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INVESTIGATION OF THE SURFACE QUALITY OF AA6082-ZrO_2-Gr MMCs USING ABRASIVE WATERJET MACHINING

RAZISKAVA KAKOVOSTI POVRŠINE KOMPOZITA NA OSNOVI AA6082-ZrO_2-Gr ZARADI NJEGOVE ABRAZIVNE MEHANSKE OBDELAVE Z VODNIM CURKOM

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Aluminium metal matrix composites have wide applications in the aerospace and automotive industries due to their excellent physical properties like hardness, tensile strength, etc. The reinforcement of ZrO_2 hard ceramic particles and soft solid lubricant graphite on AA6082 produces a high-strength composite. This research aims to fabricate AA6082-ZrO_2-Gr MMCs with different compositions and evaluate the abrasive-waterjet-machining (AWJM) parameters in the machining of the fabricated composites, which eliminates the thermal distortion and damage to the work material. The experiments were conducted by varying the dominant process parameters such as water pressure, traverse speed, abrasive flow rate and mesh size. The kerf taper angle was affected by the traverse speed and water pressure, while the surface roughness was affected by the abrasive flow rate, mesh size and water pressure. The abrasive mesh size of 120 provided the best surface finish.

Keywords: abrasive waterjet, composite, surface roughness, kerf angle

Kompoziti z matrico na osnovi aluminijevih zlitin se množično uporabljajo v letalski in avtomobilski industriji zaradi svojih odličnih fizikalnih lastnosti, kot so trdnost, trdota, natezna trdnost itd. Ojačitev kovinske osnove oziroma zlitine AA6082 s trdimi keramičnimi delci ZrO_2 in mehkim trdnim grafitnim mazivom omogoča izdelavo kompozita z visoko trdnostjo. V članku je opisana raziskava izdelave kompozitov vrste AA6082-ZrO_2-Gr z različno sestavo in njihovo ovrednotenje zaradi abrazivne obdelave z vodnim curkom (AWJM; angl.: abrasive waterjet machining) pri različnih procesnih parametrih. Namen raziskave je bil optimiranje oziroma termični vpliv na krivljenje in poškodbe izdelkov iz kompozitov. Preizkusi so bili izvedeni pri različnih vplivnih parametrih procesa, kot so tlak vode, hitrost vodnega curka, hitrost pretoka vode z dodatkom abrazivnega sredstva in njegove velikosti delcev. Na kot reza vplivata hitrost potovanja vodnega curka in tlak vode. Na površinsko hrapavost reza vplivajo hitrost pretoka in velikost delcev abrazivnega sredstva ter tlak vode. Pri uporabi abrazivnega sredstva razreda #120 je bila dosežena najmanjša površinska hrapavost.

Ključne besede: abrazivni vodni curek, kompozit, površinska hrapavost, kot odreza

1 INTRODUCTION

Composite materials include many combinations of metals with desirable mechanical properties. They are widely used in many industries and main parts like gears, turbine blades, dies, etc., whose performance is enhanced due to composite materials.[1] It has been demonstrated that metal matrix composites (MMC) have better properties, such as higher strength, wear resistance, abrasion resistance, creep resistance, corrosion resistance, thermal conductivity and dimensional stability.[2] The most common metal matrix composites are aluminium, titanium, magnesium and copper alloys. Aluminium and its alloys are the most commonly used metal matrix composites.[3] The primary advantages of aluminium-based metal matrix composites (AMMCs) over unreinforced materials are their high strength, good stiffness, low density (weight), controlled thermal expansion coefficient, thermal/heat management, enhanced and customized electrical performance, improved abrasion and wear resistance, control of mass (especially in reciprocating applications) and enhanced damping capabilities.[4] The commonly found reinforcements in AMMCs are SiC, TiB_2, TiC, Al_2O_3, WC and rice husk. Mechanical properties such as tensile strength and density were increased with an increase in the proportion of reinforcement and the distribution of reinforced particles was inspected using a SEM analysis.[5] The reinforcement of nano-sized particles in an aluminium matrix has demonstrated their potential superiority in increasing mechanical characteristics and microstructural properties with a higher strength-to-weight ratio. In this investigation, zirconia (ZrO_2) reinforces the AA6082 matrix, widely used in automobile, aerospace and marine industries. The reinforcement of ZrO_2 is desirable as it exhibits a density of 5.68 g/cm^3, melting point of 2715 °C, ultimate tensile strength of 425 MPa, Vickers hardness of 150 HV and Young's modulus of 98 GPa. In addition, the nano-ZrO_2 particles provide a higher impact toughness. The impact strengths of the composites with nano-ZrO_2 are higher

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than those of the other nanoparticles. Particles of ZrO_2 enhance the tensile strength and hardness while marginally decreasing the ductility. ZrO_2 reinforcement particles change the fracture surface mode from brittle to a ductile intergranular mode.[6,7]

