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ORIGINAL ARTICLE

Drilling of hybrid Al-5%SiC_p-5%B_4C_p metal matrix composites

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Abstract Hybrid metal matrix composites consist of at least three constituents—a metal or an alloy matrix and two reinforcements in various forms, bonded together at the atomic level in the composite. Despite their higher specific properties (properties/unit weight) of strength and stiffness, the nonhomogeneous and anisotropic nature combined with the abrasive reinforcements render their machining difficult. The work piece may get damaged and the cutting tools experience high wear rates, which may lead to an uneconomical production process or even make the process impossible. This work reports on the drilling of Al-5%SiC_p-5% B_4C_p hybrid composite with high-speed steel (HSS), not expensive PCD, or carbide drills in an attempt to explore the viability of the process. Drilling of Al-5%SiC-5%B_4C composites with HSS drills is possible with lower speed and feed combination. The cutting conditions for minimized tool wear and improved surface finish are identified. Characterization of tool wear and surface integrity are also carried out.

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Keywords Hybrid metal matrix composites · Drilling · Tool wear · Surface integrity

1 Introduction

Metal matrix composites are materials which combine a tough metallic matrix with a hard ceramic reinforcement. The inclusion of an additional reinforcement phase makes them hybrid composites. Metal composites, in general, possess certain superior properties like low density, high specific stiffness and strength, controlled coefficient of thermal expansion, increased fatigue resistance, and superior dimensional stability at elevated temperature. But their poor machinability attributed to the presence of ceramic reinforcements, resulting in very high rates of tool wear, restricts their widespread use. Though diamond and diamond coated tools are useful for such difficult to machine materials, the increased cost of those tools is a major impediment. In the case of drilling, however, high-speed steel (HSS) drills are still used as cemented carbide drills and diamond drills are very expensive and not widely available.

2 Literature review

Several studies are carried out on the machining of metal matrix composites. Reduction in tool wear and improving surface finish during machining of metal composites has been the bone of contention of researchers worldwide. HSS tools are reported as not the viable option for machining metal composites. Tool wear is excessive and surface finish inadmissible in most cases. PCD, CBN, and coated tools are suitable at certain levels of cutting speed and feed rates

Table 1 Chemical composition of 1100 aluminum

Element	Si	Fe	Cu	Mn	Mg	Zn	Others	Al
Wt.%	0.95		0.05–0.2	0.05	–	0.1	0.05–0.15 max	99.0 min

with satisfactory surface finish [1–8]. The tool wear is found to be influenced more by the feed rate than by the cutting speed [9–12]. Use of coolant improves the performance of these tools in terms of improved tool life and better surface finish of the machined surface [13, 14]. HSS tools, however, could not be excluded from the realm of machining of metal composites. R Teti, while stating that feed rate and not the drilling speed had any effect on the life of PCD tipped drills, also proclaims that even with HSS drills, the wear reduces with the feed rate [15]. The wear mechanism is by microcutting with the worn surface of the drills characterized by grooves oriented parallel to the cutting direction. Narutaki explains that at low speeds, increase in feed rate reduces tool wear because of the reduced cutting time [16]. Gul Tosun and Mehtap Muratoglu reported on better performance by HSS drills with 130^o point angle while drilling Al 2124/17SiC_p at low speeds and high feed rates [17]. TiN-coated HSS drills are economical than solid carbide drills. The surface roughness decreases with increased feed rate at each spindle speed of drilling Al 2124/17SiC_p composite with HSS drills. The surface roughness decreases with increase in point angle of the drill [18]. S. 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 [19]. They reported that ceramic–graphite reinforced composite has better machinability than those reinforced with silicon carbide particles only. Hayajneh et al. studied effect of cutting speed, cutting feed, and volume fraction of the reinforced particles of self-lubricated aluminum/alumina/graphite hybrid composites on the thrust force and cutting torque using experimental techniques and ANN [20].

