Süleyman Demirel Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
Cilt 20, Sayı 3, 434-441, 2016

Süleyman Demirel University
Journal of Natural and Applied Sciences
Volume 20, Issue 3, 434-441, 2016

DOI: 10.19113/sdufbed.72984

Investigations on Machinability of Al_2O_3 Reinforced Al6061 Metal Matrix Composites

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(Alınış / Received: 14.06.2016, Kabul / Accepted: 10.10.2016, Online Yayınlanma / Published Online: 20.10.2016)

Keywords
Metal-matrix composites (MMCs),
Statistical properties/methods,
Surface analysis,
Machining

Abstract: In this study, six different MMCs containing Al6061 matrix and Al_2O_3 reinforcements with particle sizes of 32 µm and 66 µm and weight fraction of 10%, 15% and 20% were produced using the vortex method. Machinability tests were conducted at different feed rates and cutting speeds to determine the surface roughness and cutting forces. Result of the tests indicated that the cutting forces positively correlated with the feed rates. Increasing in the cutting speed result in decrease in the cutting forces. The cutting forces did not remarkably vary with respect to the particle size for the same feed rates. The surface roughness negatively correlated with the particle weight fraction. Better surface qualities were obtained at lower feed rates and higher cutting speeds.

Al_2O_3 Katkılı Al6061 Metal Matrisli Kompozitlerin İşlenebilirliğinin İncelenmesi

Anahtar Kelimeler
Metal Matrisli Kompozitler(MMK),
İşlenebilirlik,
Yüzey kalitesi,
Talaşlı imalat

Özet: Bu çalışmada Al6061 matrisli ve 32 ve 66 µm tanecik boyutlu ve %10, %15 ve %20 ağırlık oranlı Al_2O_3 katkılı, metal matris kompozitler vorteks metodu ile üretilmiştir. Üretilen kompozitlerin yüzey pürüzlülükleri ve kesme kuvvetlerinin belirlenmesi amacıyla değişik ilerleme oranlarında ve kesme hızlarında işlenebilirlik deneyleri gerçekleştirilmiştir. Deney sonuçları, kesme kuvvetlerinin ilerleme oranları ile doğru orantılı olduğunu göstermiştir. Kesme hızının arttırılması ise kesme kuvvetlerinin düşmesine neden olmuştur. Aynı ilerleme oranlarında kesme kuvvetleri tanecik boyutu ile belirgin bir değişim göstermemiştir. Yüzey pürüzlülüğü parçacık ağırlık oranı ile ters orantılı olarak ortaya çıkmıştır. Düşük ilerleme oranlarında ve yüksek kesme hızlarıyla daha iyi yüzey kalitesi elde edilmiştir.

1. Introduction

MMCs are a new class of materials that have been used for four decades in areas that require enhanced mechanical properties and low density. These composites offer a large variety of properties by combining many possible matrices and reinforcements [1]. Aluminum, magnesium and titanium alloys are the most commonly used substrate materials. Aluminum has been proven to be the most advantageous matrix material due to its combination of properties, e.g., low density, high atmospheric corrosion resistance and superior properties at high temperatures [2]. Reinforcements may be included in the form of particles, continuous fibers, short fibers, whiskers, and mono-filaments [3]. Particulate-reinforced MMCs have some advantages over other MMCs, such as their cost effective manufacturability, isotropic properties and ability to be produced in large quantities [4]. Commonly used reinforcement materials for particulate MMCs are alumina (Al_2O_3) and silicon carbide (SiC).
Much manufacturing research has focused on the manufacturability of MMCs due to the presence of hard and highly abrasive reinforcing agents, which drastically shorten tool lives and result in relatively poor surface finishes [5].

Studies of the machinability of MMCs may be classified based on several aspects:

- Wear performance, cutting forces and the resultant surface roughness of different cutting tools used to machine MMCs
- Effects of cutting parameters, such as the cutting speed, feed rate, and depth of cut on the tool life, surface quality and cutting force
- Modeling the machining of MMCs

Durante et al. conducted a set of turning, drilling and milling tests to compare the performances of

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tungsten carbide, polycrystalline diamond and experimental CVD diamond-coated carbide tools on three types of MMCs reinforced with Al_2O_3 and SiC particles. They stated that A359+20% SiC is very difficult to machine with coated inserts. Diamond coating prolonged tool life, but the coating detached frequently at the tests [6]. Hung and Zhong used WC, CBN and PCD on 10% and 20% SiC-reinforced A359 alloys and 15% and 20% Al_2O_3-reinforced Al6061 alloys in their studies. They observed that the wear resistance of CBN and PCD tools is better than that of WC tools [7]. Manna and Bhattacharyya carried out studies to properly select tooling for optimum machining at minimum cost. The rotary circular tooling (RCT) system exhibited superior wear resistance compared to fixed circular, fixed rhombic and fixed squared tooling systems. However, RCT resulted in very poor surface quality [8].

