Optimization and Analysis of Laser Beam Machining Parameters for Al7075-TiB₂ In-situ Composite

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Abstract. The paper focuses on laser beam machining (LBM) of In-situ synthesized Al7075–TiB₂ metal matrix composite. Optimization and influence of laser machining process parameters on surface roughness, volumetric material removal rate (VMRR) and dimensional accuracy of composites were studied. Al7075–TiB₂ metal matrix composite was synthesized by in-situ reaction technique using stir casting process. Taguchi’s L₉ orthogonal array was used to design experimental trials. Standoff distance (SOD) (0.3 – 0.5mm), Cutting Speed (1000 – 1200 m/hr) and Gas pressure (0.5 – 0.7 bar) were considered as variable input parameters at three different levels, while power and nozzle diameter were maintained constant with air as assisting gas. Optimized process parameters for surface roughness, volumetric material removal rate (VMRR) and dimensional accuracy were calculated by generating the main effects plot for signal noise ratio (S/N ratio) for surface roughness, VMRR and dimensional error using Minitab software (version 16). The Significant of standoff distance (SOD), cutting speed and gas pressure on surface roughness, volumetric material removal rate (VMRR) and dimensional error were calculated using analysis of variance (ANOVA) method. Results indicate that, for surface roughness, cutting speed (56.38%) is most significant parameter followed by standoff distance (41.03%) and gas pressure (2.6%). For volumetric material removal (VMRR), gas pressure (42.32%) is most significant parameter followed by cutting speed (33.60%) and standoff distance (24.06%). For dimensional error, Standoff distance (53.34%) is most significant parameter followed by cutting speed (34.12%) and gas pressure (12.53%). Further, verification experiments were carried out to confirm performance of optimized process parameters.

1. Introduction
In the present scenario particulate reinforced aluminum based matrix composites have emerged as the trusted engineering materials with higher specific modulus, thermal stability and good tribological properties. These types of materials find a larger application in the emerging industries such as, automobile, aeronautical and structural construction [1-2]. The liquid metallurgy route is a cost efficient and simplest method among several methods available to synthesis particulate reinforced aluminium composites [3]. The latest studies on processing of MMCs have shown that the In-situ technique influences on the size reduction, good bond between matrix and reinforcement [4-5]. Machining of MMC’s by conventional technique is a difficult task because of higher hardness of material due to the presence of ceramic reinforcement which results in higher tool wear and fracture of reinforcement [6-7]. Hence non – conventional technique is well suited for the machining of MMC’s [8-9]. Already some of researches carried out on EDM, but the presence of ceramic reinforcement in aluminium alloy reduces the electrical conductivity which in turn reduces quality of machining [10-11]. On the other hand laser beam machining finds its major application in producing complex shapes.
and it is well suited for machining of aluminium and ceramics, due to its capacity of machining materials regardless of mechanical property [12-14]. Already some of the studies concentrated on laser beam machining of aluminium alloys and composites. Adalarasan et al [15] have studied optimization of aluminium composite using grey based response surface methodology (GRSM) and they found that the optimum condition for kerf width, surface finish and cut edge slope. These characteristic is observed for different combination of process parameter such as, laser power, pulsing frequency, cutting speed and assist gas pressure. They have reported that GRSM is a effective technique in predicting the optimal setting of laser machining parameters. Riveiro et al [6] have studied influence of assist gas nature on the surface obtained by laser cutting of Al-Cu alloys and they have reported that argon is the more efficient assist gas to obtain best quality cut. Arun kumar pandey et al [2] are studied multiple quality characteristic of duraluminium sheet cutting and optimization using Taguchi based fuzzy logic. They have concentrated on influence of process parameter like, gas pressure, pulse width, pulse frequency, cutting speed on the characteristic like, geometrical accuracy, kerf width, kerf deviation and they have reported that gas pressure is the most significant parameter followed by pulse frequency in laser machining of duralumin. Adelmann et al [18] have studied fast laser cutting optimization algorithm. In which they tried to get burr free laser cut of 1mm aluminium sheet. They used laser power, velocity, standoff distance (S.O.D), gas pressure and position of focus as the variable process parameter. They have reported that all these parameter have major influence on quality and time of machining. Avanish kumar dubey et al [19] have studied optimization of kerf deviation and kerf width using Taguchi quality loss function with gas pressure, pulse width, pulse frequency and cutting speed as variable process parameter and reported that gas pressure and pulse frequency are significant parameter for kerf quality, very limited work has been carried out in exploring possibility of utilizing laser machining process for machining of aluminium based In-situ composites. In light of above, the present investigation focuses on optimization and influence of laser beam machining (LBM) process parameter (cutting speed, gas pressure, standoff distance) on surface roughness, volumetric material removal rate (VMRR) and dimensional accuracy of In-site Al7075 – TiB₂ metal matrix composites.

