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ORIGINAL ARTICLE

Drilling of a hybrid Al/SiC/Gr metal matrix composites

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Abstract The present study investigates the influence of cutting parameters on cutting force and surface roughness in drilling of Al/20%SiC/5%Gr and Al/20%SiC/10%Gr hybrid composites fabricated by vortex method. The drilling tests are conducted with diamond-like carbon-coated cutting tools. This paper is an attempt to understand the machining characteristics of the new hybrid metal matrix composites. The results indicate that inclusion of graphite as an additional reinforcement in Al/SiCp reinforced composite reduces the cutting force. The cutting speed and its interactions with feed rate are minimum. Feed rate is the main factor influencing the cutting force in both composites. The surface roughness value is proportional with the increase in feed rate while inversely proportional with cutting speed in both composites. For all cutting conditions, Al/20%SiC/10%Gr composite has lower surface roughness values than Al/20%SiC/5%Gr composite. The surface is analyzed using scanning electron microscope.

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Keywords Hybrid MMCs · Machinability · Graphite · Cutting forces

1 Introduction

Al-based metal matrix composites (MMCs) are well-known for their high-specific strength, hardness, and attractive tribological properties. The silicon carbide-reinforced aluminum composites are increasingly used as substitute materials for cylinder heads, liners, pistons, and brake disks in automobile industry. The main purpose of the particulate-reinforced metal matrix composite production is to obtain materials having high-wearing resistance, light weight, and high-specific strength in order to reduce the costs of technological applications and fuel consumption [1–4]. Hybrid aluminum matrix composites are used for high performance "ceramic" brake disks as it is able to withstand extreme temperatures. The silicon reacts with the graphite in the carbon–carbon composite to become carbon fiber-reinforced silicon carbide. The SiCp particles scuff the counterpart leading to greater wear loss. The addition of solid lubricant particles such as graphite along with SiCp as hybrid reinforcements effectively improves the tribological properties of the composites [3].

Despite the advantages listed above, particulate composites have not yet found a wide employment in the commercial applications because the hard particles embedded inside the matrix cause very serious problems in machining such as high drilling forces, tool wear, and poor surface finish [1, 5]. Therefore, because of the poor machining properties of MMCs, researches on the improvement of the machinability of MMCs has been performed either to find new composites with better machinability or by testing the effect of the machining parameters on these new reinforced MMCs

[1, 6]. The machinability during turning of Al/Si/Gr composites was studied by Brown and Surappa [5]. They found that the machining forces were considerably reduced for the graphitic composites. Songmene and Balazinzki [7] worked on drilling and milling of Al/SiCp, Al/SiCp–Gr and Al/Al2O3–Gr composite and they found that incorporation of graphite particle into aluminum MMCs improve the machinability of the composites. Basavarajappa et al. prepared two different metal matrix composites—Al2219/15SiCp and Al2219/15SiCp–3Gr—by stir casting technique and performed drilling studies on them. They reported that ceramic–graphite-reinforced composite has better machinability than those reinforced with silicon carbide particles only [2, 6].

Polycrystalline diamond, cubic boron nitride tools are recommended for machining SiC-reinforced metal matrix composites [6–9]. But these cutting tools are very expensive. Owing to their low cost, diamond-like carbon (DLC) tools are readily selected in this study. DLC can exhibit properties close to those of diamond. DLC films have many beneficial properties including high hardness, low friction coefficient, high thermal conduction, and low thermal expansion coefficient. At this present study, the application of diamond and DLC films in cutting tools have been being studied extensively. But the cutting data of DLC-coated cutting tools in published literature are very different. This means that the quality of DLC-coated cutting tools made by different units is different, and the cutting performance depends greatly on the quality of the coated tools, the cut materials, and cutting parameter [10, 11].

Most of the current literatures present experimental results when drilling ceramic-reinforced MMCs. However, limited information is available on the drilling of graphitic ceramic-reinforced composites. The main objective of the paper is to study the influence of cutting parameters on cutting force and surface roughness in drilling of Al/20%SiC/5%Gr and Al/20%SiC/10%Gr hybrid composites fabricated by vortex method.

