October 2011

Role of garnet and silicon carbide abrasives in abrasive waterjet cutting of aluminum-silicon carbide particulate metal matrix composites

Dr.S. Srinivas

Department of Mechanical Engineering, BMS College of Engineering, Bengaluru-560 019, India,
ss_bms@yahoo.co.in

N. Ramesh Babu

Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai – 600 036, India,
nrbabu@iitm.ac.in

Follow this and additional works at: <https://www.interscience.in/ijarme>

Part of the [Aerospace Engineering Commons](#), and the [Mechanical Engineering Commons](#)

Recommended Citation

Srinivas, Dr.S. and Ramesh Babu, N. (2011) "Role of garnet and silicon carbide abrasives in abrasive waterjet cutting of aluminum-silicon carbide particulate metal matrix composites," *International Journal of Applied Research in Mechanical Engineering*: Vol. 1 : Iss. 2 , Article 9.

DOI: 10.47893/IJARME.2011.1022

Available at: <https://www.interscience.in/ijarme/vol1/iss2/9>

This Article is brought to you for free and open access by the Interscience Journals at Interscience Research Network. It has been accepted for inclusion in International Journal of Applied Research in Mechanical Engineering by an authorized editor of Interscience Research Network. For more information, please contact sritampatnaik@gmail.com.

Role of garnet and silicon carbide abrasives in abrasive waterjet cutting of aluminum-silicon carbide particulate metal matrix composites

¹Dr.S. Srinivas*, ²N. Ramesh Babu

¹Department of Mechanical Engineering, ²Department of Mechanical Engineering

¹BMS College of Engineering, ²Indian Institute of Technology Madras
Basavanagudi

¹Bengaluru-560 019, India, ²Chennai – 600 036, India

*Corresponding author

E-Mail:ss_bms@yahoo.co.in, nrbabu@iitm.ac.in

Abstract : This paper covers studies on machinability of aluminum-silicon carbide particulate metal matrix composites (Al-SiCp MMCs) with abrasive waterjets (AWJs) produced by two different types of abrasives. Four different compositions of Al-SiCp MMCs were processed with 60, 80 and 120 mesh size garnet and SiC abrasives with a view to identify the correct type and size of abrasive for effective processing of MMCs with AWJs. The maximum penetration ability of AWJs in different MMCs was examined by conducting the experiments on a wedge shaped Al-SiCp MMC specimens, prepared with stir casting method. Optical micrographs of MMC samples and scanning electron microscopic (SEM) examination of AWJ cut surfaces enabled to explain the trends of material removal with both types of abrasives. Analysis of results clearly indicated the choice of 80 mesh size SiC abrasives for effective processing of Al-SiCp MMCs with AWJs.

Keywords: Abrasive waterjet cutting, Metal matrix composites, Stir casting, Abrasives

1. Introduction

Metal matrix composites (MMCs) possess certain unique properties such as high strength and modulus, good dimensional stability, and excellent resistance to fatigue, creep, corrosion, and wear. All these properties have made these materials to be used extensively in automobile, marine, aerospace, and electronic industries [1-2]. Though these composite products are made to near net shape, certain internal and external features are to be machined precisely to utilize them for certain functional applications [3].

The major problem of machining MMCs with conventional cutting tools is excessive wear of tools that make direct contact with abrasive reinforcement. Worn out tool produces higher cutting forces, poor finish and eventually results in large processing costs [4]. In order to overcome the interrupted use of cutting tools for processing of MMCs, several nontraditional machining methods such as electro discharge machining (EDM), laser beam machining (LBM) and abrasive water jet cutting (AWJC) have emerged. Among these methods, AWJC is preferred since it does not have the problems like recast layer formation and thermal distortion that are noticed with EDM and LBM processes. Moreover, AWJC is a cool cutting process that removes the material by

erosion and plastic deformation when high velocity waterjet with abrasives interacts with target materials. In AWJC, a large number of process parameters such as hydraulic parameters i.e. orifice diameter and water pressure, abrasive parameters i.e. type and size of grit, and flow rate of abrasives, mixing parameters like diameter and length of focusing nozzle, cutting parameters such as standoff distance and traverse rate of jet and the target material properties influence the process outcomes such as material removal rate, depth of penetration and the quality of kerf.

Efforts on AWJC of MMCs were limited to certain feasibility studies that evaluated the ability of AWJs for cutting different types of MMCs. Influence of jet traverse rates (1 mm/s to 4 mm/s), abrasive flow rates, in the range of 0.1 kg/min to 1 kg/min and water pressures of 172 MPa to 310 MPa on the roughness produced on cut surface of aluminum-silicon carbide (Al-SiC) and magnesium-silicon carbide (Mg-SiC) MMCs were investigated [5]. Specimens with 7%, 11%, 15% of SiC reinforced in cast aluminum alloy and 26.5% of SiC reinforced in magnesium alloy were employed for AWJC studies. Roughness measurements made on cut surface at 12.7 mm depth indicated an increase in roughness with increasing jet traverse rate. Moreover, the roughness has increased from 5 to 8 microns from the top to bottom of cut. Interestingly, higher abrasive flow rates reduced the roughness on cut surface from 6 to 4 microns. Most of the AWJC experiments were conducted on rectangular block of 15% SiC-Al357 MMC produced through casting route and the maximum depth of cut was observed to be around 58 mm. Metallographic examination of cut surfaces have clearly showed that the shearing of SiC in matrix material by AWJs. Garnet, SiC and alumina abrasives of 80 and 150 mesh sizes were used to perform linear cutting tests on 0.79 to 12.7 mm thick, Al-SiC_p MMC specimens, having 15% and 25% SiC reinforcement in aluminum matrix [6]. This study was essentially focused on the determination of cutting rates, surface finish and the life of focusing nozzle. Jet traverse