2. Experimentation

Al7075–10Wt%TiB₂ metal matrix composite were prepared using Al7075 alloy and Al10%Ti, Al3%B master alloys. All three were melted together in a stoichiometric ratio in a 6kw of melting furnace (Graphite crucible is used for the process). Molten metal mixture was maintained at a temperature of 800°C for duration of 30 minutes. This is stirred for duration of 2 minutes at the interval of 10 minutes, using a mechanical stirrer which rotates at 300rpm. Chlorine based tablets were used for degasifying of molten alloy and then it was poured into a 100*100*20 mm metallic mould [16].

Cast plates were then milled to a dimension of 100*100*5mm and subjected to laser beam machining operation. AMADA LCG 3015 CO₂ laser cutting machine was used to carry out the experimental trials. It is an optic laser system, in which the cutting head moves is x, y and z axes to process the work piece. It consists of an advanced 3.5kw CO₂ resonator and 7.5” lens. During the experimental trials power was maintained at 3500w, air was used as assisting gas and the nozzle diameter was maintained constant. Al7075 – TiB₂ plates of dimension 100*100*5mm were used for the experimental trials. The schematic diagram of laser beam machine is as shown in Figure 1. Experimental process layout is shown in Figure 2.

Taguchi L⁹ orthogonal array was used for design of experiments (D.O.E.) (Table 2). Standoff distance (S.O.D.), Cutting speed and gas pressure were considered as variable input parameters at three different levels as shown in Table 1.
After the experiments were conducted according to Taguchi L9 orthogonal array, surface roughness test was carried out on the cutting edge using tally surf (Mitutoyo made Suftest SJ-210), value of $Ra$ is tabulated. Dimensional accuracy test was carried out using digital vernier caliper (Mitutoyo made Absolute digimatic CD-6"-CSX), by measuring length, width and thickness of the specimen for 5 different trails and mean of the trails were tabulated. The ratio of the volume of the metal removed to time taken for machining were calculated and tabulated which is the volumetric material removal rate (VMRR).

The mean and variance of the output of each combination of orthogonal array is combined into single performance measure known as $S/N$ ratio [17]. Minitab software (version: 16) was used to calculate
the S/N ratio, by which the optimized process parameters were identified. The influence of process parameters on response characteristics were calculated using analysis of variance (ANOVA).

**Table 1.** Input Process Parameters and its Levels.

| Input parameters     | Levels |
|----------------------|--------|
|                      | 1      | 2      | 3      |
| Standoff distance (S.O.D.) (mm) | 0.3    | 0.4    | 3      |
| Cutting speed (m/hr) | 1000   | 1100   | 0.5    |
| Gas pressure (Bar)   | 0.5    | 0.6    | 1200   |

**Table 2** Design of Experiments (D.O.E.) as per L9 Orthogonal Array

| #Run | Parameters/Levels |
|------|-------------------|
|      | Standoff distance (S.O.D.) (mm) | Cutting speed (m/hr) | Gas pressure (Bar) |
| 1    | 0.3                | 1000               | 0.5                |
| 2    | 0.3                | 1100               | 0.6                |
| 3    | 0.3                | 1200               | 0.7                |
| 4    | 0.4                | 1000               | 0.6                |
| 5    | 0.4                | 1100               | 0.7                |
| 6    | 0.4                | 1200               | 0.5                |
| 7    | 0.5                | 1000               | 0.7                |
| 8    | 0.5                | 1100               | 0.5                |
| 9    | 0.5                | 1200               | 0.6                |

**3. Results and Discussions**

3.1 Optical Microscopy

**Figure 3.** Optical Micrograph of Al7075-TiB₂ Composite
Figure 3 shows optical micrograph of Al7075–10%wtTiB$_2$ 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 S/N ratio
Following by experimental trails as per Taguchi L$_9$ orthogonal array, the response output values were measured and calculated i.e. surface roughness, volumetric material removal rate (VMRR), dimensional error. These values are represented in Table 3.

| Run | Input process parameter | Response output values |
|-----|-------------------------|------------------------|
|     | Standoff distance (S.O.D)(mm) | Cutting speed(m/hr) | Gas pressure(Bar) | VMRR (mm$^3$/min) | Ra (µm) | DIMENSIONAL ERROR (mm$^2$) |
| 1   | 0.3                      | 1000                   | 0.5               | 5480.14286        | 0.396   | 17.4404                  |
| 2   | 0.3                      | 1100                   | 0.6               | 9227.83875        | 0.867   | 15.4433                  |
| 3   | 0.3                      | 1200                   | 0.7               | 9149.298          | 0.922   | 17.0141                  |
| 4   | 0.4                      | 1000                   | 0.6               | 7806.07204        | 1.002   | 17.9624                  |
| 5   | 0.4                      | 1100                   | 0.7               | 6843.08102        | 1.163   | 17.5624                  |
| 6   | 0.4                      | 1200                   | 0.5               | 6816.05776        | 1.171   | 18.2839                  |
| 7   | 0.5                      | 1000                   | 0.7               | 6033.912          | 0.516   | 18.9827                  |
| 8   | 0.5                      | 1100                   | 0.5               | 6844.41861        | 1.047   | 17.5278                  |
| 9   | 0.5                      | 1200                   | 0.6               | 6827.12978        | 0.813   | 17.9888                  |

