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Tribological aspects of machining aluminium metal matrix composites

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ABSTRACT

In this paper, tool wear, surface integrity and chip formation are studied under both dry and wet cutting conditions. The turning results showed that the influence of coolant on tool life was more pronounced at higher cutting speeds than at lower cutting speeds. This is mainly because of the dominance of the mechanical wear mechanisms at lower cutting speeds and the lack of formation of a lubricating layer/film that can reduce the friction between the abrasive particle and the cutting tool. When turning at higher speeds, under wet conditions, the tool life was increased. However, the surface quality was deteriorated. This was mainly due to the flushing away of the partially debonded particulates from the machined surface, thus, forming higher percentage of pit holes and voids. The formation of chips with serrated edge was more pronounced during wet cutting, as a result of high thermal gradient. The microhardness measurements on the aluminium matrix beneath the machined layer showed higher values when cutting under wet conditions.

1. Introduction

As advanced engineering materials, metal matrix composites are used in many applications that require high wear resistance such as cylinder liners, helicopter blades, ventral fins and lower drag brace landing gears in modern fighter planes [1–3]. Compared to the monolithic alloys, the wear resistance of MMCs is greatly enhanced by the introduction of a secondary phase in the form of abrasive ceramics into the ductile aluminium matrix [4]. By this way, the wear properties of the MMCs can be substantially varied through the changes in the microstructure, morphology, volume fraction and mechanical properties of the reinforcing particulates. Since most of the reinforcing phases in the MMCs form the base material for common cutting tool materials, it is expected that they are difficult to machine. It is generally agreed that cutting tools harder than the reinforcements perform well in terms of tool life, surface finish and metal removal rate [5–7]. However, the harder tools like PCD may not always be the most cost-effective tool material for MMCs [8].

Several comprehensive studies have been undertaken in the past to investigate the effect of cutting fluids on the machinability of MMCs [9–14]. The findings revealed inconsistent results. During the drilling of MMCs reinforced with different particulates like silicon carbide, aluminium oxide and boron carbide, the drill life was reported to be reduced by one-sixth as a result of usage of interior coolant [9]. The authors reported similar results during milling of the same material. Temperature distributions in the primary and secondary shear zones during cutting aluminium metal composites were predicted using finite element studies by Zhu and Kishawy [15]. Coolant helps the matrix in retaining its strength and reducing the temperature in the cutting zone, thus, causing higher tool wear [9]. The effect of cutting fluid on the machinability of MMCs was investigated by Hung et al. [10]. Their findings were contradictory to the earlier research

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Table 1 – MMC material properties

Material	Particle volume fraction	Average particle size (μm)
A356 MMC	20% SiC	12
7075 MMC	10% alumina	15

conducted by Cronjager et al. [9]. They reported that the application of coolant neither worsens nor improves tool life and that the surface finish and cutting forces were insensitive to cutting speed when machining with a new tool. The main reason cited for this was due to lack of a lubricating film. During the machining of MMCs the usage of coolant prevents the formation of built-up-edge. This results in an excellent surface finish comparable to ground surface [16]. Although the built-up-edge protects the cutting edge from sliding against the loose abrasive particulates and improves the tool life, in some cases, however could be detached and smeared along the path of the cutting tool thus deteriorating the surface quality [17].

Tribology plays a decisive role in the cutting operations. Tool wear, chip structure, and the quality and integrity of the workpiece are greatly affected by tribological conditions. Protective layers produced due to chemical interactions between the metallic workpiece surface and additives in the cutting fluids can contribute in reducing friction and tool wear. However, the tribological conditions experienced during machining MMCs are greatly different compared to aluminium alloys. This paper investigates the processes occurring in the narrow contact zone between the cutting tool and the workpiece. It is also of great interest to understand the role played by the coolant and loose abrasive particulates during cutting MMCs.

2. Experimental procedure

2.1. *Workpiece material*

For the turning tests, A356 silicon carbide particulate reinforced aluminium matrix composite was chosen. This workpiece material is considered as a potential replacement for the conventional A356 aluminium alloy in the manufacturing of automotive ancillary parts. 7075 alumina-reinforced aluminium composite was used for studying the machining induced subsurface damages. 7075 aluminium alloys are used in the manufacture of sensitive aircraft parts that require superior fatigue and creep performance. The material properties of the MMCs are listed in Table 1. The tool material represents an important parameter in turning metal matrix composites. Coated carbide cutting tools are less expensive than the diamond cutting tools and have been recommended for rough machining [10]. Therefore, the present investigation on machinability was performed with a coated tungsten carbide cutting tool. Properties of the cutting tool used are detailed in Table 2. The properties of the coolant chosen for wet cutting tests are given in Table 3. The selected emulsion contained additives based on sulphur and phosphorous and had higher water content for better cooling effect.

Table 3 – Coolant properties

Type	Emulsion
Phosphorous additives (%)	6
Sulphur additives (%)	5
Viscosity, cSt @ 40 °C	34
Density @15 °C (kg/L)	0.89
Coolant concentration (%)	20

Table 4 – Cutting conditions

Process parameters	Levels of independent parameters
Cutting speed, V (m/min)	60, 120, 240
Feed, f (mm/rev)	0.15
Depth of cut, a_p (mm)	2
Tool nose radius, R (mm)	0.8
Cutting environment	Wet and dry

2.2. *Turning tests*

Dry and wet turning tests were carried out on A356 MMC using coated tungsten carbide cutting tools on a 10HP standard modern lathe. Table 4 shows the different process parameters employed in this investigation. The machining forces were collected using a three component piezoelectric dynamometer (Kistler^{TM} type 9251A). The surface roughness measurements were conducted using a Mitutoyo SJ-201 surface roughness tester. The cutting tools were ultrasonically cleaned in 10% NaOH and then thoroughly in acetone to remove dirt, chips, and built-up-edge. Flank wear was then measured with a toolmaker's microscope. Each cutting tool was examined and the tool flank wear measurements were repeated three times. Inspection of the worn inserts and subsurface damage was carried out by scanning electron microscopy (SEM). Chemical compositions of deposits on the rake face and the flank face of the cutting tool were also determined.

3. Results

3.1. *Machining forces*

Fig. 1 shows a comparison of the magnitude of forces generated during machining A356 MMC under wet and dry cutting conditions. The recorded forces showed magnitude differences of about 10–20 N during wet and dry cutting at the tested cutting speed. This difference in the generated forces is considerably smaller. The possible reason for this is due to rapid abrasion of the cutting tool by the particles even under wet cutting conditions. Though the coolant used was efficient in reducing the heat generation, did not form any protective film to reduce the frictional conditions existing at the tool flank face. Consequently, the cutting tool deteriorated at the same or

Table 2 – Cutting tool properties

Material	Tool hardness KHN (GPa)	Nose radius (mm)	Rake angle (degree)	Clearance angle (degree)
Coated tungsten carbide	17	0.8	0	7