Studies on parametric optimization for abrasive water jet machining of Al7075-TiB$_2$ in-situ composite

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Abstract. The study focuses on optimization and determination of significant process parameter for Abrasive Water Jet Machining of Al7075-TiB$_2$ metal matrix composite. Al-TiB$_2$ metal matrix composite is synthesized by stir casting using in-situ technique. Optimization of machining parameters is done using Taguchi’s L$_{25}$ orthogonal array for the experimental trials, with cutting speed, stand-off distance and Abrasive Flow rate as input parameters at five different levels. Analysis Of Variance (ANOVA) method is used for identifying the effect of machining parameters on volumetric material removal rate, surface roughness and dimensional accuracy. Then the results are validated by conducting verification experiments.

1. Introduction

Metal matrix composites proved to be an important class of materials due to their superior strength to weight and weight to cost ratio for application in the field of structural, thermal, electrical and transportation when compared to equivalent monolithic commercial Aluminium alloys [1]. Aluminium based metal matrix composites have emerged as high performance engineering materials for use in chemical, automobile and aerospace industries because of their higher Elastic modulus, increased resistance to wear property and improved strength over conventional base alloy [2]. TiB$_2$ reinforcement into the Aluminium matrix causes significant rise in modulus and specific strength of composites. This is due to the outstanding features of Ti-B$_2$ such as higher hardness (960VH), high melting point of 2790°C, good thermal stability and higher elastic modulus of 530GPa [4]. The recent studies on synthesis of composites have shown that the In-situ technique eliminates the problem of thermodynamic instability of reinforcing ceramics with the matrix. In-situ process with added advantages of kinetic control of reaction, good interfacial bond, reduced size due to uniformly distributed reinforcing particles has evolved as an economic process [5]. AWJM has emerged as an eminent technology which is convenient to machine most of the materials ranging from metals to non-metals with varying chemical and mechanical properties. This is due to the presence of fine abrasive particles which exerts lower mechanical load during erosion and low thermal stresses (no heat affected zones) because of water flow [6]. There are several process parameters those characterize the entire process on its efficiency, economy and the process quality [7].

Zoran Jurkovic et al. carried out researches to study the influence of parameters of AWJM on surface roughness such as effects of abrasive flow rate, stand-off distance, traverse rate, sample thickness and type of materials (Stainless steel and Aluminium) using factorial design and orthogonal experiment plan. They had conducted experiments using Taguchi’s methodology (two level orthogonal array, L8) and calculated S/N ratio as the measure of the quality deviating from the desired value to...
achieve more efficient cutting parameters and they have reported that SOD, water pressure and thickness had no significant effect on surface roughness [8]. M. A. Azmir et al. conducted experimental investigations on AWJM of glass fiber reinforced epoxy composites to assess the effect of process parameters on surface roughness. The study revealed that all of the parameters considered in the study except cutting orientation have significant influence on surface roughness. They have worked on prediction by developing mathematical model and were successful in predicting the roughness value of an AWJ machining of glass/epoxy laminate in terms of cutting parameters [9]. M.Chithirai Pon Selvam et al. have evaluated the influence of abrasive water jet cutting process parameters on depth of cut of stainless steel, by conducting the experiment in varying abrasive flow rate, traverse speed, water pressure and stand-off distance. They have developed an empirical model using regression analysis for prediction of depth of cut in AWJC of stainless steel and experimentally verified the model when cutting stainless steel within practical range of process variables [10]. Preethi and Vishal Gupta et al. carried out a detailed study on measuring material removal rate of Marble by AWJM and investigated the effect of water pressure, stand-off distance and abrasive flow rate. This study has concluded that, as the water pressure and abrasive flow increased the material removal rate increased [11]. C.Ma, R.T. Deam evaluated the kerf geometry of cut in AWJ machining using an optical microscope. They have illustrated velocity profile of jet and its effect on the developing stage and fully developed stage of kerf width developed on the work and concluded that the kerf width increases with low cutting speed and narrows down at high cutting speed [12]. Guilin Yang described the prediction of surface quality of AWJ cutting using neural network. YL12 aluminum alloy material was machined and 1000 group data were collected, using these data BP neural network was trained and its forecast function was obtained. According to the given material thickness, pressure, abrasive flow rate and roughness, traverse speed was predicted, the prediction was verified by cutting the YL12 aluminum alloy using neural network. YL12 aluminium alloy material was machined and 1000 group data were collected, using these data BP neural network was trained and its forecast function was obtained. According to the given material thickness, pressure, abrasive flow rate and roughness, traverse speed was predicted, the prediction was verified by cutting the YL12 aluminum alloy using neural network. YL12 aluminium alloy material was machined and 1000 group data were collected, using these data BP neural network was trained and its forecast function was obtained. According to the given material thickness, pressure, abrasive flow rate and roughness, traverse speed was predicted, the prediction was verified by cutting the YL12 aluminum alloy using neural network.