The lamellar structure of graphite, a self-lubricant reinforcement, enhances the anti-friction characteristics. A solid lubricant creates a coating on the contact surface to reduce friction. Graphite is considered as one of the most frequently used self-lubricants due to its excellent lubricating properties and low cost. The reinforcement and interfacial strength between the matrix and reinforcement elements increase the strength of the prepared MMCs. The addition of graphite improves the machinability.[8] Adding graphite particles to Al alloys allows a new approach to producing tribological materials more resistant to wear and tear. The composites reinforced with high-strength ceramic and graphite particles exhibit more excellent tribological properties than those reinforced with mono-particulate materials, according to a new study.[9] The machinability has been increased by 7 % in volume, and the tool life has also been increased by 130 % when graphite particles are added to Al/SiC/Gr composites.[10]

There are many techniques for fabricating AMMCs, such as mechanical alloying, ball milling, squeeze casting, stir casting and powder metallurgy.[11] Among them, the stir-casting process is well known for its easy preparation and low cost. It minimizes the damage of the reinforcing particles even in a large-scale production.[12] The stirring action provides for a uniform dispersion in the matrix, making the process promising. Mechanical properties are increased with a rigid reinforcement, while machining of such a hybrid composite is difficult with traditional machining processes. It also has been observed that many difficulties in the selection of machining parameters and correct tool type are experienced.[13] Among the generally used non-conventional machining techniques, the AWJM outperforms other processes because of its quick set-up, excellent component precision, high machining versatility, small cutting forces, great flexibility and low heat generation during the process.[14,15] AWJM was first used in quarry companies to replace conventional diamond-coated saws for cutting stones. Then metals were cut by a high-velocity narrow stream of water with abrasive particles, proving that any material could be cut using AWJM. However, the control parameters such as water pressure, traverse speed, abrasive flow rate and mesh size can all affect the cut surface quality and kerf taper angle.[16] This research investigates the effect of cutting parameters of abrasive waterjet machining on machining AA6082-ZrO_2-Gr hybrid metal matrix composites with different compositions.

2 EXPERIMENTAL PART

2.1 Fabrication of hybrid composites

Different volume proportions of zirconia ((5, 10 and 15) % volume) and 5 % volume (φ/%) of self-lubricant graphite were used to reinforce an aluminium matrix. Particles of ZrO_2 (100–150 µm) and graphite (5 µm) were used as the reinforcement as shown on the FE-SEM images from **Figure 1**. The compositions of the composites are shown in **Table 1**. First, AA6082 billets were placed in a crucible and heated using an electric furnace. The melting process was continued until the temperature reached 800 °C. Next, the molten material was actively stirred using a metal stirrer. Then, the preheated zirconia and graphite were added to the molten material, stirred at the revolutions of 120 min^{-1}, and heated for 15 min. Then, the molten material was poured into a mild steel die for casting. Three samples were fabricated, each with dimensions of (100 × 100 × 10) mm and used for testing and machining. SEM images of AHC5, AHC10 and AHC15 are seen in **Figures 1a**, **1b** and **1c**, respectively.

Table 1: Composites and their properties

Composites	ZrO_2 (φ/%)	Graphite (φ/%)	Aluminium (φ/%)	Tensile strength (MPa)	Vickers hardness (HV)
AHC5	5	5	90	132	84
AHC10	10	5	85	157	112
AHC15	15	5	80	180	128

2.2 Testing of mechanical properties

A Vickers hardness tester was utilized to evaluate the extent of the hardness of the material that was fabricated. The indentation load of 20 kgf for 10 s was measured ac-

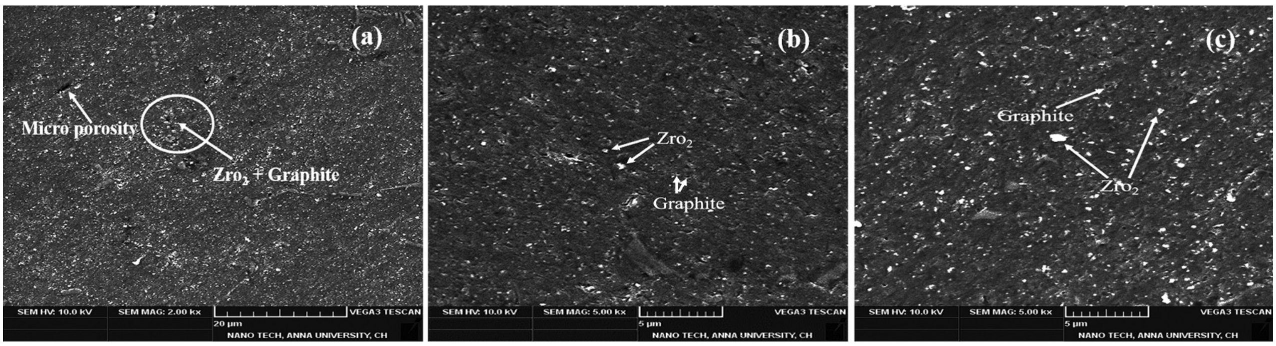

Figure 1: SEM images of fabricated composites: a) AHC5, b) AHC10, c) AHC15

Figure 2: Equipment used: a) tensile testing machine, b) surface roughness tester, c) video measuring system

cording to the ASTM E92-16 standard. The tensile strength of the material was determined using a universal testing machine according to the ASTM A370 standard. The hardness of the composite was increased with an increment in the proportion of the reinforcement. The matrix gained strength due to the addition of ZrO_2 particulates. The combination of ZrO_2 and graphite increased the composite tensile strength. In addition, an excellent interfacial binding was formed with an increase in the volume percentage of the reinforcing particles, increasing the tensile strength. **Table 1** shows the tensile strength and hardness of the prepared samples with different zirconia amounts.

