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Investigation of machinability in Al-MgO composites produced by melt-stirring

Abstract: In this study, Al-MgO reinforced metal matrix composites of 5%, 10% and 15% reinforcement-volume ratios were produced by melt-stirring and subjected to machining tests by carbide and coated carbide cutting tools. Machining tests were conducted with 150, 200, 250 and 300 m/min cutting speeds, 0.075, 0.15 and 0.225 mm/rpm feed rates and 1 mm depth of cut. Piezoelectric quartz crystal type dynamometer was used to measure cutting forces. As a result of the tests, it was observed that the increase in cutting speed first led to an increase and then a decrease in main cutting force values (Fc), and the increase in feed rate was accompanied with increased main cutting forces. The most consistent results in terms of Fc values were displayed by 10% MgO reinforced composites. While no abrasion occurred on the surfaces of cutting tools, build up edge formation was observed in the machining tests.

Keywords: casting; machining; metal matrix composites (MMCs); MgO.

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1 Introduction

At present, there are many kinds of composite materials and production types which are increasing day by day. One of these composite materials is the metal matrix composites (MMCs). Almost all engineering materials can be used as a matrix for MMCs [1, 2]. Aluminum, magnesia and their alloys are the most commonly used matrix materials in the production of MMCs due to their lightness and ductility. Materials such as SiC, SiO_2, Al_2O_3 and MgO are generally used as reinforcement elements [3, 4]. Different methods are employed for the production of MMCs, namely casting, melt-stirring, powder metallurgy, *in situ* and infiltration [5–7]. Molten metal mixing, as one method of production of particle reinforced MMCs, has a good potential for production of low-cost MMCs in general practice [8]. Main cutting force is the significant determinant while examining the cutting forces in the machining of MMCs. The relevant studies have indicated that, in general, the increase in cutting speed and feed rate is accompanied by both increased cutting force and tool abrasion [9, 10]. It is reported that the main cutting force is higher than the feed rate, and under same machining conditions, feed rate is not significantly affected by cutting speed while the main cutting force shows a decrease [11]. Based on the findings in the literature, feed rates were found to affect cutting forces during the lathe machining tests of MMCs. Increased feed rates resulted in increased cutting forces and increased formation of build up edge (BUE) leading to higher abrasion on tools [12, 13].

In the first part of this study, MMC specimens of 5%, 10% and 15% reinforcement-volume (R-V) ratios were produced by melt-stirring, and the effects of varying R-V ratios on composite structure were examined by scanning electron microscope (SEM), energy-dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) analyses. Distribution of reinforcement element, pore structure and matrix wetting capability of the reinforcement element were examined in the composite structure. One of the most significant criteria for the commercial use of MMCs is their behavior against machining. In the second part of the study, produced composite specimens were subjected to machining tests by turning method with two cutting tools and their cutting forces were measured at that moment.

2 Experimental study

2.1 Production of composite specimens

EN AW 1050 A Al alloy and MgO particles of -105 μm size were used, respectively, as matrix and reinforcement elements in the production of composite specimens. The chemical compositions of the matrix material Al and reinforcement element MgO are given in Table 1.

Table 1 Chemical compositions of matrix material Al and reinforcement element MgO.

Norm	Al %	Fe %	Si %	Cu %	Zn %	Ti %	Rest
EN AW 1050 A	99.50	0.40	0.25	0.05	0.05	0.04	0.03
	MgO %	FeO %		SiO_2 %		CaO %	
	98	0.6		1		0.4	

For the production of composite specimens, matrix material Al was put in the crucible shown in Figure 1; the melting process was started and continued until the temperature of the liquid matrix reached 750°C. Stirring apparatus was immersed in the liquid metal and stirring was started. Stirring revolution was gradually increased to 500 rpm and the appropriate amount of MgO powder proportionate with reinforcement volume fraction was added in the liquid metal by a funnel during the stirring process. After the addition of reinforcement element MgO in liquid matrix Al, the mixture was stirred for about 4 min at 500 rpm in order to allow homogeneous distribution of MgO particles in the mixture. When stirring was completed, the crucible was taken out of the furnace, the liquid melt was poured in to steel containers of 30 mm diameter and 100 mm height and was allowed to cool down to room temperature. The same processes were applied separately for each R-V ratio. SEM, EDS and XRD photos of obtained composite specimens were taken to examine their microstructures.