Ding et al. compared the wear resistance of polycrystalline cubic boron nitrate (PCBN) and PCD tools at different cutting speeds during the machining of Al-SiC MMC. Binderless PCBN tools resulted in the lowest flank wear among all the PCBN tools. The PCBN tool exhibited lower wear resistance than the PCD tools [9]. Ramulu et al. carried out several drilling studies on 10% and 20% Al_2O_3-reinforced Al 6061 utilizing high speed steel, carbide tipped and polycrystalline diamond drills. As observed in the turning experiments, PCD tools showed the best wear resistance in drilling MMCs. PCD tools were also the most advantageous in terms of the required force [10]. Gatto et al. conducted high speed turning experiments on alloy machined 10% Al_2O_3-reinforced Al6061 using uncoated and CVD coated carbide tools and found that the flank wear decreases as the feed rate increases up to certain values at any cutting speed. Significant correlations between the cutting parameters and surface roughness is a new phenomenon and it has not yet been investigated in detail [11].

Sahin et al. İnvestigated the machinability of 2024 Al alloy composites reinforced with varying sizes and weight fractions of Al_2O_3 produced via the vortex method. They machined the composites by turning the material with TiN (K10)-coated carbide tools and TP30-coated carbide tools at different cutting speeds. This study concluded that the tool life positively correlated with the cutting speed for both cutting tools. Moreover, the life of the TiN (K10) tool was significantly longer than that of the TP30 tool [12]. Manna and Bhattachayyara performed experiments to analyze the influence of different cutting parameters on the machinability of Al/SiC using fixed rhombic tooling. The flank wear rate was higher at low cutting speeds owing to the high cutting forces and formation of the built up edge. They recommended cutting speeds between 60 and 150 m/min, which allows for cutting forces that are relatively independent of the cutting speed. The feed rate was observed to be less sensitive to the flank wear than the cutting speed. A high speed, low depth cut and low feed were recommended to improve the surface finish [13]. Turker et al. studied the effects of reinforcement and cutting speed on tool wear and surface roughness in a cubic boron nitride (CBN) cutting tool. They concluded that flank wear is the dominant wear mode of the CBN cutting tool in the machining of MMCs containing 30 μm- and 45 μm-sized particles. Conversely, cutting edges and nose fractures were encountered during the machining of MMCs containing 110 μm-sized particles. MMCs containing 110 μm-sized particles resulted in very high tool wear compared to other MMCs. A cutting speed of 150 m/min resulted in the lowest flank wear for 30 and 45 μm particulate MMCs [14].

Muthukrishnan et al. used 3 different grades of PCD inserts to determine the machinability of 15% SiC containing aluminum-based MMC. The minimum specific power to machine the MMC is required for maximum values of the cutting speed, feed and depth of cut for PCD inserts with grades 1300, 1500 and 1600. The surface finish was found to be better at high cutting speeds and low feed rates [15]. Kishavy et al. reported that increase in the particle size and volume fraction can be correlated with the increase in the average dislocation density [16]. Kumar et al. viewed the effect of cutting parameters on the surface roughness and tool wear for AA 7075/SiC MMC. They stated that cutting speeds between 180 to 220 m/min, feed rates from 0.1 to 0.3 mm/rev and depth of cut values from 0.5 to 1.5 mm were the best parameters for optimum surface roughness. They also suggested cutting speeds, feed rates and cut depths of less than 200 m/min, 0.1 mm/ rev, and 0.5 mm, respectively, to minimize flank wear [17].

