Material Science Research India Vol. **11**(2), 114-120 (2014)

Review on Machining of Aluminium Metal Matrix Composites

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http://dx.doi.org/10.13005/msri/110204

(Received: October 09, 2014; Accepted: October 27, 2014)

ABSTRACT

Metal matrix composites have superior mechanical properties in comparison to metals over a wide range of operating conditions. This make them an attractive option in replacing metals for various engineering applications. This paper provides a literature review, on machining of Aluminium metal matrix composites (AMMC) especially the particle reinforced Aluminium metal matrix composites. This paper is an attempt to give brief account of recent work to predict cutting parameters & surface generated in AMMC. By suitably selecting the machining parameters, machining of AMMC can be made economical.

Key words: AMMC, Reinforcement, Cutting speed, Feed, Depth of cut, Surface finish, Machinability etc.

INTRODUCTION

Composite materials consist of two or more materials that differ in chemical and physical properties and are not soluble in one another. The primary constituent in a composite material is the matrix phase that provides load transfer and structural integrity, while the reinforcement to enhance mechanical properties. The matrix and reinforcement materials can either be organic (polymers), inorganic (ceramic or glass) or metallic (aluminum, titanium, etc.). The most common forms of reinforcement materials are fibers (long and short), or particulates.

Composite materials have superior specific properties (high strength to weight ratio) compared to metals, high stiffness and good damage resistance over a wide range of operating conditions, making them an attractive option in replacing conventional materials for many engineering applications. Important properties of composite materials are: improved strength & stiffness, excellent fatigue resistance, high heat resistant, high wear resistant, high corrosion resistant, low weight etc. By suitable arrangement of metal matrix and reinforcement addition, it is possible to obtain desired properties for a particular application.

Matrix materials in Metal Matrix Composites (MMC) are aluminium, magnesium and titanium alloys. Reinforcing materials in MMC are silicon carbide, boron carbide, alumina and graphite in the form of particles, short fibers (whiskers) or long fibers. In Aluminium Metal Matrix Composites (AMMC), matrix material is aluminium and reinforcement materials are silicon carbide, aluminum oxide, boron carbide, graphite etc. in the form of fibers, whiskers & particles. This paper discusses the important aspects of machining of MMC especially the Aluminium metal matrix composites.

Machining of Aluminium Metal Matrix Composite: A Review

Though MMCs are manufactured to near net shape, a need often exists for machining. Machining characteristics depends on the reinforcement material, type of reinforcement (particle or whisker), distribution of reinforcement in the matrix, and volume fraction of the reinforcement and matrix. Machining results of MMC are different than metal machining due to presence of hard and brittle reinforcements. While machining tool encounters matrix and reinforcement materials alternatively, whose response to machining is entirely different. The main problem in machining MMC is the high tool wear, which leads to an uneconomical production process or makes the process impossible. Thus, machining of composite materials imposes special demands on the geometry and wear resistance of the cutting tools.

Figure 1 shows phenomenon of MMC machining. It is similar to machining of conventional metals. In machining of MMC, there is excessive wear of cutting tool. The dominant wear mechanism is abrasion, which is generated by impacts at the cutting edge and by the sliding motion of the particles relative to the rake and clearance face. Different wear mechanisms are responsible for the abrasive tool wear. These are known as microploughing, microfatigue, microcutting and microcracking. The process of ploughing occurs due to material deformation and displacement by rounded part of the cutting edge BC. This is the plastic deformation zone where no chip is formed. In addition to ploughing, particle fracture and displacement also takes place in this region. The particle fracture and displacement is considered to occur mainly along the cutting line CD.

