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Review

Interaction of the cutting tools and the ceramic-reinforced metal matrix composites during micro-machining: A review

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ABSTRACT

High performance ceramic-reinforced metal matrix composites (MMCs) are becoming widely popular in industry and the mechanical machining method is one of the most suitable manufacturing techniques for near net shape MMC components. This paper provides a comprehensive literature review to enhance the fundamental understanding of the tool–workpiece interactions in micro-scale during cutting process on engineered-heterogeneous materials. The paper focuses on mechanical properties, fracture mechanism and machinability of ceramic-reinforced MMCs, with significant emphasis on the chip formation mechanism considering different dominant effects, such as materials strengthening mechanisms, micro-structural effect, size effect and minimum chip thickness effect. It also includes some work that, while not directly focused on micro-scale cutting ceramic-reinforced MMCs, but provided important insight to the field of cutting engineered-heterogeneous materials (non-eutectic). Furthermore, process modeling studies for micro-scale cutting are also surveyed, including the cutting force modeling, dynamics modeling and surface generation modeling. The comments on future needs and directions are provided at the end.

Contents

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1. Introduction

Metal matrix composite materials (MMCs) have been applied in numerous fields that include energy, defense, aerospace, biotechnology, optics and automobile, because of their reinforced high performance mechanical properties and reduced weight. In recent decades, substantial progress has been achieved in the development of MMCs. This enables the advanced heterogeneous materials to be considered in more applications, specifically, avionics packaging, micro-fluidic channels for fuel cells, micro-scale holes for fiber optics, micro-nozzle array for multiplexed electrospray systems, micro sensors and actuators [1–6]. These applications require outstanding mechanical properties, including light weight, high strength, high creep resistance, long fatigue life, high corrosion/oxidation resistance, low thermal expansion and good wear resistance.

On the other side, emerging miniaturization technologies are perceived as key technologies of the future in a broad spectrum of applications [2,3]. Due to the high surface-to-volume ratio, miniature components can provide lower power consumption, higher heat transfer, and are more flexible and efficient. Using miniature components under appropriate circumstances can further improve energy efficiency.

In aforementioned applications, both the small size and outstanding mechanical properties are required. Ceramic particle-reinforced metal matrix composites, such as aluminum-based MMCs (Al-MMCs) or magnesium-based MMCs (Mg-MMCs), with light weight and high toughness, are excellent candidates for making components for such applications. Thanks to the hard ceramic particles reinforcement, the mechanical properties are improved significantly. It was found that these composites exhibit much better mechanical properties, such as higher strength and superior wear resistance than pure Mg/Al and their alloys [7–9].

There exist a number of different fabrication methods to make miniaturized components, made of ceramic-reinforced MMCs. Since components made of advanced MMC materials usually contain complex 3-Dimensional (3-D) features, the traditional silicone-based fabrication methods for micro-electro-mechanical systems (MEMS) are not adequate. Several micro-manufacturing methods have been reported in the literature for SiC reinforced MMCs. Müller et al. [10] studied the capability of manufacturing SiC particle-reinforced aluminum matrix composites using EDM method. The results showed that the removal rate was low due to the poor electrical conductivity of SiC particles. In addition, electrode wear was severe and thus inevitably increased the manufacturing cost. Laser machining is another alternative method and is capable of making small diameter holes and cutting metal matrix composites. However, the surface quality was relatively poor and the microstructure of materials was changed under the effect of laser heating [11].

Compared to the above methods, the mechanical micro-machining process is promising to mass produce MMCs parts. This approach is cost-effective, flexible, and controllable, precise (relative accuracy as 10^{-3} to 10^{-5}), and capable to make arbitrary 3D pattern [2,10,11]. Using micro-machining technique, small components can be manufactured more efficiently with lower cost and higher quality.

However, the remarkably enhanced mechanical properties of MMCs, in terms of yield strength, fracture strength, wear resistance and shear modulus, bring great challenges for mechanical micro-machining. Comparing with micro-machining homogeneous metals, cutting forces when machining MMCs are much larger due to the existence of the ceramic particle reinforcement. Tool wear is more severe and tool life is shortened. Due to the elevated cutting force amplitude, tool vibration and tool deflection are more significant. As a result, both dimensional accuracy and surface quality are adversely affected. In order to achieve good machining efficiency and quality, it is important to fully understand the strengthening mechanism and the influence of reinforcement particles on the entire micro-cutting process, especially the chip formation process.

Fig. 1 illustrates the relationships among material properties, strengthening mechanisms and cutting mechanisms in different scales during mechanical micro-machining.

- In the micro-scale level, the fundamental microstructure and strengthening mechanisms of the MMCs establish the foundation for cutting mechanics and dynamics. Core research topics involve mechanical properties and fracture mechanisms of the material.
- In the meso-scale level, fundamental chip formation mechanism is different from traditional machining and micro-machining of homogeneous materials, due to the effect of heterogeneity, size effect and the minimum chip thickness effect, etc. The influence of material's microstructure and strengthening mechanism on chip formation is the key. The fundamental material removal mechanism for heterogeneous materials further establishes the theoretical foundation, which differentiates cutting regimes in macro-scale level. The chip formation modeling involves material strengthening effect, tool edge radius effect, size effect, minimum chip thickness effect; it is built to further predict dynamic cutting force during machining.
- In the macro-scale level, the research should focus on modeling the process states, including cutting forces and tool vibration, as well as the final machined surface integrity, in terms of dimensional accuracy and surface roughness.

Thorough understanding the tool-workpiece interaction mechanism and the chip formation physics will facilitate the modeling work of the entire micro-cutting process. With this purpose, this review paper specifically focuses on the interaction of the cutting tools and the ceramic-reinforced MMCs. Based on the process models, the productivity, machined surface integrity, and tool life can all be improved through optimizing the cutting conditions for specific ceramic-reinforced MMCs composite materials. The remainder of this paper is organized as follows. Section 2 reviews the properties of the ceramic-reinforced MMCs, including mechanical properties, fracture mechanisms and micro-machinability. Section 3 examines the chip formation process with emphasis on microstructural effect, strengthening effect, size effect and minimum chip thickness effect, as well as their influences on the cutting mechanism. In Section 4, the process modeling work is summarized for the micro-cutting process. Cutting force modeling, dynamics modeling and surface generation modeling are also covered. Section 5 concludes and provides future directions.

2. Ceramic-reinforced metal matrix composites

2.1. Mechanical properties

Ceramic-reinforced metal matrix composites (MMCs) have potential to replace conventional light-weight metallic materials,