The use of metal matrix composite (MMC) in the automotive, railway, and aerospace industries has been limited by the following aspects: the high machining costs due to the short standard tool life; PCD tooling and cemented carbide drills are not available for complex-shape cutting tools (e.g., taps or very small diameter drills and reamers) and are very expensive as well. Owing to their low cost, HSS tools are readily selected. This paper aims to identify the cutting parameters which give better surface finish with HSS drills besides performing a study on the tool wear and surface integrity aspects on a newer hybrid metal composite.

3 Experimental procedure

3.1 Preparation of the composite

The hybrid composite comprises 1100 aluminum alloy as matrix and SiC and B_4C as reinforcements. Aluminum reinforced with 10 vol.% SiC has been prepared by various researchers. The volume fraction was adjusted between B_4C and SiC to study the effect of addition of B_4C on the properties of the hybrid composite, particularly its machinability. Moreover, B_4C is understood to have neutron absorbing capability [21], and hence, this composite may well be suited for applications in nuclear reactors. Samples of the composites were prepared by stir casting route. The melting was carried out in a resistance furnace. Scraps of 1,100 aluminum were preheated at 450°C for 3 to 4 h before melting. Table 1 gives the chemical composition of the matrix material. The SiC and B_4C particles were also preheated at around 1,000°C to 1,200°C to make their surfaces oxidized. The average particle size of the SiC particles was 10 μm, and the average particle size of B_4C was 65 μm. The preheated aluminum scraps were first heated above the liquidus temperature to melt them completely. They were then slightly cooled below the liquidus to maintain the slurry in the semisolid state. This procedure has been adopted while stir casting aluminum composites [22–24]. The preheated reinforcements were added and mixed manually. Manual mixing was used because it was very difficult to mix using automatic device when the alloy was in a semisolid state. The composite slurry was then reheated to a fully liquid state, and mechanical mixing was carried out for about 10–15 min at an average mixing speed of 150–300 rpm. The final temperature was controlled to be within 750°C±10°C, and pouring temperature was controlled to be around 720°C. After thorough stirring, the melt was poured into steel molds of 20 mm diameter and 30 cm in length and allowed to cool to obtain cast rods. Table 2 shows the properties of the prepared composite. The microstructure of the composite is shown in Fig. 1.

The circular rod was transformed into a square rod by milling. It was then split into two pieces in the longitudinal direction by grinding. Small pieces with

Table 2 Properties of Al-SiC-B_4C composite

Composite	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Hardness HBW
Al-5%SiC_p-5%B_4C_p	81.37	134.62	2.2	63; 5/750

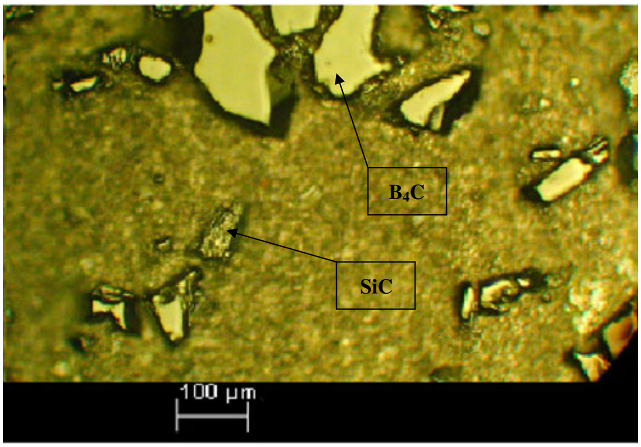


Fig. 1 Microstructure of the hybrid composite

length sufficient to accommodate nine holes were cut out of the split pieces.

3.2 Machining

Table 3 shows the various machining parameters and their levels. The levels were chosen to be representative of the low, medium, and high ranges available in the machine. The experiments were performed at different speeds of 160, 315, and 630 rpm and feed rates of 0.125, 0.200, and 0.315 mm/rev as given in Table 4. All drilling tests were performed on a vertical drilling machine. Drills used throughout the tests were all 5 mm diameter drills. The point angles were 118°, and helix angles were 30°±3. HSS was the material of the drills. Coolant was not used in all of the drilling tests.

