

An investigation on surface roughness of aluminium metal matrix composites cut by abrasive waterjet

PRABHU SWAMY N R^{1*} AND S S RINIVAS²

^{1& 2} BMS college of Engineering, Bengaluru, India

*Author for correspondence (nrprabhuswamy@gmail.com)

Abstract. Abrasive waterjet cutting is a new, growing technology and is used to cut difficult to cut materials. Surface roughness of abrasive waterjet cut materials is an important output parameter. In this study an attempt is made to investigate the average surface roughness value of aluminium 6061 and its composites along the depth of penetration. Trapezoidal shaped aluminium-silicon particulate metal matrix composites manufactured by stir casting method with 5, 10 and 15 weight percentage of silicon carbide particles reinforced in aluminium 6061 alloy are cut by abrasive waterjet employing # 80 mesh size. The average surface roughness value is increasing as the depth of penetration increases in aluminium 6061 base material and its composites. Also, it increases with the increase in percentage of silicon carbide particles in the metal matrix composites. The waterjet pressure and traverse speed of the jet has a significant effect on average surface roughness of cut samples.

Keywords. Abrasive waterjet; metal matrix composites; depth of penetration; average surface roughness.

1. Introduction

Abrasive water jet (AWJ) is used in cutting of materials ranging from soft to hard, brittle to ductile and thin to thick materials such as mild steel, aluminium, tool steel, titanium, brass, concrete, rock, glass, polymer matrix composites, ceramic matrix composites and metal matrix composites (MMCs) [1,2]. The machining capabilities of AWJ cutting include cutting of complicated shapes, no thermal distortion, narrow kerf width, negligible heat affected zone, minimal cutting force and environmental friendliness [3,4]. AWJ cutting is influenced by various parameters such as hydraulic, abrasive, cutting and work material properties. In AWJ cutting, the material removal takes place in two modes namely cutting wear and deformation wear [5-7]. The surface topography is an important output parameter for any AWJ cut surface. The average surface roughness (R_a) is a measure of surface roughness.

The surface topography of aluminium samples cut by AWJ reveals that the cutting wear region is dominated by microstructure roughness and the deformation wear region is dominated by macro structure waviness. The R_a increases with increasing the size of the abrasive particles. In the cutting wear region, microchipping takes place during cutting, making the cut surface smooth. Whereas during cutting in the deformation wear region the discontinuous and three dimensional cutting takes place. Also the inclination and oscillation of the jet contributes for the waviness and rougher R_a value in the region [8]. A smooth surface finish at the top of the cut and the rough surface finish with striations towards the bottom of the cut was seen on AWJ cut ceramic, perspex, aluminium and mild steel plates. High kinetic energy cuts the upper zone and the kinetic energy decreases with the depth of penetration



(DOP). During the lower part of the cutting the jet loses its kinetic energy and as a result striations are formed in the lower zone of the cut. The fluctuations of the AWJ, vibration of the work piece and nozzle and oscillations of the jet are also the reasons for the striations formation [9]. AWJ cutting experiments are conducted on aluminium reinforced with 7%, 11%, and 15% SiC particles and magnesium reinforced with 26.5% SiC particles. R_a measurement is done at depth of 12.7 mm from the top of the cut on the MMC samples. A low R_a value of 5 microns is seen for cutting with higher waterjet pressure and higher abrasive flow rates. The R_a has increased with higher jet traverse speed and low abrasive flow rates [10]. Low traverse speed and high abrasive flow rates have given better R_a on aluminium reinforced with 15% and 25% of silicon carbide MMCs cut by AWJ [11]. The R_a measurement are carried at 1 mm, 2.5 mm and 4 mm along the direction of the cut on AWJ machined Al6061-30% SiC MMCs. The upper half of the cut had a smooth surface roughness of R_a value 1.75 microns but the lower half resulted in the rougher surface roughness with R_a value of 2.4 microns [12]. The waterjet pressure has the highest influence on the R_a , followed by traverse speed and standoff distance. Experiments were conducted on R_a of AWJ cut Aluminum-graphite MMCs produced by squeeze casting. A regression equation for R_a is developed and the experimental results are compared with it [13].