Recently Al-TiB$_2$ composites are extensively being used for Automotive, Aerospace and Electronic applications. However, due to presence of TiB$_2$ ceramic particle, machining of Aluminium composites is an issue of great importance. Concerning to above aspects, in this preliminary study an attempt is made to optimize the process parameters for Abrasive Water Jet Machining of Al7075-TiB$_2$ composite to achieve desired output values such as volumetric material removal rate, surface roughness and dimensional accuracy.

2. Experimentation

2.1. Composite preparation

Al7075 alloy, Al3%B and Al10%Ti master alloys were used to prepare Al7075-TiB$_2$ metal matrix composite. The master alloys are melted together with a stoichiometric ratio in a graphite crucible using 6 KW melting furnace. The molten metal mixture was maintained at a temperature of 800$^\circ$C for duration of 30 minutes [8]. This mixture was stirred for two minutes constantly at an interval of 10 minutes, with ceramic coated mechanical blade rotating at a speed of 300 rpm. To degasify the molten alloy chlorine based tablets were used then the molten mixture was transferred directly to a metallic mould of dimension 100*100*20 mm.

Developed composite was subjected to optical microstructure studies and XRD to confirm the formation of TiB$_2$ and to study the morphology of the particles. X-ray diffraction analysis was carried out using Philips X’perto X-Ray Diffractometer at IISc, Bengaluru. Optical microstructure studies were carried out at Advanced Metallurgical Laboratory, Peenya, Bengaluru, using Nikkon metallurgical microscope.
2.2. Abrasive Water Jet Machine
The Hydrojet Abrasive water jet machine with 50 HP pump was employed for experimentation. Composite pieces of dimension 20*15*15 mm were machined under varied input parameters within the practical range of cutting for aluminium alloy. Cutting pressure was maintained at 3400 bar throughout the process. Silica Sand was used as an abrasive material. The schematic of AWJM is as shown in Figure. 1.

![Schematic diagram of Abrasive Water Jet Machine.](image)

Traverse speeds were varied from 100 to 500 mm/min in steps of 100 mm/min (5 levels). Stand-Off Distance from 0.5 to 2.5 mm in steps of 0.5 mm and Abrasive Flow Rate from 100 to 300 grm/min in steps of 50 grm/min.

| Input parameters                  | Levels  | 1     | 2     | 3     | 4     | 5     |
|-----------------------------------|---------|-------|-------|-------|-------|-------|
| Traverse speed (mm/min)           |         | 100   | 200   | 300   | 400   | 500   |
| Stand Off Distance (SOD) (mm)     |         | 0.5   | 1     | 1.5   | 2     | 2.5   |
| Abrasive mass Flow Rate (AFR) (gms/min) |     | 100   | 150   | 200   | 250   | 300   |

The experimental trials were designed as per Taguchi’s L_{25} orthogonal array to optimize input parameters: traverse speed, stand-off distance (SOD) and abrasive mass flow rate (AFR) varying at five different levels.

Signal to Noise ratio is another wing of Taguchi’s technique which is a combined performance measure of mean and variance of the output for each level in the orthogonal array. In the present study S/N ratio is calculated using MINITAB software (version-16).

3. Results and discussions

3.1 Optical microscopy
Figure.2 shows optical micrograph of Al7075 – 10% wt TiB\(_2\) composite. It is observed that TiB\(_2\) particles are distributed in fairly uniform manner throughout the matrix alloy. The particle size is in the range of 5-20 µm.
3.2 X-Ray Diffraction
Figure 3. shows X-ray diffraction pattern of Al7075-TiB₂ In-situ composite. XRD reconfirms presence of TiB₂ particles within the aluminium matrix. Further, in addition to TiB₂, Al₃Ti particles (brittle phase) were also observed in the XRD pattern.

