Abstract

This paper presents experimental study into the influence of machining parameters of Ytterbium fiber laser during drilling of Al-15wt%Al₂O₃-MMC. The response surface methodology (RSM) is used to achieve optimum responses i.e. minimum tapering and maximum material removal rate (MRR) [1]. A comprehensive mathematical model for correlating the interactive and higher-order influences of Ytterbium fiber laser machining parameters such as laser power, modulation frequency, gas pressure, wait time, pulse width on metal removal rate and tapering phenomena has been developed for achieving controlled over fiber laser machining process. Test results reveal that MRR is increased with decrease of wait time and laser power. At wait time 17.5 s and laser power 500 w the MRR is maximum i.e 0.23 g/s. Due to less wait time, the possibility of heat loss is less so MRR increases.

Key words: Ytterbium fiber laser machining; response surface methodology; Material Removal Rate(MRR); hole tapering; Analysis Of Variance (ANOVA); Response Surface Methodology(RSM).

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1. Introduction

An Ytterbium laser machine YLR 1000 with CNC system RP 3015 was used for experiments. The experimental scheme had designed in such a way as to explore the influence of the various predominant laser machining process parameters, based on response surface methodology to obtain the optimal scheme for multi-variable experimentation and to perform investigations for exploring the interactive and higher order effects of the various parameters on the most important machining characteristics.

| Nomenclature |
|---------------|
| D | measured diameter at the top of the hole |
| d | measured diameter at the bottom of the hole |
| t | thickness of the work piece or hole |

2. Experimental set up

Fig.1 shows Ytterbium laser machining setup used for machining of Al-15 wt%Al₂O₃-MMC work-piece.

Table 1, Machining parameters, actual setting values and their coded levels

| Machining Parameters | symbol | units | level |
|----------------------|--------|-------|-------|
| Laser power (W)      | x₁     | Watt  | -2    | 400   | 500   | 700   | 900   | 1000  |
| Modulation frequency(Hz) | x₂ | Hz    | -1    | 600   | 700   | 800   | 900   | 1000  |
| Gas pressure (bar)   | x₃     | bar   | 0     | 15    | 16    | 17    | 18    | 20    |
| Wait time (s)        | x₄     | s     | 1     | 0.1   | 0.15  | 0.2   | 0.25  | 0.3   |
| Pulse width (%)      | x₅     | %     | 2     | 75    | 80    | 90    | 95    | 100   |

Table 1, represents the different parameters such as laser power, modulation frequency, gas pressure, wait time,
pulse width and their levels considered for experimental investigation. The range of input variables and their initial setting values are coded for simplification of experimental data analysis. Based on few trail experiments the coded levels of different input variables are decided (Table 1)[2].

\[ Taper, \text{radian} = \left[ \tan^{-1}\left( \frac{D-d}{2t} \right) \right] \cdot \frac{\pi}{180} \]  

(1)

Where, \( D = \) Measured diameter at top of the machined hole, mm; \( d = \) Measured diameter at bottom of the machined hole, mm; \( t = \) Thickness of the work-piece in mm

3. Mathematical Modelling and Process Optimization

An experimental plan for studying the relationship between the controllable parameters and the various machining criteria has been made based on central composite second-order rotatable design is shown in Table 2. Table 2 also represents the experimentally obtained results for response 1 and response 2, i.e. MRR and hole taper respectively.

| Experiment no. | X1 | X2 | X3 | X4 | X5 | Response1 (MRR) g/s | Response2 (Taper) rad |
|----------------|----|----|----|----|----|---------------------|---------------------|
| 1              | -1 | -1 | -1 | -1 | 1  | 0.205               | 0.0006              |
| 2              | 1  | -1 | -1 | -1 | -1 | 0.218               | 0.0003              |
| 3              | -1 | 1  | -1 | -1 | -1 | 0.217               | 0.0010              |
| 4              | 1  | 1  | -1 | -1 | 1  | 0.216               | 0.0011              |
| 5              | -1 | -1 | 1  | -1 | 1  | 0.209               | 0.0012              |
| 6              | 1  | -1 | 1  | -1 | 1  | 0.208               | 0.0010              |
| 7              | -1 | 1  | 1  | -1 | 1  | 0.192               | 0.0010              |
| 8              | 1  | 1  | 1  | -1 | -1 | 0.203               | 0.0011              |
| 9              | -1 | -1 | -1 | 1  | 1  | 0.210               | 0.0006              |
| 10             | 1  | -1 | -1 | 1  | 1  | 0.294               | 0.0005              |
| 11             | -1 | 1  | -1 | 1  | 1  | 0.204               | 0.0005              |
| 12             | 1  | 1  | -1 | 1  | -1 | 0.211               | 0.0005              |
| 13             | -1 | -1 | 1  | 1  | 1  | 0.211               | 0.0004              |
| 14             | 1  | -1 | 1  | 1  | 1  | 0.211               | 0.0005              |
| 15             | -1 | 1  | 1  | 1  | -1 | 0.205               | 0.0008              |
| 16             | 1  | 1  | 1  | 1  | 1  | 0.205               | 0.0008              |
| 17             | -2 | 0  | 0  | 0  | 0  | 0.209               | 0.0008              |
| 18             | 2  | 0  | 0  | 0  | 0  | 0.203               | 0.0009              |
| 19             | 0  | -2 | 0  | 0  | 0  | 0.210               | 0.0010              |
| 20             | 0  | 2  | 0  | 0  | 0  | 0.203               | 0.0011              |
| 21             | 0  | 0  | -2 | 0  | 0  | 0.205               | 0.0004              |
| 22             | 0  | 0  | 2  | 0  | 0  | 0.208               | 0.0006              |
| 23             | 0  | 0  | 0  | -2 | 0  | 0.210               | 0.0011              |
| 24             | 0  | 0  | 0  | 2  | 0  | 0.203               | 0.0008              |
| 25             | 0  | 0  | 0  | -2 | 0  | 0.203               | 0.0013              |
| 26             | 0  | 0  | 0  | 2  | 0  | 0.247               | 0.0009              |
| 27             | 0  | 0  | 0  | 0  | 0  | 0.203               | 0.0009              |
| 28             | 0  | 0  | 0  | 0  | 0  | 0.209               | 0.0012              |
| 29             | 0  | 0  | 0  | 0  | 0  | 0.203               | 0.0014              |
| 30             | 0  | 0  | 0  | 0  | 0  | 0.215               | 0.0012              |
| 31             | 0  | 0  | 0  | 0  | 0  | 0.203               | 0.0009              |