2.3 Abrasive waterjet machining of the composites

The fabricated composites were machined using an abrasive waterjet machine (OMAX Corporation Model: 2626). The predominant process parameters were the water pressure (125, 200 and 275) MPa, traverse speed (60, 90 and 120) mm/min, abrasive mass flow rate (240, 340 and 440) g/min and mesh size 80, 100 and 120 were varied during the experimentation. The least contributing parameters, such as the stand-off distance of 1.5 mm and the angle of jet strike against the workpiece of 90° were set as fixed parameters. The controllable parameter levels were varied during the experimentation, while the other parameters were set to the middle level. Three replications were made for each trial and the average value of observations was considered for further analysis. **Table 2** shows the AWJM parameters and the range of operations used in composite machining. A non-contact type optical-interferometry profiling system (model: Bruker, Contour GT-K, USA) was employed for measuring the surface roughness. A video measuring system (model: 2010F) was used to measure the kerf angles of the machined samples. The top and bottom kerf widths of the machined samples were measured using VMS and the kerf angles were calculated.[17] The photographic images of the tensile strength and surface roughness tester are shown in **Figure 2**. The dimensions of the machined sample are shown in **Figure 3**.

Table 2: AWJM parameters

Process parameters	Range
Orifice diameter (mm)	0.25
Nozzle diameter (mm)	0.75
Focusing tube length (mm)	75
Focusing tube diameter (mm)	1
Impinging angle	90°
Abrasive type	Garnet
Mesh size (M)	80, 100, 120
Abrasive flow rate (g/min)	240, 340, 440
Water pressure (MPa)	125, 200, 275
Traverse speed (mm/min)	60, 90, 120
Stand-off distance (mm)	1.5

3 RESULTS AND DISCUSSION

3.1 Impact of the water pressure

Kerf taper angles of the machined composites formed by different water pressures are shown in **Figure 4a**. The