2 Materials and methods

2.1 Materials

Aluminum (LM2) is used as the main matrix material. The Al-Si-Cu matrix alloy has a composition (% by weight) Si (12 max), Cu (0.7–0.9), Fe (0.7 max), Mn (0.25 max), Mg (0.02 max), Zn (0.3 max), Ni (0.03 max), Ti (0.03 max), Pb (0.09 max), and Al (balance). The materials Al(LM2)/20SiCp-5Gr and Al(LM2)/20SiCp-10Gr are fabricated under similar conditions. The average sizes of SiCp and graphite particles are 53 and 90 μm, respectively. During the production of the samples, the matrix alloy was melted in a furnace (crucible capacity about 10 kg) which was originally developed for MMC production using liquid-phase method. The furnace was heated up to 700°C for 30 min; then the liquid was stirred with a steel impeller coated with Al_2O_3 by plasma spraying to avoid aluminum–iron interaction, and SiCp and graphite particles were introduced into the created vortex. After the mixing was completed, the temperature was allowed to reach 700°C and the mixture was stirred for 20 s to prevent settling of the particles; then poured in to a heat-treated squeeze cast steel mold which was heated to 500°C. The solidification was completed under 50 MPa pressure and the composites were obtained so. The melting, introduction of the particles, and mixing treatments were all carried out under a protective argon gas atmosphere. This method was used by other researchers too [4, 12, 13]. The microstructures of the graphitic composites at given content are shown in Fig. 1. It is possible to see from optical micrographs of Al/20%SiC/10%Gr in Fig. 1b that the density of graphite

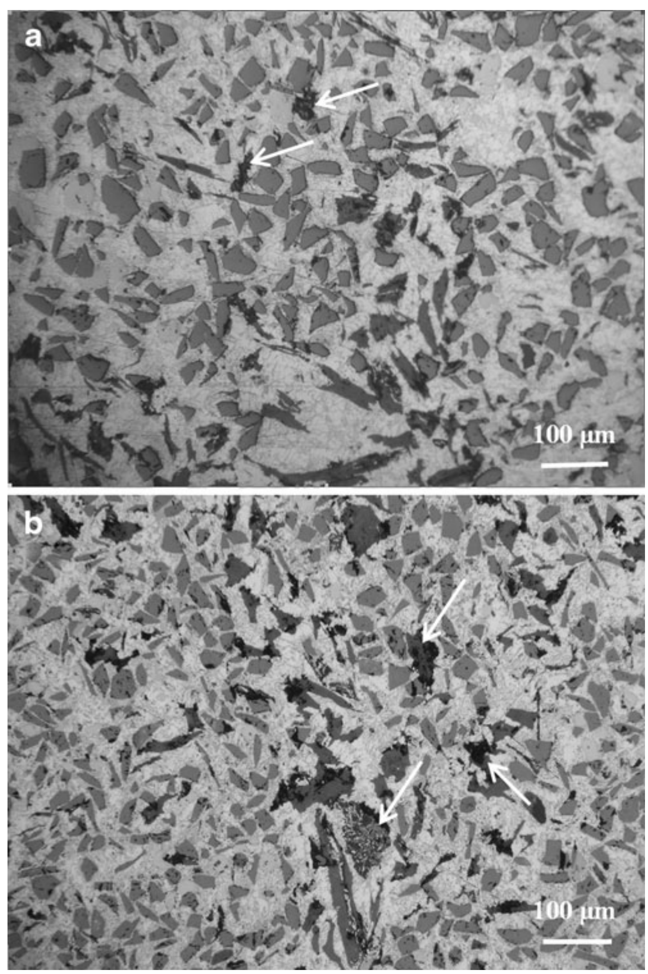

Fig. 1 Optical micrographs of the hybrid composites **a** Al/20%SiC/5%Gr and **b** Al/20%SiC/10%Gr

particles (indicated by arrows) in the aluminum matrix is increased.

2.2 Experimental procedure

Drilling tests were conducted on JohnFord vertical CNC machining center. The machining samples were prepared in the form of 100×10×10 mm blocks for each material. The diamond-like carbon (DLC Drill regular NACHI DLCDR5.0 LIST 9520)-coated cutting tools of 5 mm diameter was used. A fresh tool was used to drill each material (three holes) for all cutting conditions. The point angles were 118°. Coolant was not used in all of the drilling tests. The brief summary of the experimental conditions were shown in Table 1. All drilling tests were performed on a vertical drilling machine. KISTLER 9265B type dynamometer, KISTLER 5019b type charge amplifier and DynoWare analysis program were used to record the cutting force. The experiments were repeated twice to circumvent the possible experimental errors. The Mahr surface roughness tester was used to measure the surface roughness of the drilled holes. The surface finish is recorded at four different locations and average results are considered for the analysis.

3 Results and discussion

3.1 Cutting forces

Cutting speed and feed rate are the two major drilling parameters that are considered in the experiments. Figure 2 shows the variation of cutting force with increasing feed rate for various spindle speeds of 3,500, 4,000, and 4,500 rpm for both workpiece materials. The results reveal that as the feed rate increases from 0.1 to 0.16 mm/rev, the cutting force increases for all the spindle speeds for both the