3.3 S/N ratio
After the experimentation according to Taguchi’s L₂₅ orthogonal array, the response output values of surface roughness(Rₐ), Volumetric Material Removal Rate (VMRR) and dimensional accuracy are measured and calculated.
Table 2. Taguchi’s L25 orthogonal array and response output values of experimental design for AWJM of Al7075-TiB2.

| Run | Traverse speed (mm/min) | Input process parameter | Response output values |
|-----|------------------------|-------------------------|------------------------|
|     | SOD (mm) | AFR (gms/min) | VMRR (mm³/min) | Ra (µm) | DIMENSIONAL ERROR (mm³) |
| 1   | 100      | 0.5       | 100        | 4430.091 | 2.941 | 28.909 |
| 2   | 100      | 1.0       | 150        | 4540.033 | 2.941 | 38.739 |
| 3   | 100      | 1.5       | 200        | 4543.261 | 2.767 | 56.603 |
| 4   | 100      | 2.0       | 250        | 4550.52  | 2.457 | 43.967 |
| 5   | 100      | 2.5       | 300        | 4656.397 | 2.423 | 61.48 |
| 6   | 200      | 0.5       | 150        | 17956.604 | 3.432 | 31.698 |
| 7   | 200      | 1.0       | 180      | 18059.468 | 3.206 | 42.734 |
| 8   | 200      | 1.5       | 200        | 18477.642 | 3.117 | 138.69 |
| 9   | 200      | 2.0       | 300        | 18485.38 | 3.116 | 29.821 |
| 10  | 200      | 2.5       | 300        | 17523.544 | 3.65  | 38.228 |
| 11  | 300      | 0.5       | 200        | 26354.18 | 3.885 | 295.375 |
| 12  | 300      | 1.0       | 250        | 26554.399 | 3.884 | 162.432 |
| 13  | 300      | 1.5       | 300        | 26671.586 | 3.78  | 105.028 |
| 14  | 300      | 2.0       | 100        | 26214.9  | 4.022 | 163.152 |
| 15  | 300      | 2.5       | 150        | 26325.64 | 3.933 | 43.401 |
| 16  | 400      | 0.5       | 250        | 42441.81 | 4.081 | 125.802 |
| 17  | 400      | 1.0       | 300        | 42835.09 | 4.022 | 28.026 |
| 18  | 400      | 1.5       | 100        | 40633.42 | 5.41  | 140.584 |
| 19  | 400      | 2.0       | 150        | 40683.33 | 4.667 | 238.5 |
| 20  | 400      | 2.5       | 200        | 42153.372 | 4.261 | 409.623 |
| 21  | 500      | 0.5       | 300        | 53997.43 | 5.61  | 112.296 |
| 22  | 500      | 1.0       | 100        | 46667.66 | 6.41  | 148.56 |
| 23  | 500      | 1.5       | 150        | 49608.53 | 6.41  | 2.226 |
| 24  | 500      | 2.0       | 200        | 51068.63 | 5.981 | 83.694 |
| 25  | 500      | 2.5       | 250        | 52674.36 | 5.936 | 178.41 |
The above output functions are converted into Signal – Noise ratio by using MINITAB software. There are three conditions to be specified for optimization in Taguchi’s technique viz. smaller is better, nominal is better and larger is better. The present case of AWJM of Al7075-TiB2 larger VMRR, smaller surface roughness and smaller dimensional error are the required optimum conditions which are indicated as the peak values in the plots of S-N ratios. The main effect plots for S-N ratio of VMRR, surface roughness and dimensional error are shown in the figureure 4, 5 and 6 respectively.

![Figure 4](image1.png)

**Figure. 4.** Main effects plot for Volumetric Material Removal Rate.

The above main effect plot for S/N ratio indicates that the Traverse speed - 500 mm/min, Stand Off Distance (SOD) - 2.5 mm, Abrasive mass Flow Rate (AFR) -300gms/min is the optimized set of parameters to achieve larger Volumetric Material Removal Rate.

The main effect plot for S/N ratio in the figureure 5 indicates that the Traverse speed - 100 mm/min, Stand Off Distance (SOD) – 2mm, Abrasive mass Flow Rate (AFR) -300gms/min is the optimized sets of parameters for smaller surface roughness.

![Figure 5](image2.png)

**Figure. 5.**Main effects plot for Surface Roughness.
The above main effect plot for S/N ratio in figure 6 indicates that the Traverse speed - 100 mm/min, Stand Off Distance (SOD) – 1 mm, Abrasive mass Flow Rate (AFR) -150 gms/min is the optimized sets of parameters for minimum dimensional error.

3.4 Analysis Of Variance (ANOVA)
ANOVA was used to determine the effect of input machining parameters on the response characteristics. The significant process parameters and contribution of each parameter on VMRR, surface roughness and dimensional accuracy was calculated.

3.5 Volumetric Material Removal Rate
Figure 4 shows main effects plot for S/N ratio of VMRR. Analysis of variance for this S/N ratio gives influence of process parameter on VMRR i.e. Table 3.