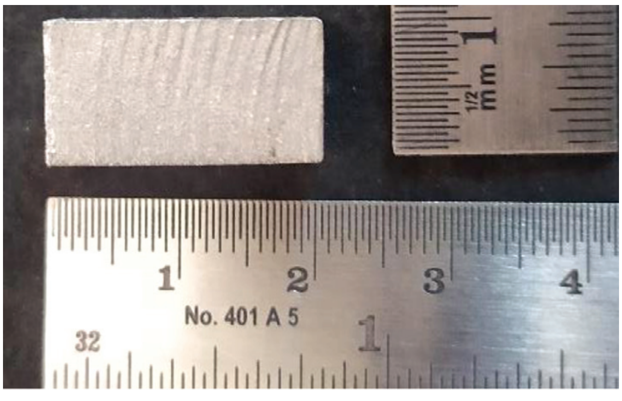

Figure 3: Sample machined with AWJM

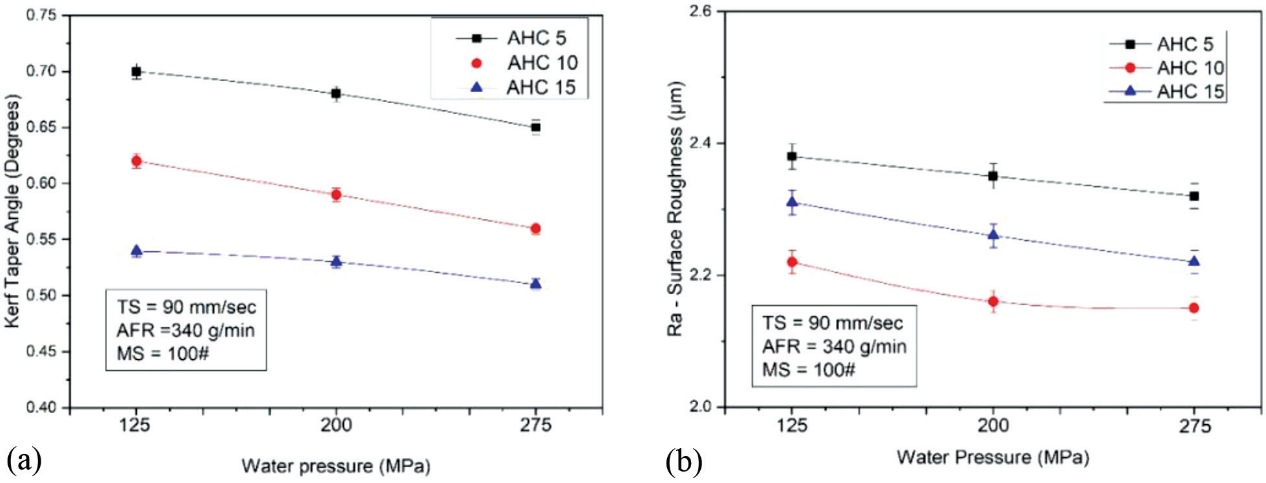

Figure 4: Water pressure: a) vs kerf taper angle and b) vs surface roughness

kerf taper gradually reduces when the waterjet pressure is increased. A higher water pressure leads to highly localized machining, which results in a deeper cut; hence, the kerf taper is low. In combination with the other variables like the traverse speed and abrasive flow rate, a lower water pressure results in a higher kerf taper angle.[17] The hard nature of ZrO_2 makes the machining rate low because the unmachined ceramic particles escape the collision of mesh particles under a low water pressure. The abrasive particles are carried, with a large amount of energy, by the waterjet with the increased kinetic energy due to the increased water pressure. The hard reinforced particles lose energy and velocity during deeper machining, resulting in a reduced material removal at the bottom surface. Hence, a low kerf width is formed at the bottom, and a less tapered slot occurs.

The strength and interface of the reinforcement of the particles affect the kerf taper angle. An increase in graphite particles influences the cutting quality by increasing the kerf taper angle. As illustrated in **Figure 4b,** an increased water pressure reduces the surface roughness of the machined composite. A higher water pressure and lower traverse speed do not significantly impact the reinforced matrix. In contrast, a higher traverse speed can dislodge the ceramic particles from the ductile aluminium matrix, resulting in a finer surface quality. The cutting ability is harmed at a low pressure due to an erroneous coordinative impact on the traverse speed, resulting in micro-cutting and rough patches, as seen in **Figure 5a**. The inability of the jet at a lower water pressure creates voids, cracks and craters on the surface that lead to a poor surface finish of the machined composite. Increasing the reinforcement particles causes machining difficulties and affects the surface roughness of the machined composite. Constant erosion dislodges reinforcing particles, causing cracks and tears on the composite surface, as illustrated in **Figure 5a**, whereas a smoother surface texture is observed in **Figure 5b.** The 10 φ/% ZrO_2 composite has a low surface roughness due to the prior machining around the reinforcement particles as well as the graphite particles, whereas the other two

