to matrix plowing deformation and particle fracture were formulated respectively with the aid of the slip-line field theory of plasticity and the Griffith theory of fracture. However, the chip–tool friction force due to reinforcement particles was not considered.

III.DRILLING OF MMC

Considerable research in the field of drilling MMC had been done to improve tool life, and for optimize the cutting conditions for different drills. Normally used drills in these studies include PCD tipped drills, high-speed steel (HSS) drills, diamond-coated HSS drills, coated carbide drills (tungsten carbide (WC) and TiN), and TiAlN coated drills. Cronjager and Meister studied the effect of cutting speed on the tool wear of two different drills. It was found that the tool

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wear of WC drills increases with the increase in the drilling speed. However, the drilling speed has no noticeable effect on the wear of PCD twist drills in the range of low-to-medium cutting speeds of 15–300 m/min. The tests were carried out on Aluminum alloy 2,628 with 15% SiC reinforcements. The results in Fig. 4.13 show that PCD-tipped drill bits perform the best under different cutting conditions among all the drill materials. They also reported that the cutting speed was not a significant factor affecting tool life which confirms the earlier findings reported by Lane.

IV. MILLING OF MMC

One of the earliest studies in milling of MMC was carried out by Lane [39] on newly casted MMC with different types of tools; namely HSS and coated tools. These tools were proved to be not economically for the task, however, TiC or TiN coatings offered slight advantage.

V. CONCLUSION

From several studies it is concluded that there are different types of MMCs available. The aim behind these studies is to provide optimum cutting condition by improving some of the response the affect the machining quality of MMCs . From most of the studies it has been concluded that poor machinibility is due to abrasive nature of the reinforcements and hardness of MMC material. It is also concluded that with increase in the hardness and volume fraction of partical machinibility decreases. Analytical and numerical studies have been carried out in an effort to quantify these effects and some satisfactory results were obtained. Even though, for the conventional alloys the deformation behavior and the friction law governing chip–tool interface friction during machining has not yet been well defined. In addition, the effect of reinforcement particles on the deformation mechanisms during machining of MMCs is also not fully understood. There is still research required to clarify these interactions before we can go deep into the new possible concepts and further developments regarding MMCs and machining.

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