Parametric Studies of Abrasive Waterjet Machining parameters on Al/LaPO4 using Response Surface Method

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Abstract. In the Al6061 matrix composite, 15% weight percent of lanthanum phosphate (LaPO4) is added as a reinforcement to prepare a composite material. The composite is fabricated using a 2-Stage stir casting process. The machinability characteristic of the fabricated composite is measured using abrasive water jet machine at varied machining conditions. Water pressure, Stand-off distance and cutting speed are taken as dependent response to measure the kerf angle and surface finish. Water pressure and the cutting speed show a significant impact on kerf taper angle and surface profile roughness with a contribution of 40%. The effect of soft ceramic, LaPO4 in the matrix has low significance as it is easily removed with the cutting conditions and the influence caused by LaPO4 on kerf angle and surface finish is considerably low compared to other hard ceramic reinforcements.

Keywords: Abrasive Water jet machine; Al/LaPO4; stir casting; kerf angle; surface roughness

1. Introduction

To meet the engineering needs, researchers are continuously progressing on materials development to enhance the properties. Specific materials are added as reinforcements in the base metal either in the form of powder production or through liquid fabrication techniques to produce a new composite component [1]. Over the available method, the stir casting process has found to be a suitable technique for the fabrication of the composite materials. Though the process has some disadvantages like insufficient dispersion of particles, casting defects, etc, besides the secondary process was established to enhance the efficiency of the stir casting system [2]. Ultrasonication assisted stir casting technique found to be a suitable process in the fabrication of composite with least casting defects. Aluminum has proven to be a suitable material that can accept any foreign materials and form an excellent bonding with the reinforcements. Al6061 alloys because of its composition found to have excellent engineering applications such as structural, corrosion resistance, etc [3]. The addition of hard ceramic
particles in the aluminum matrix will introduce hardness and provide enhance materials property. Usually, silicon carbide, alumina, SiO2, etc are found to be the most preferred elements as reinforcements in the metal matrix composites.

Generally, ceramic materials are hard, corrosion resistance, thermal resistance, etc. Among the available ceramic materials, Lanthanum Phosphate (LaPO4) was proven to be a soft ceramic with a monazite structure [4]. The addition of LaPO4 in the ceramic matrix composites improve the toughness property of the material and make it convenient with the conventional machining process [5]. LaPO4 as reinforcement in the zirconia matrix composites introduced excellent bonding behavior among the elements available in the mixture [6].

Abrasive Waterjet Machine (AWJM) was identified to be a green manufacturing process as the cutting operation provide almost zero thermal defects on the test sample. Like other machining processes, AWJM also has some disadvantages like noisy operation, taper cut, surface distortion, etc. However, the proper selection of the AWJM parameter considerably reduces the defect that usually occurs on the test sample [7]. Irrespective of AWJM parameters, material properties will also predominantly determine the cutting efficiency of the system [8]. SiC reinforced with aluminum provide a very coarse surface finish when compared to pure aluminum. From the above statement, it is very clear to convey that SiC plays a significant role in determining the surface quality of the machining process. To predict the optimum machining condition, various methods have been adopted. Among them response surface method is proven to be the best suitable technique for the prediction of optimum machining conditions [9].

In the present work, LaPO4 powder that is synthesized through the sol-gel process with the particle size of 50-80 nm was added as reinforcement in Al6061 matrix composites. LaPO4 with a weight ratio of 15% was identified as a suitable composition in the matrix which was identified from the earlier studies. The machinability characteristics of the fabricated composites were measured through AWJM with response surface methodology technique.

2. Materials and methods

Nano size rare earth lanthanum phosphate for successfully fabricated through the Sol-Gel process. 15 % of the fabricated powder is added as reinforcement in the aluminum matrix composite. The fabrication process of the composite was performed using a 2-stage stir process. Ultrasonicator was introduced to reduce the agglomeration of the particle. The composite was compressed uniaxial compression load of 2 ton per square inch. The samples are subjected to AWJM machining conditions. Garnet has a mesh size of 80 microns is used as the abrasive for the entire operation. The flow rate of the abrasive is fixed to be constant at a rate of 120gms/min. the nozzle is kept perpendicular to the direction of cut. Jet Pressure (JP), Stand-Off Distance (SOD), and Traverse Speed (TS) are taken as the AWJM parameters to measure the Kerf Angle (KA) and surface profile roughness (Ra). Each machining parameter is considered to have three levels such as JP with 220, 240, and 260 bar, SOD as 1, 2, and 3mm, finally TS with 20, 30, and 40 mm/min. The effect of each parameter of AWJM was estimated using RSM. To measure the kerf angle, Equation 1 is used. The surface profile roughness (SJ -411) is used to measure the Ra, here the length of measurement is 5mm. three observations are taken and the average is calculated as Ra. The experimental observation of Al composite in AWJM is shown in Table 1.

\[
\text{Kerf angle} = \tan^{-1} \left( \frac{x_1 - x_2}{t} \right)
\]

(1)