The research work to assess the cutting forces, cutting temperature, tool wear, surface roughness and sub-surface damage during machining of particulate metal matrix composites has been extensively studied experimentally in the past. R. Teti [1] concluded that main problem in machining MMC is the high tool wear which makes machining uneconomical. Another critical factor is damage of the reinforcement in the subsurface zone which reduces the properties of the finished MMC part. D'Errico et al.[2] turned MMC parts using PCD & CVD tools and concluded that these tool materials can be used for machining MMC. Gallab et al. [3] presented comprehensive tool wear models for Aluminium particulate MMC. They concluded that for evaluating temperatures and stresses generated in the cutting tool, numerical methods, such as the finite element method, offer a more promising approach compared to direct measurement techniques. Tay et al. developed 2-D model to compute the temperature distribution in the tool, chip and workpiece. Marusich and Ortiz developed a Lagrangian finite element model of orthogonal high speed machining. Both ductile and brittle fracture initiation and propagation were accounted for during processing; an essential feature for determining shear-localized chip morphologies [4]. Shetty et al. [5] applied Taguchi's technique in machining of MMC. The method helps in proper selection of machining parameters. Study found that tool wear is predominantly caused by abrasion of hard reinforcement particles in the MMC.

Kemal et al. [6] analyzed particle distribution in particulate MMC. Study shows that there is usually particle clustering or agglomeration occurs in PMMC. This clustering significantly decreases the local property of the PMMC. However, uniform distribution of particles in the final product is essential in the PMMCs to obtain desired mechanical and thermal properties.

Kilickap *et al*. [7] investigated machining parameters on tool wear & surface roughness for 5% SiC-p Al-MMC. They found that cutting speed is the most influential machining parameter on tool wear. Feed rate is the second influential machining parameter. Higher depth of cut, slightly increased tool wear. Kannan et al. [8] investigated the effect of cutting parameters and particulate properties on the microhardness variations of the aluminium matrix beneath the machined surface. They concluded that geometrical defects like microcracks, voids, pits and craters were predominantly formed due to particulate fracture and/or pull-out and interfacial debonding.

Pramanik et al. [9] developed a mechanics model to predict the forces for machining aluminum alloy based MMCs reinforced with ceramic particles. The resultant cutting force was considered to consist of components due to chip formation, ploughing and, particle fracture and displacement. They showed that force due to chip formation is much higher than those due to ploughing and particle fracture. Pramanik et al. [10] investigated matrix deformation and tool-particle interactions during machining using finite element method. They showed that magnitude and distribution of stresses/strains in the MMC material and interaction of particles with the cutting tool are the main reasons for particle fracture and debonding during machining of MMC.

Dabade et al. [14] analyzed chip formation mechanism in machining of AMMC, using Taguchi method based experimentation, and concluded that at lower cutting speed (40mmin”1) thin flakes, needle type as well as segmented chips are formed, whereas at higher cutting speed (120mmin”1) generally, semi-continuous, continuous chips are formed. The length of chip and the number of chip curls increases with an increase in feed rate at given cutting speed and depth of cut.

Dandekar et al. [19] concluded that for mechanics modeling of machining, methods used are: finite element modeling (for machining at the macroscale), molecular dynamics studies(simulating nanometric cutting to capture atomic interactions) and multi-scale modeling(to bridge the gap between the atomistic and continuum scale). A number of methods have been proposed to reduce the computational cost for carrying out multimillion atom simulations necessary to simulate micromachining using only MD. The hybrid FE-MD modeling provides an atomistic description (MD) near the region of interest and the FE modeling describes the rest of the substrate.

Chandrasekaran et al. [21] applied soft computing techniques in machining performance prediction and optimization. They concluded that soft computing techniques are being preferred to physics-based models for predicting the performance of the machining processes and optimizing them. Dhavamani et al. [22] applied multi-objective optimization (based on Taguchi Method) for drilling processes of composite materials, as it increases the flexibility for selecting the optimal cutting parameters.

Machining Parameters and their Effects

In any conventional machining operation the primary machining parameters are cutting speed, feed, depth of cut etc. Properties of AMMC depend on matrix & reinforcement. Hence to assess the machining behavior of AMMC parameters like reinforcement orientation and tooling are also considered.