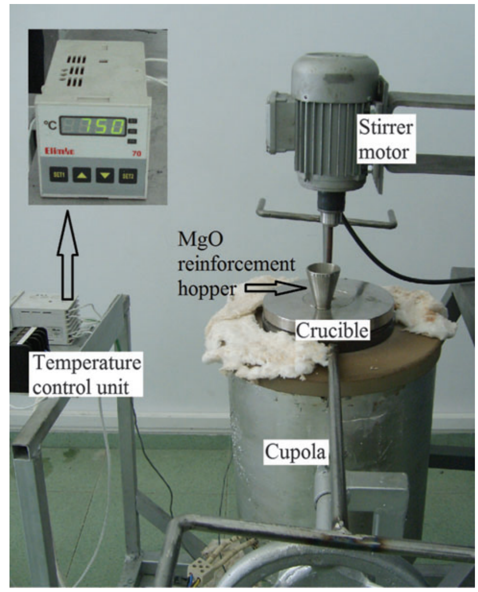


Figure 1 Melt-stirring experiment apparatus (Kırıkkale University, Metallurgy and Material Department Laboratory).

Table 2 Cutting parameters and associated values used in machining tests.

Cutting speed (V), m/min	Feed rate (f), mm/rpm	Depth of cut (a), mm
150-200-250-300	0.075-0.15-0.225	1.0

2.2 Machining tests

The machining tests were conducted under dry cutting conditions, on a computer numerical controlled (CNC) turning lathe with four different cutting speeds, three different feed rates and a constant depth of cut. The cutting parameters and associated values are given in Table 2.

A fixing apparatus was produced for machining of the composite specimens using easy, sensitive and fast machining conditions and machining tests were started. The specimens were fixed on the CNC lathe and machining tests were conducted with the selected cutting tools.

The cutting forces generated during the machining tests were measured by means of a three-component piezoelectric quartz crystal KISTLER 9257B type dynamometer and the obtained values were recorded, plotted and then interpreted.

The plots showing the changes in the cutting force components were obtained by using the Kistler Dynoware software for each test. A photograph of the test setup for machining tests and the fixing apparatus is given in Figure 2. Subsequent to the machining tests, the SEM photos of the composites were taken to examine the abrasion behaviors of the cutting tools used in the tests.

Two different cutting tools were used in machining tests, namely Sandvik brand carbide (C) and coated carbide (CC) cutting tools, and their geometrical and technical characteristics are given in Table 3.

3 Results and discussion

3.1 Microstructural examination of composite materials

The SEM and EDS photos of the composites of different R-V ratios produced by melt-stirring are given in Figures 3 and 4.

As indicated by the SEM photos, different homogeneity patterns were seen in each of the three specimens of three different R-V ratios. The lowest homogeneous distribution was observed in the 5% MgO reinforced specimen and homogeneous distribution was more improved with the 10% MgO R-V ratio. As clearly seen from the 15% MgO reinforced specimen, the increase in MgO fraction resulted in improved homogeneous distribution and

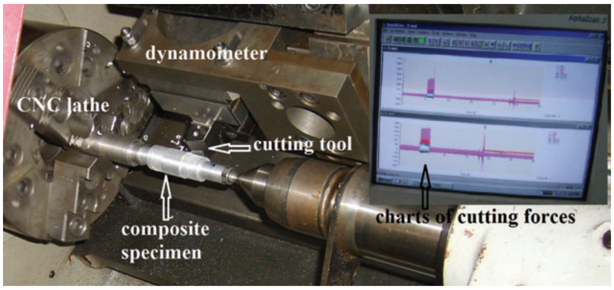


Figure 2 Test setup for the machining tests (JOHNFORD TC-35 CNC Lathe, Taiwan).