rates did not influence the cutting rates observed on two different MMCs, prepared with 15% and 25% of SiC reinforcement in aluminum alloy. But, the roughness on cut surface has increased from 1.4 microns to 4.2 microns with jet traverse rates and abrasive flow rates varied from 180 mm/min to 1140 mm/min and 0.113 kg/min to 0.45 kg/min respectively. In any case, the cutting rates observed on aluminum alloy were slightly higher than that observed on MMCs. Cutting rates observed with SiC and alumina were about 2 to 5 times higher than the cutting rates observed with garnet abrasive. But, the nozzle lasted only for 5 minutes with SiC and alumina abrasives. Slot cutting experiments on 5 mm thick 30% SiC/6061-T6 Al-MMC plates were conducted to examine the geometry of kerf in terms of kerf width, kerf taper and roughness on cut surface with AWJs employing garnet abrasive of 80, 100 and 150 mesh sizes [4]. With increasing size of abrasive particles and jet traverse rates, kerf taper has increased. Examination of cut surface revealed that the mechanism of material removal is due to both cutting and deformation wear modes. 150 mesh size garnet abrasives was used to conduct linear cutting experiments on 13 mm thick Al-SiC_p MMC specimens prepared with 25%, 30% and 40% SiC reinforcement in aluminum matrix material [7]. This study essentially focused on the geometry of kerf produced in MMCs by AWJs. Kerf width was found to decrease from 0.8 mm to 0.42 mm over the depth of cut observed from top to bottom of cut section. A similar trend was observed on MMCs with increasing percentage of SiCs and with jet traverse rates varied from 0.85 mm/s to 1.69 mm/s. An increase in taper on cut surface, with increasing percentage of SiC was attributed to higher resistance offered by SiC to jet penetration. The model developed for prediction of depth of cut in ductile materials is suggested for predicting the depth of cut in MMCs [8]. The influence of garnet abrasive with mesh sizes of 80 and 100 and abrasive flow rates in the range of 0.114 kg/min to 0.2766 kg/min at shallow impact angles of 5°, 10°, 15°, 18° and 20° on erosion rates was investigated [9]. With any particular abrasive flow rate, higher impact angles are found to increase the erosion rates. However, 100 mesh size abrasive produced lower rates of erosion over that noticed with 80 mesh size. Erosion in composite material has occurred due to microcutting of aluminum matrix material and shoveling of SiC_p with AWJs. Machinability of AA2618/SiC/20p and A356/SiC/35p with different processes such as EDM, LBM and AWJC was investigated [10]. AA2618/SiC/20p MMC specimen was produced through spray deposition of 10-13 µm size SiC_p on base aluminum alloy whereas A356/SiC/35p MMC specimen was produced through powder metallurgy route by employing 13 µm size SiC_p in aluminum alloy. 80 mesh size garnet abrasives were chosen to conduct AWJC experiments on 3 mm thick MMC

specimen. The material removal mechanism was observed to be due to ductile shearing of aluminum with garnet abrasives. Smaller size SiC_p in MMCs were pulled out by large particles of garnet abrasive. Roughness (R_a) varied from 4.51 µm to 5.98 µm but smoother surface was observed at lower values of jet traverse rates. From the above, it is clear that AWJC studies were attempted on MMCs with different percentages of SiC reinforcement in matrix material. But, the choice of abrasives employed for AWJC studies was seen to be arbitrary. The methods chosen for preparing MMC specimen mostly produced the samples with a maximum thickness of 12.7 mm. Form the review of literature, it is clear that attempts made on the machinability of Al-SiC_p MMCs with different composition of SiC in aluminum matrix are limited. Further, there is no attempt to simultaneously examine the role of different types of abrasives and their sizes on the penetration ability of AWJs in different Al-SiC_p MMCs. Hence there exists a need to study the role of different abrasives in AWJC of different types of Al-SiC_p MMCs. In addition to this it is also important to assess the maximum penetration ability of AWJs in of Al-SiC_p MMCs. In order to address these aspects, the present study attempts to conduct machinability experiments on wedge shaped specimens of MMCs with AWJs produced by 60, 80 and 120 mesh sizes of garnet and silicon carbide abrasives.

