Experimental Investigations on Material Removal Rate in Abrasive Water jet machining of Al/B₄C /ZrSiO₄ Hybrid Metal Matrix Composites

1P. Thamizhvalavan, 2M. Kanthababu, 3S. Arivazhagan and 4S. Gowri

1, 2Department of Manufacturing Engineering, College of Engineering Guindy, Anna University, Chennai -600 025, India
3Professor, Department of Mechanical Engineering St. Joseph’s College of Engineering, Chennai 600119, India

Received: 12 May 2015; Accepted: 18 July 2015; Available online: 30 July 2015

ABSTRACT

This work investigates the machinability of Hybrid MMCs consisting of aluminum alloy 6063 (Al 6063) reinforced with boron carbide (B₄C) and zirconium silicate (ZrSiO₄) in different proportions in the form of particulate for achieving higher material removal rate (MRR). The results are compared with that of unreinforced Al 6063. Experimental investigations were carried out by varying the abrasive mesh size, abrasive flow rate, water-jet pressure and traverse rate using Box Behnken method of Response Surface Methodology (RSM). The significant AWJM process parameters and their levels are identified using response graphs for achieving higher MRR, in the Hybrid MMCs and unreinforced Al 6063. Response surface graphs indicate that low abrasive mesh size; high abrasive flow rate, high water-jet pressure and low traverse rate result in higher MRR, in all the materials studied.

Keywords: Abrasive Water-jet Machining, Metal Matrix Composites, Aluminum Alloy 6063, Boron Carbide, Zirconium Silicate, Response Surface Methodology, Garnet Abrasive.

INTRODUCTION

Metal Matrix Composite (MMCs) is mostly used in defense, aerospace and transportation industry as well as in military applications. Composite materials generally exhibit in homogeneity, anisotropy and non-ductile behavior. There is a continued interest in metal matrix composites (MMCs) in developed countries and developing countries. Form 1950s various researchers tried numerous combinations of matrixes and reinforcement in MMCs. Further in 1960s ceramics as reinforcement were used for high temperature application in aircraft engine. In the last 20 years MMCs evolved from laboratories to world class materials with numerous applications and commercial markets. The hybrid metal matrix composites (HMMCs) are born by adding the matrix of more than two materials as it will improve the properties of MMCs. The HMMCs are unique materials fabricated by reinforcement of at least two types of ceramic particles in a tough metal matrix. The widely used application in HMMCs consisting of Al (SiC/B₄C), Al (SiC₂ + Gr), (Al/Al₂O₃/Gr) and (Al6061/SiC/Al₂O₃) [1,2]. From the available literature on machining MMCs, it is obvious that the morphology, distribution and volume fraction of the reinforcement phase as well the matrix properties, are all factors that affect the overall cutting properties. However in view of the growing engineering applications of these composites, a detailed and systematic study of their machining characteristics and machinability was envisaged. Use of HMMCs is limited by their poor machinability, which is the result of their highly abrasive nature. Due to cutting of ceramics reinforced aluminum matrix composite there is excessive tool wear. To overcome this drawback, among the unconventional machining processes used, abrasive water jet machining process (AWJM) would be more suitable. In AWJM, there is no thermal distortion on the work piece and minimum stress on target materials besides its versatility and high flexibility. There are large number of variables which have influence on the cutting performance such as size of orifice, mixing
tube, nozzle, the properties of work piece materials, type of abrasive mesh size, standoff distance and machining parameters.

Literature review indicates that several works have been carried out by researchers [3-19] to machine aluminum based MMCs reinforced with SiC. It is reported that machining of MMCs due to anisotropic and non-homogeneous structure of reinforcing constituent resulting in damage to workpiece and very rapid wear development in the cutting tool [3]. From the literature it is observed that no attempt has been made to identify significant AWJM process parameters for HMMCs consisting of Al 6063 reinforced with B$_4$C and ZrSiO$_4$.HMMC consisting of Al6063, B$_4$C and ZrSiO$_4$ has several potential advantages such has high hardness, high stiffness and high thermal stability. Therefore, in the present investigation an attempt is made for the first time on machinability studies of HMMCs consists of Al 6063 reinforced with B$_4$C and ZrSiO$_4$ in two proportions viz. 5 % and 10 %, and 15% in order to achieve higher MRR .