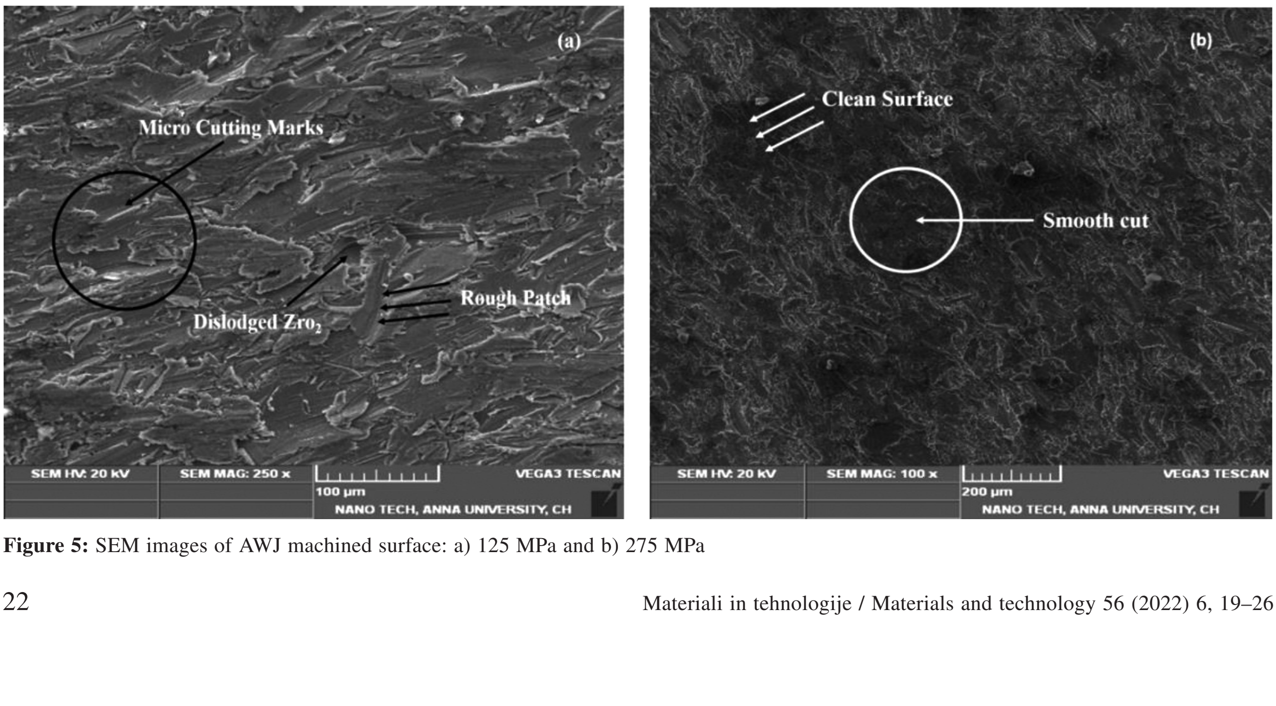

Figure 5: SEM images of AWJ machined surface: a) 125 MPa and b) 275 MPa

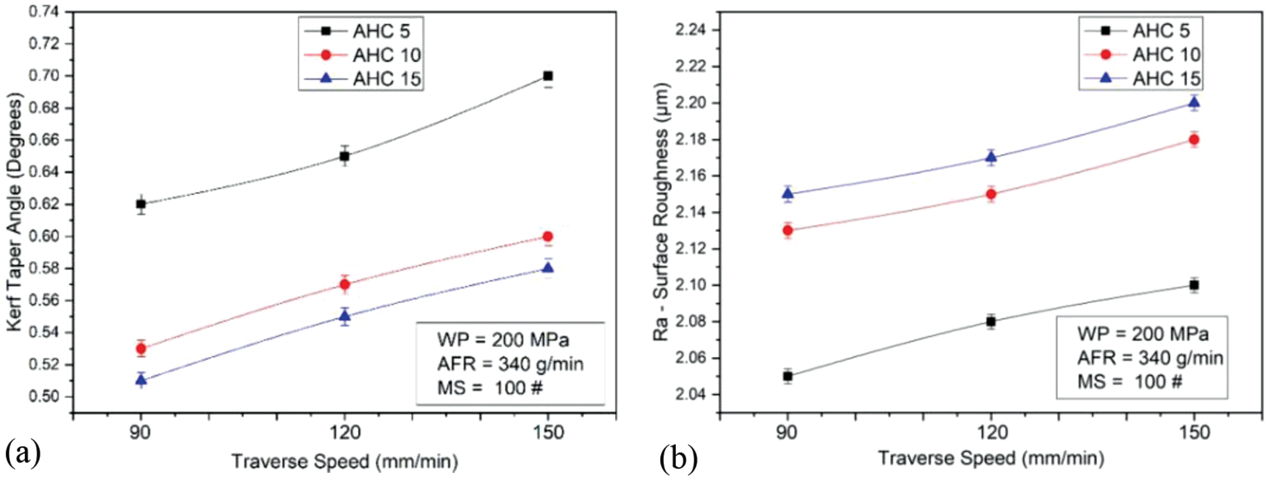

Figure 6: Traverse speed: a) vs kerf taper angle, b) vs surface roughness

composites exhibit a bit higher surface roughness because of the lower order of machining.

3.2 Impact of the traverse speed

The traverse speed has a significant impact on the kerf taper angle. The jet energy momentum causes a reduction in its kinetic energy. When the jet traverse speed is increased, the kerf taper angle is also increased. The quality of the material cutting is also reduced due to the high speed.[18] The top has a broader kerf, while the bottom has a narrower kerf. The kerf taper angle is lower for AHC15 due to an even breakage of the reinforcement particles (**Figure 6a**). This shows that a low traverse speed improves the cutting quality.

The traverse speed has an impact on the surface roughness. **Figure 6b** shows that a high traverse speed increases the surface roughness. Huge voids are formed on the surface when the erosion made by the self-lubricant is significant, making the reinforcement particles unstable. The garnet particles are also washed away due to the high traverse speed. **Figure 7** shows SEM images of the surface AWJ machined at different transverse speeds.

3.3 Impact of the abrasive flow rate

The material property determines the range of abrasive flow rate. Other factors that influence the abrasive flow rate are jet nozzle and jet speed. The abrasive flow rate determines the cutting speed and machining time. A rise in the abrasive flow rate increases the kerf taper angle due to the expansion of its diameter. **Figure 8a** shows that a lower kerf taper angle is observed with a lower abrasive flow rate. A minimum number of abrasive particles requires a material removal at a lower level of the abrasive flow rate. Hence, the interaction of the abrasive particles with reinforcements (ZrO_2 and graphite) is minimum at a lower abrasive flow rate. A minimum kerf taper angle can be achieved with the nominal abrasive