The literature review reveals that, the R_a measurements is done arbitrarily at some distance from the top of the cut. However R_a is to be measured along the DOP to clearly understand the process performance. Hence this research work is carried out to investigate the R_a along the DOP in aluminium-silicon carbide composites. To access the DOP, it is planned to use 70 mm thick trapezoidal MMC blocks. Hence stir casting method will be used to manufacture the MMC blocks of different compositions. Surface roughness is measured with non contact confocal microscopy followed by analysis.

2. Experimentation

To manufacture aluminium 6061 and silicon carbide particles (Al6061-SiC) MMCs, aluminium 6061 (Al6061) was chosen as matrix material and silicon carbide particles (SiC) of #80 mesh size was chosen as reinforcement.

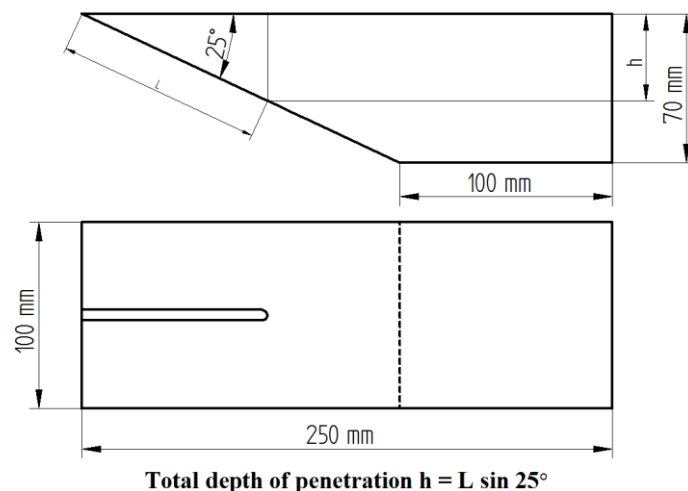


Figure 1. Geometry of trapezoidal specimens.

Al6061-SiC MMCs were produced by stir cast method. Since stir casting method is capable of producing a large-size specimen of any thickness, the present work employed this method to prepare trape-

zoidal shaped Al6061-SiC MMCs specimen. Figure 1. shows the geometry of trapezoidal specimens [14,15]. The specimens were prepared by adding different weight percentage of SiC particles (5%, 10% and 15%) to the Al6061 matrix material. To prepare a specimen, about 5 kg of Al6061 was heated in an electric furnace and furnace was set to a temperature of 800°C. The molten metal was overheated beyond the melting point of Al6061 is to ensure that there was some clearance time before it started cooling into solid state again. After the melting is complete, the molten Al6061 in the crucible was taken out from the furnace and hexachloroethane tablets were dipped into molten metal. The hexachloroethane reacted with Al6061 and releases air bubbles trapped inside the molten metal during melting inside the furnace. Thus the pure molten Al6061 was left out in the crucible. The molten Al6061 was stirred using a stirrer at a speed of about 400 revolutions per minute. As the stirring continued, calculated amount of the SiC reinforcement were added to the crucible. Along with the particulate reinforcements, small amount of magnesium bits were added to increase the wettability between SiC and Al6061. The magnesium and SiC added during stirring was preheated to about 250°C so that there were no adverse reactions due to huge temperature difference between the matrix and reinforcements. Thus molten slurry was prepared. A custom-made split die of C-40 steel was used for the preparation of the specimen. The die was cleaned and its inner walls were pre-coated with graphite paste to make sure that the solidified MMC did not stick to the inner walls of the die. The molten slurry was slowly poured into the die and was left to solidify. Once it cooled down, the die was split opened and the MMC specimen was separated from the die. The casting of Al6061-5%SiC, Al6061-10%SiC and Al6061-15%SiC were prepared. Further these specimens are subjected for AWJ cutting.