All output functions were then converted into signal noise ratio (S/N ratio) using Minitab software (version 16). This Taguchi technique have three condition for optimization i.e. smaller is better, nominal is better and larger is better. In this condition of LBM of Al7075 – TiB$_2$, smaller the surface roughness, larger the volumetric material removal rate (VMRR) and smaller the dimensional error are the optimal conditions.

Figure 4, Figure 5, Figure 6, shows the main effects plot for S/N ratio of surface roughness, volumetric material removal rate (VMRR) and dimensional error respectively.

From the main effect plot for S/N ratio of surface roughness (Figure 4), it is clearly indicates that standoff distance (S.O.D) – 0.3mm, Cutting speed – 1000 m/hr, Gas pressure – 0.5Bar, is the optimized condition which gives the minimum surface roughness.
From the main effect plot for S/N ratio of VMRR (Figure 5), it is clearly indicates that standoff distance (S.O.D) – 0.3mm, Cutting speed – 1100 m/hr, Gas pressure – 0.6Bar, is the optimized condition which gives the Maximum volumetric material removal rate (VMRR).

![Main Effects Plot for S/N ratios](image)

**Figure. 4 Main Effects Plot for Surface Roughness.**

From the main effect plot for S/N ratio of dimensional error (Figure 6), it is clearly indicates that standoff distance (S.O.D) – 0.3mm, Cutting speed – 1100 m/hr, Gas pressure – 0.6Bar, is the optimized condition which gives the minimum dimensional error.

![Main Effects Plot for S/N ratios](image)

**Figure.5. Main effects Plot for Volumetric Material Removal Rate (VMRR)**
3.3 Analysis Of Variance (ANOVA)
ANOVA was used to calculate the influence of input process parameters on the response output characteristics. Significant machining parameter and percentage contribution of each parameter on surface roughness, volumetric material removal rate (VMRR) and dimensional error were calculated.

3.4 Surface Roughness
Fig 4 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 (Table 4). Percentage contribution of each parameter was calculated and represented in a pie chart (Figure 7).

Table 4. ANOVA results for Influence of Process Parameters on Surface Roughness

| Source | Degrees of freedom (DOF) | Seq. sum of squares | Adj. sum of squares | Adj. Mean square | F – ratio (F) | P – Value (P) |
|--------|--------------------------|---------------------|--------------------|-----------------|--------------|--------------|
| S.O.D  | 2                        | 29.568              | 29.568             | 14.784          | 2.54         | 0.283        |
| Speed  | 2                        | 40.599              | 40.599             | 20.300          | 3.49         | 0.223        |
| Pressure | 2                        | 1.820               | 1.820              | 0.910           | 0.16         | 0.865        |
| Error  | 2                        | 11.649              | 11.649             | 5.824           |              |              |
| Total  | 8                        | 83.636              |                    |                 |              |              |

Table: 4 reveal that F value for cutting speed (3.49) is higher than F values of standoff distance (S.O.D) (2.54) and gas pressure (0.16). Indicating cutting speed is a significant parameter for achieving less surface roughness.
Figure 7: clearly indicates that the influence of cutting speed is more on surface roughness followed by standoff distance (S.O.D.) and gas pressure. Percentage contribution of cutting speed is 56.38%, contribution of standoff distance (S.O.D.) is 41.03% and contribution of gas pressure is very less i.e. 2.58%.

![Influence of Process Parameters on Surface Roughness](image)

**Figure. 7.** Percentage Contribution of Each Parameter for Surface Roughness.

3.5 **Volumetric Material Removal Rate (VMRR)**

Figure 5 shows main effects plot for S/N ratio of volumetric material removal rate (VMRR). Analysis of variance for this S/N ratio gives influence of process parameter on volumetric material removal rate (VMRR) (Table 5). Percentage contribution of each parameter was calculated and represented in a pie chart (Figure 8).

Table 5 reveal that F value for gas pressure (1.02) is higher than F values of cutting speed (0.81) and standoff distance (S.O.D.) (0.58). Indicating pressure is a significant parameter for achieving higher volumetric material removal rate (VMRR).