Table 3. clearly reveal that F value for speed is higher than F values of AFR and S.O.D. hence, speed is a significant parameter of VMRR.

| Source  | DF | Seq SS  | Adj SS  | Adj MS  | F       | P       |
|---------|----|--------|---------|---------|---------|---------|
| SPEED   | 4  | 1382.74| 1382.74 | 345.69  | 11072.10| 0.000   |
| SOD     | 4  | 0.10   | 0.10    | 0.03    | 0.80    | 0.546   |
| AFR     | 4  | 0.93   | 0.93    | 0.23    | 7.48    | 0.003   |
| Error   | 12 | 0.37   | 0.37    | 0.03    |         |         |
| Total   | 24 | 1384.15|         |         |         |         |

Figure 6. Main effects plot for Dimensional error.
Figure 7. Percentage contribution of each parameter for VMRR.

Figure 7. clearly indicates that the influence of speed is significant on VMRR followed by SOD & AFR. Percentage contribution of speed is 99.925%, contribution of SOD is .00721% and contribution of AFR is 0.0675%.

3.6 Surface Roughness

Figure 3 shows main effects plot for S/N ratio of surface roughness. Analysis of variance for this S/N ratio gives influence of process parameter on roughness i.e. Table 4.

Table 4 clearly reveal that F value for speed is higher than F values of AFR and SOD. Thus, speed is a significant parameter for surface roughness.

| Source | DF | Seq SS  | Adj SS  | Adj MS  | F      | P     |
|--------|----|---------|---------|---------|--------|-------|
| SPEED  | 1  | 139.391 | 139.391 | 139.391 | 560.51 | 0.000 |
| SOD    | 1  | 0.027   | 0.027   | 0.027   | 0.11   | 0.744 |
| AFR    | 1  | 7.218   | 7.218   | 7.218   | 29.02  | 0.000 |
| Error  | 21 | 5.222   | 5.222   | 0.249   |        |       |
| Total  | 24 | 151.859 |         |         |        |       |

Figure 8 clearly indicates that the influence of speed is more on surface roughness followed by AFR & S.O.D. Percentage contribution of speed is 95.05%, contribution of SOD is 0.01% and contribution of AFR is very less i.e. 4.92%.
3.7 Dimensional error

Figure 6 shows main effects plot for S/N ratio of dimensional error. Analysis of variance for this S/N ratio gives influence of process parameter on dimensional error i.e. table 5.

Table 5 clearly reveal that F value for Speed is higher than F values of SOD and AFR. Speed is a significant parameter of dimensional error, followed by AFR & SOD.

| Source | DF | Seq SS | Adj SS | Adj MS | F   | P   |
|--------|----|--------|--------|--------|-----|-----|
| SPEED  | 4  | 469.75 | 469.75 | 117.44 | 1.38| 0.297 |
| SOD    | 4  | 109.47 | 109.47 | 27.37  | 0.32| 0.857 |
| AFR    | 4  | 483.35 | 483.35 | 120.84 | 1.42| 0.285 |
| Error  | 12 | 1017.90| 1017.90| 84.82  |     |     |
| Total  | 24 | 2080.46|        |        |     |     |

Figure 9. Percentage contribution of each parameter for dimensional error.
This clearly indicates that the influence of Speed is more on dimensional error followed by SOD & AFR. Percentage contribution of Speed is 44.23%, contribution of SOD is 10.25% and contribution of AFR is 45.51%.

4. validation
The machining trials were conducted under optimized input parameter set and the response output values are verified. The performances under optimized conditions are tabulated in the Table 6. The results obtained in the verification experiments are matching the optimized conditions performances that are obtained using the Taguchi’s techniques, thus validating the Taguchi’s approach of optimization of AWJM for machining Al7075-TiB₂ composites.

| Parameters      | Initial parameter readings | Optimized parameter readings |
|-----------------|----------------------------|-----------------------------|
| VMRR (mm³/min)  | Surface roughness (µm)     | VMRR (mm³/min)              |
| SPEED           | 500                        | 100                         |
| S.O.D.          | 1.5                        | 2.5                         |
| AFR             | 250                        | 300                         |
| RESPONSE OBTAINED | 52674.36                  | 2.423                       |

5. Conclusion
Al7075 – TiB₂ In-situ composite were machined successfully using AWJM process as per Taguchi L₂⁵ orthogonal array and the optimized process parameters were investigated. Using analysis of variance (ANOVA) method significant process parameter for VMRR, surface roughness and dimensional error were determined. It is observed that the influence of speed (99.925%) is significant on VMRR followed by SOD (0.00721%) & AFR (0.0675%). For surface roughness the influence of speed (95.05%) is more followed by AFR (4.92%) & S.O.D. (0.01%). The influence of Speed is more on dimensional error followed by SOD & AFR. For dimensional error traverse speed is more significant factor (44.23%) followed by AFR (45.51%) & SOD (10.25%). The performance of AWJM at optimum process parameters was verified.

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