Hung and Zhong provided a technique to study the cumulative tool wear of facing and turning tools. A simple facing operation can be used to determine the machinability of different materials or the effectiveness of cutting tools [18]. Zhang et al. developed a mechanical model to predict forces that occur during the machining of aluminum-based MMCs. They considered the resultant cutting force to be the sum of the components of forces due to chip formation, plowing and particle fracture and displacement. The force due to chip formation was revealed to be much higher than those due to particle fracture and plowing [19]. Joshi et al. developed an ANN-based model to predict surface roughness for the machining of composites and showed that the size of reinforcements in composites significantly influences the surface quality of machined surface when its magnitude is comparable to that of the tool nose radius and the feed rate. The optimum surface quality was obtained at the lowest feed rate, the largest tool nose radius and the smaller particle size [20]. Kok adopted the Taguchi method and performed a variance analyses (ANOVA) to examine the effects of size, cutting speed and volume fraction of the reinforcement on the surface roughness during the machining of an Al_2O_3 reinforced Al alloys. Many mathematical models were developed for the surface roughness using multiple linear regressions depending on mentioned parameters for machining with K10 and TP30 cutting tools. It was found that surface roughness value of TP30 tool is lower than that of K10 tool. In addition cutting speed was found to most significantly influence the surface roughness during machining with the TP30 cutting tool, followed by the volume fraction of particles and size. The volume fraction most strongly influenced the surface roughness for the cutting tool K10, followed by the interaction of the particle size with the volume fraction of particles [21]. Sikder and Kishawy presented an analytical model that accounts for the particle fracture and particle contribution to the friction force generated along the chip tool interface. The friction force along the chip-tool interface and the forces due to plowing are calculated, added to the other forces encountered when cutting traditional material and used to predict the tool-generated forces during machining of MMCs [22].

The above studies clearly demonstrate that most of the investigations of machinability focused on SiC-reinforced MMCs. A few studies examined the effects of particle size and volume fraction of the reinforcing agent on machinability. In this study, six different revisions of MMCs with an Al6061 matrix reinforced with 2 different particle sizes and three different weight fractions were examined. Thus, the influence of the cutting speed and feed rates on the cutting forces and surface roughness was investigated during the machining of MMC with varying particle sizes and weight fractions.

2. Material and Method

2.1. Material details

Composite materials containing 6061 aluminum matrix and Al_2O_3 particles as the reinforcing element were used in the current study. The chemical analysis of the matrix material and Al_2O_3 particles are given in Table 1 and Table 2, respectively. Cylindrical specimens with a 40 mm outer diameter and 140 mm height were used. To produce the aforementioned composites, 6061 aluminum alloy was melted under an argon-protected atmosphere in an electric induction furnace that had a power of 2 kW.

Table 1. Chemical composition of 6061 Al matrix (wt.%)

Si	Mn	Cr	Zn	Ti	Mg	Cu	Al
0.6	0.15	0.35	0.25	0.15	0.1	0.15	96

Table 2. Chemical composition of Al_2O_3 particles (wt. %)

Al_2O_3	TiO_2	CaO	Fe_2O_3	Other
min 93	min 1.8	max 1.1	max 0.8	max 0.2

The specimens were produced with the vortex method. The melting process was performed in a graphite crucible and a graphite mixer with four channels, and a diameter of 55 mm was used to generate the vortex. The mixing speed of the stirrer was 900 rev/min. The particle addition rate was 5 g/min. Mixing was continued 5 minutes after particle addition. The mixture was then poured into a cast iron cylindrical mold with a 40 mm inner diameter and 200 mm height. The pouring and mold preheating temperatures were 700 °C and 550 °C, respectively. All melting and mixing processes were conducted under an argon-protected atmosphere. The argon gas was divided into two branches in the system. One of the branches sent the gas over the crucible to protect the molten alloy from the surrounding air, and the other branch was connected to the reinforcing particle unit to control its addition rate. Immediately after the casting process, 6 MPa of pressure was applied to the mold for 5 minutes via a hydraulic press to solidify the molten material under pressure and prevent porosity in the composite specimen. The temperature of the specimens was approximately 350 °C immediately after the application of pressure.

The material used in the experiments was 6061 Al alloy reinforced with 32 μm and 66 μm Al_2O_3 particles at weight fraction of 10%, 15% and 20%.

