

AWJM Machining behaviour of AA2024-B₄C-TiC Hybrid Metal Matrix Composites

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Abstract— Abrasive water jet machining is most efficient and cost-effective non-traditional machining process to machine composites. This paper investigate machining characteristics such as surface roughness, kerf angle and metal removal rate with respect to water jet pressure, traverse speed, standoff distance on machining of Aluminium hybrid composite with different reinforcement compositions such as 5%, 10%, 15% and 20% of TiC and B₄C (equal amount). Surface roughness and kerf angle get better increase of water jet pressure. Increase in jet traverse speed and standoff distance get higher the kerf angle and surface roughness. Increasing water jet pressure, traverse speed and standoff distance get higher metal removal rate.

Keywords— Abrasive water jet machining, surface roughness, kerf angle, metal removal rate, AA2024 and metal matrix composite.

I. INTRODUCTION

In recent years, a large number of researches have been carried out in the area of metal matrix composites and they are widely applied in the automotive and aircraft structural components. Albeit many metals or alloys are employed as matrix materials, aluminium and its alloys have a dominant role because of its light weight, ductility, good thermal and electrical conductivity and cost effectiveness. A wide variety of ceramic particulates like SiC, Al₂O₃, B₄C, TiN, TiO₂ and TiC are used as reinforcement in aluminium metal matrix composites (AMMC) to get an improved mechanical and tribological properties (Sharma et al. 2014).

AA 2024 is an aluminium alloy with copper as the primary alloying element. As the alloy has high strength and fatigue resistance, it is widely used in aircraft structures, fittings, hydraulic valve bodies, missile parts and munitions. Recent years, researchers concentrate on hybrid AMMCs having two or more reinforcement since the second reinforcement further improves the mechanical and tribological properties of hybrid composites (Sharma et al., 2014). Compared to other alloys, the researches on hybrid composites using Al 2024 are found scanty. Ravindran et al. (2013) developed Al2024-SiC-Gr self-lubricating hybrid composite with powder metallurgy method

and tested the samples for wear. The presence of graphite particles improved the wear performance of the composites. In this work, two ceramic particles B₄C and TiC are reinforced with Al2024 to develop a hybrid composite and

the following are the reasons for selection of these two particles. The low density B₄C has higher

hardness compared to SiC and Al₂O₃ (Canakci and Arslan 2012). TiC provides excellent hardness and exhibits good wetting characteristics. Moreover, it is less expensive (Muskat et al., 1992). When compared to other processing techniques, liquid processing is the most economic method to produce MMCs. (Hashim et al., 1999). The Liquid phase processing is classified into different types such as stir casting, compo casting, squeeze casting, and spray casting/deposition methods. Since stir casting process is simple, viable, effective and low-cost method out of all these methods (Mohammad Ghaffari, 2011), it is chosen as the processing technique in this work. The non-traditional machining processes are needed to machine the difficult to cut materials. The machining of ceramic reinforced composites is difficult and non-viable using conventional machining because the addition of ceramic particles increases the hardness of composite and also the presence of ceramic particles reduces the tool life. In these cases, non-traditional machining processes which utilise various energy forms as tools instead of traditional physical tools have greater advantages (Youssef and El-Hofy, 2008 book). In abrasive water jet machining (AWJM), one of the non-traditional machining processes, a high velocity water jet carrying the abrasive particle hits the workpiece. The impact generated by the kinetic energy of the high energy abrasive particles causes the removal of material. When comparing the other non-traditional machining processes, AWJM has the following unique advantages: (i) the thermal distortion is low (ii) versatility is high (iii) flexibility is high (iv) machining force is low. (v) consumes less energy (vi) no adverse effect on the microstructure of the cut surface and (vii) there is no reduction in hardness of the cut surface (Gyliene et al., 2014, Akkurt 2015). In the previous researches, AWJM is employed for machining different materials such as Alumina ceramics (Wang and Guo, 2003, Shanmugam et al, 2008), Cast iron (Chithiraiponselvan and Mohanasundararaju, 2012), Transformation induced plasticity steel (TRIP) sheets (Kechagias et al., 2012), Al6061, Al2024, Brass 353, Ti6Al4V, Stainless steel AISI 304 (Pal and Tandon, 2013) Inconel 800H (Sidda Reddy et al., 2015), Glass fiber reinforced polymer composite (Mohammed Ali et al., 2014) and MMCs such as Al-SiCp (Srinivas and Rameshbabu, 2013), Al7075/B₄C (Mohankumar and Kanthababu, 2016). The performance of