almost eliminated reinforcement agglomeration. Similar findings have also been reported by other studies in the literature [15–19]. Furthermore, it is also seen that matrix material Al can wet the reinforcement element MgO and no porosity formation occurred in general at the matrix-reinforcement interface. For this purpose, EDS analysis was conducted for chemical identification of the reinforcement element MgO and the matrix material Al in the composite specimens, and the determination of possible porosity which resulted from wetting and examination of the matrix-reinforcement interface.

Figures 4A and 4B reveal the EDS image and analysis results of the 15% MgO reinforced specimen which has the highest amount of MgO particles and highest possibility for porosity formation.

The EDS image and analysis results in Figure 4 clearly depict that the composite in Zone 1 is the reinforcement element MgO and the composite in Zone 2 is the matrix material Al. Furthermore, liquid Al was found to successfully wet the reinforcement element MgO and no porosity formation occurred at the matrix-reinforcement interface. After the EDS analysis, the MMC specimen was subjected to XRD analysis for detection of any additional phase formation at the matrix-reinforcement interface (see Figure 5).

Composite specimens were produced successfully by using the liquid Al temperature of 750°C, stirring speed of 500 rpm and stirring time of 4 min and were prepared for machining tests. As revealed in a similar study, the selected production parameters (liquid Al temperature, stirring speed and stirring time) are appropriate and MMCs were produced successfully [8]. Additionally, the reinforcement of Al matrix with MgO of -105 μm particle size by melt-stirring method proved to be convenient and a successful production method. The positive structural characteristics in composite specimens can be further improved in forthcoming studies by trials of varying temperatures, stirring speeds and stirring times.

3.2 Examination of the cutting forces

Although there are no specified universal criteria for evaluating the machinability characteristics of materials, cutting forces generated during the machining process are one of the most commonly used main criteria for evaluating machinability [20]. The main cutting force component (Fc), which is the most significant determinant of machinability, is examined in the three MMCs of varying R-V ratios according to the cutting parameters and cutting tools used in the study. The change in Fc values in 5%, 10% and 15% MgO reinforced MMC specimens according to the cutting tools by varying feed rates and cutting speeds are depicted in Figures 6–8. Depending on the production method, it is difficult to obtain a fully homogeneous structure in the composite materials and the porous structure affects both mechanical and machinability characteristics negatively [10]. Due to these characteristics of composite materials, the exposure of the cutting tool to the rigid phase in the composite leads to unexpected increases in cutting forces, and the pores generated by detached MgO particles from the matrix material Al during machining lead to sudden decreases in cutting forces. The unexpected deviations in the cutting forces obtained from the machining tests in this study can be attributed to these structural characteristics of MMCs.

Figure 6 indicates that Fc generally increased with the increase in cutting speed but started to decrease gradually after the cutting speed of 250 m/min. The lowest Fc value (88.6 N) was recorded in the 15% MgO reinforced MMC specimen with the C cutting tool at 0.075 mm/rpm feed rate. CC cutting tools generated lower Fc values by increased cutting speeds in the three MgO reinforced specimens compared to the Fc values generated by C cutting tools. This can be explained by lower generation of heat and BUE in the coating of CC tools during cutting process. The highest Fc value (116.75 N) was recorded in 5% MgO reinforced MMC specimen at 250 m/min cutting speed with

Table 3 Characteristics of cutting tools used in machining tests [14] (Sandvik Coromant, Sweden).

