Influence of particle size on Cutting Forces and Surface Roughness in Machining of B₄Cₚ - 6061 Aluminium Matrix Composites

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Abstract. Amongst advanced materials, metal matrix composites (MMC) are gaining importance as materials for structural applications in particular, particulate reinforced aluminium MMCs have received considerable attention due to their superior properties such as high strength to weight ratio, excellent low-temperature performance, high wear resistance, high thermal conductivity. The present study aims at studying and comparing the machinability aspects of B₄Cₚ reinforced 6061Al alloy metal matrix composites reinforced with 37µm and 88µm particulates produced by stir casting method. The micro structural characterization of the prepared composites is done using Scanning Electron Microscopy equipped with EDX analysis (Hitachi Su–1500 model) to identify morphology and distribution of B₄C particles in the 6061Al matrix. The specimens are turned on a conventional lathe machine using a Polly crystalline Diamond (PCD) tool to study the effect of particle size on the cutting forces and the surface roughness under varying machinability parameters viz., Cutting speed (29-45 m/min.), Feed rate (0.11-0.33 mm/rev.) and depth of cut (0.5-1mm). Results of micro structural characterization revealed fairly uniform distribution of B₄C particles in the 6061Al matrix. The specimens are turned on a conventional lathe machine using a Polly crystalline Diamond (PCD) tool to study the effect of particle size on the cutting forces and the surface roughness under varying machinability parameters viz., Cutting speed (29-45 m/min.), Feed rate (0.11-0.33 mm/rev.) and depth of cut (0.5-1mm). Results of micro structural characterization revealed fairly uniform distribution of B₄C particles in the 6061Al matrix. The surface roughness of the composite is influenced by cutting speed. The feed rate and depth of cut have a negative influence on surface roughness. The cutting forces decreased with increase in cutting speed whereas cutting forces increased with increase in feed and depth of cut. Higher cutting forces are noticed while machining Al6061 base alloy compared to reinforced composites. Surface finish is high during turning of the 6061Al base alloy and surface roughness is high with 88µm size particle reinforced composites. As the particle size increases Surface roughness also increases.

1. Introduction

Composite materials are important engineering materials due to their superior mechanical and physical properties. The properties which make them superior than others are high specific strength, hardness, stiffness, corrosion resistance, high wear resistance and low thermal coefficient of expansion. These
properties contribute to the larger reduction in weight, which is desired in automotive and aerospace applications [1]. Therefore, these materials tend to replace conventional materials in various fields. The properties of a composite material are controlled by the matrix, the reinforcement and the interface. Usually light weight materials are preferred as Matrix materials, and especially ceramic reinforcements such as Al₂O₃, SiC, TiB, TiC and B₄C are added to get high specific strength. Ceramic reinforcements are added in the form of whiskers, particulates, short fibers, continuous fiber and monofilament. The characteristics of composites fabricated will be changed depending on the fabrication procedure and composite system. The fabrication techniques can be divided into three types [2]. These are solid phase, liquid phase and semi solid phase process. Stir casting and Infiltration account for the largest volume in primary production (67%) but, due to the low cost of these processes, represent only about 25% of the MMC market by value [3]. The difficulties encountered during synthesis are, the incorporation of ceramic reinforcements into the matrices, agglomeration and poor wettability between reinforcing particles and matrices. A homogeneous distribution of reinforcing particles in the matrices is desired to maximize the mechanical properties and improve the machinability of MMCs [4]. The process of stir casting generally involves the admixture of ceramic particulate reinforcement with a molten metal matrix. The particulates are distributed and suspended in the molten metal via high energy mixing or by other appropriate process. The suspended slurry is then cast as a foundry ingot, extrusion billet or rolling bloom.

Al6061 exhibits good machinability and weldability, which is used in automotive, aerospace, electronics and medical industries. B₄C reinforcement is to provide stiffness and hardness to the matrix. MMCs with B₄C reinforcement provide high neutron absorption for nuclear containment. The objective of the present work is to fabricate, characterize and investigate the machinability behavior of the Al6061-B₄C MMC produced by Stir casting route.