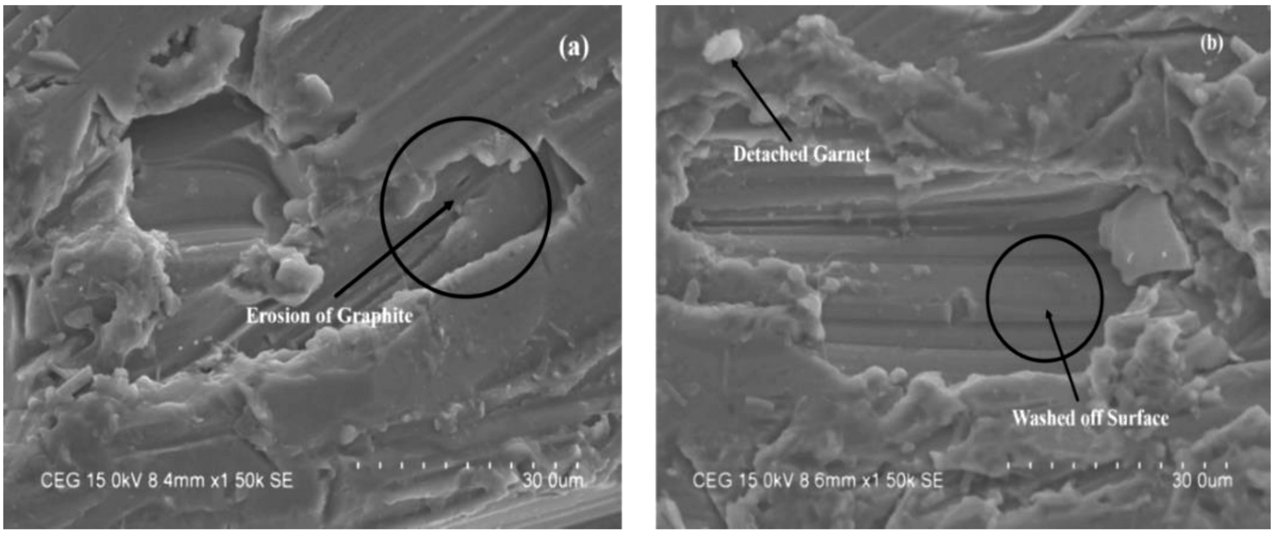

Figure 7: SEM images of the AWJ machined surface: a) 60 mm/min and b) 120 mm/min

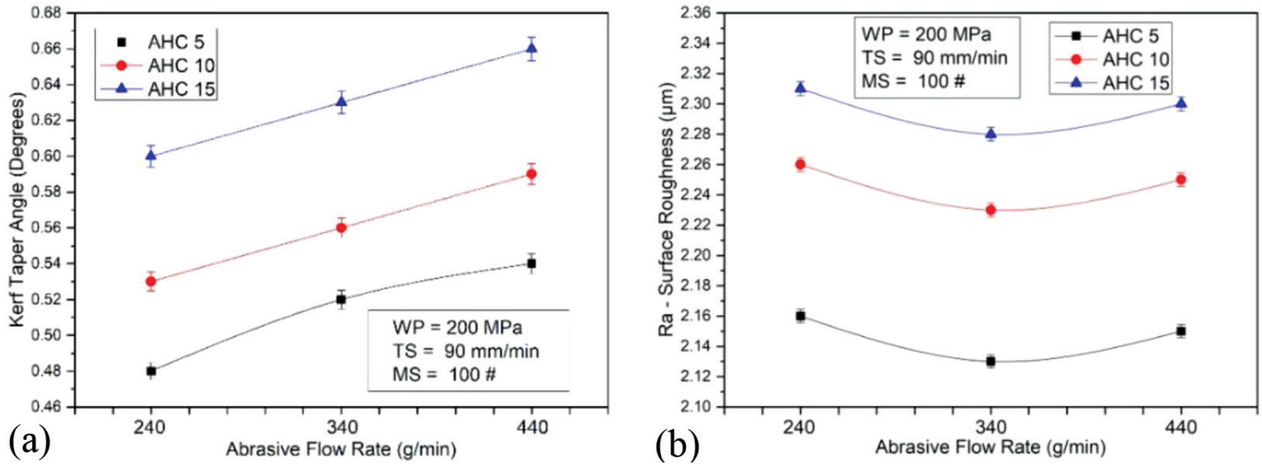

Figure 8: Abrasive flow rate: a) vs kerf taper angle and b) vs surface roughness

flow rate without any further abrasion. A higher abrasive flow rate causes the garnet particles to be destroyed, resulting in a higher kerf taper angle.[18] Due to an intense contact, the reinforcement particles are ejected from the composite surface, resulting in a higher kerf taper angle.

The effect of the abrasive flow rate on the surface roughness for the three different composites is shown in **Figure 8b**. The surface roughness is decreased when the abrasive flow rate is increased. At lower abrasive flow rates, erosion occurs due to the separation of the garnet particles and reinforcement in the composite. The surface finish becomes poor due to further erosion. When the grooved line developed as a result of the cutting wear mechanism is removed, an increased abrasive flow rate leads to more garnet particles being involved in the cutting, as shown in **Figure 9a**. When the abrasive flow rate is increased, more garnet particles are involved in the cutting process, resulting in a smoother machining surface and lower surface roughness. However, in the composites with a higher proportion of reinforced particles, the interaction between the garnet particles and reinforcement particles restrain the erosion of the aluminium matrix around the reinforced particles. As a result, as shown in **Figure 9b**, extruded zirconium dioxide particles are exposed on the surface, and a void formed by soft graphite particles is pushed away from the cutting surface.