Cutting tool code	Quality producer code	Main carbide structure	ISO geometry identification code
C	Sandvik 432 H1P	WC-TiCTaC+Fastener: Co	SNMA120408
CC	Sandvik 432-KR	WC-TiCTaC+Fastener with coated TiN-Al_2O_3	SNMA120408-KR

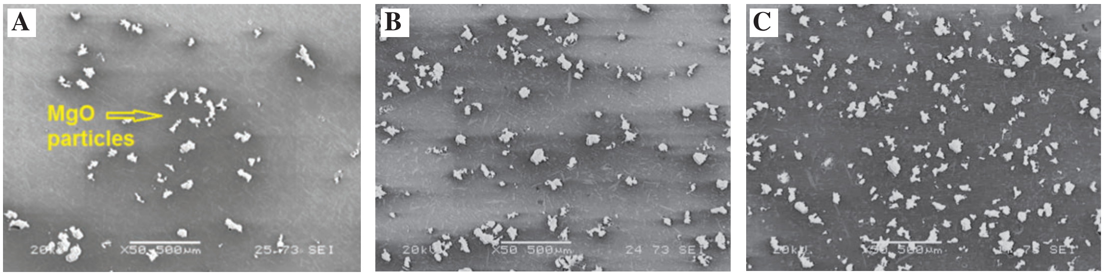
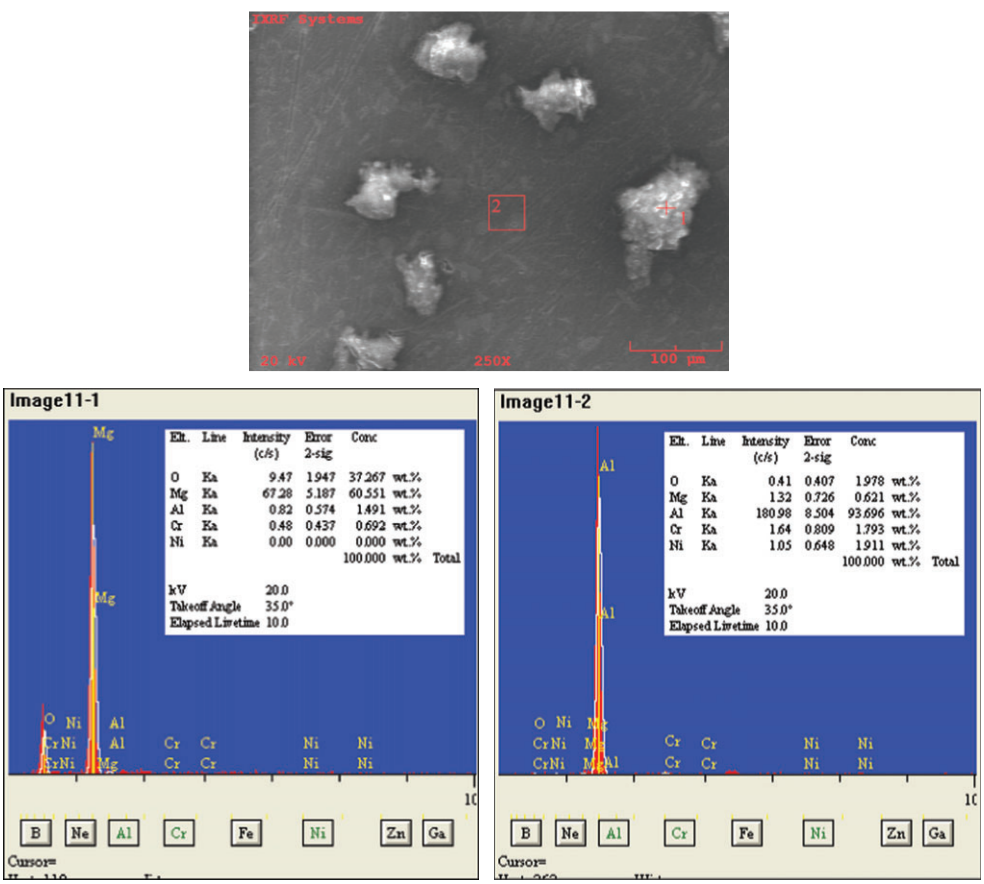


Figure 3 Microstructural images of composite specimens by SEM. (A) 5%, MgO, (B) 10%, MgO, (C) 15%, MgO (JEOL JSM-6060 LV, Scanning Electron Microscope, Japan).