3. Experimental method

3.1. Manufacture of Al-SiC_p MMCs

Al-SiC_p MMCs are generally produced by reinforcing SiC particles in aluminum matrix material which can be in solid, liquid or vapor states. Powder metallurgy and diffusion bonding methods consider the matrix and reinforcement in solid form to produce MMCs. Stir casting, infiltration, and spray deposition methods essentially combine solid reinforcement in liquid matrix. In physical vapor deposition (PVD) method, MMCs are produced by mixing the matrix with reinforcement in vapor states. In powder metallurgy, the appropriate amount of reinforcement is mixed in matrix metal, degassed, hot compacted and sintered to make the components of MMCs through forging, rolling or extrusion routes [11]. With these methods, the thickness of plate is limited to around 20 mm [12]. In deposition techniques, individual fibers of SiC are coated with the matrix material, and are then subjected to diffusion bonding to make consolidated shape [13]. It is well known that the manufacture of MMCs with deposition techniques is quite cumbersome [2]. In stir casting method, MMCs are produced by introducing reinforcement into molten matrix material by stirring action and then by solidifying it in the die. In infiltration method, the melt is introduced into the interstices of an assembly preform made from reinforcing phase. In this method, the cost of tooling is very high [14]. The dispersed refractory reinforcement is created in the matrix material as a

result of precipitation from the melt during its cooling and solidification in in-situ process [2]. In spray deposition technique, the droplet stream is produced from a molten bath, or by continuous feeding of cold metal into a zone of rapid heat injection and then directing an atomized stream of droplets onto a substrate. Ceramic reinforcement is injected into the spray to produce MMCs. Among the various methods, powder metallurgy (PM) and stir casting methods are widely accepted routes to manufacture MMCs. Since PM can only produce thin samples, stir casting is generally seen as a promising route to produce large sized MMC components. Moreover, it is a simple and flexible process that can produce large quantities at lower cost [15]. Hence, the present work considered stir casting route to prepare thicker samples needed for the proposed investigations.

Figure 1 shows the geometry of specimen chosen for performing AWJC studies. This specimen is wedge shaped with an included angle of wedge as 25° . This particular geometry is generally chosen for investigating the maximum penetration ability of abrasive water jets in different materials [16-18]. In fact, the wedge shaped specimen allows to determine the full penetration jet into the target material with any particular energy of jet. By measuring the length of cut on slant surface of the wedge shaped specimen (L), the maximum depth of penetration (h_t) of jet in the target materials with chosen set of parameters can be determined by employing the relation: $h_t = L \sin 25^\circ$.

To produce the specimens of different types of Al-SiC_p MMCs, different percentages of 80 mesh size SiC_p reinforcement is mixed in silicon based LM9 aluminum alloy matrix material. Chemical composition of LM9 alloy obtained with optical emission spectrometer is: Si 10.315%, Fe 1.172%, Cu 0.154%, Mn 0.319, Mg 0.625%, Zn 0.005%, Ti 0.023%, Ca 0.002%, P 0.001%, V 0.012%, Zr 0.003% and Al 87.371%. This particular alloy with nearly 10% silicon was chosen as the matrix material since it can easily be cast. Figure 2 shows the photograph of a three phase electrical resistance furnace with temperature controlling device to prepare the melt. To prepare the specimen of MMCs, ingots of LM9 with 100%, 95%, 90%, 85% and 80% of aluminum alloy by weight are superheated to a temperature of 800°C in graphite crucibles under a cover of small quantity of flux in order to minimize the oxidation of the molten metal and hydrogen adsorption. The superheated molten metal was degassed by adding 1.2% of hexachloro ethane tablets at a temperature of 780°C in order to avoid dewetting problem [19]. The molten metal maintained at 720°C was vigorously stirred by a stirrer at a speed of 550 rpm. This vigorous stirring formed a vortex at the surface of the melt. At the side of the vortex, preheated SiC_p of 80 mesh size was added to the melt to prepare a mixture of a composite

material. By adding different percentages such as 5%, 10%, 15% and 20% of SiC_p to the melt, the molten material needed for preparing different compositions of Al-SiC_p MMC specimens were made. During stirring, 0.3% of magnesium was added to the melt in order to increase the wettability of SiC_p. By stirring the molten mixture for about 5-8 minutes, SiC_p in the melt were ensured to be in a state of suspension [15]. The molten mixture was then poured into a wedge shaped cast iron die (Figure 3) which is preheated to a temperature of 200°C. During pouring of the melt into the die, the temperature of the mix was maintained at around 680°C which was then allowed to solidify in the die itself. Figure 4 shows the trapezoidal shaped specimen produced by stir casting. Apart from these specimens, cylindrical specimens of 36 mm diameter by 22 mm long were also produced by the same method. Figure 5 shows the set of specimens produced for characterizing the properties of MMCs.