Fabrication of HMMCs and Experimental Details:

The following section deals with fabrication process of HMMCs, material characterization and experimental details.

Fabrication of HMMCs and Material Characterization:

Aluminum alloy (Al 6063) is used as matrix material in the fabrication of HMMCs. The chemical composition of Al 6063 alloy obtained with optical emission spectrometer as per ASTM E1251 is presented in Table1.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>SiC</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Cr</th>
<th>Ni</th>
<th>Vn</th>
<th>Ti</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 6063</td>
<td>0.692</td>
<td>0.343</td>
<td>0.273</td>
<td>0.097</td>
<td>0.779</td>
<td>0.01</td>
<td>0.063</td>
<td>0.015</td>
<td>0.012</td>
<td>0.019</td>
<td></td>
</tr>
</tbody>
</table>

The reinforcements, B$_4$C and ZrSiO$_4$ are added to the Al6063 in the form of particulate of size 64 µm, in various proportion of such as 5 %, 10 %, and 15% by weight. The unreinforced Al 6063 and HMMCs are prepared using stir casting process (Fig.1). During the preparation of HMMCs, the Al 6063 was charged in a gas fired crucible furnace and heated up to a temperature of 750°C, for melting. Simultaneously, the B$_4$C is preheated up to 800°C and ZrSiO$_4$ is preheated upto 1000°C for about an hour in a separate electric furnace in order to improve the wettability by removing the absorbed hydroxide and other gases. The molten metal and B$_4$C and ZrSiO$_4$ are added and stirred at 300 rpm for 15 minutes. During the process, degassing agent (hexa chloro ethane) of about 5 grams is also added in the molten metal in order to remove the slag. Thereafter, the prepared composites are poured in the die (trapezoidal shaped) and allowed to cool in the die at room temperature for about 3 hours. Fig. 2 shows the fabricated MNCs and unreinforcement Al 6063 (as cast). The presence of B$_4$C and ZrSiO$_4$ in the composites materials has been identified by using microscope images captured with Dewinter Metallurgical Microscope.

The presence of B$_4$C and ZrSiO$_4$ in the composites materials has been identified by using microscope images captured with Dewinter Metallurgical Microscope.

![Fig. 1: Photograph of stir casting process](image)

![Fig. 2: Photograph of the fabricated work pieces](image)
a) AL6063  b) AL6063 5%B 4C&5%ZrSiO4  
c) AL6063 10%B 4C 5% ZrSiO4    d) AL6063 15%B 4C 5% ZrSiO4

Fig. 3: Microscopic images of the fabricated materials.

Precision Water Jet Machining Center (Model: 2626) manufactured by M/s OMAX Corporation, is used in this work (Fig. 5). The input process parameter such as abrasive mesh size, abrasive flow rate, water jet pressure and traverse rate are varied at three levels shown in Table 2. The machining is carried out using garnet abrasives. Experiments were conducted using orifice diameter of 0.25 mm focusing nozzle diameter of 0.75 mm and jet impacting angle at 90° on a trapezoidal shaped work-piece based on the response Surface Methodology (RSM) using Box-Behnken method. Fig. 6 shows a typical machined work-piece. The significant AWJM Process parameters and their levels are identified using response graphs for achieving higher MRR, in all the three fabricated workpieces using Design of Expert software.