MMC offer advantages such as light weight, high stiffness, stability at high temperature and good wear resistance; however, they have certain disadvantages like high cost and difficulty in machining. The semi solid metallurgy technique is the most economical of the entire available route for MMC production. It allows very large sized components to be fabricated, and is able to sustain high productivity rates. Naher et al [2] has shown that the cost of preparing composite materials using a casting method is about one third to one half that of competing methods.

Machining of Metal matrix composites is one of the major problems, which resists its wide spread engineering applications [5]. From some early conventional turning tests on Al/SiC MMC [6, 7], it is found that tool wear is excessive and surface finish is very poor while carbide tip tools are used for machining. The hard ceramic particles of MMCs act as small cutting edges like those of a grinding wheel on the cutting tool edge, which in due course is worn out by abrasion and resulting in the formation of poor surface finish [8]. J. Paulo Davim et al [9, 10 and 10] studied the machinability of MMCs reinforced with SiCₚ (20%) using PCD tools having in consideration the evolution of the cutting time of the tool wear, the cutting forces and the surface roughness. N. P. Hung, et al. [12] carried out experimental studies on the cumulative tool wear during the machinability of aluminium matrix reinforced with aluminium oxide/silicon carbide particles. They have concluded that the slope of cutting speed v/s tool life line is independent of heat treatment. The machinability behaviour of various MMCs during turning is reported in the literatures [13, 22]. However, less work addressed the machinability of Al6061 – B₄Cₚ MMC produced by stir casting technique. In the present work an attempt has been made to investigate the influence of cutting speed, feed rate and depth of cut on cutting force, surface roughness and tool tip temperature during turning of the Al6061 – B₄Cₚ MMC produced with different volume fractions.
2. Experimental Details

In the current study, 6061 aluminium alloy with the density of 2700 kg/m$^3$ is used as the matrix material while B$_4$C particulates with mesh size of 37µm and 88 µm with a density of 2520 kg/m$^3$ are used as reinforcement. The specimens of the unreinforced 6061Al alloy and 6061Al reinforced with 5 wt% B$_4$C particles are prepared via stir casting method. The chemical composition of the 6061Al was analyzed using Atomic Absorption Spectroscopy (VARIAN) and is presented in Table 1. The mixture containing B$_4$C particulates and hexafluorotitanate (K$_2$TiF$_6$) in the ratio 0.3 is preheated to a temperature of 250°C to overcome the poor wettability of B$_4$C before introducing into the melt. The SEM image and the EDX spectrum taken on the mixture is presented in Fig. 1 (a-b). The melting of the 6061Al alloy at a temperature of 750°C was carried out using Graphite crucible in an electric furnace under the cover flux. Solid hexachloroethane (C$_2$Cl$_6$) tablets were added into the charge to release all the absorbed gases. A steel rod coated with Zirconia is used for stirring the molten metal to create vortex. The stirring was carried out at a spindle speed of 250 RPM for 5-8 min. The preheated mixture containing B$_4$C$_{30}$ and K$_2$TiF$_6$ salt was introduced into the vortex in two stages to avoid agglomeration of the B$_4$C particulates. The melt is poured into a preheated metallic mould having dimensions of 40mm dia. and 165mm long. The micro structural characterization of the prepared composites is done using SEM equipped with EDX analysis (Hitachi Su – 1500 model) to identify morphology and distribution of B$_4$C particles in the 6061 Al matrix. The fabricated composites are turned on a conventional, self centered three jaw chuck, medium duty lathe (HMT make, LTM 20, 3kW, 4 HP). The work piece length is 150 mm and diameter 35 mm. The turning operations are carried out using the brazed PCD tool of grain size 10µm with the following geometry: rake angle: 0°, clearance angle: 7°, cutting edge angle: 85° and Nose radius: 0.8 mm. Machining tests were conducted in dry cutting conditions. The machining parameters used in the present study are given in Table 2.

| Table 1 Chemical composition of 6061Al |
|--------------------------------------|
| Elements | Mg | Si | Fe | Cu | Mn | Cr | Zn | Ti | Al |
| % by Weight | 0.95 | 0.54 | 0.22 | 0.17 | 0.13 | 0.09 | 0.08 | 0.01 | Balance |