3.2. Characterization of Al-SiC_p MMC specimens

In order to characterize the properties of specimen produced by stir casting, standard methods employed for measuring the density of MMCs and the distribution of SiC_p in MMCs were followed [19]. 5 mm thick plates of MMC cut from a cylindrical bar were polished on belt grinder with 100 mesh size abrasives. These plates were subsequently polished by using 180, 220, 400 and 550 mesh sizes of emery paper. While polishing these specimens with 400 mesh size emery paper, water was continuously supplied to the zone of polishing. These specimens were further polished by using diamond paste and the surfaces were etched with kellers reagent (190 ml water, 5 ml nitric acid, 3 ml hydrochloric acid, 2 ml hydrogen fluoride). All these polished specimens were dried with hot air. These surfaces of polished specimens were observed under optical microscope to know the distribution of SiC_p in different composition MMCs. Volume fraction of SiC_p in each of the specimen was determined by using the image processing software supplied with optical microscope. To analyze the effect of SiC_p on hardness variation over different specimens, hardness was measured at the centre and outer periphery of the specimen by means of Vickers hardness tester. In this test, load of 5 kg was applied on the specimen for a duration of 15 seconds. These measurements were made twice on each specimen at identified locations and the average hardness of each specimen was found out. Density of MMCs was measured by employing Archimedes principle. The buoyant force on a submerged object is equal to the weight of the fluid displaced. This principle is useful for determining the volume and therefore the density by measuring its mass in air and its effective mass when submerged in water. This effective mass under water will be its actual mass minus the mass of the fluid displaced. The difference between the real and effective masses therefore gives the mass of the

displaced water and allows the volume of the object to be calculated. Mass divided by the volume thus determined gives the density of the object. Then the density of each specimen was obtained by averaging the four readings taken over the plates. In order to examine the nature of interaction of AWJ with composite material and the surface produced by AWJC, a small portion of cut surface was examined under Scanning Electron Microscope (SEM) at different magnifications varied between 120 and 300.

3.3. Experimental procedure

To study the influence of type and size of abrasives, cutting experiments were conducted on different specimens of Al-SiC_p MMCs by using an injection type AWJC system. Figure 6 shows the arrangement of wedge shaped specimen under the cutting head of the system. The specimen was rigidly held in a fixture so as to avoid its displacement during cutting trials. In AWJC system, the intensifier is capable of generating a maximum water pressure of 360 MPa with a rated discharge of 2.2 l/min. All the experiments were conducted with a standoff distance of 2 mm maintained between the tip of focusing nozzle and the work. The jet was made to strike the specimen at an angle of 90 degrees and then traversed over the length of the specimen only once in order to observe its maximum penetration into the specimen. The maximum penetration of jet into the target material was realized by observing the splashing of jet. Table 1 presents the details of work specimens and the values chosen for each of the process parameters. In this study, it is proposed to consider the base alloy i.e. matrix material and four different compositions of Al-SiC_p MMCs. The cutting experiments were conducted on each specimen by considering the four input parameters (factors) with each of the factor being varied at three levels. Full factorial experimentation requires 81 (3⁴) experiments on each specimen, thus 405 experiments over five specimens. In order to reduce the time and cost for experimentation, the present study considered L9-a fractional factorial experimental plan. With this, the total number of experiments on each sample will be reduced to 9 (3⁴⁻² = 9). Each set of experiments were conducted at different locations of the sample in order to take care of non-uniform distribution of SiC particles in matrix material. Each set of experiments on each specimen was repeated and the average of two depths was taken as the maximum depth of penetration with each setting. Thus, the total number of experiments conducted on these specimens amounts to 90. These experiments were conducted by using both garnet and SiC abrasives in the waterjet. Therefore, the total number of experiments conducted were 180. For all these experiments, the size of focusing nozzle chosen was approximately five times the size of abrasive particle, and 3-4 times the size of orifice [20-21]. The maximum depth of penetration (h_i) with each set of

parameters was determined by following the procedure outlined in the section 3.1.

4. Results and discussions

In table 2, the material properties of base metal, different MMCs and properties of abrasives are presented. From these results, it can be seen that the volume fraction of SiC in different specimens was slightly lesser than the actual percentage of SiC_p added to the melt during the manufacture of different MMCs. This could be attributed to the nature of mixing SiC_p in the melt and uneven distribution of SiC_p in the casting. Addition of SiC_p in LM9 alloy improved the density and hardness of MMC specimens. These properties are found to agree very well with the properties of MMCs produced with other methods of manufacture [19].

Figure 7a and Figure 7b show the optical micrographs taken on polished specimens, of Al-SiC_p MMCs, with 10% SiC_p in matrix material. Figure 7a shows the unreinforced area on MMC i.e. aluminum matrix material. At higher magnification of 1000x, silicon flakes in aluminum matrix material i.e. eutectic mixture can be observed. At higher magnification of 500x, proper bonding between reinforcement and matrix can be observed at some locations in Figure 7b. At the center of the same image, fractured SiC particle is observed. It might have occurred while cutting the sample from cylindrical specimens or while polishing the specimens for microstructural analysis. Black color envelope can be noticed around SiC particles. This can be due to the following. i) the nucleation of Si and enrichment of the same in the melt around SiC, ii) gas layer surrounding the SiC particles avoids intimate contact between reinforcement and matrix and this porosity may appear as black in color, iii) the sample may not be planar and hard ceramic reinforcement in soft matrix may protrude if polishing is done for a longer time or iv) the presence of reaction product (Al₄C₃). Figure 7c to Figure 7f show the optical micrographs taken on polished specimens, chosen from Al-SiC_p MMCs, having 5%, 10%, 15% and 20% of SiC_p in matrix material respectively. It can be seen from these images that the distribution of SiC_p in these specimens is more or less uniform when the composition of SiC_p in LM9 alloy is up to 15%. Even at lower percentages of SiC_p in MMCs, segregation of SiC_p reinforcement can be observed. However, this is more severe with higher percentage of reinforcement in matrix material. Close observation of the micrograph taken on 20% SiC_p MMC showed more agglomeration of SiC_p. This can be due to the fact that the dispersed SiC particles will be pushed by the growing dendrites into the last solidifying interdendrite regions due to the lower heat diffusivity of SiC particles compared to aluminum melts.