C cutting tool. Fc values slightly decreased at 300 m/min cutting speed.

Figure 9 displays the BUE formations on C cutting tools at 150 (a), 200 (b), 250 (c) and 300 (d) m/min cutting speeds. As seen in the images, the cutting edges of tools failed to perform cutting and instead, BUE acted like the cutting edges (see Figure 9A). The BUE is thought to lead to an increase in Fc by narrowing the cutting tool machining angle. Additionally, with respect to abrasion behavior of cutting tools, almost no lateral surface abrasion was identified. This fact supports the idea of ineffectivity of cutting edges during cutting process.

As seen in Figure 7, Fc increased significantly when cutting speed was increased from 150 m/min to 200 m/min. However, Fc values started to decrease after the cutting speed of 200 m/min. This is attributed to the lower BUE formation that resulted from increased feed rate and cutting speed. The high Fc values at 200 m/min cutting speed are attributed to the existence of optimum temperature for BUE formation. The same finding was observed



A B

Figure 4 EDS analysis results of the composite taken from two different zones. (A) Analysis of Zone 1, (B) analysis of Zone 2 (JEOL JSM-6060 LV, Scanning Electron Microscope, Japan).

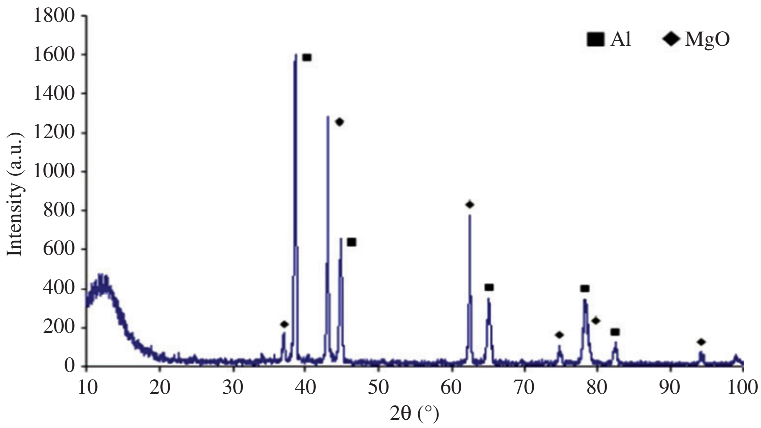


Figure 5 XRD result of composite. XRD analysis shows two main phases of Al and MgO. There are not any additional phases at the matrix-reinforcement interface (BRUKER D8 Advance X-ray diffraction, Germany).

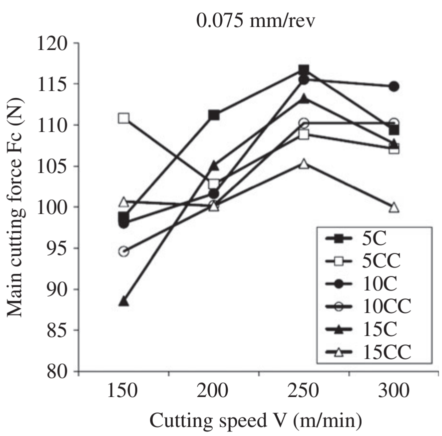


Figure 6 Changes in Fc values in 5%, 10% and 15% MgO reinforced MMC specimens by cutting speed (C and CC cutting tools; 0.075 mm/rpm feed rate). (KISTLER 9257B type dynamometer, Kistler Dynoware Software, Switzerland).