2.1 AWJ cutting

To study the influence of dynamic parameters and their interactions on DOP in different MMCs, 3³ full factorial experiments were considered. AWJ cutting experiments with #80 mesh size garnet abrasives were conducted on both Al6061 base alloy and Al6061-SiC MMCs of different compositions such as 85%Al6061 + 15% SiC, 90%Al6061 + 10% SiC, 95%Al6061 + 5% SiC. The dynamic parameters such as waterjet pressure, abrasive flow rate and jet traverse speed were varied at three different levels. Hence, 27 experiments were conducted on each specimen considered for experimentation. Orifice diameter of 0.25 mm, mixing tube diameter of 0.76 mm and stand off distance of 2 mm is used during AWJ cutting of Al6061 base alloy and Al6061-SiC MMCs. Table 1 refers to the process parameters employed for considering the full factorial experiments. Initial experiments of AWJ cutting on Al6061 base alloy were conducted to consider the process parameters levels and arrive at these values. The cutting experiments were conducted by keeping the focusing nozzle at a distance of 2 mm from the work piece material. The jet was made to strike the material at an angle of 90° and traversed over the length of the specimen only once in order to observe the maximum penetration depth on the specimen. To determine the maximum penetration of jet into the work piece material, the jet was traversed over the work material until the splashing of jet was noticed. Jet splashed when it could not penetrate further into the material. In total, 108 cutting experiments were carried out on the samples of Al6061, Al6061-5%SiC, Al6061-10%SiC and Al6061-15%SiC.

2.2 Measurement of DOP and R_a

The DOP measurement was carried out on all the 108 cutting experiments samples. The DOP was measured by measuring the slant length of cut (L), the penetration of jet (h), for each set of parameters. The DOP was determined using the relation, $DOP = L \sin 25^\circ$ [14,15]. The DOP was also measured with vernier height gauge to minimize the error. The measurement was done twice for each specimen in order to minimize the errors.

Table 1. Process parameters used in the experiments.

Process parameters	Level-1	Level-2	Level-3
Water jet pressure (MPa)	100	200	300
Abrasive flow rate (kg min^{-1})	0.195	0.304	0.406
Traverse speed (mm min^{-1})	100	200	300
Abrasive type and mesh size	Garnet, 80 mesh		
Orifice diameter (mm)	0.35		
Orifice material	Sapphire		
Focusing nozzle diameter (mm)	1.02		
Focusing nozzle material	Tungsten carbide		
Standoff distance	2 mm		

The 108 cutting experiments samples were cut and subjected for R_a measurement. The R_a measurement is carried on a non-contact confocal microscopy at x5 optical zoom with scan field of 2.56 mm x 2.56 mm. The R_a is measured along the surface of DOP from the top to bottom of the kerf insteps of 2.56 mm. The average reading of this area is taken as the R_a .

3. Results and discussions

3.1 DOP and R_a results

Table 2 shows the experimental values of DOP for the Al6061 base alloy and Al6061-SiC MMCs. From the table it is clear that the maximum DOP are 54.62 mm, 54.44 mm, 54.40 mm and 54.32 mm for Al6061 base alloy, Al6061-5%SiC, Al6061-10%SiC and Al6061-15%SiC MMCs respectively was observed at maximum waterjet pressure of 300 MPa, abrasive flow rate of $0.406 \text{ kg min}^{-1}$ and at least traverse speed of 100 mm min^{-1} . In most of the experimental DOP values, the DOP decreases with increase in reinforcement percentages in Al6061-SiC MMCs. This can be attributed to the fact that with the increase in the percentage of SiC particles, the hardness of the specimen is increased, thereby the cutting ability of the waterjet has decreased. In general, the DOP has increased with increase in waterjet pressure and abrasive flow rate, but decreased with increase of jet traverse speed. The increase in waterjet pressure increased the cutting ability of the jet so that jet could penetrate to the larger depths. Marginal increase of DOP can be seen with increase of abrasive flow rate. With the increase in abrasive flow rate, more abrasives are available for the interaction with the work piece material. At the same time more abrasive may accumulate in the mixing tube and obstruct the flow of high velocity water also there can be improper mixing of abrasive with the waterjet. The abrasives can inter collide among themselves and damage the cutting edges of the abrasives. This reduces the cutting ability of the waterjet at very high abrasive flow rates. With the increase of traverse speed, less time was available for the cutting action, which has reduced the DOP.