the AWJM is measured using parameters such as material removal rate (MRR), depth of cut, kerf width and surface roughness (Patel and Tandon, 2015). The performance of the AWJM process is influenced by (i) operational parameters such as jet pressure, standoff distance, nozzle traverse rate, angle of cutting (ii) abrasive parameters such as abrasive type, size, shape, abrasive flow rate (iii) hydraulic parameters such as pump pressure, water flow rate and (iv) nozzle parameters such as nozzle diameter (Kechagias et al., 2012). Since the MRR decides the efficiency and economy of the process and kerf angle and surface roughness are the measures of quality, these three parameters are considered as performance parameters in this work. The jet pressure and nozzle traverse speed influence the MRR and surface roughness (Chithiraiponselvan and Mohanasundararaju, 2012). Though low nozzle traverse rate minimises the kerf taper angle, it is not economical since it reduces the MRR (Shanmugam et al 2008). Standoff distance (Kechagias et al., 2012) and traverse speed (Gyliene et al, 2014) plays a major role in surface roughness. Hence the jet pressure, standoff distance and traverse speed are considered as the process parameters of this work. The paper discusses the influence of various process parameters on performance parameters when machining the composite with AWJM..

II. EXPERIMENTAL DETAILS

A. Materials

AA2024 is an aluminium alloy having chemical composition of 4.85%Cu, 1.31%Mg, 0.667%Mn, 0.254%Fe, 0.11%Si, 0.079%Zn, 0.033% Cr, 0.008% Ti and remaining Al in weight percentage. The selected particles are B4C having average particle size of 150µm and density of 2.5278g/cm³; TiC having average particle size of 150µm and a density of 4.52g/cm³. The hybrid composites were produced by two step stir casting process. First Al2024 alloy was melted in a resistance furnace to a temperature of 640°C and then cooled to 490°C. The alloy was in slurry state and the slurry was stirred by a stirrer to create a vortex. While stirring the slurry, the two preheated ceramic particles were added in equal volume percentage to it. Now the slurry with ceramic particles was again heated to 640°C±10°C and stirring was carried out for 10 minute with average stirring rate of 300 rev/min. The molten mixture was poured in the dies and then cooled. The procedure was followed to prepare specimens of composites with particles of 5% (2.5%B4C+2.5% TiC), 10% (5%B4C+5% TiC), 15%(7.5%B4C+7.5% TiC) and 20% (10%B4C+10% TiC), to the size of 100 × 100 × 15 .

The experiments were conducted on water Jet cutter (Model DWJ1313-FB) which was equipped with SL-V50 pressure pump with the designed pressure of 300 MPa, traverse speed of 0-60mm/min. Experimental set up of an abrasive water jet cutting process is shown in figure 1. The garnet with 80 mesh size was used as abrasive particles. The water jet was impinged vertically downward direction on the work piece. The orifice assembly has a 0.7mm diameter size carbide nozzle. The mass flow rate of abrasive particles was maintained at 3.1 lit/min for entire machining.

The most influencing parameters such as jet pressure, traverse speed and stand of distance were selected in

machining of hybrid composites and Table 1 shows the process parameters and their levels. The average surface roughness was measured on the water jet machined surface using a Mitutoyo Surface tester (Model SJ401).



Figure 1 Experimental Setup

The kerf width at the top and bottom are measured with the help of optical microscope and the kerf angle is calculated using the equation 1. The experiments were conducted based on L27 orthogonal array. Each trial was repeated three times and the average of three values were recorded. The measurement of average surface roughness of work piece was

measured using Mitutoyo Surf test- SJ401 measurement device. The measurements were taken at a distance of 10mm top of cut surface. The MRR is found using the equation 2.

$$\text{Kerf Angle } \tan\theta = (\text{Top width} - \text{bottom width}) / 2t \quad (1)$$

$$\text{MRR} = ((\text{Top width} + \text{bottom width}) / 2) * \text{thickness of work piece} * \text{cutting velocity} \quad (2)$$

TABLE I EXPERIMENT PARAMETERS

Parameters	Symbol	Level 1	Level 2	Level 3
Water jet Pressure (MPa)	A	220	240	260
Stand-off distance(mm)	B	1	2	3
Traverse speed(mm/min)	C	20	30	40

TABLE II DESIGN OF EXPERIMENT

Std order	Run order	Water jet pressure MPa	Transverse speed mm/min	Standoff distance Mm
4	1	240	20	3
16	2	220	30	1
20	3	240	40	3
14	4	220	20	1
9	5	240	40	1
18	6	220	40	1
12	7	240	30	3
24	8	220	40	3
17	9	260	20	2
1	10	240	30	1
10	11	260	40	3
23	12	220	40	2