2.2. Determination of densities and porosities

The densities of the produced composites were measured using an Archimedes scale that utilizes the Archimedes Principle. The porosity ratios were then calculated with Eq. 1 by using the difference between the calculated theoretical and measured densities of composites.

$$\%Porosity = \frac{\rho_{theoretical} - \rho_{measured}}{\rho_{theoretical}} x100 \qquad (1)$$

2.3. Hardness measurements

A ball indenter with 2.5 mm diameter was used to measure Brinell hardness of specimens. The preload was 10 kg-f, and the test load was 62.5 kg-f. Five locations were tested for each specimen, and the average values of the hardness were tabulated.

2.4. Cutting conditions

The tool lives for various cutting conditions for the machining of six different composites were determined with a machining test. A Johnford TM35 trademark industrial type CNC lathe was used to conduct the turning test at different conditions. The technical properties of the machine used are listed in Table 3.

The PSBNR 2525 M12 tool holder was selected to fit the fixing apparatus of the dynamometer from Mitsubishi Carbide. The properties of the cemented carbide cutting tool produced by Mitsubishi Carbide Company are given Table 4.

Table 3. Technical properties of JOHNFORD TC 35 BSD CNC lathe

Trademark	Johnford TC 35
Maximum workpiece diameter	450 mm
Maximum workpiece length	1200 mm
Continuous rotational speed of spindle	10 – 3500 rev/min
Maximum tool number	12
Spindle power	10 kW
Controller type	Fanuc OT

Table 4. Properties of cutting tool

Cutting tool code	Producer quality code	Main carbide structure	ISO geometry code	Tool geometry Shape
SK (c)	Sandvik 432 HIP	WC-TiCTac Bond:Co	SNMA1204 08	Square

Note: Properties of used tool geometry Clearance Angle:0^0, Tolerance class: M, Type: a (without chipbreaker, with hole), Cutting edge length: 12 mm, Thickness: 4.76 mm, Corner radius: 0.8 mm

The machinability tests were conducted by machining the specimens produced with vortex method at a cutting depth of 1 mm, cutting speeds of 130, 180, 230 and 280 m/min and feed rates of 0.1, 0.15 and 0.2 mm/rev. 72 tests were conducted, and 3000 mm3 chips were removed from the specimens during each test.

The cutting forces were observed with a KISTLER 9257B model dynamometer that can measure the Fx, Fy and Fz components of the cutting force. The Dynoware software was used to graphically transfer the cutting force values to the computer. Surface roughness of the specimens was also measured at three locations for each specimen using a Mahr Perhrometer M1 stylus instrument. The properties of the roughness measurement instrument are given in Table 5.

Table 5. Properties of used surface roughness measurement apparatus

Trademark and model	Mahr Perthometer M1
Traversing speed	0.5 mm/s
Measuring force	0.75 mN
Stylus radius	2 µm
Measuring range	100-150 µm
Profile resolution	12 mm
Filter	Gaussian
Cutoff length	0.25, 0.8, 2.5 mm
Measurement length	1.75, 5.6, 17.5 mm
Measured parameters	Ra, Rz, Rmax

3. Results

3.1. Evaluation of composite production method

Several test samples were generated to obtain a homogenous composite structure, and the produced specimens were inspected with a scanning electron microscope (SEM). When the casting temperatures were excessive, the Al_2O_3 particles sunk in the matrix material and were deposited at bottom of the crucible. At lower casting temperatures, the reinforcement particles remained in the upper part of the crucible. If the stirring speeds were excessive, the reinforcing particles were forced to the outer surface of the crucible, which increased the density in the periphery. At low mixing speeds, the stirrer could not push the particles into the molten metal, and the particles were collected on the metal surface. The mixture solidified upon being poured into the mold, and the pressure required to reduce the porosity could not be applied when the mold temperature was low. At higher mold temperatures, the solidification rate was low, and the Al_2O_3 particles gravitated down in the matrix.

The optimum production parameters were determined based on several trials: a metal melting temperature of 700 ºC, stirring rate of 900 rev/min, mold temperature of 550 ºC, reinforcing particle addition rate of 5 g/min, mixing time after reinforcing particle addition of 5 min and pressure of 6 MPa.

3.2. Evaluation of density measurements and porosities

The calculated theoretical and measured densities of the produced composites were compared to the particle sizes and ratios in Fig. 1. The porosity values are also presented in Fig. 2.