Table 3 shows the depth of penetration on different MMCs with different process parameters. From the results, it can be noticed that the variation in depth of

penetration, on different MMCs with varying percentage of SiC_p , is quite arbitrary. Depth of penetration in base material and different MMCs from 5 to 15% SiC_p in aluminum matrix, with waterjet pressure of 100 MPa, abrasive mass flow of 0.044 kg/min, traverse speed of 80 mm/min and SiC abrasive of 80 mesh size decreased steadily. Contrastingly, the depth of penetration noticed on 20% SiC_p -MMC was higher even though the hardness of the target material is higher than the other materials. Similar trends are more or less seen with other conditions also. Such fluctuating results could arise due to the non-uniform distribution of SiC particles in MMCs prepared by stir casting. Further, the improper bonding between the matrix and the reinforcement, the agglomeration of SiC_p in Al- SiC_p MMCs and voids/gas porosity/chemical reaction products could cause such results. Similar trends of material removal were noticed with both types of abrasives i.e. garnet and SiC abrasives. A careful study of results presented in Table 3 show that the combination of input parameters is found to influence the penetration of jet into the target materials quite significantly. Waterjet pressure of 175 MPa, abrasive mass flow rate of 0.074 kg/min, traverse speed of 50 mm/min and abrasive size of 80 gave a maximum depth of penetration in all types of MMCs with both garnet and SiC abrasives. In contrast to this, waterjet pressure of 175 MPa, abrasive mass flow rate of 0.044 kg/min, traverse speed of 110 mm/min and 60 mesh size abrasives of garnet and SiC abrasives produced very low depths of cut in all materials. This clearly illustrates the significant change in depth of penetration with a change in abrasive mass flow rate, jet traverse rate and size of abrasive. But, with 50 mm/min traverse speed, waterjet pressure of 250 MPa, abrasive flow rate of 0.044 kg/min and 120 mesh size of abrasives yielded only 15-20% lower depth of penetration than the maximum depth of penetration. Thus, the change in depth of penetration could be due to a change in waterjet pressure, abrasive mass flow rate and size of abrasive. Careful observation of the results clearly indicates that 80 mesh size abrasive gave higher depth of penetration in all MMCs irrespective of the process parameter chosen. Similarly, AWJ with SiC abrasives has higher penetration ability in different materials over that generated with garnet abrasives. However, the exact influence of these parameters on depth of penetration cannot be known from this analysis. In order to identify the prominent role of process parameters and abrasive materials, the results are further analyzed by statistical methods. In this, mean effects plot for depth of penetration can show the trends of variation in depth of penetration with different parameters.

Figure 8 and Figure 9 show the trends of variation in mean depth of penetration observed with different parameters such as water pressure, abrasive flow rate, jet traverse rate and the size of garnet and SiC abrasives. Mean depth of penetration increased with

increasing water pressure. Increased waterjet pressure increases the kinetic energy of waterjet and this energy is imparted to abrasive particles which can thus result in higher depth of penetration. Beyond 175 MPa, the increase in depth of penetration is marginal which indicates the existence of critical threshold value of waterjet pressure for maximum penetration of jet into MMCs [20]. With increasing flow rate of abrasives, the mean depth of penetration has increased steadily due to the participation of large number of abrasives in eroding the target material. On the contrary, an increase in jet traverse rate reduced the mean depth of penetration. This can arise due to shorter dwell time of waterjet impacting the target material and due to lesser number of abrasive particles participating in erosion of target material. But the trend of variation in the mean depth of penetration with different sizes of abrasives is completely different. When the size of abrasive is changed from 60 to 80 mesh size, the depth of penetration has increased. But the abrasives with a mesh size of 120 have again reduced the mean depth of penetration. Smaller size of abrasives are likely to possess lesser kinetic energy thus resulting in smaller depths of penetration. Theoretically speaking, larger size abrasives should result higher kinetic energy and can produce larger depths of penetration. To accommodate larger size abrasive particles, larger size of focusing nozzle are generally used. But, larger size of focusing nozzle decreases the jet energy density and thus makes the entrainment of abrasive in the jet as inefficient which can in turn reduce the cutting performance of AWJs [17, 20 and 22]. A closer look at the trends of mean depth of penetration with different types of abrasives show that the change in depth of penetration observed with SiC abrasives is marginal over that noticed with garnet abrasives. However, with 80 mesh size silicon carbide abrasive, this change is quite significant. This can be clearly seen from the results presented in Table 3. Since SiC abrasives possess higher hardness (18-25 GPa) than garnet abrasives (12-13 GPa), they can penetrate to a greater extent into the target material.