Table 2: Process Parameter of AWJM

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mesh size (#)</td>
<td>80</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>Abrasive flow rate (g/min)</td>
<td>240</td>
<td>340</td>
<td>440</td>
</tr>
<tr>
<td>3</td>
<td>Water-jet pressure (MPa)</td>
<td>125</td>
<td>200</td>
<td>275</td>
</tr>
<tr>
<td>4</td>
<td>Traverse rate (mm/min)</td>
<td>60</td>
<td>90</td>
<td>120</td>
</tr>
</tbody>
</table>

The output parameter MRR is calculated using the following

Material removal rate

\[
\text{MRR} = \frac{\text{Volume of material removed}}{\text{Time taken}} \quad (\text{mm}^3/\text{min})
\]

\[
\text{Volume of material removed} = \frac{(\text{Depth of cut} \times \text{Lengt.h})}{2} \times \text{kerf width} \quad (\text{mm}^3/\text{min})
\]

\[
\text{Time taken} = \frac{\text{Lengt.h}}{\text{Traverse rate (mm/min)}} \quad (\text{min})
\]

Table 3: The experimental design and output response MRR

<table>
<thead>
<tr>
<th>S. No</th>
<th>Input process parameter</th>
<th>Material removal rate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abrasive mesh size (#)</td>
<td>Abrasive flow rate (g/min)</td>
</tr>
<tr>
<td>1</td>
<td>80</td>
<td>240</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>240</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>440</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>440</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>340</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>340</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>340</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>340</td>
</tr>
<tr>
<td>9</td>
<td>80</td>
<td>340</td>
</tr>
<tr>
<td>10</td>
<td>120</td>
<td>340</td>
</tr>
<tr>
<td>11</td>
<td>80</td>
<td>340</td>
</tr>
<tr>
<td>12</td>
<td>120</td>
<td>340</td>
</tr>
<tr>
<td>13</td>
<td>100</td>
<td>240</td>
</tr>
<tr>
<td>14</td>
<td>100</td>
<td>440</td>
</tr>
</tbody>
</table>
The regression models for MRR generated using the results obtained from experimental results are given in Equations 4 to 7. Each regression model is then used for generating the 3D surface graphs in order to analysis the effect of various combinations of input parameters on the MRR for all materials.

Fig. 6 shows typical response graphs of MRR obtained with different combinations of AWJM input parameters.

(a) Mesh size Vs Abrasive flow rate (at high water jet pressure and low traverse rate) Abrasive flow rate and high water jet pressure)

(b) Mesh size Vs Water pressure (at high)

(c) Mesh size Vs Traverse rate (at high water jet pressure and traverse rate) Abrasive flow rate and low traverse rate) abrasive flow rate and high water jet pressure)

(d) Abrasive flow rate Vs Water pressure
e) Traverse rate Vs Abrasive flow rate (at low)

f) Traverse rate Vs Water jet pressure. (low (at low mesh size vs. Traverse rate) abrasive mesh size and high water pressure) mesh size and high abrasive flow rate)

**Fig. 6:** Response surface of MRR (unreinforced Al6063) for various combinations.

### 3.1. Analysis of Unreinforced Al 6063 for MRR:

Fig. 6 shows the response surface graphs that are resulted in higher MRR with various combinations of AWJM process parameters and their levels in the unreinforced Al 6063. Fig. 6a shows that the higher MRR is achieved by varying the abrasive mesh size (#80 – 120) and abrasive flow rate (240 – 440 g/min), while water-jet pressure and traverse rate are maintained at any one of the levels (low, medium and high). Among these combinations, it is observed that by varying the abrasive mesh size (#80 – 120) and abrasive flow rate (240 – 440 g/min), the water-jet pressure is held at high level (275 MPa) and the traverse rate is held at low level (60 mm/min) which leads to higher MRR. The MRR value achievable with the above combinations is found to be around 640 mm³/min (Fig. 6a). Similarly, it is observed that higher MRR of about 640 mm³/min can also be achieved with different combinations of AWJM process parameters. They are detailed below.