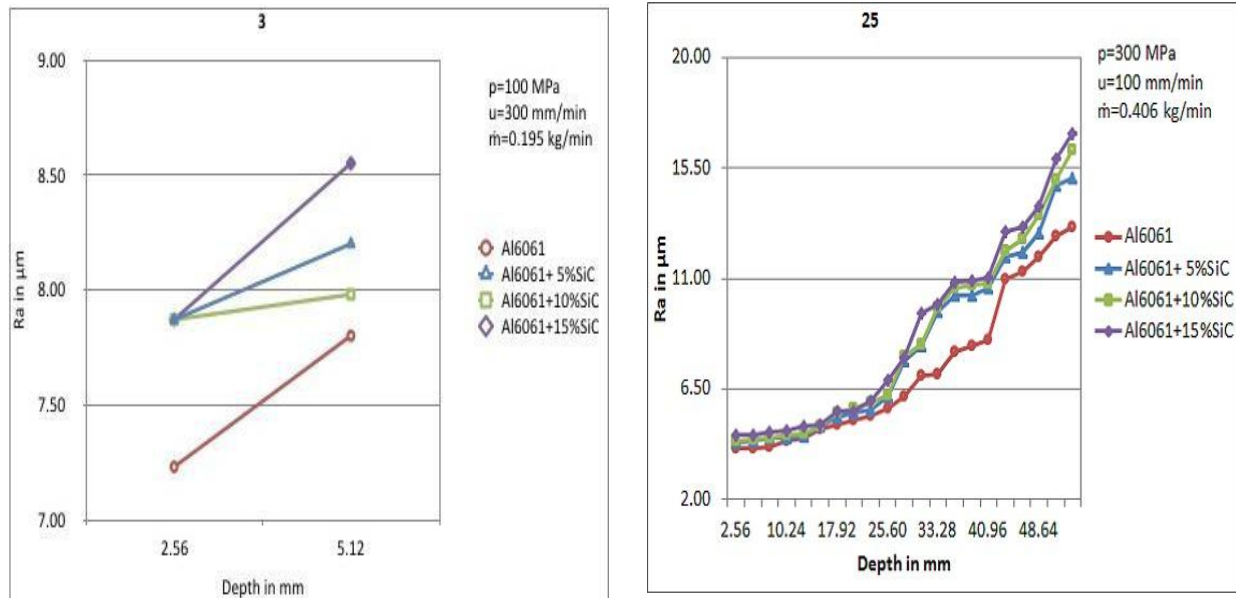
Table 2. DOP of Al6061 and Al6061-SiC MMCs.

Exp. no.	Pressure (Mpa)	Abrasive flow rate (kg min ⁻¹)	Traverse speed (mm min ⁻¹)	DOP(mm)			
				Al6061	Al6061 + 5%SiC	Al6061 + 10%SiC	Al6061 + 15%SiC
1	100	0.195	100	11.70	11.40	11.30	11.30
2	100	0.195	200	5.89	5.76	5.69	5.48
3	100	0.195	300	5.20	5.10	5.06	5.02
4	200	0.195	100	28.72	28.00	27.34	27.35
5	200	0.195	200	17.30	17.08	16.70	16.30
6	200	0.195	300	12.60	11.30	11.00	11.02
7	300	0.195	100	49.36	48.10	47.35	45.92
8	300	0.195	200	29.88	27.76	27.86	24.84
9	300	0.195	300	19.66	19.30	19.18	18.42
10	100	0.304	100	11.84	11.44	11.40	11.38
11	100	0.304	200	6.31	6.06	5.69	5.20
12	100	0.304	300	5.72	5.62	5.48	5.42
13	200	0.304	100	29.70	29.70	29.18	28.10
14	200	0.304	200	17.50	17.30	17.25	16.36
15	200	0.304	300	12.64	12.40	12.36	12.34
16	300	0.304	100	52.62	52.42	52.36	52.30
17	300	0.304	200	30.10	29.86	29.50	29.30
18	300	0.304	300	21.60	21.40	21.11	21.00
19	100	0.406	100	11.90	11.58	11.48	11.46
20	100	0.406	200	6.46	6.18	5.78	5.40
21	100	0.406	300	6.30	6.10	6.00	5.81
22	200	0.406	100	29.71	29.70	29.50	28.91
23	200	0.406	200	17.60	17.48	17.36	16.78
24	200	0.406	300	13.38	12.58	12.54	12.36
25	300	0.406	100	54.62	54.44	54.40	54.32
26	300	0.406	200	32.86	31.60	31.08	31.06
27	300	0.406	300	21.68	21.60	21.12	21.08