In order to understand the mechanism of material removal in AWJC of MMCs with different types of abrasives prepared, a small portion of cut surface was observed under the SEM. Figure 10a and 10b show SEM micrograph of cut surface on 20% SiC_p -MMC cut with abrasive water jet generated by employing water pressure of 250 MPa, abrasive mass flow rate of 0.026 kg/min, jet traverse rate of 110 mm/min and 80 mesh size garnet and SiC abrasives respectively. Figure 10c and 10d show the micrographs of cut surface on 10% SiC_p -MMC cut by AWJ produced by water pressure of 250 MPa, abrasive mass flow rate of 0.074 kg/min, jet traverse rate of 80 mm/min and 60 mesh size garnet and SiC abrasives respectively. Figure 10e and Figure 10f show micrographs on cut surface on 20% SiC_p -MMC cut by water jet with water pressure of 175 MPa, abrasive mass flow rate

of 0.026 kg/min, jet traverse speed of 80 mm/min and 120 mesh size garnet and SiC abrasives respectively. From all these micrographs, it is clear that the type of fracture on matrix material appears to be non-planar and ductile fracture. In contrast to this, the planar fracture observed on SiC_p in MMC clearly indicates brittle fracture. Ploughing of reinforcement can be observed in the Figure 10d. This selective erosion of material with high velocity AWJ can be attributed to i) differences in hardnesses of particulate (25 GPa) and matrix materials (67.1 MPa), ii) voids or gas porosity around SiC particle indicating improper bonding between the reinforcement and matrix material, iii) ploughing of reinforcement due to insufficient energy to cut the reinforcement but sufficient to cut the matrix material. In all these micrographs, the fracture surface on the matrix material show up a texture that can result due to the interaction of randomly oriented abrasives striking the material at different impact angles [9].

From these observations, it is clear that the mode of material removal is due to fracture and ploughing of reinforcement in MMC and ductile fracture of matrix material. However, there is no significant change in the mode of material removal in different MMCs with garnet and SiC abrasives. From all the above, it is clear that the choice of 80 mesh size SiC abrasive is important for effective processing of Al-SiC_p MMCs.

5. Conclusions

In this work, an attempt is made to investigate the penetration ability of AWJs, formed with 60, 80 and 120 mesh sizes of garnet and SiC abrasives, on Al-SiC_p MMCs with 5, 10, 15 and 20 percentages of SiC_p in LM9 aluminum alloy. These studies were conducted on 70 mm thick wedge shaped specimens produced by stir casting method. Optical micrograph images showed that the distribution of SiC_p is almost uniform in 5% to 15% Al-SiC_p MMCs. But, 20% Al-SiC_p MMC showed agglomerates of SiC_p. Experimental investigations revealed the choice of 80 mesh size SiC abrasive for achieving the higher depth of penetration of AWJ in Al-SiC_p MMCs. SEM examination of as-cut surfaces clearly disclosed the possible mechanism of material removal as fracturing and ploughing of SiC_p and ductile fracturing of matrix material. Perhaps, the choice of abrasive material and the size of abrasive used in AWJC of Al-SiC_p MMCs can depend on the size of SiC particulate in matrix material and the size of focusing nozzle employed in AWJC system.

6. Acknowledgements

The authors are thankful to Dr.M.K.Venkatesha, former Principal, Dr.K.Radhakrishna, former Head, Department of Mechanical Engineering, BMS College of Engineering, Bengaluru, India who gave the permission to use the stir casting facility and Dr. M. Ramachandra of the same college for his help in producing MMCs.