Where \(x_1 = \) width of the top surface in mm, \(x_2 = \) width of bottom surface in mm \(t = \) sample thickness in mm.
Table 1. AWJM parameters with the output responses

| S.No | Jet Pressure (bar) | Standoff Distance (mm) | Traverse Speed (mm/min) | Kerf Angle (Deg) | Surface roughness (μm) |
|------|--------------------|------------------------|-------------------------|-----------------|-----------------------|
| 1    | 220                | 1                      | 20                      | 0.296           | 1.2505                |
| 2    | 220                | 2                      | 30                      | 0.413           | 1.3485                |
| 3    | 220                | 3                      | 40                      | 0.529           | 1.7345                |
| 4    | 220                | 1                      | 30                      | 0.366           | 1.3875                |
| 5    | 220                | 2                      | 40                      | 0.462           | 1.6015                |
| 6    | 220                | 3                      | 20                      | 0.389           | 1.4035                |
| 7    | 220                | 1                      | 40                      | 0.455           | 1.5455                |
| 8    | 220                | 2                      | 20                      | 0.349           | 1.1985                |
| 9    | 220                | 3                      | 30                      | 0.453           | 1.5675                |
| 10.  | 240                | 1                      | 20                      | 0.383           | 1.2905                |
| 11.  | 240                | 2                      | 30                      | 0.501           | 1.5905                |
| 12.  | 240                | 3                      | 40                      | 0.608           | 1.8565                |
| 13.  | 240                | 1                      | 30                      | 0.455           | 1.5535                |
| 14.  | 240                | 2                      | 40                      | 0.545           | 1.7415                |
| 15.  | 240                | 3                      | 20                      | 0.506           | 1.5745                |
| 16.  | 240                | 1                      | 40                      | 0.502           | 1.7105                |
| 17.  | 240                | 2                      | 20                      | 0.384           | 1.3905                |
| 18.  | 240                | 3                      | 30                      | 0.559           | 1.7155                |
| 19.  | 260                | 1                      | 20                      | 0.439           | 1.4825                |
| 20.  | 260                | 2                      | 30                      | 0.553           | 1.7905                |
| 21.  | 260                | 3                      | 40                      | 0.702           | 2.0255                |
| 22.  | 260                | 1                      | 30                      | 0.497           | 1.6315                |
| 23.  | 260                | 2                      | 40                      | 0.645           | 1.9405                |
| 24.  | 260                | 3                      | 20                      | 0.607           | 1.7045                |
| 25.  | 260                | 1                      | 40                      | 0.583           | 1.7515                |
| 26.  | 260                | 2                      | 20                      | 0.484           | 1.6575                |
| 27.  | 260                | 3                      | 30                      | 0.689           | 1.9065                |

2.1. Regression modelling
To study the effect of erosion variables (TiC reinforcement % (A), impact angle (B) and, erodent velocity (C) on the erosion rate (Y), a second-order polynomial regression model was formulated using the expression Equation 2,

\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ij} X_i X_j \]  

(2)

where \( \beta \) is the regression coefficients, \( y \) is the output variable \( x \) is the input variable, and \( k \) is the total number of input variables, respectively.

The second-order response equation for the erosion rate (Y) of Al 6061 hybrid composite can be expressed as the function of \( A, B, \) and \( C \) as Equation 3,
\[ Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 AB + \beta_5 AC + \beta_6 BC \] (3)

Using the coded variables and actual variables, the final mathematical equation was found using the design expert software package.

3. Results and discussion

Generally, RSM has used in the manufacturing process in the estimation of machining parametric conditions and also to predict the machinability characteristics. The influence of each machining parameters can be studied using the interaction surface plot.

3.1. ANOVA for KA

The major defect in the AWJM is the formation of KA with the through cut. A considerable reduction in the KA will produce a straight cut in the sample. Always the cut material property predominantly determines the KA. The ANOVA obtained through RSM is shown in Table 2. The influence of AWJM parameters on machining Al composite is found in the order of jet pressure followed by traverse speed and stand-off distance as JP shows the highest contribution of 40%. The interaction effect of the AWJM parameters is recorded to be low, as JPxSOD shows a significant result of 1.13% of contribution to KA.

The second-order polynomial equation obtained for KA through RSM is shown as Equation 4. LaPO₄ soft machinable ceramic breakage ensures that the addition of these reinforcements produces the least KA difference at all the machining conditions.

\[
\text{KA} = -1.60 + 0.0097 \text{JP} - 0.175 \text{SOD} + 0.0318 \text{TS} - 0.000013 \text{JP}^2 + 0.0190 \text{SOD}^2 - 0.000235 \text{TS}^2 + 0.000750 \text{JP}\times\text{SOD} - 0.000038 \text{JP}\times\text{TS} - 0.00085 \text{SOD}\times\text{TS} \ldots \ldots \ldots \ldots \ldots \ldots (4)
\]

The effect of each parameter on the other AWJM parameters can be studied through the surface plot. Figure 1 shows the surface plots of JP, SOD, and TS with the normal probability plot. From Figure 1(a), it can be stated that the effect of SOD is considerably higher when compared to JP. Figure 1(b) confirms that the significance of JP and TS are almost similar in producing the KA of the cut surface. Figure 1(c) conveys that the TS shows a greater impact on KA than cutting distance. Higher the cutting speed lowers the abrasive flow rate and progress to yield a tapered cut surface. From Figure 1(d), all the measurements
taken through AWJM on the cutting of Al/LaPO4 composite are found to be in the acceptable range. This can be verified through the residual square observation from the ANOVA table as 93.53%. The small variation noted on the last two observation slightly reduce the R2 percentage levels.