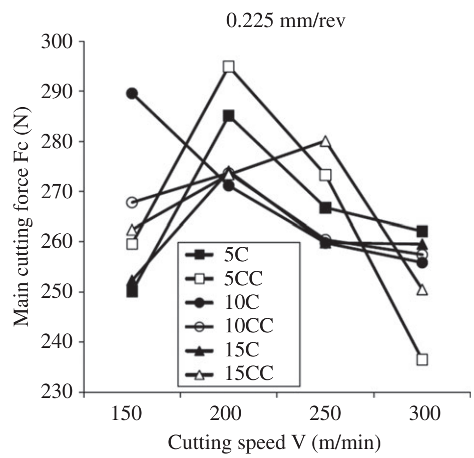


Figure 8 Changes in Fc in 5%, 10% and 15% MgO reinforced MMC specimens by cutting speed (C and CC cutting tools; 0.225 mm/rpm feed rate).

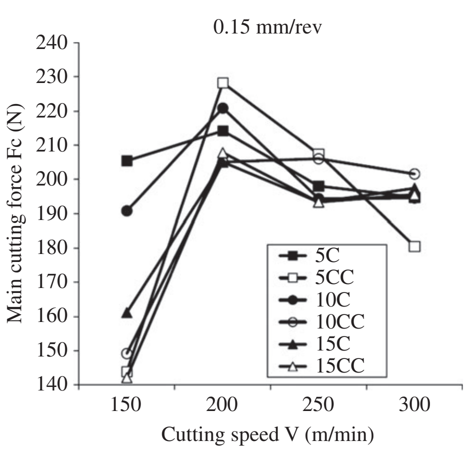


Figure 7 Changes in Fc values in 5%, 10% and 15% MgO reinforced MMC specimens by cutting speed (C and CC cutting tools; 0.15 mm/rpm feed rate).

at 0.075 mm/rpm feed rate, and when the feed rate was increased to 0.15 mm/rpm, BUE formation on cutting tool edge started to decrease earlier which led to a decrease in Fc values after 200 m/min cutting speed.

Figure 10 clearly shows the BUE formations on CC cutting tools at 150 (a), 200 (b), 250 (c) and 300 (d) m/min cutting speeds. Similar to C tools, no abrasion was observed in the cutting edges and BUE acted like cutting edges in CC tools as well. Similar findings have also been reported by other studies [21, 22].

The lowest Fc value (142.13) was recorded in the 15% MgO reinforced MMC specimen with CC cutting tool at 150 m/min cutting speed, and the highest Fc value (228.22 N) was recorded in the 5% MgO reinforced MMC specimen at 200 m/min cutting speed with CC cutting tool due to the effect of BUE.