Effect of Cutting Speed

During machining of MMCs, at low cutting speeds, a built-up edge (BUE) has been observed by Manna et al. & Kilickap et al. [24-26]. Due to the BUE the cutting force at low cutting speeds is lower than the cutting force observed at higher cutting speeds. The presence of a BUE increases the actual rake angle of the tool resulting in a lower cutting force. Wang et al. & Manna et al. have shown a decrease

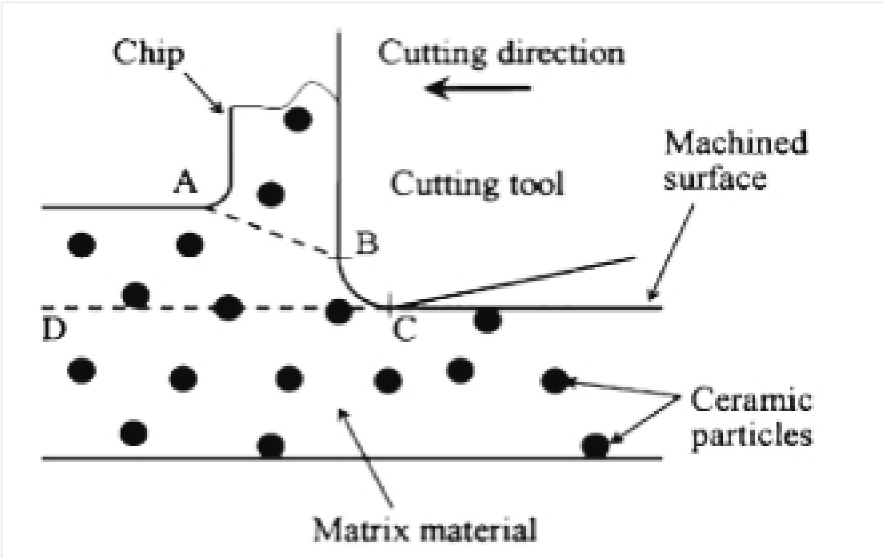

Fig. 1: Machining of metal matrix composites [46].

in the cutting forces with an increase in the cutting speed [27-28]. In the study conducted by Manna and Bhattacharya [28], the effect of the cutting speed on the feed force and cutting force during turning of an Al/SiC composite was measured. It was observed that the feed force and the cutting force decreased with an increase in the cutting speed.

The tool life decreases while the surface finish improves only slightly with an increase in cutting speed, since the tool temperature increases with cutting speed, thereby softening the tool material and consequently accelerating the diffusion wear [8, 29, 30]. Overall, the variation of surface roughness with cutting speed is not significant as the surface roughness is dominated by the size of reinforcement and the feed [29-31]. In terms of tool life, Manna and Bhattacharya [24-25] conducted studies using carbide tooling for machining of an Al/SiC composite and observed that the flank wear increased 2.5–3 times for an increase in cutting speed from 60 to 180 m/min. Another observation of flank wear variation with cutting speed is the very rapid increase in flank wear at cutting speeds above 100 m/min and hence cutting speed range of 60–100 m/min was suggested for machining of these composites. Ozben et al. [26] and Joshi et al. [32] both machined an aluminum matrix reinforced with SiC particles and observed that the cutting speed was one of the dominant factors in limiting the machinability of the composite.

Effect of Feed

Feed has considerable effect on the cutting forces as the cutting forces rise considerably with an increase in the feed [10, 33]. Many force prediction models for machining of MMCs have been given by researchers. Kishawy et al. [34] developed an energy-based analytical model to predict the forces in orthogonal cutting of an MMC using a ceramic tool at a low cutting speed. Pramanik et al. [10] developed a mechanics-based model for prediction of the cutting forces based on the mechanisms of chip formation, and the presence of the matrix and particle. Feed negatively affects the surface roughness, where the surface finish deteriorates with an increase in feed [29, 35]. Furthermore feed has the largest effect on the damage observed in the sub-surface [4,36]. El-Gallab and Sklad concluded that the failure in the composite initiates along the voids generated around the SiC particles due to the high cutting forces observed at higher feeds. The voids join up to form microcracks and subsequent fracture along the shear band. On the other hand feed tends to have less influence on the tool wear. A high feed can reduce the tool-wear rate due to the improvement in the conduction of heat from the cutting zone to the workpiece [8]. Feed increases the flank wear but only marginally as compared to cutting speed. At a cutting speed of 60 m/min increasing the feed three folds increased the flank wear 1.6 times, while increasing the speed three folds at a feed of 0.35 mm/rev the flank wear increased three times [24, 37].