Figure 2a, b & c compares the variation of R_a with DOP for lowest, highest and medium DOP obtained. The smooth surface finish with lowest R_a values varying from 4.06 μm to 10.18 μm is noted from the top of the cut to bottom of the cut along the DOP for Al6061 base alloy with 54.62 mm of DOP, while cutting with 300 MPa waterjet pressure, 100 mm min^{-1} jet traverse speed and 0.406 kg min^{-1} abrasive flow rate. With the same cutting conditions, the smooth surface finish with lowest R_a values ranging from 4.33 to 14.40 μm with 54.44 mm of DOP, 4.37 μm to 14.68 μm with 54.40 mm of DOP and 4.60 μm to 15.94 with 54.32 mm of DOP are obtained from the top of the cut to bottom of the cut along the DOP for Al6061-5%SiC, Al6061-10%SiC and Al6061-15%SiC MMCs respectively. The highest R_a values varying from 7.23 μm to 7.80 μm along DOP from the top of the cut to the bottom of the cut along the DOP with 5.20 mm of DOP are obtained with 100 MPa waterjet pressure, 300 mm min^{-1} jet traverse speed and 0.195 kg min^{-1} abrasive flow rate cutting conditions. Similarly the highest R_a values of the range of 7.87 μm to 8.20 μm along DOP with 5.10 mm of DOP, 7.87 μm to 7.98 μm along DOP with 5.06 mm of DOP, 7.87 μm to 8.55 μm along DOP with 5.02 mm of DOP are obtained from the top of the cut to bottom of the cut along the DOP for Al6061-5%SiC, Al6061-10%SiC and Al6061-15%SiC MMCs respectively with same cutting conditions. Similarly the average DOP of 29.70, 29.70, 29.18 and 28.10 are obtained for Al6061 base alloy, Al6061-5%SiC, Al6061-10%SiC and Al6061-15%SiC MMCs respectively while cutting with 200 MPa of waterjet pressure, 0.304 kg min^{-1} of abrasive flow rate and 100 mm min^{-1} of traverse speed. The R_a values varied from 4.81 to 13.85 μm , 5.59 to 13.83 μm , 5.83 to 13.89 μm and 5.87 to 14.23 μm for Al6061 base alloy, Al6061-5%SiC, Al6061-10%SiC and Al6061-15%SiC MMCs respectively. For all the cutting conditions the lower R_a values are seen for Al6061 base alloy and the higher R_a values are seen for Al6061-15%SiC MMCs from the top of the cut to bottom of the cut. The R_a varies gradually from the top the cut to bottom of the cut. Smoother surface with low R_a is seen on the upper half of the cut, and the striations or waviness surface with rougher surface finish having higher R_a are seen from the middle to the bottom of the cut along the DOP. This is same for all the cutting conditions used for the experimentation. The waterjet has the highest kinetic energy while cutting at the top and this kinetic energy gradually reduces during further cutting as the energy is being utilized during cutting. As this energy reaches to the minimum there will be no further cutting possible. The waterjet is thinner at the top of the cut with more number of abrasive particles entrainment in water. The more number of abrasive particles are available for the interaction with the work piece at any point of cut. This removes the work piece material by micro chipping [8]. With higher waterjet pressure, higher abrasive flow rate and lower traverse speed of the jet, more amount of kinetic energy and more number of abrasive particles are available for larger interaction time with work piece at a point during the cutting process. This causes a smoother R_a at the point of cut. This produces the surface with lesser R_a for larger depth along the DOP. As the kinetic energy reduces during cutting, the waterjet becomes wider, the transfer of kinetic energy to abrasive particles reduces, and thereby the abrasive particles with lesser kinetic energy are available for subsequent cuts. With wider waterjet, the number of abrasive particles available for interaction at point of cut on the work piece reduces. Also as the jet energy reduces, the inclination of the jet opposite to the direction of cutting takes place. With lesser kinetic energy the waterjet starts oscillating. As the waterjet losses its kinetic energy with DOP, the deflection and oscillation of the jet produces rough surface with striations or waviness towards the bottom of the cut. This combined effect of waterjet cuts the work piece with rougher R_a towards the bottom of the cut. This gradually increases the R_a of the cut surface towards the bottom of the cut. But with low waterjet pressure, lesser abrasive flow rate and lower traverse speed of the jet, less amount of kinetic energy and less number of abrasive particles are available for less interaction time with work piece at a point during the cutting process. This increases the R_a of the cut surface. This clearly indicates that to produce a good surface with lesser R_a , higher waterjet pressure with higher abrasive flow rate and lesser traverse speed of the jet are to be adapted.