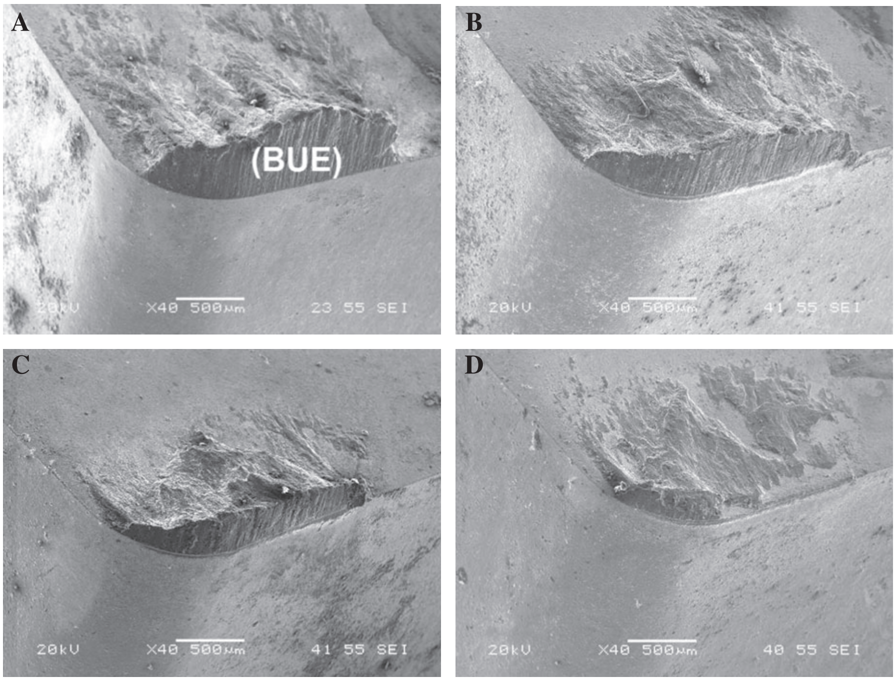


Figure 9 SEM photos of cutting edges in the 10% MgO reinforced MMC specimen with C tool at 0.075 mm/rpm feed rate and 150 (A), 200 (B), 250 (C) and 300 (D) m/min cutting speeds. The SEM images (C) and (D) indicate that in higher cutting speeds, an amount of BUE moved away from the cutting tool edge and BUE formation was lower. This reduced the effect of machining in the cutting area and led to lower cutting forces compared to those at 250 m/min cutting speed (JEOL JSM-6060 LV, Scanning Electron Microscope, Japan).

The relationship between increasing cutting speed and decreasing cutting forces is an expected pattern which is in agreement with the literature [10, 11, 18, 22]. The outcome of this relationship can be explained as follows: increased cutting speed generates increased temperature on the cutting area which leads to lower plastic

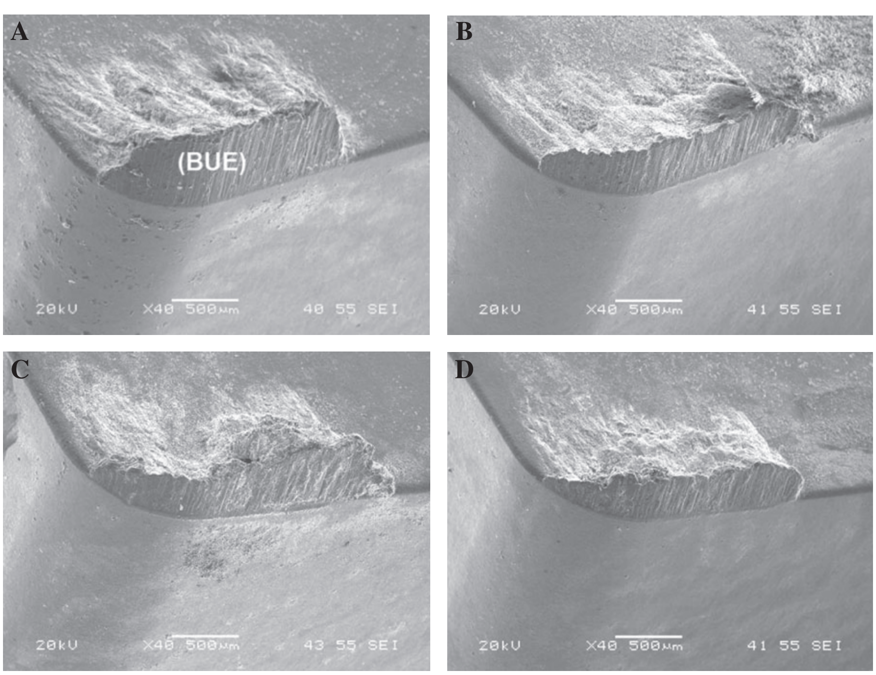


Figure 10 SEM photos of cutting edges in the 10% MgO reinforced MMC specimen with CC tool at 0.15 mm/rev feed rate and 150 (A), 200 (B), 250 (C) and 300 (D) m/min cutting forces (JEOL JSM-6060 LV, Scanning Electron Microscope, Japan).

deformation and friction on the chip-tool interface (due to thermal softening), eventually resulting in a smoother chip flow [20, 23].