8	13	240	20	1
5	14	220	30	3
7	15	260	20	3
11	16	240	30	2
19	17	220	20	2
2	18	260	40	2
27	19	240	40	2
3	20	220	20	3
22	21	260	30	3
26	22	240	20	2
6	23	260	40	1
15	24	240	20	3
13	25	260	20	1
25	26	220	30	2
21	27	260	20	2

III. RESULTS AND DISCUSSION

A. Mechanism of Material Removal

The characteristics of material influence the mechanisms of material removal of AWJM. While cutting the hybrid metal matrix composite, the abrasive water jet needs to interact with two different types of materials that are one ductile metal matrix and the other brittle ceramic particles. In ductile matrix, the material removal is either by micro-cutting or by plastic deformation (Paul et al, 1998). Micro-cutting occurs at shallow angle of impingement and plastic deformation occurs at large angles (Mohamed Hasish, 1984). The abrasive particles hit at shallow angle in the upper part of the kerf and the material removal is high and when the material removal proceeds further along the depth of the kerf, the angle of inclination gradually increases leads to lesser material removal (Finnie). In the case of ceramics, the material removal occurs by plastic flow at the impact site and by network fracture in the surroundings of the impact site. When a high velocity jet impacts the material, if the force is smaller there will be a plastic flow. When the force exceeds the threshold value for crack initiation, the microcracks are formed. These microcracks coalesce to form a larger crack and it propagates laterally (Choi and Choi, 1996). The crack propagation is transgranular or intergranular and in these two the intergranular cracking is more dominant (Zeng and Kim, 1996). When abrasive jet impacts the ceramic reinforced metal matrix composite, the abrasive erosion due to microcutting occurs in the matrix material and the jet ploughs away the particulates (Ramulu et al, 1993). During ploughing the jet either pulls or cuts the ceramic particle (Savrun and Taya, 1988). The dislodging of the particles occurs at places where the bonding between matrix and particles is poor (Neusan et al., 1987).

B. Influence of Parameters on Material Removal Rate

From the Figure 2, it is understood that either increase in water jet pressure or increase in stand-off distance or increase in traverse speed increases the MRR. The material removal depends on the momentum of the abrasive particles during the impact on the material (Choi and Choi, 1997). When the jet pressure is high, the abrasive particles gain momentum from the water jet and hence the increase in water jet pressure increases the MRR. When the particles strike the surface the material removal rate increases with increasing impact angle (Paul et al, 1998). The increase in

SOD causes expansion of the jet and the abrasive particles of the jet strike the surface with larger impact angle causing more material to remove. The traverse speed influences the depth of cut. In this work, as the thickness of the material is small, it is through cut by the jet. Hence the increase in traverse rate causing continuous material removal and increases the material removal rate. As the reinforcement increases the number of ceramic particles in unit volume of material also increases. When the jet cuts the material, more energy is required to pull or cut these hard and brittle particles. Hence the material removal rate decreases with increasing percentage addition.

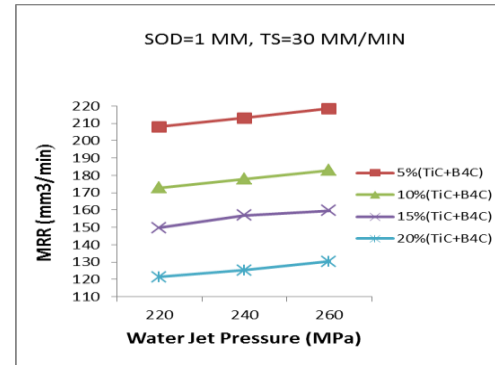


Figure 2 Water Jet Pressure

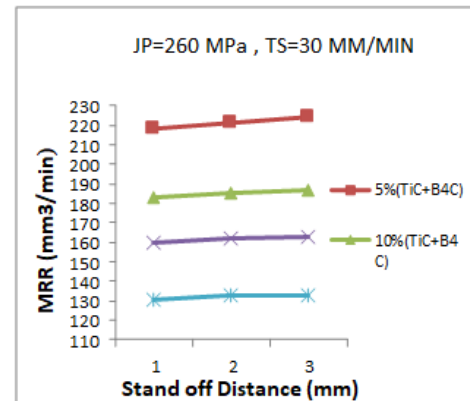


Figure 3 Standoff Distance

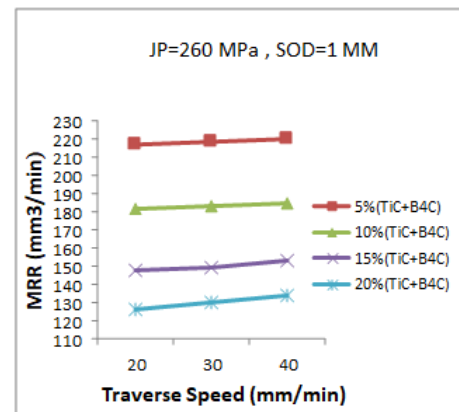


Figure 4 Traverse Speed

C. Influence of Parameters on Kerf Angle

The Figure 5 shows the kerf angle variation with jet pressure, standoff distance and traverse speed.