**Table 5.** ANOVA results for Influence of Process Parameters on VMRR

| Source    | Degrees of freedom (DOF) | Seq. sum of squares | Adj. sum of squares | Adj. Mean square | F – ratio (F) | P – Value (P) |
|-----------|--------------------------|---------------------|---------------------|------------------|---------------|---------------|
| S.O.D     | 2                        | 3.086               | 3.086               | 1.543            | 0.58          | 0.634         |
| Speed     | 2                        | 4.329               | 4.329               | 2.164            | 0.81          | 0.552         |
| Pressure  | 2                        | 5.449               | 5.449               | 2.724            | 1.02          | 0.495         |
| Error     | 2                        | 5.342               | 5.342               | 2.671            |               |               |
| Total     | 8                        | 18.205              |                     |                  |               |               |

Figure 8 clearly indicates that the influence of gas pressure is more on volumetric material removal rate (VMRR) followed by cutting speed and standoff distance (S.O.D.) Percentage contribution of gas
pressure is 42.32%, contribution of cutting speed is 33.60% and contribution of standoff distance (S.O.D.) is 24.06%.

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\text{Influence of Process Parameters on Volumetric Material Removal Rate (VMRR)}
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Figure 8. Percentage Contribution of Each Parameter for VMRR.

3.6 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 (Table 6). Percentage contribution of each parameter is calculated and represented in a pie chart (Figure. 9).

| Source  | Degrees of freedom (DOF) | Seq. sum of squares | Adj. sum of squares | Adj. Mean square | F – ratio (F) | P – Value (P) |
|---------|--------------------------|---------------------|---------------------|-----------------|---------------|---------------|
| S.O.D   | 2                        | 1.05320             | 1.05320             | 0.52660         | 80.42         | 0.012         |
| Speed   | 2                        | 0.67367             | 0.67367             | 0.33684         | 51.44         | 0.019         |
| Pressure| 2                        | 0.24737             | 0.24737             | 0.12368         | 18.89         | 0.050         |
| Error   | 2                        | 0.01310             | 0.01310             | 0.00655         |               |               |
| Total   | 8                        | 1.98733             |                     |                 |               |               |

Table 6 reveal that F value for standoff distance (S.O.D.) (80.42) is higher than F values of cutting speed (51.44) and gas pressure (18.89). Indicating standoff distance (S.O.D.) is a significant parameter for achieving lesser dimensional error.

Figure 9 clearly indicates that the influence of standoff distance (S.O.D.) is more on dimensional error followed by cutting speed and gas pressure. Percentage contribution of standoff distance (S.O.D.) is 53.34%, contribution of cutting speed is 34.12% and contribution of gas pressure is 12.53%.
4. Verification Experiments

Experiments were conducted to ensure performance on optimum condition and results were tabulated (Table 7). From the results it is observed that optimized condition gives good surface finish, dimensional accuracy and larger volumetric material removal rate (VMRR). The initial reading of surface roughness, VMRR and dimensional error was 0.396µm, 9227.83mm³/min, and 15.44 mm², respectively. After setting the parameters to the optimized values; the response characteristics has been changed to 0.390µm, 9227.92 mm³/min and 15.125 mm² respectively.

Table 7. Verification Experiments of Optimized Condition

| Parameters          | Initial Parameter Readings | Optimized Parameter Readings |
|---------------------|----------------------------|-----------------------------|
|                     | Surface roughness (µm)     | VMRR (mm³/min)              | Dimensional error (mm²) | Surface roughness (µm) | VMRR (mm³/min) | Dimensional error (mm²) |
| Standoff distance (S.O.D.) | 0.3                        | 0.3                         | 0.3                      | 0.3                        | 0.3                  | 0.3                      |
| Cutting speed       | 1000                       | 1100                        | 1100                     | 1000                       | 1100                  | 1100                     |
| Gas pressure        | 0.5                        | 0.6                         | 0.6                      | 0.5                        | 0.6                   | 0.6                      |
| RESPONSE OBTAINED   | 0.396                      | 9227.83875                  | 15.4433                  | 0.390                      | 9227.9257            | 15.1253                  |
5. Conclusion

Al7075 – TiB$_2$ In-situ composite were machined successfully using laser beam process as per Taguchi L9 orthogonal array; the optimized process parameters were investigated. Using analysis of variance (ANOVA) method significant process parameter for surface roughness, VMRR and dimensional error were identified. It is observed that, for surface roughness, cutting speed (56.38%) is most significant parameter followed by standoff distance (41.03%) and gas pressure (2.6%). For volumetric material removal rate (VMRR), gas pressure (42.32%) is most significant parameter followed by cutting speed (33.60%) and standoff distance (24.06%). For dimensional error, Standoff distance (53.34%) is most significant parameter followed by cutting speed (34.12%) and gas pressure (12.53%). The performance of optimum process parameters was confirmed by verification experiment.

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