3.1 Mathematical models for MRR and taper

Considering five variables (Table 1) and utilizing the experimental results from 63 experiments (i.e. 31 experiments x 3-replication of each experiment), and according to the equation 4 the mathematical models for MRR and taper angle are developed. The developed mathematical model based on RSM for correlating the MRR with various predominant laser machining process parameters as considered in the experimental design as follows[3]
\[ Y_{MRR} = 0.197 - 0.011 x_1 + 0.017 x_2 - 0.012 x_3 - 0.024 x_4 - 0.020 x_1 x_2 - 0.050 x_3 x_4 + 0.09 x_1 x_4 + 0.013 x_1 x_5 + 0.066 x_2 x_3 - 0.029 x_2 x_4 - 0.017 x_2 x_5 + 0.051 x_3 x_4 + 0.021 x_3 x_5 + 0.017 x_4 x_5 + 0.002 x_1^2 + 0.002 x_2^2 + 0.007 x_3^2 + 0.001 x_4^2 + 0.025 x_5^2 \]  

(2)

Similarly, the developed mathematical model for taper is

\[ Y_{Taper} = 0.001 - 7.7E-05 x_1 - 0.0001 x_2 + 0.0002 x_3 - 0.0004 x_4 - 0.0003 x_1 x_3 + 0.0002 x_1 x_2 - 6.1E-05 x_1 x_3 + 0.00037 x_1 x_4 + 0.00037 x_1 x_5 - 0.0007 x_2 x_3 + 9.5E-05 x_2 x_4 + 0.0003 x_2 x_5 - 0.0003 x_3 x_4 + 0.0007 x_3 x_5 + 8.1E-05 x_4 x_5 - 0.0002 x_1^2 - 7.99E-05 x_2^2 - 0.0006 x_3^2 - 0.0001 x_4^2 - 7.6E-05 x_5^2 \]  

(3)

3.2 Analysis of variance and Model fitment Test

The analysis of variance (ANOVA) test has been performed to test the adequacy of the developed models for establishing the mathematical link between the response and the machining parameters of laser machining process[4,5]. The ANOVA test module has been designed to estimate the sum of squares of the response into the contribution due to the second order and a lack of fit component which measures the deviations of the responses from the fitted surface as well as a measure of the experimental errors.

As per ANOVA table, it is concluded that the laser power, modulation frequency, gas pressure, wait time, pulse width are significantly influencing for controlling MRR and taper as their P-value 0.0029 and 0.0183 respectively, and both are less than 0.05. The F-test values for both the responses at 95% confidence level are 6.0312 and 3.7352 respectively. The R² value for MRR is 0.92. The value of R²(adj) for MRR is 0.77. These values are above the average value and developed second order models fits the data, therefore, the data for both the response are well fitted in the developed second order models.

4. Parametric analysis on machining characteristics of Ytterbium fiber laser

The influences of the various process parameters of Ytterbium fiber laser on both the responses i.e. MRR and taper during laser machining of 5 mm thick Al-15wt.%Al₂O₃-MMC have been analyzed based on the developed mathematical modes established utilizing response surface methodology (RSM).

4.1 Parametric Influence on MRR

From Fig2 it is seen that MRR increases with increase of laser power and assist gas pressure simultaneously. At laser power 750W and assist gas pressure 17.5 bar the MRR is maximum.
From fig 3, it is clear that at high wait time MRR is less, because with increase of wait time the material gets enough time to solidify, so MRR is less.
Fig 4 shows that taper is maximum with moderate laser power and assist N\textsubscript{2} gas pressure. At low and high laser power as well as assist gas pressure taper is minimum. From fig 5, it is clear that at high wait time taper is less, because with increase of wait time the material gets enough time to solidify, so taper is less.

5. Conclusion

Based on the machining of Al-15wt\%Al\textsubscript{2}O\textsubscript{3}-MMC by Ytterbium fiber laser the following outcome can be concluded on the basis of the developed mathematical relations as follows:

- MRR increases with increase of laser power and assist gas pressure simultaneously. At laser power 750W and assist gas pressure 17.5 bar the MRR is maximum.
- MRR increases with increases of pulse width and modulation frequency. At 98\% pulse width and 1000 Hz modulation frequency, the MRR is maximum i.e. 0.24g/s.
- At high wait time and low laser power the hole taper is minimum. At wait time 0.28 s and laser power 500 W the hole taper is zero.
- At high wait time taper is less, because with increase of wait time the material gets enough time to solidify, so taper is less.

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