3.3 Surface roughness and tool wear

The surface finish of the hole walls was measured with a Talysurf having a diamond stylus and traverse length of 5 mm. Surface finish values were recorded for every hole at 60° intervals around the circumference, and mean values were determined.

The wear on a drill is difficult to measure because the entire cutting edge is in contact with the work piece, and therefore, there is no unused cutting edge to use as a datum. Drill tool wear measurements were made using a special fixture. The flank wear was measured by a Toolmaker's microscope. After drilling, a scanning electron microscopy (SEM) was used to investigate the tool wear. The gross tool wear was viewed at a low magnification, while localized damage was evaluated at a higher magnification.

Table 3 Experimental parameters and their values

Parameters	Values
Drill type	HSS, parallel shank
Drill size	Ø 5 mm
Drill point angle (°,α)	118
Feed rate (mm/rev, s)	0.125, 0.2, 0.315
Spindle speed (rpm, n)	160, 315, 630

Table 4 Variable factor levels

S.No	Feed mm/rev	Speed rpm
1.	0.125	160
2.	0.125	315
3.	0.125	630
4.	0.200	160
5.	0.200	315
6.	0.200	630
7.	0.315	160
8.	0.315	315
9.	0.315	630

4 Results and discussion

4.1 Variation of tool wear with cutting parameters

The tool wear was measured using the Toolmaker's microscope. Measurement of tool wear in drill is comparatively more difficult than measuring the wear of a single point tool. The accurate wear of the cutting edges can be measured only if they are made as horizontal. A special fixture was fabricated with a drilled hole inclined at 59° to the horizontal. The drill tool was supported by a bush in the fixture. Tapped screws at the front and bottom of the fixture

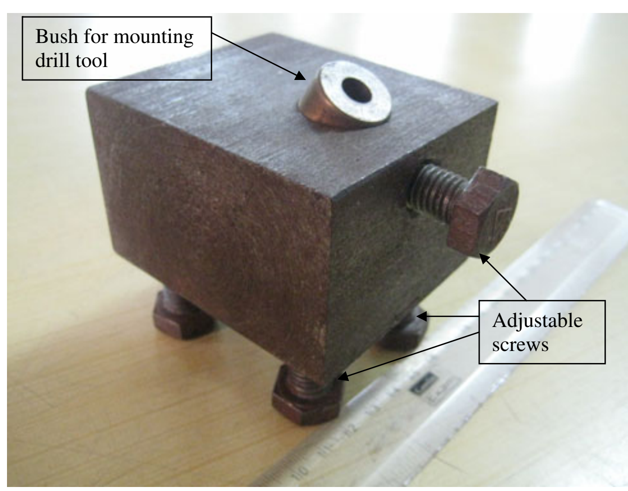


Fig. 2 Fixture for determining drill wear

were adjusted to make the cutting edge perfectly horizontal. Figure 2 shows the fixture used for determining tool wear. Figure 3 shows the variation of tool wear with speed at different feeds. The contact of the tool with the composite decides the tool wear. When the harder reinforcement(s) comes into contact with the tool, abrasive wear is promoted. SiC particles with hardness≈3500 HV and B_4C particles with hardness≈4200 HV grind the cutting edges in a manner akin to the grinding process [11]. At lower speed and lower feed rate, the tool-work contact duration increases. This has resulted in increased tool wear. This can be attributed to the fact that abrasive form wear on the flank face of the drill is predominant at low speeds. At low speeds, increase in feed rate reduces tool wear because of the reduced cutting time [16]. The bar chart presented in Fig. 4 gives complete details of tool wear for different cutting speeds and feed rates. The area and time of contact between the cutting tool and work piece material are to be understood. Assuming that a unit volume of material is to be removed, the area swept by the cutting edge is the product of the width of cut and feed rate. For a given width and depth of cut, the contact area between the tool and work piece is proportional to the feed rate. The area of contact for abrasion between the hard SiC and B_4C particles of the work piece and the drill is greatest at the lowest feed rate, thereby, giving rise to increased drill wear.