7. References

1. Teti R (2002) *Machining of composite materials*. *Annals of the CIRP* 51(2):611-634
2. Surappa M K (2003) *Aluminium matrix composites: Challenges and opportunities*. *Sadhana* 28(1-2):319-334
3. Ramulu M, Faridnia M, Garbini J L and Jorgensen J E (1991) *Machining of Graphite/Epoxy composite materials with Polycrystalline diamond (PCD) tools*. *J Eng Mater Technol* 113:430-436
4. Hamatani G and Ramulu M (1990) *Machinability of high temperature composites by Abrasive waterjet*. *J Eng Mater Technol* 112:381-386
5. Neusen K F, Rohatgi P K, Vaidyanathan C and Alberts D (1987) *Abrasive waterjet cutting of metal matrix composites*. In: *Proceedings of the 4th U.S Waterjet Conference, Berkeley, California, U.S.A, August 1987*, pp 272-283
6. Hashish M (1988) *Machining of advanced composites with abrasive-waterjets*. In: *Proceedings of the Winter annual meeting of the ASME, Chicago, Illinois, U.S.A, December 1988*, pp 1-18
7. Hashish M (1991a) *Advances in composite machining with abrasive-waterjets*. In: *Proceedings of the Winter annual meeting of the ASME, Atlanta, Georgia, U.S.A, December 1991*, pp 93-111
8. Hashish M (1989) *A model for Abrasive waterjet (AWJ) machining*. *J Eng Mater Technol* 111:154-162
9. Ramulu M, Raju SP, Inoue H and Zeng J (1993) *Hydro-abrasive erosion characteristics of 30vol. %SiC_p/6061-T6 Al composite at shallow impact angles*. *Wear* 166:55-63
10. Müller F and Monaghan J (2000) *Non-conventional machining of particle reinforced metal matrix composite*. *Int J Mach Tools Manuf* 40:1351-1366
11. Miracle D B (2005) *Metal matrix composites-From science to technological significance*. *Composite science and Technol* 65:2526-2540
12. Warren H. Hunt, JR (2000) *Particulate reinforced MMCs*. In: Clyne TW (ed) *Comprehensive composites*, V3, 1st edn. Elsevier, Amsterdam, pp 701-715
13. Rosso M (2006) *Ceramic and metal matrix composites: Routes and properties*. *J of Mater Process Technol* 175:364-375
14. Brian Ralph, Yuen H C and Lee W B (1997) *The processing of metal matrix composites-an overview*. *J of Mater Process Technol* 63:339-353
15. Hashim J, Looney L and Hashmi MSJ (1999) *Metal matrix composites: Production by the stir casting method*. *J Mater Process Technol* 92-93:1-7
16. Sitarama chakravarthy P and Ramesh Babu N (2000) *A hybrid approach for selection of optimal process parameters in abrasive water jet cutting*, *Proc Instn Mech Engrs*, 215:781-791
17. John Rozario Jegaraj, J. and N. Ramesh Babu (2005) *A strategy for efficient and quality cutting of material with abrasive waterjets considering the variation in orifice and focusing nozzle diameter*, *Int J Mach Tools Manuf*, 45(12-13):1443-1450
18. Srinivasu DS and Ramesh Babu N (2008) *An adaptive control strategy for the abrasive waterjet cutting process with the integration of vision-based monitoring and a neuro-genetic control strategy*, *Int J Adv Manuf Technol* 38:514-523
19. Ramachandra M and Radhakrishna K (2006) *Sliding wear, slurry erosive wear and corrosive wear of aluminium/SiC composites*. *Mater sci-Poland* 24(2/1):333-349
20. Hashish M (1991b) *Optimization factors in Abrasive-Waterjet Machining*. *Trans ASME J Eng Ind* 113:29-37
21. Chalmers E J (1991) *Effect of parameter selection on abrasive waterjet performance*. In: *Proceedings of the 6th American Waterjet Conference, Houston, USA, August 1991*, pp 345-354

22. Zeng J and Kim T J (1992) Development of an abrasive waterjet kerf cutting model for brittle materials, In: Proceedings of the 11th International conference on Jet cutting Technology, St. Andrews, Scotland, September, 1992, pp 483-501

Captions for figures

Fig.1 Geometry of MMC specimens used for depth of penetration experiments

Fig.2 Furnace used to prepare specimens of Al-SiC_p MMCs

Fig.3 Various parts of wedge shaped die

Fig.4 Shape of MMC specimens used for depth of penetration experiments

Fig.5 Cylindrical MMC specimens for characterization experiments

Fig.6 Setup for AWJC of wedge shaped MMCs

Fig.7a. Aluminum alloy with silicon flakes resulting eutectic mixture (1000X)

Fig.7b. Higher magnified micrograph of SiC_p (500X)

Fig.7c. Distribution of SiC particles in 5% SiC_p-MMC (100X)

Fig.7d. Distribution of SiC particles in 10% SiC_p-MMC (100X)

Fig.7e. Distribution of SiC particles in 15% SiC_p-MMC (100X)

Fig.7f. Distribution SiC particles in 20% SiC_p-MMC (100x)

Fig.8 Main effect plot (data means) for depth of penetration with garnet abrasives

Fig.9 Main effects plot (data means) for depth of penetration with SiC abrasives

Fig.10a. SEM photograph showing cutting of SiC reinforcement by 80 mesh size garnet abrasives in AWJ (20%SiC_p-MMC)

Fig.10b. SEM photograph showing cutting of SiC reinforcement by 80 mesh size SiC abrasives in AWJ (20% SiC_p-MMC)

Fig.10c. SEM photograph showing cutting of SiC reinforcement by 60 mesh size garnet abrasives in AWJ (10%SiC_p-MMC)

Fig.10d. SEM photograph showing cutting and ploughing of SiC reinforcement by 60 mesh size SiC abrasives in AWJ (10%SiC_p-MMC)

Fig.10e. SEM photograph showing cutting of SiC reinforcement by 120 mesh size garnet abrasives in AWJ (20%SiC_p-MMC)

Fig.10f. SEM photograph showing cutting of SiC reinforcement by 120 mesh size SiC abrasives in AWJ (20%SiC_p-MMC)