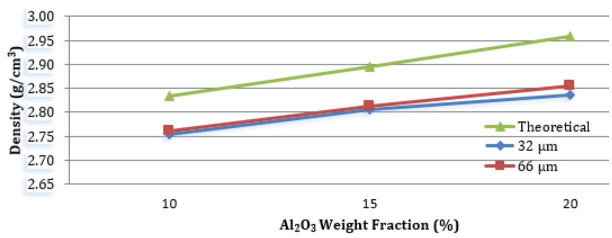

Figure 1. Variation of theoretical and measured densities with Al_2O_3 weight fraction.

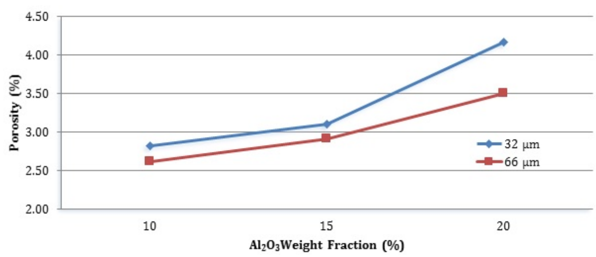

Figure 2. Variation of porosities with Al_2O_3 weight fraction

When take into consideration Figure 1 and Figure 2 it can be seen that the measured densities linearly increased with the particle weight fractions in the matrix, but the rate of increase was lower than the theoretical rate. Conversely, the porosity positively correlated with the particle weight fraction and negatively correlated with the particle size.

Increasing the weight fraction of reinforcing particles results in more areas to be wetted around particles, and some of the particles cannot be wetted. This situation results in porous composites. Conversely, smaller particles present a larger surface area to be wetted with respect to volume. Thus, the particle size negatively correlates with the porosity of the composite.

3.3. Evaluation of hardness measurements

The hardness measurements of the produced specimens are given in Fig. 3.

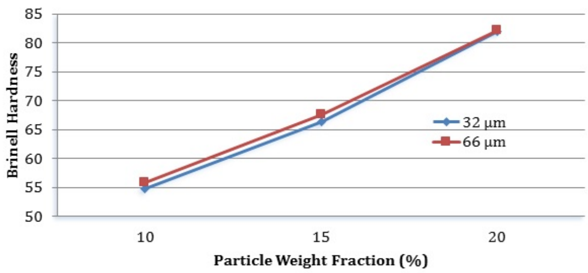

Figure 3. Variation of hardness of composites with Al_2O_3 weight fraction

The hardness values continuously positively correlated with the particle weigh ratio. However, increases in the particle size only slightly increased the hardness because the indenter is much larger than the reinforcing particles, which allows it to displace the particles in the matrix material during the hardness measurement. The particle weight fraction positively correlates with the hardness. Nevertheless, larger particles are more resistant to being displaced in the matrix material, while fewer particles are contained in the matrix when the particles are large, which restrains the increase in hardness.

3.4. Evaluation of microstructures

Fig. 4 gives the microstructure images of the specimens. Al_2O_3 particles with 66 μm particles are mixed more homogenously than those containing 32 μm particles. Moreover, the porosities are more uniform in the 32-μm particle-reinforced composites, as evidenced by the dark areas between particles.

Growing dendrites push the small reinforcing particles during solidification, which allows them to accumulate at the intersection of several dendrites. Dendrites also push the larger reinforcement particles, but they are trapped because of their size and remain along in the matrix.

3.5. Surface roughness

Average surface roughness values (Ra) of the specimens were determined after each machining. Variations in the roughness values with respect to the material properties, i.e., the particle size and weight fraction of the reinforcement and feed rate, cutting speed and cutting parameters, are illustrated in Fig. 5.

The figure 5 shows that the surface is generally rougher in composites with low particle weight ratios. This trend is more significant for composites with 66 μm-sized particles. However, this increase is not universal, which may explain the adhesion of the matrix material to the cutting tool. Hard Al_2O_3 particles sweep away adhered matrix material from the cutting tip. Thus, low particle rates result in more built up edges, which increases the deformation of the cutting tool. The wear and deformed shape of the cutting tool result in a rougher surface. Moreover, the reinforcement particle size positively correlates with the roughness. This relationship is more pronounced for low reinforcement weight fractions and may be due to increases in the built up edge because of a low number of particles per unit volume to sweep matrix material from the cutting tip.