4.2 Variation of surface roughness with cutting parameters

Under a given set of process parameters, surface finish depends on the material, geometry of the tool, type of chip produced, work material, and vibration of the machining system. The surface roughness produced in drilling operation in composite comprises of three parts: one originates inherently as feed marks depending upon the tool geometry and the magnitude of speed and feed, the second one gradually appears due to deterioration of the cutting edges and vibration, and the third is due to the particle pull out and damages.

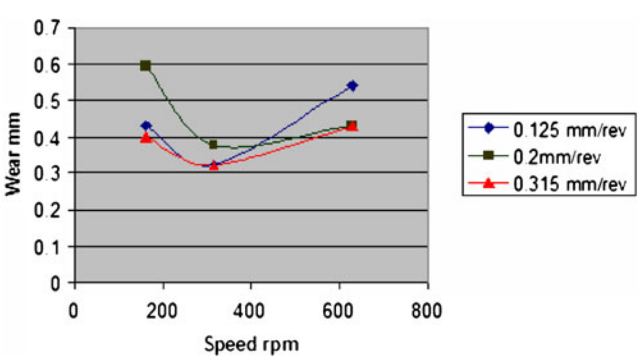


Fig. 3 Variation of tool wear with speed at different feeds

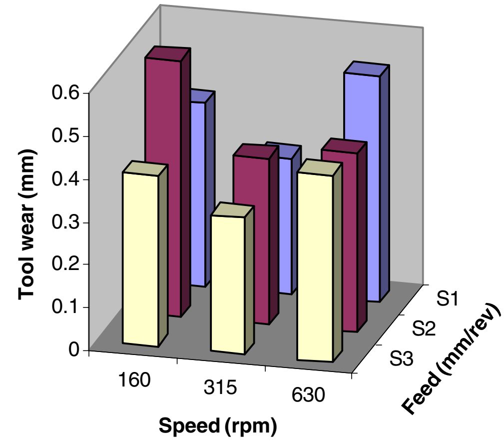


Fig. 4 Variation of tool wear with speed and feed

Work piece surface roughness values (R_a) were measured after machining. The variation of surface roughness with different speeds and feeds is presented clearly in Fig. 5. It can be seen that at low feed rate and speed the surface roughness is least. High feeds and high speeds increased the roughness. High feed rates increase the heat generated and hence, the cutting temperature, which accelerate diffusion and adhesion wear with thermally weakened tool. Tool chatter also increases with feed, which leads to increased surface roughness.

At low speed, the burnishing or honing effect produced by the action of small reinforcement particles trapped between the flank face of the tool and the surface of the work piece might be the reason for decreased surface roughness. This result is supporting the observation of Monaghan et al. [25]. At high speeds, fracture of cutting edges due to higher cutting forces increases the surface roughness. This is because HSS drills have lower hardness values when compared to coated or other drills and therefore, less wear resistant. Hence, increase in speed

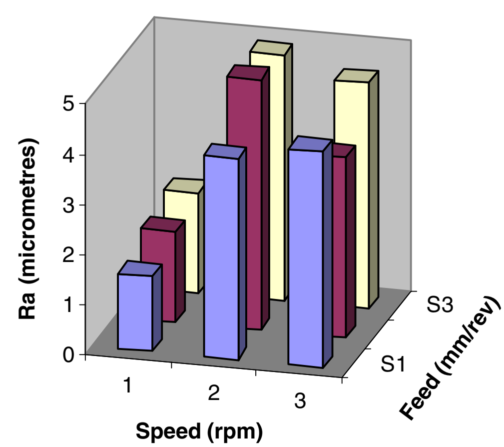
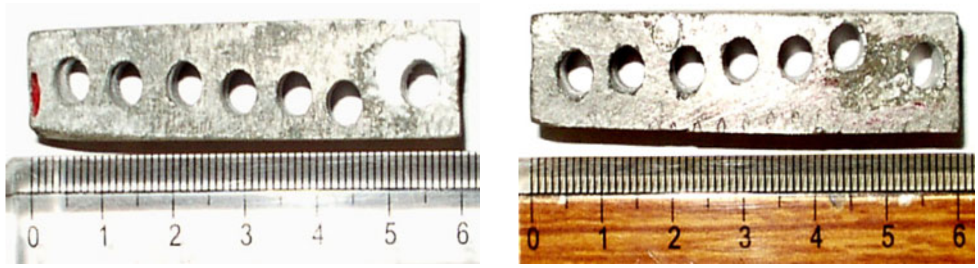