As revealed by Figure 8, similar to 0.15 mm/rpm feed rate, the highest Fc values at 0.225 mm/rpm feed rate were obtained at 200 m/min cutting speed. The cutting speed of 200 m/min provides convenient conditions for BUE formation, which also leads to high Fc values. With the increase of feed rate up to 0.225 mm/rpm, Fc values started to decrease sharply after cutting speeds of 200 and 250 m/min. This pattern is more prominent particularly in CC cutting tools which can be explained by lower generation of heat and BUE in the coating of CC tools during cutting process.

The highest Fc value was recorded in the 5% MgO reinforced MMC specimen with CC cutting tool at 200 m/min cutting speed, and the lowest Fc value was recorded in the same specimen at 300 m/min cutting speed. As seen in all graphics, in general, the increase in Fc values depends on the increase in feed rates. The Fc values ranged between 85 and 120 N at 0.075 mm/rpm feed rate, between 140 and 230 N at 0.15 mm/rpm feed rate and between 230 and 300 N at 0.225 mm/rpm feed rate. The increasing tendency in cutting forces associated with increasing feed rates is an expected pattern which resulted from increasing the chip cross section. Cutting forces increase proportionally with increasing chip cross-sectional area [most generally, the main cutting force (Fc) is the product of chip cross-sectional area (A) and specific cutting pressure (ks)] [14].

The fluctuations in cutting forces can be attributed to the sustained contact of the cutting tool with Al matrix due to the very low R-V ratio. Additionally, depending on the extent of homogeneous distribution of MgO particles in composite specimens, cutting forces of cutting tool edges displayed fluctuations. The MgO particles or partial porosities encountered by the cutting edge during cutting slightly affected the Fc. Aluminum has a tendency for high BUE formation at low and moderate cutting speeds due to its high ductility. Therefore, to prevent BUE formation, sharp cutting edge form, wider cutting angle and grinded cutting tool surface are recommended [10, 14]. However, the cutting tools used in the study were selected considering the hard phase of MMC material in varying R-V ratios. Hence, more consistent results were obtained in higher R-V ratios.

4 Conclusions

The results obtained in the machining tests of Al-MgO composites of 5%, 10% and 15% R-V ratios produced by melt-stirring are summarized below:

- A generally stable microstructure was observed in the composites produced by melt-stirring, and improved homogeneous distribution of MgO reinforcement was identified with increased R-V ratios. The positive structural characteristics in composite specimens can be further improved in forthcoming studies by trials of varying production parameters (stirring time, stirring speed, liquid Al temperature, R-V ratio, etc.).
- There was no porosity and additional phase formation at the matrix-reinforcement interface based on the results of EDS and XRD analyses.
- BUE formation on the cutting tool edge affected Fc values, and lower BUE formation led to decreased Fc values.
- Fc values started to decrease after 250 m/min cutting speed at 0.075 mm/rpm feed rate and after 200 m/min cutting speed at 0.15 and 0.225 mm/rpm feed rates. This pattern is in agreement with the literature.
- The machining tests conducted in this study indicated that the increase in Fc values depends on the increase in feed rates.
- The lowest Fc value (88.6 N) occurred in the 15% MgO reinforced MMC specimen at 0.075 mm/rpm feed rate and 150 m/min cutting speed with C cutting tool.
- The highest Fc value (295 N) was recorded in the 5% MgO reinforced MMC specimen at 0.225 mm/rpm feed rate and 200 m/min cutting speed with CC cutting tool.
- The most consistent results in terms of Fc values were displayed by 10% MgO reinforced specimens.
- No significant differences were observed between C and CC cutting tools in terms of Fc values in the machining tests conducted with varying feed rates.

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