Effect of Depth of Cut

Depth of cut has a negative effect on the surface finish and the sub-surface damage. An increase in depth of cut decreases the quality of the surface finish and the subsurface damage. Chambers [38] conducted a study on machining of a 15% by volume fraction of SiC in A356 aluminum alloy and concluded that the depth of cut did not significantly alter the tool life, with tool life decreasing with an increase in the depth of cut. Although the effect of depth of cut on tool wear is not significant, it has a stronger effect on the tool wear as compared to the feed as shown in machining of an Al/SiCp/15% composite with uncoated tungsten carbide tools [8, 24]. Additionally, an increase in the depth of cut increases the machining forces during the machining of MMCs.

Effect of Reinforcement

The presence of the reinforcement affects the machinability of composites substantially. The hard ceramic particles in the matrix cause problems such as excessive tool wear. The size and the percentage volume fraction of the reinforcement play a significant role on the machinability of composites. Surface finish is mainly dependent on the average size and volume fraction of the particles. Ciftci et al. [39] machined an Al/SiCp composite with SiC particle size of 30, 45 and 110 μm and a reinforcement of 16% volume using both coated and uncoated carbide tools. They concluded that the tool wear and the surface finish are negatively affected by the particle size. This observation was further proved by Kannan et al. [8] while machining a composite with 10% by volume fraction of alumina particles in an Al 6061 matrix, with average particle size of 9.5, 17, 20 and 25 μm. An increase in particle volume fraction also results in increased tool wear and subsequently affects the surface finish of the machined work piece. Higher tool wear is the result of the hard ceramic particles seen at a higher frequency by the cutting tool [8, 29, 39]. Ozben et al. [26] machined an aluminum matrix reinforced with SiC particles in 5, 10 and 15% by volume fraction and observed that the cutting speed and percentage volume fraction of the particles were the dominant factors in limiting the machinability of the composite. Joshi et al. [40] studied the effect of feed (0.084–0.17 mm/rev), cutting speed (22–88 m/min), tool inclination angle (15 and 45_) and percentage volume fraction of SiC particles in aluminum (10 and 30%) on machining of the MMC with a carbide tool and arrived at an empirical relationship between flank wear and cutting time as a function of the aforementioned parameters. The authors concluded that the cutting speed and the percentage volume fraction of the particles had the most significant effect on the tool life.

Effect of Tooling

While machining MMC the most commonly used tool material is polycrystalline diamond (PCD), although Chemical vapor deposition diamond (CVD), cubic boron nitride (CBN), alumina, silicon nitride and tungsten carbide (WC) tooling are also used as cutting materials.

PCD diamond tools are the most preferred, while carbide tools are preferred over ceramic tools [3, 29, 36, 41]. In case of carbide tooling low-cutting speeds and high-feed rates are utilized to maximize the tool life [8, 42]. High tool wear observed while machining of these composites is generally associated with carbide tooling. At higher cutting speeds ([350 m/min), the carbide tool shows catastrophic failure and hence the cutting speed is generally limited up to 300 m/min [29, 30, 36, 41, 43-45]. In other tool materials, Tomac and Tonnessen [42] compared the performance of chemical vapor deposition (CVD) coatings of TiN, TiCN and Al_2O_3 and concluded that the inserts with TiN coating performed the best in maximizing the tool life. To improve the tool life in carbide tools, Manna and Bhattacharya [24] machined at cutting conditions that sustained a stable built-up edge (BUE) so as to protect the cutting tool. To minimize the surface roughness and sub-surface damage PCD tools are preferred since the wear rate associated with them is the lowest among available tool materials. Although PCD tools are used for machining Al/SiC composites, the high cost associated with them limits their use [29, 30, 36, 41].

CONCLUSION

The paper has provided a literature review on machining of particulate Aluminium metal matrix composites. Tremendous attempts have been made in the machining of AMMCs. The process remains still challenging due to the distribution and orientation of reinforcement in the matrix and non-homogeneous and anisotropic nature of composite as a whole. By suitably selecting the machining parameters, machining of AMMC can be made economical.

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