Fig. 5 Variation of surface roughness with different speeds and feeds

Fig. 6 Macrographs of the drilled holes at entry and exit sides



a) Entry side **b) Entry side**

increases the surface roughness [18]. Furthermore, the cutting temperature increases which weakens the bonding strength of the matrix because of which the SiC and B_4C particles get pulled out easily, thereby, increasing the roughness. Also cracks and voids present in the composite contribute to the observed values.

4.3 SEM image characterization

In order to examine the surface damages of the work piece and tool wear in detail, the drilled hole surface and worn cutting tools were investigated using the SEM.

4.3.1 Surface integrity aspects

Macrographs of the drilled holes at entrance and exit sides are presented in Fig. 6. The SEM micrographs of the drilled surface and subsurface are given. Figure 7 shows the surface of the drilled hole. Smoother surface could be observed. Brighter particles or dislodged particles from the matrix material also can be seen at higher magnification. During the drilling operation, the particles rub against the tool causing tool wear. At the same time, the mutual rubbing of abrasive particles in the drilled hole surface of the drilled hole improves the surface finish.

At higher speed and feed rate, the contact duration of the tool with the work material is reduced. Hence, the tool wear is decreased. However, higher cutting speed and increased feed rate increase the temperature at the tool-work surface. This leads to softening by plastic deformation. It further causes pull out of particles from the work surface. The worst surface finish can be seen from Fig. 8. Grooves-like structure is observed at higher magnification. The dislodged abrasive particles generate grooves on the surface of the work piece when the tool edge comes in contact with hard and brittle particles. Careful examination of the worn surface reveals that a high speed causes an extensive surface damage in composites due to higher contact pressure. In addition to the above damage features at higher load, Al/SiC/B_4C also exhibited cracks at the SiC and B_4C particle/Al matrix interface and particle pull out. The occurrence of such pull out was found to increase as the contact pressure increased. If the SiC particles are pulled out during cutting, cracks and pits are formed on the surface and these result in poor surface finish. SEM image indicates

Fig. 7 SEM image of the surface of drilled hole (speed 160 rpm/feed 0.2 mm/rev, ×60)

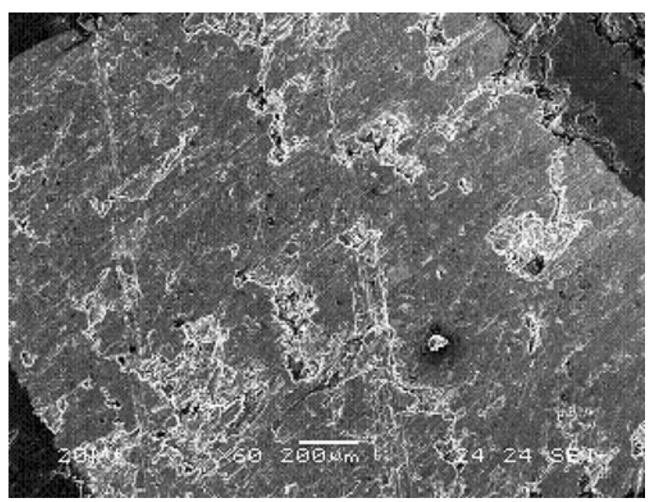


Fig. 8 SEM image of the surface of drilled hole (speed 160 rpm/feed 0.315 mm/rev, ×60)

the existence of grooves on the machined surface. The grooves are due to SiC and B_4C particles being pulled out of the composite material and dragged over the machined surface causing "scratches."