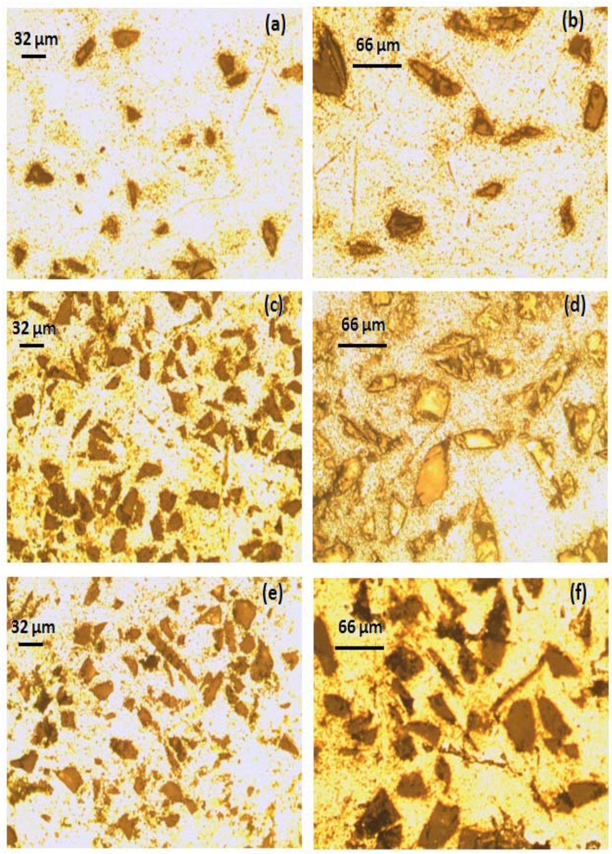

Figure 4. Microstructure images of 6061 Al alloy reinforced with Al_2O_3 particles weight fractions and particle sizes of a) 10%, 32μm, b) 10%, 66μm, c) 15%, 32μm, d) 15%,66μm, e) 20%, 32μm, f) 20%, 66μm

Increase in cutting speed and decrease in the feed rate result in improve in the surface quality. The lowest roughness value was 0.93 μm and obtained at a cutting speed of 280 m/min and feed rate of 0.1 $m.min^{-1}$ for a 66-μm particle size and 20% particle ratio. Conversely, the highest roughness value was 3.61 μm and obtained at a cutting speed of 130 m/min and speed of 0.15 m/min for a 66-μm particle size and 10% particle ratio.

3.6. Cutting forces

The cutting forces were measured and recorded with a dynamometer and a data logger. The experiments were conducted by removing a 3000-mm3 chip volume with 1 mm constant cutting depth. The changes in the cutting forces with respect to the cutting speed, particle size, particle weight fraction and feed rate are presented in Fig. 6.

It can be seen from Fig. 6 increasing in cutting speed result in linearly decrease in cutting forces. Increasing the strain rate by increasing the cutting speed is expected to increase the cutting forces. However, the softening of the matrix material due to local temperature increases near the cutting tip as a result of higher speeds dominates this effect. Although the feed rates and cutting forces did not linearly correlate, increasing the feed rates slightly increased the cutting forces. Remarkable variations in the cutting forces have not been investigated with respect to the particle sizes.

4. Discussion and Conclusion

In this study, metal matrix composite specimens consisting of a 6061 Al alloy matrix were produced by adding 32- and 66-µm Al_2O_3 reinforcing particles at weight fractions of 10%, 15% and 20%. Variations in the porosities and hardness were determined as functions of the particle sizes and weight fractions. Furthermore, the cutting forces and surface roughness were measured for each version of the composite. The following results can be summarized from this study.

The optimum parameters for the production of Al_2O_3-reinforced 6061 Al alloy were a metal melting temperature of 700 °C, stirring rate of 900 rev/min, mold temperature of 550 °C, reinforcing particle addition rate of 5 g/min, mixing time after reinforcing particle addition of 5 min and pressure of 6 MPa.