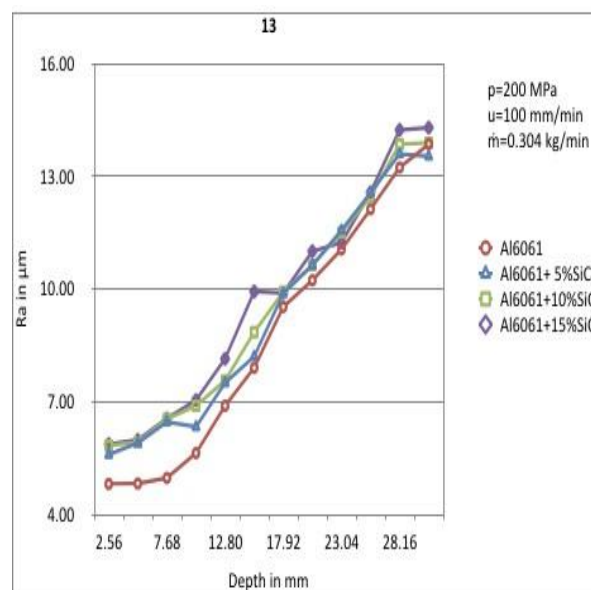
Even among the MMCs, the Al6061-15%SiC MMC has the highest R_a values for the top of the cut to bottom of the cut for any cutting conditions. This indicates the R_a values increases with the increase in percentage of SiC in MMCs. The increase of R_a values in cutting of MMCs can be due to various

reasons. The hardness of MMCs is due to the presence of the SiC in the matrix of Al6061. During cutting of the MMCs, sharpness of the garnet abrasive reduces; also the SiC present in the matrix of MMCs may peel off from their positions and mix with garnet abrasive leaving rougher regions in the place of absence of SiC in the region. In addition, the SiC mixed with the garnet abrasives may interact with garnet abrasives and damage the cutting edges of garnet abrasives for further cutting.



(a) smallest DOP

(b) largest DOP



(c) medium DOP

Figure 2. Variation of R_a along the DOP.

3.2 SEM analysis

In order to understand the mechanism of material removal in MMCs cut with AWJs, cut surface was observed under the Scanning Electron Microscope (SEM). Figure 3a & b shows the images taken on the surface of Al6061-15% SiC MMC cut with AWJ, with water pressure of 300 MPa, abrasive rate of $0.406 \text{ kg min}^{-1}$, jet traverse rate of 100 mm min^{-1} . From figure 3a, it is clear that the type of fracture on matrix material appears to be non-planar and the fracture is ductile in nature. In contrast to this, in figure 3b the planar fracture is observed on SiC in MMC clearly indicates the nature of fracture as brittle and ploughing of reinforcement can be observed. This selective erosion of material with high velocity AWJ can be attributed to i) differences in hardness of particulates and matrix materials ii) voids or gas

