Journal of Material Science and Mechanical Engineering (JMSME)
Print ISSN: 2393-9095; Online ISSN: 2393-9109; Volume 2, Number 4; April-June, 2015 pp. 283-287

http://www.krishisanskriti.org/jmsme.html

# Simultaneous Optimization of Laser Cutting Parameters with Multiple Performance Characteristics of Al7075/SiC$_P$ Composite

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**Abstract—***An effectual aspect for the optimization of laser cutting process of Al7075/SiC$_p$ metal matrix composite with multiple quality characteristics based on the grey relational analysis is dilineated in this paper. Twenty seven experimental runs based on the Taguchi method of orthogonal arrays were carried out to find out the best factor level condition. The response table and response graph for each level of the machining parameters were obtained from the grey relational grade. In this study, the laser cutting parameters such as laser power, pulse frequency, assist gas pressure and pulse width are optimized with consideration of multiple-performance characteristics, such as work piece surface roughness, top kerf width and width of heat affected zone (HAZ). By analyzing the grey relational grade, it is observed that the pulse width has more effect on responses. It is clearly shown that the above performance characteristics in laser cutting process can be enhanced effectively through this approach.*

## 1. INTRODUCTION

Laser cutting is a technology which finds wide application in various manufacturing industries due to its versatility, reduced tooling costs and setup times. Laser Beam Cutting (LBC) is a non-contact thermal process, which is executed by moving a focused laser beam on the surface of the work piece with appropriate scanning speed. It does not involve any mechanical cutting forces and tool wear. Due to converging–diverging shape of laser beam profile a kerf taper always exists in cut sheet specimens [1]. There are many input parameters distressing the quality of laser cutting such as laser type and power, type and pressure of assist gas, cutting speed, sheet material composition and its thickness, and mode of operation of laser beam (Continuous or Pulsed mode). To attain acceptable echelon of cut quality characteristics, it is necessary to choose optimum amalgamation of input process parameters as these parameters impact on the special microscopic and macroscopic characteristics of the finished parts, as signified by the kerf width, the width of the heat affected zone (HAZ) and the surface roughness after dispensation [2]. Widespread research studies were conceded out to pick up the performance of laser cutting process beforehand. Ghany and Newishy [3] evaluated the optimum laser cutting parameters for 1.2mm austenitic stainless steel sheets by using pulsed and continuous wave (CW) Nd: YAG laser beam and nitrogen or oxygen as assist gases, each one separately. It was shown that the laser cutting quality depends mainly on the laser power, pulse frequency, cutting speed and focus positions. Although, nitrogen produced brighter and smoother cut surfaces with smaller kerf, it was more expensive compared to oxygen. The cutting speed was increased more than 8 m/min in CW mode compared with pulsed one. Li et al. [4] reported an investigation into achieving striation-free laser cutting of EN 43 mild steel sheets of 2mm thickness. It was shown that at cutting speeds above critical cutting speed, surface roughness got worse. Kaebernick et al. [5] developed a model to predict the kerf width at the beam entry side as a function of cutting speed for different pulse widths with the aim to identify optimal cutting conditions. The model showed that the kerf width appeared to increase slightly and then decreased after a critical cutting speed was reached. Lamikiz et al. [6] speckled the main laser cutting parameters such as power, gas pressure, cutting speed and focus position in order to study their control on the quality and geometry of cutting in the different types of AHSS sheet steels. It was advised that the power should be increased to 300W to avoid the risk of the manifestation of pitting which was higher as the cutting speed was increased. Ghany et al. [7] investigated the effects of different laser cutting parameters such as laser power, cutting speed, different gas types and pressures and focus position on the cutting quality characteristics of attached dross, kerf width and cut surface roughness. It was experimentally shown that zinc coated steel material could be cut by Nd: YAG using laser powers of less than 400W and speeds of up to 6 m/min.

From the control of operating parameters on the performance characteristics, the optimal operating parameters are very difficult to be forbidden and greatly intricate. In such complex and multi-variate systems, the relationship between factors is uncertain. The conventional arithmetical measures may not investigate these systems in a tolerable or consistent manner without large data sets that gratify certain geometric criteria. The grey relation theory, on the other hand, can handle both imperfect information and unclear problems very specifically. This conjecture was first anticipated by Deng [8] and also has been functional to the different fields of machining processes. For example, Chiang and Chang [9] used grey relational analysis to determine optimal wire electrical discharge machining (WEDM) parameters for machining $Al_2O_3$ particle reinforced material with multiple-performance characteristics Palanikumar et al. [10] optimized the turning parameters based on the multiple-performance characteristics including material removal rate, tool wear, surface roughness and specific cutting pressure by using grey relational analysis method.