3.4 Impact of the mesh size

Figure 10a shows the effect of the mesh size on the kerf taper angle. There is a decrease in the kerf taper angle when there is an increase in the mesh size. The reinforcement particles on the surface are not damaged, and perfect machining is performed due to finer garnet particles. It also increases the surface quality. The cutting depth and quality are decreased because of the smaller grit particles. The formation of craters on the machine surface is restricted, and smooth machining is obtained with the 120 mesh size and smaller grit particles. The cutting quality decreases when the reinforcement particles are increased in the composite. It is observed that as the amount of reinforcement particles increases, the kerf

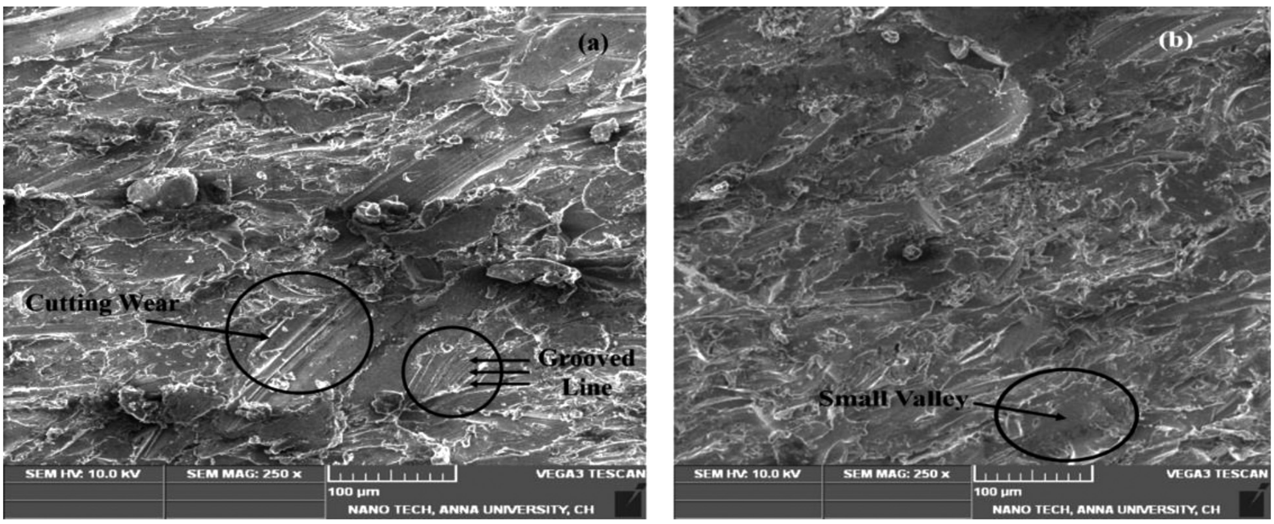

Figure 9: SEM images of the AWJ machined surface: a) 240 g/min and b) 440 g/min

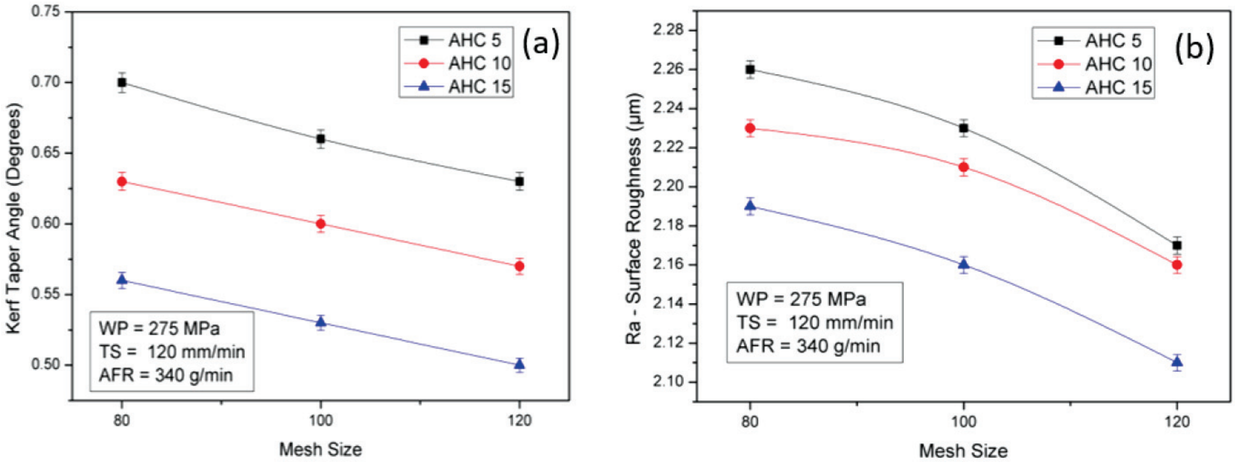

Figure 10: Mesh size: a) vs kerf taper angle and b) vs surface roughness

taper angle increases. AHC 5 produced a smaller kerf taper angle due to larger garnet particles and smaller reinforcement particles. The cutting quality is increased with finer grain particles. Due to the reduced mesh size of AHC 15, a smaller path is created between the garnet particles, resulting in a higher kerf taper angle. The garnet particles restrict the machining due to their impact on zirconia. The composite is efficiently machined at a higher mesh or smaller garnet particles.