![Figure 1. Interaction surface plot of KA](image1)

3.2. ANOVA for Ra
Surface profile parameters will determine the end quality of the product. ANOVA table acquired from RSM is shown in Table 3. The profile of Ra is greatly determined by cutting speed with a contribution of 41.46% followed by jet pressure and cutting distance with 36% and 17%, separately. The interaction effect of Ra is similar to KA, in both the case of Ra and KA, JPxSOD displays the same contribution of 1.74%. Higher the cutting speed significant in Ra, as the bottom surface of the Al/LaPO4 composite has an excess amount of wear tracks and striations. The curvy cut regions are visible all over the surface progress to have higher Ra. The regression equation obtained for Ra through RSM is shown in Equation 5. The bulk deformation of materials is removed with the applied load condition infers the reinforcement soft nature.

![Table 3. ANOVA for Ra](image2)
|                | Linear | JP 0.187409 | SOD 0.100000 | TS 0.245549 | Square 3 | JP*JP 0.216678 | SOD*SOD 0.100000 | TS*TS 0.100000 | 2-Way Interaction 3 | JP*SOD 0.007256 | SOD*TS 0.000968 | Error 10 | Total 19 | R-sq = 97.12% R-sq(adj) = 94.53% |
|----------------|--------|-------------|-------------|-------------|----------|----------------|-----------------|-----------------|-------------------|----------------|----------------|----------|---------|-------------------------------|
| Linear         | 0.187409 | 110.08      | 95.15%      |
| JP             | 0.216678 | 127.27      | 36.67%      |
| SOD            | 0.100000 | 58.74       | 16.92%      |
| TS             | 0.245549 | 144.22      | 41.46%      |
| Square         | 0.002503 | 1.47        | 1.27%       |
| JP*JP          | 0.000511 | 0.30        | 0.04%       |
| SOD*SOD        | 0.007256 | 4.26        | 1.09%       |
| TS*TS          | 0.000807 | 0.47        | 0.14%       |
| 2-Way Interaction | 0.001365 | 0.80        | 0.69%       |
| JP*SOD         | 0.002965 | 1.74        | 0.50%       |
| JP*TS          | 0.000162 | 0.10        | 0.03%       |
| SOD*TS         | 0.000968 | 0.57        | 0.16%       |
| Error          | 0.001703 | 13.60       | 2.88%       |
| Total          | 10      | 100         |             |

Ra = -2.39 + 0.0225 JP - 0.369 SOD + 0.0291 TS - 0.000034 JP*JP + 0.0514 SOD*SOD - 0.000171 TS*TS + 0.000963 JP*SOD - 0.000022 JP*TS + 0.00110 SOD*TS……

To understand the machining effect of each parameter is estimated using the surface plot obtained in RSM and it is shown in Figure 2. From Figure 2(a), it can be stated that the increase of Ra is considerably higher in SOD than the jet pressure. Higher the cutting distance creates a wider water beam cut on the surface. The abrasives inside the water beam collide itself and increase the width of the water beam. The partial and sharp boundary lost abrasives as it hits the surface produces less impact energy on cutting the composite rather than the full acceleration energy gained abrasives. Figure 2(b) shows the effect of TS is higher than JP. The increase of cutting speed reduces the abrasives flow rate on the bottom portion of the composite cut surface creates a waver surface with surface distortion. Figure 2(c) shows the impact of TS as it raises steadily with an increase of levels when compared to cutting distance. All the observations except the first and the last observations show some deviation may this cause the reduction of R2 observation in the ANOVA table and this can be verified from the probability plot of Figure 2(d).
3.3. Optimization study

For any machining condition optimizing the parameters is a typical task for the manufactures. The optimization plot obtained for the present study is shown in Figure 3. From the plot, it is confirmed that the low-level operating condition will provide an acceptable range of output responses. The three experimental runs were conducted for the identified optimized condition. In the entire test runs, more than 98% of the observations are found to be in a satisfactory limit.

4. Conclusion
The machinability characteristic of the Al/LaPO₄ composite in AWJM is performed using RSM. The effects of AWJM are measure on kerf taper angle and surface profile roughness. The determination of the quality characteristics of KA and Ra greatly depends on jet pressure and cutting speed. In both study cases, the effect of cutting distance is significantly low however from the contribution obtained through ANOVA, it cannot be neglected. The effect of AWJM on the reinforcements is nowhere reported because of the soft nature of the composite. As the high-pressure water easily erodes all the elements present in the composite and hen the low-level operating condition of AWJM will yield better observation for the considered output responses at the given condition.

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