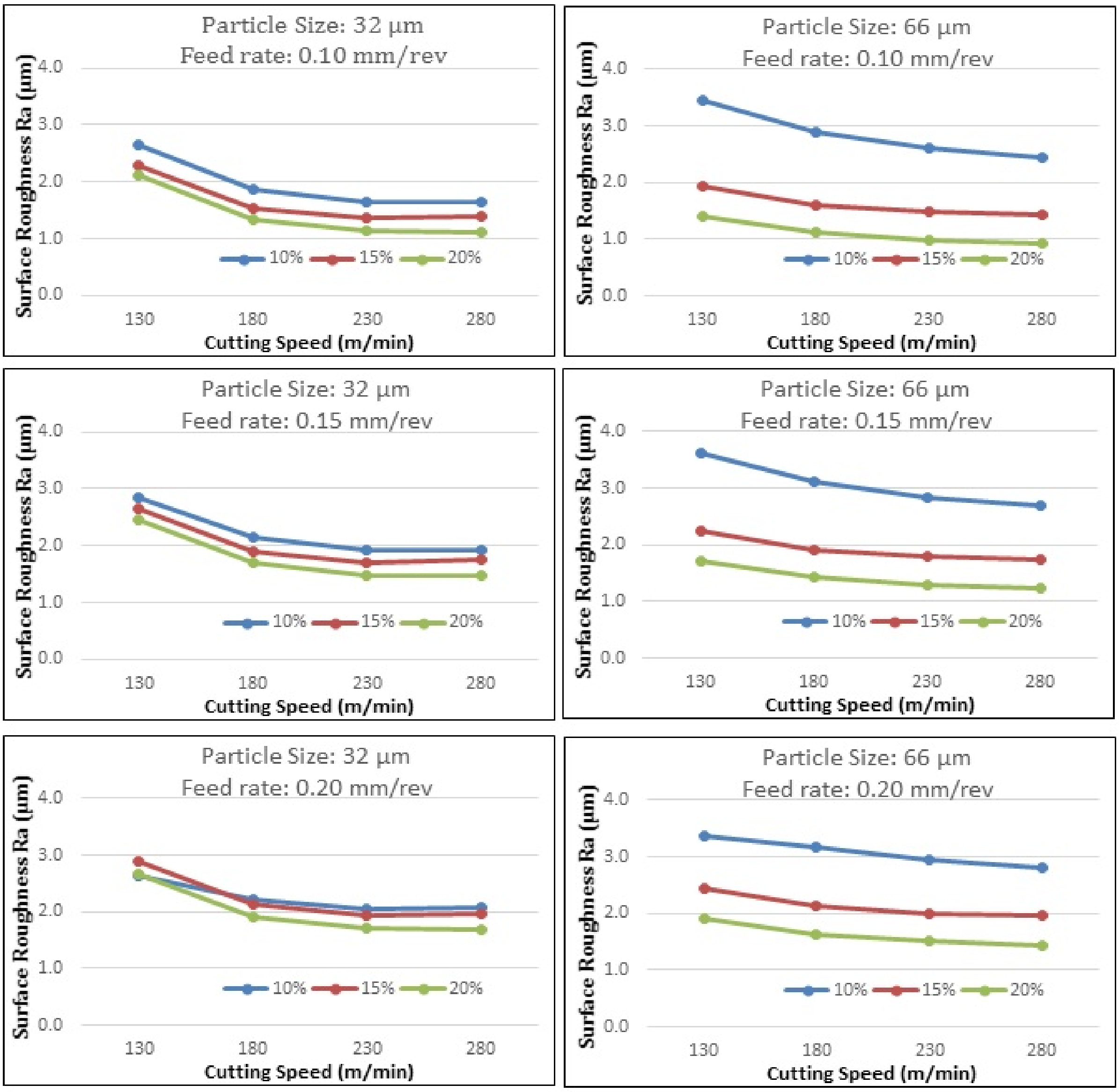

Figure 5. Variation of surface roughness based on material properties and cutting parameters.