As for the higher MRR of 640 mm³/min, it can be achieved by varying abrasive mesh size (#80 – 120) and water-jet pressure (275 – 25 MPa) with high abrasive flow rate and low traverse rate. The response surface for the above combination is shown in Fig. 6b. From the Fig. 6b it is observed that low abrasive mesh size (#80) and high water-jet pressure (275 MPa), leads to higher MRR. Similarly, higher MRR can be achieved by varying the abrasive mesh size (#80 – 120) and traverse rate (60 – 120 mm/min) with high abrasive flow rate and high water-jet pressure. The response surface for the above combination is shown in Fig. 6c. From the Fig. 6c, it is observed that low abrasive mesh size (#80) and low traverse rate (60 mm/min), leads to higher MRR. Similarly, higher MRR can also be achieved by varying abrasive flow rate (240 – 440 g/min) and water-jet pressure (275 MPa) with low mesh size and low traverse rate. The response surface for the above combination is shown in Fig. 6d. From the Fig. 6d, it is observed that high abrasive flow rate (440 g/min) and high water-jet pressure (275 MPa), lead to higher MRR. Similarly, higher MRR can also be achieved by varying abrasive flow rate (240 – 440 g/min) and traverse rate (60 – 120 mm/min) with low abrasive mesh size and high water-jet pressure. The response surface for the above combination is shown in Fig. 6e. From the Fig. 6e, it is observed that high abrasive flow rate (440 g/min) and low traverse rate (60 mm/min), leads to higher MRR. Higher MRR can also be achieved by varying water-jet pressure (125 – 275 MPa) and traverse rate (60 – 120 mm/min) with low mesh size and high abrasive flow rate. The response surface for the above combination is shown in Fig. 6f. From the Fig. 6f, it is observed that high water-jet pressure (275 MPa) and low traverse rate (60 mm/min), leads to higher MRR.

From the above analysis, it is observed that the combinations of AWJM input process parameter and their levels such as low abrasive mesh size, high abrasive flow rate, high water-jet pressure and low traverse results in higher MRR in the unreinforced Al 6063.

The relationship between the input process parameters and the response (MRR) for unreinforced Al 6063 is expressed in the form of regression equation and it is given below.

$$\text{MRR} = 753.02391 + 0.50986 \times A + 2.43650 \times B + 4.23839 \times C - 1.89981 \times D + 0.0047 \times E + 0.0007 \times F + 0.010064 \times G + 0.094781 \times H + 0.0028 \times I + 0.005 \times J + 0.011945 \times K + 0.011907 \times L + 0.075359 \times M + 0.004 \times N - 0.011907 \times O - 0.062157 \times P \times Q$$

### 3.2. Analysis of HMMC for MRR:

From Fig. 6, it is observed that the higher MRR for unreinforced Al 7075 is found to be 640 mm³/min. Similar analysis is carried out for HMMCs consisting of Al 7075 + 5% B₄C + 5% ZrSiO₃ and Al 7075 + 10% B₄C + 5% ZrSiO₃. The higher values of MRR for the HMMCs are found to be 535 mm³/min and 520 mm³/min, 510 mm³/min respectively. This clearly indicated that with the increase in percentage volume of B₄C particles and ZrSiO₃ presents in the HMMCs, the MRR is found to be decreased.

This is due to the fact that the presences of B₄C and ZrSiO₃ in the HMMC leads to increased strength
and reduces the erosion rate during material removal [5]. The trend of significant process parameters and their levels for achieving higher MRR is found to be similar for HMMCs, (i.e) low abrasive mesh size, high abrasive flow rate, high water-jet pressure and low traverse rate result in higher MRR in all the HMMCs. The response equations for the HMMCs are given below.

\[ \text{MRR}_{\text{Al7075+5%B4C+5%ZrSiO}_4} = + 1151.26171 - 1.83771 \times \text{AMS} - 2.62047 \times \text{AFR} + 1.27122 \times \text{WP} - 1.12192 \times \text{TR} + 0.014901 \times \text{AMS} + 0.005 \times \text{AMS} \times \text{WP} + 0.092882 \times \text{AMS} \times \text{TR} + 0.004 \times \text{AFR} \times \text{WP} + 0.004 \times \text{AFR} \times \text{TR} + 0.014025 \times \text{WP} \times \text{TR} - 0.092344 \times \text{AMS}^2 - 0.0001 \times \text{AFR}^2 - 0.010374 \times \text{WP}^2 - 0.066267 \times \text{TR} \] (5)