From the levy of literature, it is experiential that the grey relational analysis has brought into being wide application areas for determining the optimal parameters through unlike machining processes. However, optimization of laser cutting parameters applicable with the grey relation analysis method is somewhat deficient. The rationale of the present work is to pioneer the use of grey relational analysis in selecting optimal laser cutting conditions on multi performance characteristics, namely, work piece surface roughness, top kerf width and width of HAZ. The setting of laser cutting parameters was accomplished using the Taguchi experimental design method. Furthermore, the most effectual factor and the order of significance of the opportune factors to the multi-performance distinctiveness in the laser cutting process were indomitable by using grey relational grade.

## 2. EXPERIMENTAL WORK

The experiments were conducted on an optical fibre delivered pulsed Nd: YAG laser beam system delivering maximum peak power of 16 kW. The laser beam was restationed via a 300-μm diameter step-indexed optical fibre to the cutting head, which was mounted over a six-axis robot (Model: IRB1410) manufactured by ABB. A 6mm thick Al7075/$SiC_p$ metal matrix composite was used as work piece material. The chemical composition of is provided in Table 1.

**Table 1: Chemical composition of Al7075**

| Element | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| Weight% | 0 | 1 | 2 | 0.3 | 2.5 | 0.2 | 6 | 0 | 88.9 |

Because of the large number of independent parameters that control the laser cutting process, some preliminary experiments were conducted by Nagarajan [11] in order to determine which parameters should be considered for optimization. The optimization of laser cutting process was obtained by varying laser power, pulse frequency, assist gas pressure and pulse width in this study. The summary of experimental conditions is listed in Table 2. The experimental results after laser

**Table 2: Chemical composition of Al7075**

| Control Factor | Symbol | Levels | | | | |
|---|---|---|---|---|---|---|
| | | -2 | -1 | 0 | 1 | 2 |
| Laser Power(W) | A | 210 | 220 | 230 | 240 | 250 |
| Pulse Frequency(Hz) | B | 210 | 220 | 230 | 240 | 250 |
| Assist Gas Pressure(kg/cm$^2$) | C | 8 | 9 | 10 | 11 | 12 |
| Pulse Width(ms) | D | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |

cutting were evaluated in terms of the following measured machining performances: (1) surface roughness (Ra); (2) top kerf width (wt); (3) width of HAZ. Each test piece was measured 5 times and average value taken for a more accurate reading. The surface roughness of laser cut surfaces was measured from the centerline of the cut edge using a Mitutoyo SJ-201 instrument. The sampling length of each measurement was set to 5 mm. The top kerf width and width of HAZ was measured by using a stereo zoom microscope. In order to achieve best cutting quality, Taguchi's L25 orthogonal array was used for experiment. The experimental results are summarized in Table 3.

