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ORIGINAL ARTICLE

# Modeling machining of particle-reinforced aluminum-based metal matrix composites using cohesive zone elements

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**Abstract** Finite element modeling for the machining of heterogeneous materials like particle-reinforced metal matrix composites has not been much successful as compared to homogeneous metals due to several issues. The most challenging issue is to deal with severe mesh distortion due to nonuniform deformation inside the workpiece. Other problems are related to the modeling of the interface between reinforcement particles and matrix and tool-reinforcement particle interaction. In this study, different strategies are adopted for finite element models (FEM) to cope with the above issues and comparative analyses have been performed. These 2D FE models are based on plane strain formulations and utilize a coupled temperature displacement method. The workpiece is modeled using reinforcement particle size and volume fraction inside the base matrix. The interface between the reinforcement particles and the matrix is modeled by using two approaches, with and without cohesive zone elements, and the chip separation is modeled with and without using a parting line. This allows models to simulate the local effects such as tool-reinforcement particle interaction and reinforcement particle debonding. In addition, the models can predict cutting forces, chip morphology, stresses, and temperature distributions. The effects of different methodologies on the model development, simulation runs, and predicted results have been discussed. The results are compared with experimental data, and it has been found that the utilization of cohesive zone elements (CZE) with the parting line approach seems to be the best one for the modeling of metal matrix composite (MMC) machining.

**Keywords** Finite element models (FEM) · Metal matrix composites (MMCs) · Cohesive zone elements (CZE)

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## 1 Introduction

Metal matrix composites (MMCs), like all composites, consist of at least two chemically and physically distinct phases, suitably distributed to provide properties not obtainable with either of the individual phases. Generally, there are two phases, e.g., a fibrous or particulate phase, distributed in a metallic matrix. MMCs are gradually replacing conventional metals in many engineering applications due to their superior properties like fracture resistance, higher stiffness, and extremely good strength to weight ratio. MMCs are being used in transmission lines, aerospace and automobile parts, and various cutting tools specially oil drilling inserts. Some special physical properties make them an attractive choice for superconducting magnets and thermal management applications [1, 2].

MMCs can be subdivided into three broad categories: (a) equi-axes particle reinforced, (b) short fiber reinforced which may be aligned or not, and (c) long fiber reinforced. The development of a particular MMC for some specific applications depends on the methods of synthesis and fabrication for

stock items. These issues are of particular interest to material technologists and product development engineers [3].

The key issues in the processing of MMCs are the various problems associated with machining, i.e., MMCs have poor machinability as compared to conventional metals. This is mainly due to nonhomogeneity and abrasive nature of reinforcement particles. Mostly, MMCs are fabricated with near net shape processes, but some machining and finishing cuts are indispensable for final dimensions and surface finishes. Cutting tools such as high-speed steel, cast cobalt alloys, cemented carbides, and cermets cannot be used for machining of MMCs due to high wear rate. Diamond cutting tools are found to be the best option for machining of MMCs, and they are being utilized in the last 10 years for both particle- and fiber-based MMCs [4–6].

Fiber-reinforced composites are anisotropic as fibers are not equi-axes, whereas particulate-reinforced composites are isotropic like conventional metals. The latter provide higher ductility and their isotropic nature makes them a better alternative to conventional metals and alloys. The machinability of particulate-reinforced composites depends on many factors like particulate type, its orientation, tool material, tool geometry, and cutting conditions like cutting speed, feed, etc.

Numerous studies exist in the literature to analyze machining of MMCs using experiments and mostly related to measure performance variables like tool wear, surface roughness, subsurface damage, cutting forces, cutting temperatures, and chip morphology [2]. It has been found that parameters related to the structure of composites greatly affect the machinability. These include reinforcement material, reinforcement type, volume fraction of the particles, base metal properties, and overall arrangement of constituent phases. Polycrystalline diamond inserts (PCD) are commonly employed for their machining [7, 8]. The use of other ceramic materials like cubic boron nitride (CBN), alumina, and silicon nitride is also reported but did not have a major success. The effects of cutting parameters (speed, feed, and depth of cut) on machinability of MMCs are almost similar to those found in machining of conventional metals with some differences due to the abrasive nature of particles. A built-up edge is formed while machining these composites at low cutting speeds [9, 10]. This built-up edge increases the rake angle and consequently reduces the cutting forces compared to high cutting speeds. However, some studies have shown a decrease in cutting forces with an increase in cutting speed. Manna and Bhattacharayya machined aluminum-based MMCs reinforced with silicon carbide particles (Al/SiC) using an uncoated carbide tool. They showed that cutting and feed forces decrease with an increase in cutting speed [11]. The reinforced particles tend to expel out from the base metal and slide in front of the cutting tool edge. This results in plowing through the newly generated machined surface and groove marks on it [9, 12].

A lot of research has been done to model orthogonal machining of MMCs using finite element (FE) methods. Researchers used three approaches: (a) micromechanics-based approach, (b) equivalent homogeneous material (EHM) approach, and (c) hybrid approach, i.e., the combination of two [2]. The first two approaches have both advantages and disadvantages [13]. Debonding of reinforced particle and deformation mechanism can be best modeled by the micromechanics approach. However, the approach is computationally very expensive as a very fine mesh is required in contrast to conventional modeling. The EHM approach is unable to predict local effects such as damage at the particle-matrix interface [14, 15], but it reduces simulation time and can predict some performance variables like cutting forces and temperature with a reasonable degree of accuracy. The advantages of both approaches can be obtained using a hybrid approach. A combination of the micromechanical and EHM models is developed by Rao et al. [16] to study orthogonal cutting. The effects of fiber orientation on the cutting forces, chip formation, and fiber damage were analyzed using this approach. The EHM was used to model the overall phenomenon, while the micromechanical model was used near the tool tip and tool-chip interface.

Machining of particulate-reinforced metal matrix composites (PRMMC) has been modeled by various researchers. Except for a few, most of the studies are limited to 2D modeling and plane strain formulation, which can be utilized only for orthogonal machining. On the other hand, 3D modeling requires 3D stress formulation which is computationally expensive as compared to plane strain formulation. In addition, 3D models are complex due to consideration of different tool inclinations and movement of chip in three dimensions. Monaghan and Brazil [17] utilized a 2D finite element code FORGE2 to model failure at the particle-matrix interface and the residual stresses while machining aluminum-based MMCs. However, the interface modeling between particles and matrix was not mentioned and failure was predicted based on stress distribution. A similar study was done by Ramesh et al. [18] to predict cutting forces, stress distribution, and particle debonding. Stress distributions and cutting force requirement were predicted for different tool positions with respect to reinforcement particles. El-Gallab and Sklad [19] developed a model for the machining of SiC-reinforced aluminum alloy. It was found that feed has the largest effect on the subsurface damage and the residual stresses. Both subsurface damage and residual stresses increase with increased feed rate. The study was limited to orthogonal machining and the particles were assumed to be perfectly bonded. Other researchers model the tool-reinforcement particle interaction by considering particles on, above, and below the tool path [3, 20]. Zhou et al. [21] utilized a model for modeling of machining Al/SiC MMCs with a PCD tool. First, a 2D EHM model was developed to predict stress distributions,