Total depth of penetration $h_t = L \sin 25^\circ$

Fig.1 Geometry of MMC specimens used for depth of penetration experiments

Fig.2 Furnace used to prepare specimens of Al-SiC_p MMCs

Fig.3 Various parts of the wedge shaped die

Fig.4 Shape of MMC specimens used for depth of penetration experiments

FIG. 5. Cylindrical MMC specimens for characterization experiments

Fig.6 Setup for AWJC of wedge shaped MMCs

Fig.7a. Al alloy with silicon flakes resulting eutectic mixture (1000X)

Fig.7b. Higher magnified micrograph of SiC_p (500X)

Fig.7c

Fig.7d

Fig.7e

Fig.7f

Fig.7c-7f. Distribution of SiC in 5%, 10%, 15% and 20 % SiC_p-MMC (100X)

Fig.9 Main effects plot (data means) for depth of penetration with SiC abrasives

Fig.10a. SEM photograph showing cutting of SiC reinforcement by 80 mesh size garnet abrasives in AWJ (20%SiC_p-MMC)

Fig.10b. SEM photograph showing cutting of SiC reinforcement by 80 mesh size SiC abrasives in AWJ (20%SiC_p-MMC)

Fig.10c. SEM photograph showing cutting of SiC reinforcement by 60 mesh size garnet abrasives in AWJ (10%SiC_p-MMC)

Fig.10d. SEM photograph showing cutting and ploughing of SiC reinforcement by 60 mesh size SiC abrasives in AWJ (10%SiC_p-MMC)

Fig.10e. SEM photograph showing cutting of SiC reinforcement by 120 mesh size garnet abrasives in AWJ (20%SiC_p-MMC)

Fig.10f. SEM photograph showing cutting of SiC reinforcement by 120 mesh size SiC abrasives in AWJ (20%SiC_p-MMC)

Captions for tables

Table1 Process parameters and list of target materials for experiments

Table 2 Properties of materials used in this study

Table 3 Maximum penetration depth achieved in different Al-SiC_p MMC specimens with different process parameters

Table 1 Process parameters and list of target materials for experiments

Work materials ►	100% aluminum alloy, 5% SiC-MMC, 10% SiC-MMC, 15%SiC-MMC and 20%SiC-MMC		
Process Parameters ▼	Level-1	Level-2	Level-3
Waterjet pressure (MPa)	100	175	250
Abrasive flow rate (kg/min)	0.026	0.044	0.074
Jet traverse speed (mm/min)	50	80	110
Types of abrasives :Garnet and SiC and their mesh sizes	60 (0.254mm)	80 (0.165mm)	120 (0.102mm)
Sapphire Orifice diameter (mm)	0.4	0.25	0.15
Tungsten carbide Focusing nozzle diameter (mm)	1.2	0.76	0.76

Table 2 Properties of materials used in this study

No.	Property	Work materials					Abrasive materials	
		100% Al.alloy	95% Al. alloy + 5% SiC _p	90% Al. alloy + 10% SiC _p	85% Al. alloy + 15% SiC _p	80% Al. alloy + 20% SiC _p	Garnet	SiC
1	Density (g/cm ³)	2.60	2.61	2.65	2.68	2.70	4.0	3.2
2	Volume fraction	-	4.45	8.64	12.86	16.12	-	-
3	Vickers Hardness	67.1 (MPa)	71.6 (MPa)	73.6 (MPa)	74.7 (MPa)	77.8 (MPa)	12-13 (GPa)	18-25 (GPa)

Table 3 Maximum depth of penetration achieved in different Al-SiC_p MMC specimens with different process parameters

No	P (MPa)	$\dot{m}$ (kg/min)	u (mm/min)	Abrasive size (#)	Depth of penetration (mm)									
					100% Al. alloy		95% Al. alloy + 5% SiC _p		90% Al. alloy + 10% SiC _p		85% Al. alloy + 15% SiC _p		80% Al. alloy + 20% SiC _p	
					Garnet	SiC	Garnet	SiC	Garnet	SiC	Garnet	SiC	Garnet	SiC
1	100	0.044	80	80	4.68	4.96	4.11	4.82	4.12	4.75	3.72	3.78	5.36	5.46
2	175	0.074	50	80	23.01	28.79	21.85	27.25	23.61	28.74	22.31	24.69	23.24	28.71
3	250	0.026	110	80	9.41	10.89	9.02	9.92	9.83	9.11	7.91	9.78	11.25	11.5
4	100	0.074	110	120	2.28	3.4	2.88	3.98	2.27	2.73	2.48	2.27	3.09	3.4
5	175	0.026	80	120	8.55	8.52	7.39	8.52	7.59	7.8	8.17	9.15	7.59	8.76
6	250	0.044	50	120	18.67	23.98	19.44	21.31	18.93	23.07	19.8	20.57	19	20.15
7	100	0.026	50	60	2.73	3.23	3.27	3.4	3.8	4.19	2.48	3.15	2.69	3.05
8	175	0.044	110	60	1.74	1.6	1.6	1.64	1.6	1.6	2.13	1.85	1.6	1.45
9	250	0.074	80	60	5.08	4.89	4.18	4.61	4.75	5	5.04	5.33	4.33	4.54