**Table 3: Experimental layout**

| | A | B | C | D | wt(mm) | Ra(mm) | HAZ (mm) |
|---|---|---|---|---|---|---|---|
| 1 | 210 | 210 | 8 | 0.2 | 0.3300 | 0.0031 | 0.0685 |
| 2 | 210 | 220 | 9 | 0.3 | 0.3082 | 0.0031 | 0.0697 |
| 3 | 210 | 230 | 10 | 0.4 | 0.3665 | 0.0029 | 0.0648 |
| 4 | 210 | 240 | 11 | 0.5 | 0.3130 | 0.0026 | 0.0641 |
| 5 | 210 | 250 | 12 | 0.6 | 0.323 | 0.0031 | 0.0659 |
| 6 | 220 | 210 | 9 | 0.4 | 0.3665 | 0.0028 | 0.0651 |
| 7 | 220 | 220 | 10 | 0.5 | 0.3390 | 0.0030 | 0.0658 |
| 8 | 220 | 230 | 11 | 0.6 | 0.3640 | 0.0036 | 0.0708 |
| 9 | 220 | 240 | 12 | 0.2 | 0.2990 | 0.0029 | 0.0655 |
| 10 | 220 | 250 | 8 | 0.3 | 0.3405 | 0.0025 | 0.0632 |
| 11 | 230 | 210 | 10 | 0.6 | 0.3295 | 0.0021 | 0.0608 |
| 12 | 230 | 220 | 11 | 0.2 | 0.3130 | 0.0033 | 0.0685 |
| 13 | 230 | 230 | 12 | 0.3 | 0.3129 | 0.0026 | 0.0635 |
| 14 | 230 | 240 | 8 | 0.4 | 0.3665 | 0.0028 | 0.0647 |
| 15 | 230 | 250 | 9 | 0.5 | 0.3410 | 0.0032 | 0.0675 |
| 16 | 240 | 210 | 11 | 0.3 | 0.3450 | 0.0026 | 0.0643 |
| 17 | 240 | 220 | 12 | 0.4 | 0.3665 | 0.0028 | 0.0643 |
| 18 | 240 | 230 | 8 | 0.5 | 0.3180 | 0.0033 | 0.0678 |
| 19 | 240 | 240 | 9 | 0.6 | 0.2990 | 0.0027 | 0.0664 |
| 20 | 240 | 250 | 10 | 0.2 | 0.3510 | 0.0032 | 0.0695 |
| 21 | 250 | 210 | 12 | 0.5 | 0.3665 | 0.0028 | 0.0649 |
| 22 | 250 | 220 | 8 | 0.6 | 0.3665 | 0.0034 | 0.0679 |
| 23 | 250 | 230 | 9 | 0.2 | 0.3185 | 0.0031 | 0.0667 |
| 24 | 250 | 240 | 10 | 0.3 | 0.3415 | 0.0026 | 0.0650 |
| 25 | 250 | 250 | 11 | 0.4 | 0.3490 | 0.0026 | 0.0661 |

## 3. GREY RELATIONAL ANALYSIS

The Grey theory established by Dr. Deng includes Grey relational analysis, Grey modeling, prediction and decision making of a system in which the model is unsure or the information is incomplete [12]. It provides an efficient solution to the uncertainty, multi-input and discrete data problem. The relation between machining parameters and machining performance can be found out using the Grey relational analysis.

### 3.1 Data preprocessing

In grey relational analysis, data pre-processing is required since the range and unit in one data sequence may differ from the others. Data preprocessing is a process of transferring the original sequence to a comparable sequence. For this purpose, the experimental results are normalized in the range between zero and one. Depending on the characteristics of data sequence, there are various methodologies of data pre-processing available for the grey relational analysis [13].

If the target value of original sequence is infinite, then it has a characteristic of "the larger-the-better". The original sequence can be normalized as follows.

$$y_i^*(k) = \frac{y_i^{(0)}(k) - \min y_i^{(0)}(k)}{\max y_i^{(0)}(k) - \min y_i^{(0)}(k)} \tag{1}$$

If the expectancy is the smaller-the better, then the original sequence should be normalized as follows.

$$y_i^*(k) = \frac{\max y_i^{(0)}(k) - y_i^{(0)}(k)}{\max y_i^{(0)}(k) - \min y_i^{(0)}(k)} \tag{2}$$

Where $y_i^*(k)$ is the value after the grey relational generation (data pre-processing); $max y_i^{(0)}(k)$ and $min y_i^{(0)}(k)$ are the maximum and minimum values respectively of the original sequence $y_i^{(0)}(k)$.

### 3.2 Grey relational coefficient and grey relational grade

Following the data preprocessing, a Grey relational coefficient can be calculated using the preprocessed sequences. The Grey relational coefficient is defined as follows.

$$\gamma\big(y_0(k), y_i(k)\big) = \frac{\Delta min + \delta \Delta max}{\Delta_{oi}(k) + \delta \Delta max} \tag{3}$$

$\Delta_{oi}(k)$ is the deviation sequence of reference sequence $y_0(k)$ and $y_i(k)$ namely,

$$\Delta_{oi} = \|y_0(k) - y_i(k)\|$$

$$\Delta max = \max_{\forall j \in i} \max_{\forall k} \left\|y_0(k) - y_j(k)\right\|$$

$$\Delta min = \min_{\forall j \in i} \min_{\forall k} \left\|y_0(k) - y_j(k)\right\|$$

$\delta$ is distinguishing or identification coefficient is the distinguishing coefficient, which is defined in the range $0 \le \delta \le 1$. After obtaining the grey relational coefficient, A Grey relational grade is calculated and is a weighted sum of the Grey Relational Coefficients, and is defined as follows

$$\delta(y_0, y_i) = \sum_{k=1}^{n} \alpha_k \delta\big(y_0(k), y_0(k)\big) \; ; \sum_{k=1}^{n} \alpha_k = 1 \tag{4}$$

Here, the grey relational grade represents the level of correlation between the reference and comparability sequences. If the two sequences are identical, then the value of the Grey relational grade equals to one. The Grey relational grade also indicates the degree of influence exerted by the comparability sequence on the reference sequence.