The graph shows that increase in jet pressure results in decreasing kerf angle. The effective diameter is the diameter of the water jet possessing higher energy for cutting. With the increase of jet pressure the effective diameter increases and the jet has enough energy which is able to cut even at the bottom of the material and the kerf width is wider as the top leading to the lower kerf angle (Shanmugamet al, 2008). The kerf angle increases with increasing traverse speed. When the material is exposed for a longer time to the jet the kerf angle increases.

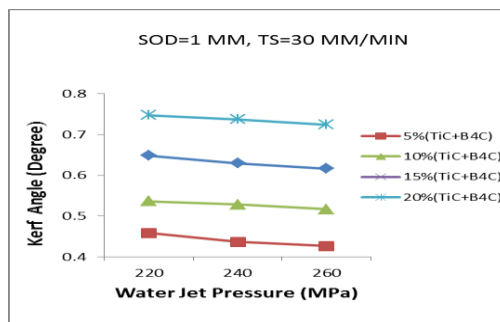


Figure 5 Water Jet Pressure

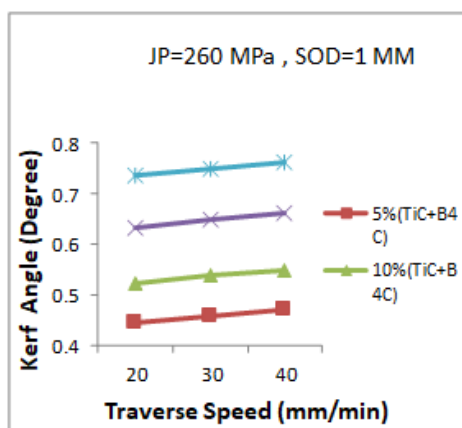


Figure 6 Traverse Speed

Since at higher traverse speed the material exposure to the jet reduces causing larger kerf angle (Shanmugam and Masood, 2009). From the graph, it is understood that there is an increase in kerf angle with increase in standoff distance. As the standoff distance is increased the lower part of the jet diverges and it does not possess sufficient energy to machine the lower part of the kerf effectively (Chen et al 1996). This reduces the lower kerf width and increases the kerf angle. The increase in ceramic particle composition increases the kerf angle. As explained earlier, the cutting or removing of ceramic particles reduces the energy of the water jet at the downstream side and reduces the kerf width causing an increase in kerf angle.

D. Influence of Parameters on Surface Roughness

Figure 7 illustrates the effect of parameters on surface roughness. It is revealed from the graph 4.a that increase in water jet pressure decreases the surface roughness and enhances the surface quality. Due to increase in pressure, during cutting the abrasive particles get fragmented and at the same time augmenting higher velocity. These smaller abrasive particles cause finer erosions on the material. Furthermore, there is an increase in energy due to increase in pressure. The excess energy after cutting is utilised for smoothing the surface (Kovacevic et al., 1988, Momber et al, 1996). The graph 4.b shows that the low traverse speed improves the surface finish. At lower traverse speed, as the surface is exposed to longer time, more number of impacting abrasive particles is available. The initial surface generated by the leading particles is refinished and smoothed by the trailing particles (Neusen et al, 1987, Wang, 1999). It is clear from the graph 4.c that the increase in standoff distance increases the surface roughness. At higher standoff distance the jet expands before impacting the surface and only few particles are present in the outer periphery of the jet. These single particles impact the surface causing more peaks and valleys and they will not be smoothed further leading to rougher surface (Ramulu and Arola, 1994). It is found that increasing the reinforcement affects the surface finish to a greater extent. This is due to that when cutting the composite having higher percentage of reinforcement the jet cuts or pulls out more number of ceramic particles causing more peaks and valleys. Moreover, the resistance provided by the ceramic particles reduces the energy of the jet which reduces the secondary smoothing action.