Figure 1(a-b) Shows SEM microphotograph of the reinforcement mixture (B$_4$C particulates and K$_2$TiF$_6$ flux) with a ratio of 0.3 used in the present study for preparing 6061Al-B$_4$C metal matrix composites and EDX taken on the mixture.
During experimentation, one parameter is varied while others are held constant to observe the effects of variation of an individual input parameter on the output parameters. A three-axis piezoelectric dynamometer with a PC-based data acquisition system is used to measure the cutting forces. Surface roughness is measured by Mitutoyo surface tester SJ 201.

3. Results and Discussions

3.1 Micro structural studies

The SEM images of the fabricated 6061Al matrix and 6061Al-5 wt% composites are shown in Fig. 2 (a-b) & (c-d) respectively. From Fig. 2(a-b) it is clear that microstructure of the 6061Al base matrix consists of α-Al dendrites and autistic Si. Eutectic Si being distributed at the boundaries is confirmed from the microstructure of the 6061Al base matrix as shown in Fig 2(a-b). The SEM images of the 6061Al-5wt%B₄C composites prepared at 750°C via melt stirring method are presented in Fig. 2 (c). Fairly uniform distribution of the B₄C particles in 6061Al matrix can be evidenced from the figures. Due to poor wettability of B₄C by Al-matrix, Kalaiselvan et al. [23] used processing temperature of 800°C in their work on Al-B₄C MMC’s. However, in the present work the use of K₂TiF₆ salt has improved the wettability of B₄C by liquid Al matrix at 750°C which is used as the flux. The formation of an oxide layer on the Al surface helps B₄C particles to break and enter into the melt thereby improving wettability. The formation of a white layer around the B₄C particle as witnessed in SEM microphotograph is a layer of Ti compound supported by EDX spectrum (Fig. 2e). The exothermic reaction between K₂TiF₆ salt and liquid Al matrix results in formation of Ti compound layer [24]. The presence of Ti compound layer around B₄C particle is also one of the reasons for improved wettability. Two stage additions of the preheated reinforcing mixture have resulted in fairly uniform distribution of the B₄C reinforcing particles in Al matrix. Two stage addition of the reinforcing mixture has an influence on viscosity of the matrix. When preheated mixture was added to liquid Al matrix all at once at 750°C, viscosity increases making stirring difficult. In contrast to this two stage addition of the reinforcing mixture controls viscosity thereby uniform dispersion of B₄C particles in Al matrix.

3.2 Machinability Studies

3.2.1 Cutting Forces

The aim of the current experimental work is to investigate the effect of B₄C particle size on cutting forces and surface finish. Three cutting speeds ranging from 29 to 65 m/min. with three feed rates varying from 0.11 to 0.33mm/rev. and depth of cut ranging from 0.5 to 1mm was used in the machining of the produced MMCs. The cutting forces were measured using a three-axis piezoelectric dynamometer with a PC-based data acquisition system. The average surface roughness (Ra) was measured using a surface roughness tester (Mitutoyo SJ 201). Microscopic examinations of the machined surfaces were carried out using SEM.
Figure 2(a-c) showing SEM Images of (a-b) 6061Al alloy matrix (c) 6061Al-7wt% B₄C composite
(d) EDX spectrum taken on white Ti layer formed around B₄C particle

Fig. 3 (a) shows the variation of cutting force with cutting speed during turning of the Al6061-B₄Cₓ MMCs. The machining operation was carried out with three speeds viz. 29, 43 and 65 m/min and constant feed rate of 0.11mm/rev and with a constant depth of cut of 0.5mm. It is evident from the graph that during turning of 6061Al-B₄Cₓ composites, cutting force decreases with increases in cutting speed at a constant feed rate and depth of cut. High cutting force is noticed while machining Al6061 base alloy compared to reinforced composites. Cutting force is less while machining MMC with a particle size of 88µm.