4.3.2 Tool wear

After drilling test, a SEM was used to investigate the tool wear. The gross tool wear was viewed at a low magnification, while localized damage was evaluated at the cutting edge. In machining of conventional metals, the cutting tools are abraded by the strain-hardened chips generated in machining process. Since the pressure between the work piece and the cutting tool is very high, much heat is generated.

Typical SEM micrographs of wear patterns of HSS cutting tools are shown in Fig. 9a, b. It can be seen that the flank wear was caused by the abrasive nature of the hard SiC and B_4C particles present in the work piece materials. Because of the high pressure generated at the tool-work piece interface, the worn flank encouraged the adhesion of the work piece material. It is suggested that tool wear in the flank was caused by both the abrasive wear and the adhesive wear mechanisms.

The reinforcement particles generated small grooves on the surface of the tool edge since they are hard and brittle particles. From the SEM images, it is identified that at higher speed crater wear was also observed, which is due to the widening of grooves that were caused by abrasion. The grooves formed on the rake face of HSS tools were filled with smeared work piece material. This form of built-up edge is beneficial, since it protects the tool rake from further abrasion. During operation, friction between tool and work piece results in increased temperature at the cutting zone. Higher cutting speeds cause higher temperatures that cause softening and reducing of the adhered material on tool.

5 Conclusion

Aluminum hybrid MMCs were fabricated successfully through stir casting route. Uniform distribution of reinforced particles B_4C and SiC is confirmed through optical microscopy.

Holes having a diameter of 5 mm were drilled on the hybrid composites.

The surface morphology of the worn out HSS tool and surface damage of the composite were studied under SEM.

The cutting conditions for minimized tool wear are identified as: cutting speed 315 rpm and feed 0.315 mm/rev.

The cutting conditions for improved surface finish are identified as: cutting speed 160 rpm and feed 0.125 mm/rev.

Abrasive and adhesive wear are found to be predominant during machining these composites.

The tool wear of HSS tools increased with increasing cutting speeds. Cutting speed is the key factor, which has greater influence on surface roughness. Irrespective of feed rates, lower speed results in smoother surface finish.

Analysis of the machined surface of Al-5%SiC_p-5% B_4C_p shows that some of the reinforcing SiC and B_4C particles are pulled out of the drilled surface, while others become fractured. Moreover, voids and cracks initiate around the particles due to plastic deformation in the matrix material.

It has been concluded that drilling of Al-5%SiC-5% B_4C composites with HSS tool has to be carried with lower speed and feed combination.

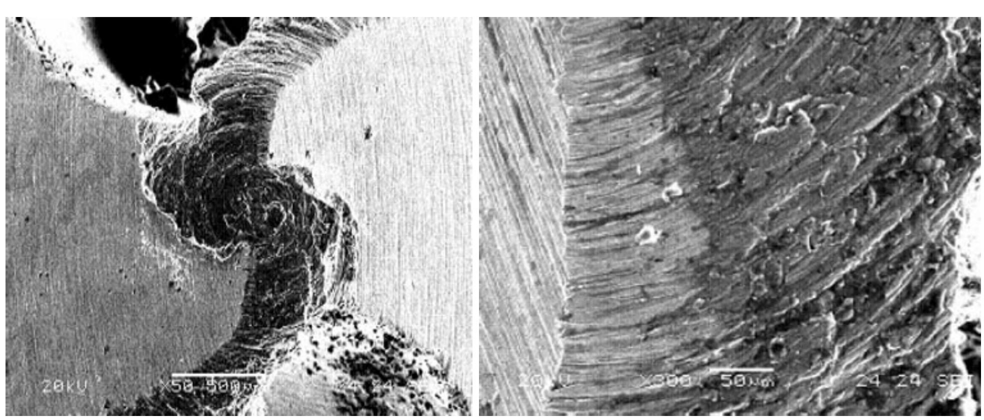


Fig. 9 SEM images of worn out drill bit with different speed–feed combinations

a) Speed 160rpm/feed 0.125 mm/rev, X50 **b) Speed 315 rpm/ feed 0.125 mm/rev, X300**

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