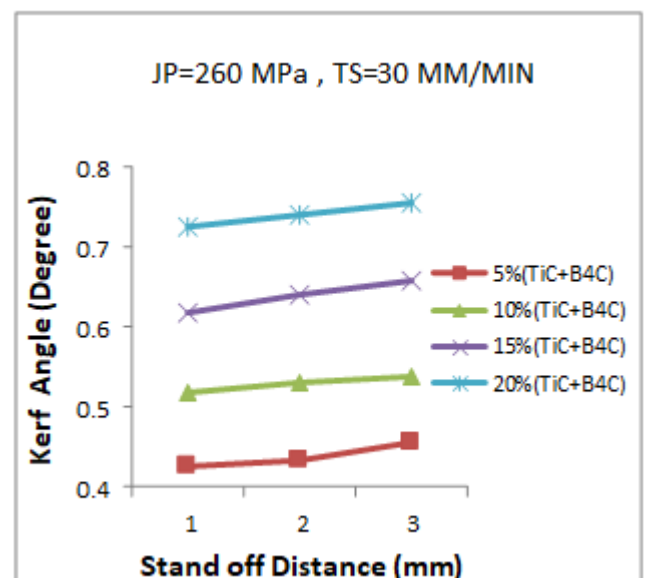


Figure 7 Standoff Distance

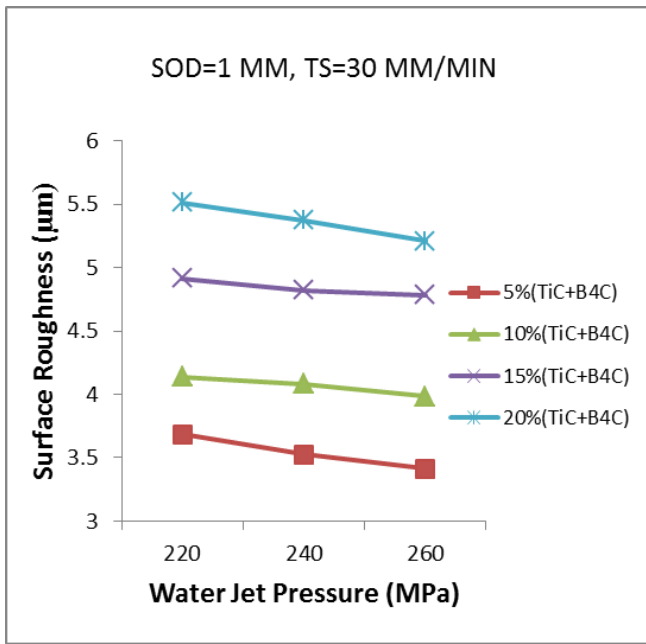


Figure 8 Wet Jet Pressure

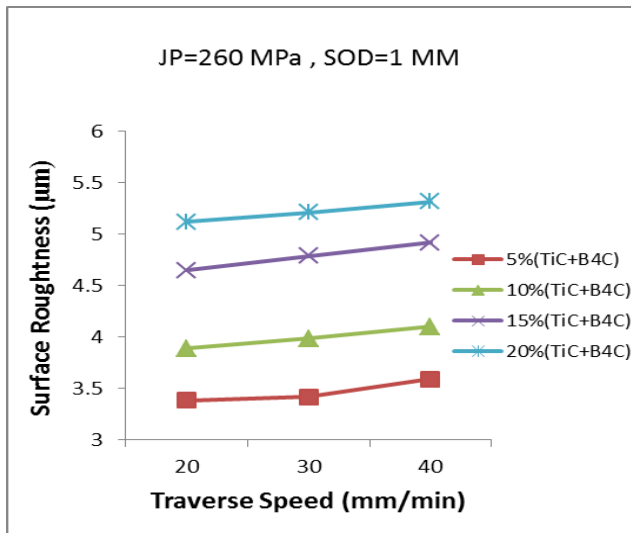


Figure 9 Traverse Speed

IV. CONCLUSION

The experimental study have been carried out of the machining behaviour of AA2024-B4C-TiC hybrid composites with different volume fraction.

- The increase in water jet pressure, stand-off distance and traverse speed increases the MRR. Increase in jet pressure causes lower kerf angle.
- Higher traverse speed reduces the kerf angle. An increase in standoff distance reduces the lower kerf width and increases the kerf angle. The increase in ceramic particle composition increases the kerf angle.
- The increase in water jet pressure decreases the surface roughness and enhances the surface quality. Lower traverse speed which improves the surface finish. The increase in standoff distance increases the

surface roughness. It is observed that increasing the reinforcement affects the surface finish to a greater extent.

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