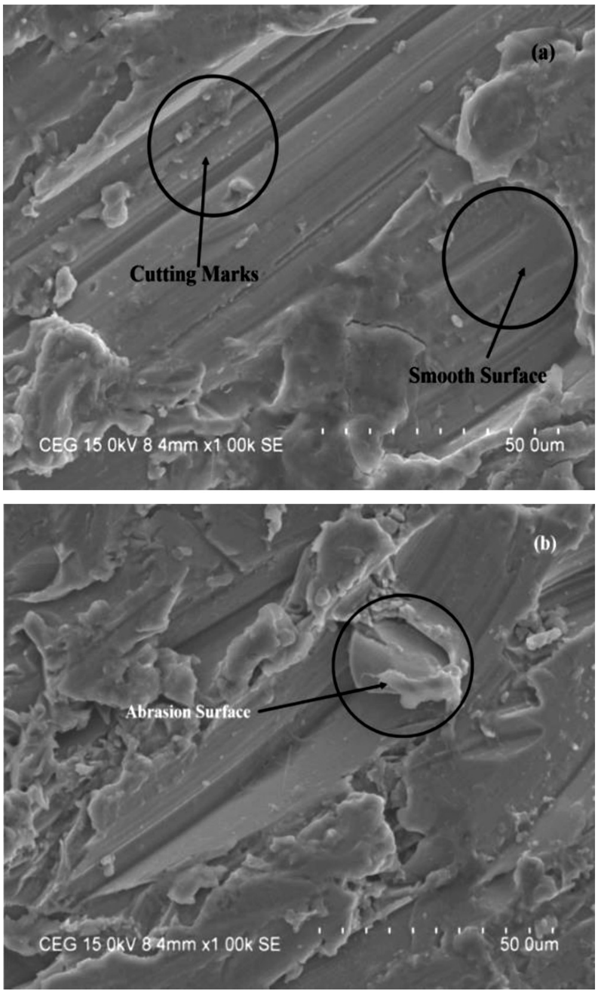

Figure 11: SEM images of the AWJ machined surface: a) mesh size 80 and b) mesh size 120

Figure 10b shows the impact of the mesh size on the machined composite. The surface roughness is decreased when the mesh size of the abrasive particle is increased due to a large size of plaguing marks. The finer grain particles removed the material with a minimal strain. **Figure 11a** shows how finer garnet particles erode the machining surface, resulting in precise cutting, visible cutting marks, and a decrease in the surface roughness. When the mesh size is constant and the reinforcement is increased, the surface roughness is also increased. The abrasive particles allowed smooth cutting. The surface roughness was further intensified by the interaction of the garnet particles with graphite particles, which resulted in a loss of graphite particles, as shown in **Figure 11b**, exhibiting an abrasion surface.

4 CONCLUSIONS

Aluminium-based MMCs (AA6082-ZrO_2-Gr) with different volume proportions of zirconia (5, 10 and 15) φ/% and 5 φ/% of self-lubricant graphite were fabricated. The fabricated hybrid composites were machined using the abrasive waterjet machining process by varying their parameters to produce a better surface cutting quality characterized by surface roughness and kerf angle. In addition, the influences of individual parameters were studied and the following conclusions were made:

Gradually increasing the reinforcement increased the hardness of the hybrid composites and provided superior strength. In addition, the solid lubricant improved its anti-frictional quality, observed on soft cutting zones.

A higher waterjet pressure made an in-depth cut and kept the kerf low throughout the cutting without a taper. At the same time, a higher waterjet pressure provided a lower surface roughness due to its excellent dislodging role in removing hard reinforced particles through the ductile aluminium matrix.

A lower traverse speed resulted in a lower kerf taper angle because of its steady cutting ability with consistent kinetic energy. In addition, the lower traverse speed allowed more abrasive particles to remove the material, increasing the smooth cutting zone. Hence, a lower surface roughness was observed at the minimum traverse speed.

A decrease in the abrasive flow rate created a lower kerf taper angle and did not allow more garnets to interact with the MMC particles. On the other hand, an increased abrasive flow rate allowed a lower surface roughness because of the excessive machining interactions between the garnets and particles, which resulted in a heavy disintegration and a smooth cut.

A decrease in the mesh size decreased the kerf taper angle because the particle size was not effective enough for dismantling the hard particles but the particles had enough energy to go through soft ductile matrix areas. Conversely, an increase in the mesh size drastically decreased the surface roughness due to the fine removal of the hard reinforced particles with their large-size garnets, resulting in clean machining and a smoother surface.

The research findings will provide the required guidelines and database for machining an AA6082-ZrO_2-Gr hybrid composite, enabling industries to meet the standards for the abrasive waterjet machining process.

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