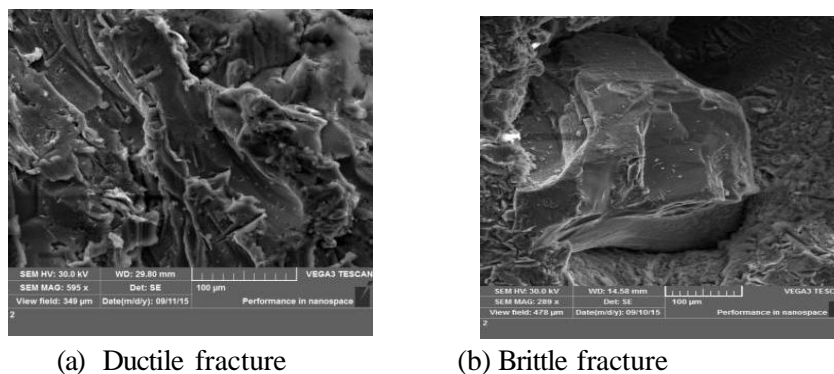


Figure 3. SEM image (a) ductile fracture (b) brittle fracture.

porosity around SiC particle indicating improper bonding between the reinforcement and matrix material iii) ploughing of reinforcement may be due to insufficient energy for fracturing the reinforcement but is sufficient to cut the matrix material. In these images, the fracture surface on the matrix material shows a texture that can result from the interaction of randomly oriented abrasives striking the material at different impact angles.

4. Conclusion

This article attempts to show the suitability of stir casting method for the production of larger-sized metal matrix composites. Consequently this effort can be considered as a database that would help to choose the parameters depending on desired R_a for Al6061 base alloy and Al6061-SiC MMCs. For a better surface finish with lower R_a values for larger depth, it is suitable to adopt, higher waterjet pressure and abrasive flow rate with low traverse speed of the jet.

Acknowledgements

The work reported in this paper is supported by B M S College of Engineering, through Technical Education Quality Improvement Programme [TEQIP-III] of the MHRD, Government of India.

References

- [1] Gokhan Aydin, Izzet Karakurt and Kerim Aydiner, 2011, *Bull. of Mat. Sc.*, **34**, 985
- [2] John Rozario Jegaraj J and Ramesh Babu N, 2005, *Int. J. of Mach. Tools and Manuf.*, **45**, 1443.
- [3] Adnan Akkrut, Mustafa Kemal Kulekci, Ulvi Sekerand Fevzi Ercan, 2004, *J. of Mat. Proc. Techno.*, **147**, 389
- [4] Kovacevic R, Hashish M, Mohan R, Ramulu M, Kim T J , and Geskin E S, 1997, *J. of Manuf. Sc. and Engg.*, **119**, 776
- [5] Kovacevic R, 1991, *J. of Manuf. Sys.*, **10**, 32
- [6] Mohamed Hashish, 1989, *J. of Engg. Mat. Techno.*, **111(2)**, 154
- [7] Hashish M, 1991, *J. of Engg. Mat. and Techno.*, **113**, 354.
- [8] Guo N S, Louis H and Meier G, 1993, *7th American Water Jet Conference*, p 1
- [9] Chen F L and Siores E, 2001, *Int. J. of Mach. Tools & Manuf.*, **41**, 1479
- [10] Neusen K F, Rohatgi P K, Vaidyanathan C and Alberts D, 1987, *Proceedings of the 4th U S Waterjet Conference*, p 272
- [11] Hashish M, 1988, *The Winter Annual Meeting of the ASME*, p 1
- [12] Hamatani G and Ramulu M, 1990, *J. of Engg. Mat. Techno.*, **112**, 381
- [13] Shanmugasundaram P, 2014, *Mat.s Phy. and Mechanics*, **19**, 1
- [14] Srinivas S and Ramesh Babu N, 2011, *Int. J. of Applied Res. in Mech. Engg.*, **1**, 109
- [15] Srinivas S and Ramesh Babu N, 2012, *Machining Sc. and Techno.*, **16**, 337