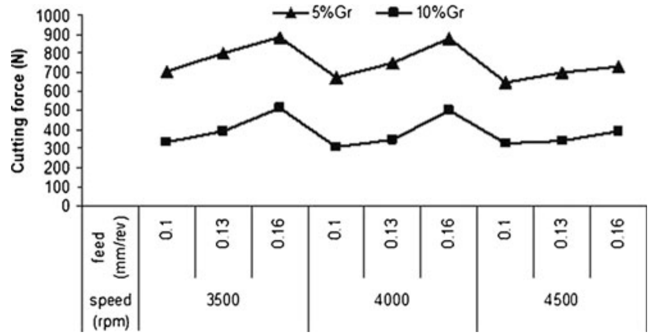

Fig. 2 Variation of cutting force for various speeds and feeds when machining Al/20%SiC/5%Gr and Al/20%SiC/10%Gr using diamond-like carbon (DLC)-coated drills

workpiece materials. The difference between the cutting forces becomes larger at higher feed rates compared to lower feed rates. The feed rate is the predominant factor. When feed rate is increased from 0.10 to 0.16 mm/rev, the value of cutting force (from 333 to 510 N) increases by almost 53% (by addition of 10% graphite and cutting speed is 3,500 rpm) whereas when spindle speed is increased from 3,500 to 4,500 rpm the value of cutting force (from 333 to 388.4 N) increases by almost 16.5% (by addition of 10% graphite and feed rate is 0.10 mm/rev). It can also be observed that there is no predominant variation in cutting force on increasing spindle speed for all feed rates considered. Similar variation is found by Ramulu et al. [14], who reported that drilling forces are significantly influenced by the feed rate when drilling both 10% and 20% Al_2O_3-reinforced 6061 composites.

Cutting forces are high for machining of Al/20%SiC/5% Gr composite compared to Al/20%SiC/10%Gr composite. The cutting force decreases with the increase in graphite content for all cutting conditions. The addition of 10% graphite reduces the cutting forces significantly, which is evident from Fig. 2. From the test results, it can be concluded that when the feed rate is 0.1 mm/rev, the addition of 10% graphite reduces the cutting force (from 703.3 to 333.4 N) by almost 53%. This is attributed to the solid-lubricating property of the graphite particles. The graphite particles reduce the interfacial friction between the tool and the workpiece materials. This helps in shearing the material along the shear plane and influences the shear flow stress. Brown and Surappa [5] reported that the reduction in machining forces with graphite reinforcement content is due mostly to a decrease in the shear flow stress rather than to lower chiprake face friction. Basaravajappa et al. [2] reported that the SiC/Gr MMC has better machinability and can be machined at higher metal-removal rates than other existing SiC reinforced composites. Sharma et al. [15] reported that when drilling ZA-7/graphite reinforced composites, the thrust force decreases with the increase in graphite content.

Table 1 Summary of experimental conditions

Machine	John Ford vertical CNC machining center
Drill type	DLC drills regular, DLCDR5.0 LIST9520 (NACHİ)
	Drill diameter (*D*): 5 mm
	Flute length (l_1): 38 mm
	Overall length (L): 82 mm
	Drill point angle (α): 118°
Work piece	Al/20%SiC/5%Gr and Al/20%SiC/10%Gr
Cutting conditions	Speed: 3,500, 4,000, 4,500 rpm (916, 1,047, 1,178 mm s^{-1})
	Feed rate: 0.1, 0.13, 0.16 mm/rev (5.83, 6.67, 7.5 mm s^{-1})
	Depth of hole drilled: 10 mm

3.2 Surface roughness

Figure 3 shows the variation of surface roughness values for various speeds and feeds for both workpiece materials. It is evident that the surface roughness values for both composites increase with the increase in feed rate while decrease with the increase in spindle speed. The increase in feed rate has a more predominant effect on surface roughness than speed. The surface roughness values always increase with the increase in feed rate and decrease with the increase in cutting speed, and the results are in agreement with other researches [6, 10]. The lowest surface roughness values (0.289 μm for Al/20%SiC/5%Gr and 0.595 μm for Al/20%SiC/10%Gr) occurred at the lowest feed rate at the highest cutting speed. This may be attributed to the burnishing or honing effect produced by the rubbing of small SiC particles trapped between the flank face of the tool and the workpiece surface [2, 6, 16].

Surface roughness values of Al/20%SiC/10%Gr composite are relatively more when compared to Al/20%SiC/5%Gr composite for all cutting conditions. The higher surface roughness values for Al/20%SiC/10%Gr composite can be attributed to the release of graphite between the workpiece and flank face of the tool. When the tool passes over these regions, the crushed graphite particles form a deep valley; and hence increase the surface roughness of the material. This graphite will reduce the friction and burnishing or honing effect that causes the increased surface roughness [6]. The removed graphite particles get smeared on the machined surface, which are evident from Figs. 4 and 5. Scanning electron microscope investigations have revealed that fine grooves, scratches, and many deep valleys have been observed over the machined surface of the composites. Cracks and pits (Figs. 4 and 5) are also observed on the composites. Figure 5 shows the existence of microcracks on the surface of the drilled hole on the composites. Comparing Fig. 4 with Fig. 5, it can be seen that the amount of cracks and pits are less on the machined composite surface.