Fig. 3 (b) presents the effect of increasing the feed rate on cutting force during machining of 6061Al-B₄Cₓ composites. The influence of feed rate was studied at feed rates of 0.11 mm/rev, 0.22 mm/rev and 0.33 mm/rev and at constant cutting speed of 29 m/min. and with constant depth of cut of 0.5mm. It can be concluded from the graph that the cutting force increases with increase in feed rate. This can be attributed to the higher friction between the tool and the workpiece. Higher cutting force is noticed while machining composites of 37µm.

Fig. 3 (c) the influence of depth of cut on cutting force that is generated during turning of 6061Al-B₄Cₓ composites. The cutting forces were predicted for three depths of cuts i.e. 0.5 mm, 0.75 mm and 1 mm with constant speed of 29m/min. and constant feed rate of 0.1 mm/rev. From the graph it is clear that the cutting force increases with an increase in depth of cut. High cutting forces are noticed while machining Al6061 base alloy specimen compared to reinforced composites. Generation of cutting force is less when machining Al6061- B₄Cₓ with 88µm particle size.
Figure 3 (a-c): shows the variation of cutting force during machinability studies of 6061Al-5wt% B₄Cₚ with different particle sizes (a) with cutting speed (b) with feed rate (c) with depth of cut.

3.2.2 Surface Roughness Measurements

MITUTOYO SJ 201 Surface Roughness Tester was used to measure the surface roughness of the machined 6061Al-B₄Cₚ composites. The stylus is capable of measuring with a speed of 0.25mm/s, 0.55mm/s and returning 0.8mm/s. The effect of cutting speed on the surface roughness of 6061Al-B₄Cₚ composites with different particle sizes of reinforcement is presented in Fig. 4 (a).

The surface roughness was measured at three different cutting speeds namely 29 m/min, 46 m/min. and 65 m/min. with constant feed rate of 0.1mm/rev and with constant depth of cut of 0.5 mm. At higher cutting speeds, the area of contact between tool and workpiece is less resulting in improved surface finish. It is evident from the graph that as cutting speed increases surface roughness decreases. Also, as the particle size increases the surface roughness also increases. Higher surface finish is observed while machining 6061Al base alloy.

The influence of feed rate on surface roughness while machining 6061Al-B₄Cₚ composites is shown in Fig. 4 (b). Surface roughness was measured at three feed rates, namely, 0.11 mm/rev, 0.22 mm/rev and 0.33 mm/rev with the constant cutting speed and depth of cut of 29 m/min. and 0.5 mm respectively. Figure clearly suggests that as the feed rate increases surface roughness increases. With increasing feed rates more and more amount of work piece will come in contact with tool surface. Higher surface roughness is noticed while machining composites with 88µm. Again, surface roughness is less while machining unreinforced alloy.
Figure 4 (a-c) shows the influence of cutting speed, feed rate and depth of cut on the surface roughness of 6061Al-B₄C₉ composites during machining.

Fig. 4 (c) shows the effect of depth of cut on the surface roughness of 6061Al-B₄C₉ composites. Here, surface roughness was measured at three depths of cuts i.e. 0.5 mm, 1.0 mm and 1.5 mm. Keeping cutting speed and feed rate constant at 29m/min and 0.1mm/rev respectively. The graph clearly reveals that as depth of cut increases surface roughness also increases. The formation of the larger amount of chips with larger c/s area leads to higher surface roughness. Surface roughness is high while machining Al6061-B₄C₉ composites with a particle size of 88µm.

Figure 5(a&b) shows the SEM microphotographs of machined surfaces of 6061Al-B₄C₉ Composites.
4. Conclusions

1. Al6061 alloy reinforced with 5 wt% B₄C particulate composites with 37 and 88μm particle sizes were successfully produced at temperature of 750°C via stir casting method.
2. Fairly uniform distribution of B₄C particulates in 6061Al matrix is achieved due to the addition of K₂TiF₆ halide salt.
3. Higher cutting forces are noticed while machining Al6061 base alloy compared to reinforced composites.
4. Surface finish is high during turning of the 6061Al base alloy and surface roughness is high with 88μm particle reinforced composites. As the particle size increases Surface roughness also increases.

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