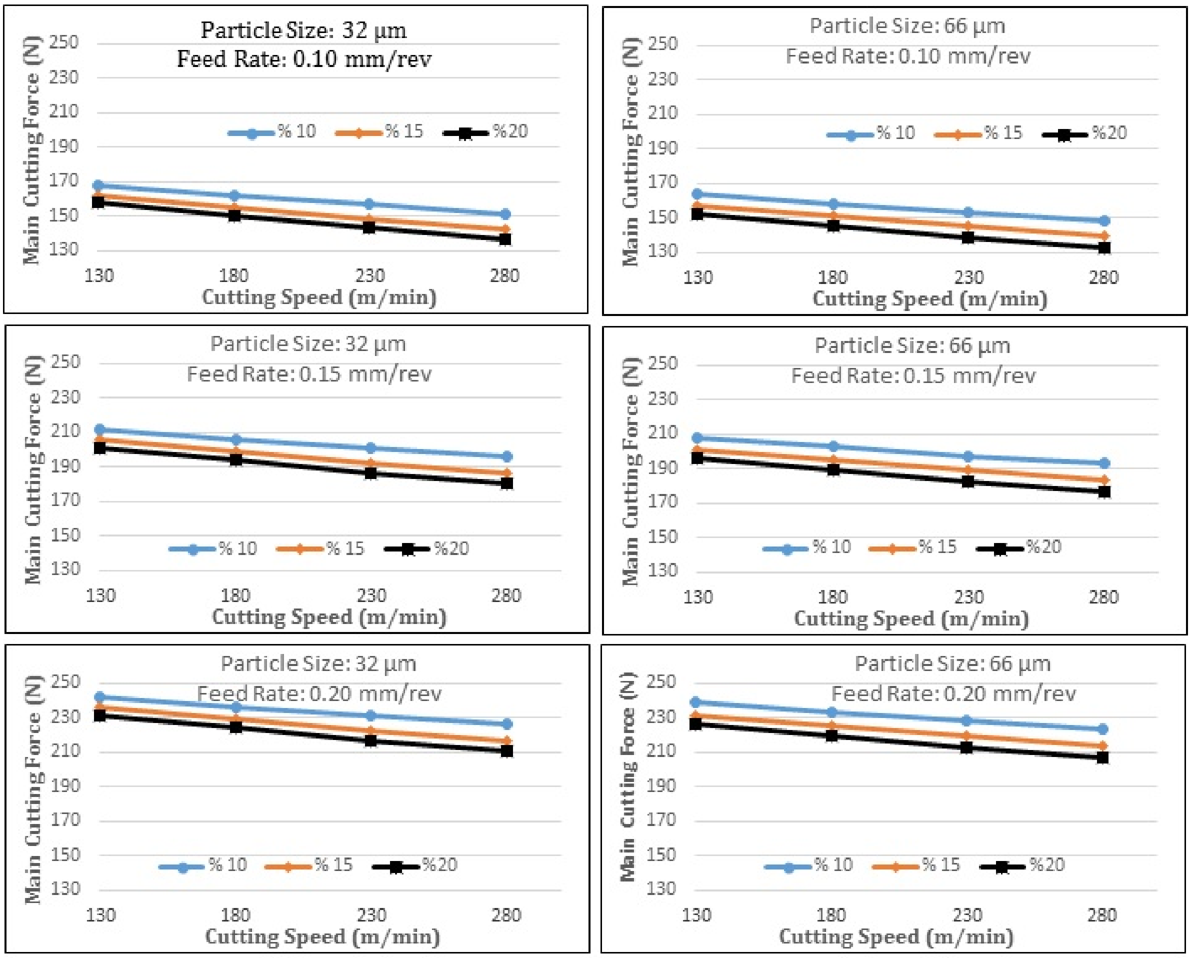

Figure 6. Variations of cutting forces cutting speed and feed rates for 15 % Al_2O_3 particles.

The porosity of the produced MMC was positively correlated with the particle weight fraction rate and negatively correlated with the particle size.

Although the hardness values positively correlated with the particle weight fraction for MMCs reinforced with 66 µm-sized particles, this relationship has not been investigated for MMCs reinforced with 32 µm-sized particles.

The microstructure is more homogenous for 66-µm particle-reinforced MMCs than for 32-µm particle-reinforced MMC.

The surface quality positively correlates with the particle weight fraction and negatively correlates with the particle size. Moreover, increase in cutting speed and decrease in the feed rate improves the surface qualities.

The main cutting force values linearly decreased as the cutting speeds increased. Although the feed rates and cutting forces did not linearly correlate, increasing the feed rate slightly increased the cutting forces. The reinforcement weight fraction was also determined as a factor that increases the cutting force. The cutting forces did not remarkably vary with respect to the particle size for the same feed rates.

Acknowledgment

The authors wish to thank Lecturer Faruk ÇAVDAR and Lecturer Mehmet Akif DOĞAN (Iskenderun Techinical University) for their contributions to this study.

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