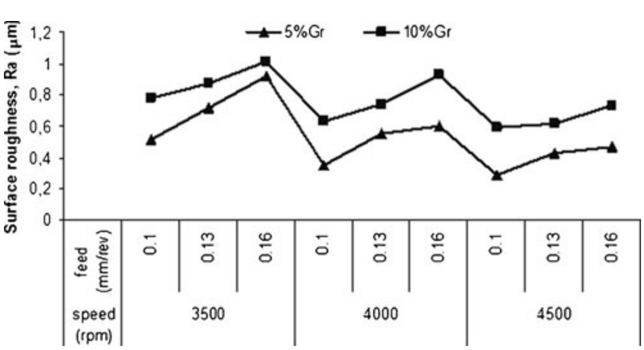

Fig. 3 Variation of surface roughness value for various speeds and feeds when machining Al/20%SiC/5%Gr and Al/20%SiC/10%Gr using diamond-like carbon (DLC)-coated drills

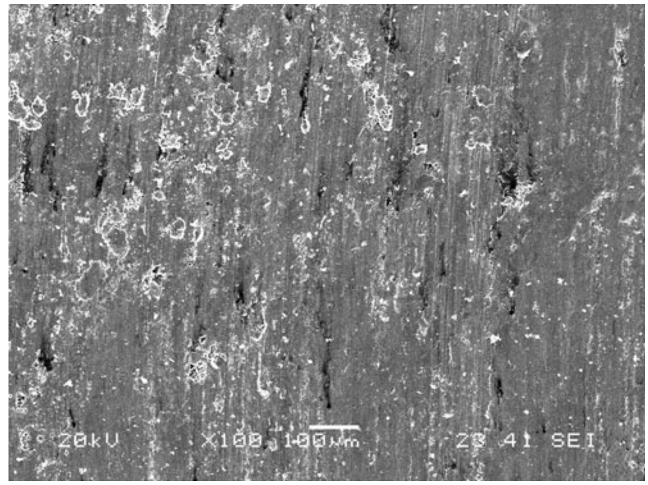

Fig. 4 Scanning electron microscope image of the surface of drilled hole on Al/20%SiC/10%Gr (speed, 4,500 rpm; feed, 0.10 mm/rev, ×100)

4 Conclusions

The following conclusions can be drawn from the present investigation on drilling of Al/20%SiC/5%Gr and Al/20%SiC/10%Gr using DLC-coated cutting tools at different cutting parameters:

1. The results indicate that inclusion of graphite as an additional reinforcement in Al/SiCp-reinforced composite reduces the cutting force. The lowest cutting force value (324 N) was recorded at drilling of Al/20%SiC/10%Gr.
2. The cutting speed and its interactions with feed rate are at minimum and can be neglected. Feed rate is the main factor which is influencing the cutting force in both composites. The cutting conditions for minimized

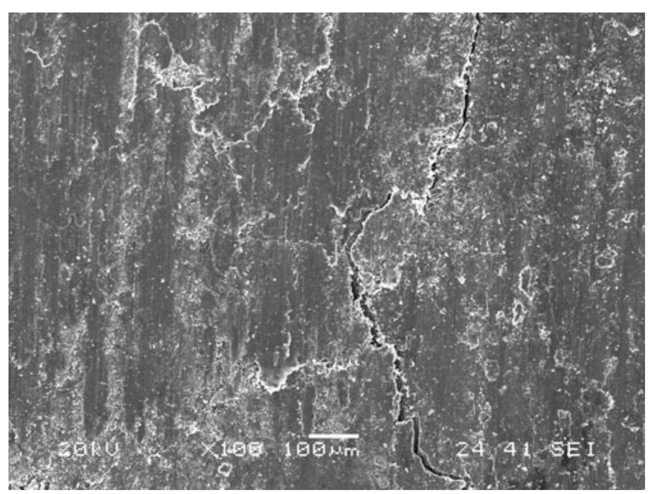

Fig. 5 Scanning electron microscope image of the surface of drilled hole on Al/20%SiC/10%Gr (speed, 4,500 rpm; feed, 0.16 mm/rev; ×100)

cutting force are identified as: cutting speed, 4,500 rpm and feed rate, 0.10 mm/rev.

3. Surface finish is poor at drilling of Al/20%SiC/10%Gr composite compared to Al/20%SiC/5%Gr composite.
4. The surface roughness value increases with the increase in feed rate and decreases with the increase in cutting speed in both composites. The lowest surface roughness values, Ra (0.289 μm for Al/20%SiC/5%Gr and 0.595 μm for Al/20%SiC/10%Gr), occurred at the lowest feed rate (0.10 mm/rev) with highest cutting speed (4,500 rpm).

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