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Surface characteristics of machined aluminium metal matrix composites

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Abstract

This paper investigates the effect of cutting parameters and particulate properties (volume fraction and average particulate size) on the microhardness variations of the aluminium matrix beneath the machined surface. Orthogonal cutting tests were carried out on different aluminium matrix composites reinforced with varying volume fractions and average sizes of alumina particulates. Characterization of the machined subsurface was made using optical, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The metallographic analysis revealed severely damaged machined subsurface with numerous geometrical defects and plastically deformed aluminium matrix. This study also yielded some interesting findings on the influence of particulate volume fraction and average size in altering the microhardness in the aluminium matrix. The lower the reinforcement volume fraction and the coarser the particulates, the higher are the variations in matrix microhardness. The microhardness measurements on the aluminium matrix beneath the machined layer showed higher values when machining under wet conditions with reduced depth of plastically deformed zone.

Keywords: Composite; Cutting; Microhardness

1. Introduction

In recent years, the critical need for less expensive structural materials that can provide an optimum level of performance has generated considerable research interest in the development and application of metal matrix composites (MMCs) [1–3]. MMC utilization provides significant benefits including performance (component lifetime, improved productivity), economic (energy savings or lower maintenance cost) and environmental (lower noise levels and fewer air-borne emissions) [4–8]. The presence of relatively large volume fraction of ceramic reinforcement profoundly affects the behavior of the aluminium matrix composites during manufacturing, heat treatment and their subsequent use in service. Some of the effects include microstructural changes, heat treatment characteristics and thermal stresses. These changes significantly alter the physical, mechanical, and tribological property limits of the composite [6].

The presence of ceramic reinforcement can also influence the solidification behavior and age hardening characteristics of several aluminium alloys [9,10]. This depends mainly on the matrix composition, the size, morphology, and volume fraction of the reinforcement and the method of composite production [9–12]. Aluminium matrix composites often experience a fabrication temperature in excess of 500 °C. When a metal matrix composite is cooled to room temperature from the fabrication or annealing temperature, thermal residual stresses are induced in the material as a result of the mismatch between the coefficient of thermal expansions of the metallic aluminium matrix and the ceramic reinforcements [13–17]. It has been reported that both tensile and compressive stresses can be found in the matrix and with the stress higher in the matrix near the particle interfaces. This is mainly due to thermal stresses induced in the matrix that are even higher than its yield strength and causes plastic flow near the interface [15]. The magnitude of thermal residual stresses developed is related to many variables including the type of reinforcement, volume fraction, size and shape. Mechanical behavior of MMCs is profoundly affected by these

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thermal residual stresses and in turn affects the fatigue and creep behavior of MMCs [13,17,18].

Significant differences in the machined part from the actual surface have been found with regard to mechanical, physical as well as metallurgical properties. These changes are mainly due to the influence of temperature, plastic deformation, tool wear, and corrosion [19]. It is generally observed that the microhardness variations in the machined surfaces for a given workpiece are dependent on cutting conditions, tool geometry, and whether or not a cutting fluid is used. It has also been found that the depth of the stressed region tends to increase with an increase in depth of cut, feed, and cutting speed. Application of coolant to some extent reduces the depth of stressed region at lower cutting speeds [20].

Several reports on the quality and integrity of the machined aluminium composites appear in the literature [8,21–24]. Subsurface damage due to machining processes of MMCs result from conventional and unconventional processes such as in turning, milling, facing and abrasive jet machining [25,26]. Most of the materials considered as difficult-to-cut require considerable energy to be spent during component manufacture. This often causes excessive damage in the machined surface, which deteriorate the fatigue performance [27]. Since the composite structure comprises of a ductile matrix reinforced with hard ceramic particles, the plastic deformation may not be homogenous [28,29]. During the machining of composites, severe friction occurs between the tool flank face and the machined surface. High temperatures are reached and rapid cooling causes thermal stress in the material [30].

During machining MMCs, ceramic particulate cracking and debonding are typical damage mechanisms that greatly affect the integrity of surface produced [31–34]. The particles pulled out by the tool during cutting process leave behind large pit holes, voids and craters that facilitate the formation of fatigue cracks [28,34]. Severe damage to the machined surface can be generated due to high temperature gradients during the cutting process. This produces residual stresses along with micro and macro cracks on the aluminium matrix that was plastically deformed causing severe hardness alterations and metallurgical transformations in the MMC material. In addition, a rapidly deteriorating cutting tool can also initiate material "side flow" due to squeezing of the aluminium material out from the interface between the tool flank face and workpiece. During cutting MMCs, the aluminium matrix being ductile is subjected to high compressive stresses by the cutting tool leading to non-homogenous plastic deformation [31,33]. Subsequently, small pieces of the workpiece material adhere to the cutting tool and are welded firmly due to high temperature and pressure during cutting process. As the cutting progresses, the conglomeration of workpiece material at the tool edge becomes larger and unstable. Consequently, when they shear off with the chip they create micro defects on the new surface.

The purpose of the present investigation is to understand thoroughly the extent of machining induced damages, in view of the higher unit cost per machined part and service life span of MMC components. The objective of this paper is to determine the effects of process parameters on the matrix hardness alteration on the machined surface and subsurface layer. The key role played by reinforcement properties like the volume fraction and average particle size on the microhardness variations of the aluminium matrix will also be analyzed in detail.

2. Experimental procedure

Orthogonal cutting experiments were conducted on Al_2O_3 particulate reinforced aluminium metal matrix composites. The different aluminium matrices alongwith the levels of particulate volume fraction and average sizes used in the experiments are shown in Table 1. Cutting tests were performed on a 10 HP standard lathe using uncoated tungsten carbide cutting tools with rake angle of 0° and clearance angle of 7°. The cutting conditions are given in Table 2. The machining forces were collected using a three component piezo-electric dynamometer (Kistler^{TM} type 9251A). The surface roughness measurements at different sections were conducted using a Mitutoyo SJ-201 surface roughness tester. The cutting tools were ultrasonically cleaned in 10% NaOH and then thoroughly in acetone. Flank wear was then measured with a tool maker's

Table 2
Cutting conditions

Process parameters	Cutting conditions
Cutting speed, V (m/min)	24, 60, 100
Uncut chip thickness, h (mm)	0.1, 0.3
Width of cut, b (mm)	3
Cutting environment	Dry and wet

Table 1
MMC material properties

Material	Matrix	Particulate volume fraction	Average particle size, d (μm)	Condition
Class 1	7075	10% alumina	15	T4
Class 2	6061	10% and 20% alumina	17, 23	T4
Class 3	6061	10% alumina	9.5, 20	T6

T4-Solution heat treatment: 560 °C, 2 h, water quenched and aged at room temperature for more than a month.
T6-Solution heat treatment: 560 °C, 2 h, water quenched and aged at 177 °C (10 h).