\[ \text{MRR}_{\text{Al7075+10%B4C+5%ZrSiO}_4} = + 1118.82899 - 9.36284 \times \text{AMS} - 3.29622 \times \text{AFR} + 3.33291 \times \text{WP} + 4.47039 \times \text{TR} + 0.019038 \times \text{AMS} + 0.001 \times \text{AMS} \times \text{WP} + 0.063919 \times \text{AMS} \times \text{TR} + 0.002 \times \text{AFR} \times \text{WP} + 0.002 \times \text{AFR} \times \text{TR} + 0.0006 \times \text{WP} \times \text{TR} - 0.043263 \times \text{AMS}^2 + 0.001 \times \text{AFR}^2 - 0.011046 \times \text{WP}^2 - 0.068345 \times \text{TR} \] (6)

\[ \text{MRR}_{\text{Al7075+15%B4C+5%ZrSiO}_4} = + 2023.09387 - 22.15543 \times \text{AMS} - 4.17418 \times \text{AFR} + 1.88635 \times \text{WP} + 2.81115 \times \text{TR} + 0.015026 \times \text{AMS} \times \text{AFR} - 0.001 \times \text{AMS} \times \text{WP} + 0.072000 \times \text{AMS} \times \text{TR} + 0.003 \times \text{AFR} \times \text{WP} - 0.001 \times \text{AFR} \times \text{TR} + 0.001 \times \text{WP} \times \text{TR} + 0.025643 \times \text{AMS}^2 + 0.003 \times \text{AFR}^2 - 0.005 \times \text{WP}^2 - 0.047098 \times \text{TR} \] (7)

From Fig. 6, it is generally found that low abrasive mesh size (#80) is the most influencing factor for higher MRR in all the materials studied in this work. Mesh size (#80) (0.177 mm) abrasive is bigger than that of the other mesh size of abrasives used in this work. This is due to the fact that bigger sizes of abrasives posses higher energy, which leads to higher MRR. In the case of abrasive flow rate, higher abrasive flow rate leads to higher MRR. This is due to the fact that an increase in abrasive flow rate results in increased number of abrasive particles impinging on the target material, which leads to higher MRR. In the case of water-jet pressure, high water-jet pressure increases higher MRR. This is due to fact of higher water-jet pressure, increases the kinetic energy of the jet and leads to higher MRR. In the case of traverse rate, it is found that a low traverse rate, results in higher MRR. This is due to the fact that during lower traverse rate, more number of abrasive particles will impact and participate in material removal process and hence results of higher MRR.

**Conclusion:**

The influences of the AWJM process parameters such as mesh size, abrasive flow rate, water-jet pressure and traverse rate are analyzed on the MRR while machining unreinforced Al 7075 and HMMCs consists of Al 7075+B4C+ZrSiO4 with different weight fractions (5 % and 10 %and 15%) prepared through stir casting process. The experiments are carried out as per RSM Box Behken method. It is found that combinations of the AWJM process parameters and the levels such as low level abrasive mesh size (#80), high level abrasive flow rate (440 g/min), high level water-jet pressure (275 MPa) and low traverse rate (60 mm/min) resulted in higher MRR in all the materials studied in this work. Hence, these combinations are recommended for the AWJM of Al/B4C/ZrSiO4 in order to achieve a higher MRR. However, these combinations have to be verified for achieving the lower Rse. Regression equations are also established for the MRR easier predication. The user can use directly these equations without performing any trial run. The above research work will be useful for the machining aspects of HMMC (Al 7075/B4C+ZrSiO4) using AWJM.

**Acknowledgement**

The authors would like to acknowledge the financial support provided under Special Assistance Programme (SAP) by the University Grants Commission (UGC), Government of India, and New Delhi, India to carry out this research work under the sanctioned project titled “Abrasive Water Jet Machining for High Strength Materials (UGC Ref. No. F.3-41/2012 (SAPII) dated 01.11.2012). The authors would also like to appreciate Mr. N. Rajesh Kumar for his able assistance in operating the machine during the experimental work.

**References**