## 4. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

In the present study, the work piece surface roughness, top kerf width and width of HAZ in different pulsed laser cutting parameters and the experimental runs are listed in Table 3. Typically, lower values of the surface roughness, top kerf width and width of HAZ as the target values are desirable. Therefore, the data sequences have a-smaller-the- better characteristic. Table 4 lists all of the sequences following data pre-processing using Eq. (2). Also, the deviation sequences $\Delta_{oi}$; $\Delta max$; $\Delta min$ can be calculated as follows:

$$\Delta_0(1) = |y_0(1) - y_1(1)| = |1.00 - 0.54418| = 0.4559$$

$$\Delta_0(2) = |y_0(2) - y_1(2)| = |1.00 - 0.45| = 0.55$$

$$\Delta_0(3) = |y_0(3) - y_1(3)| = |1.00 - 0.1923| = 0.807$$

and the results are given in table 5. The distinguishing coefficient $\delta$ can be substituted for the grey relational coefficient in Eq. (3). If all the process parameters have equal weighting, $\delta$ is 0.5. Table 6 lists the grey relational coefficient and grade for each experiment of the L25 orthogonal array by applying Eqs. (3) and (4).

According to performed experiment design, it is clearly observed from Table 6, the laser cutting parameters' setting of experiment no. 8 has the highest grey relation grade. Thus, the fourth experiment gives the best multi-performance characteristics among the 25 experiments.

**Table 4: The sequences after data preprocessing**

| Ex. No | wt(mm) | Ra(mm) | HAZ (mm) |
|---|---|---|---|
| 1 | 0.544 | 0.450 | 0.192 |
| 2 | 0.865 | 0.465 | 0.100 |
| 3 | 0.007 | 0.549 | 0.477 |
| 4 | 0.794 | 0.692 | 0.531 |
| 5 | 0.654 | 0.440 | 0.392 |
| 6 | 0.007 | 0.592 | 0.452 |
| 7 | 0.412 | 0.510 | 0.402 |
| 8 | 0.044 | 0.225 | 0.015 |
| 9 | 1.000 | 0.545 | 0.423 |
| 10 | 0.390 | 0.750 | 0.597 |
| 11 | 0.552 | 0.930 | 0.785 |
| 12 | 0.794 | 0.330 | 0.192 |
| 13 | 0.796 | 0.690 | 0.581 |
| 14 | 0.007 | 0.592 | 0.485 |
| 15 | 0.382 | 0.420 | 0.269 |
| 16 | 0.324 | 0.720 | 0.515 |

| | | | |
|---|---|---|---|
| 17 | 0.007 | 0.593 | 0.515 |
| 18 | 0.721 | 0.370 | 0.246 |
| 19 | 1.000 | 0.670 | 0.354 |
| 20 | 0.235 | 0.380 | 0.115 |
| 21 | 0.007 | 0.615 | 0.469 |
| 22 | 0.007 | 0.305 | 0.238 |
| 23 | 0.713 | 0.455 | 0.333 |
| 24 | 0.375 | 0.685 | 0.462 |
| 25 | 0.265 | 0.705 | 0.377 |

**Table 5: Deviation sequences**

| Deviation Sequences | $\Delta_{0i}(1)$ | $\Delta_{0i}(2)$ | $\Delta_{0i}(3)$ |
|---|---|---|---|
| 1 | 0.4559 | 0.5500 | 0.8077 |
| 2 | 0.1353 | 0.5350 | 0.9000 |
| 3 | 0.9926 | 0.4510 | 0.5231 |
| 4 | 0.2057 | 0.3080 | 0.4692 |
| 5 | 0.3456 | 0.5600 | 0.6077 |
| 6 | 0.9926 | 0.4085 | 0.5485 |
| 7 | 0.5882 | 0.4900 | 0.5985 |
| 8 | 0.9559 | 0.7750 | 0.9846 |
| 9 | 0.0000 | 0.4550 | 0.5769 |
| 10 | 0.6103 | 0.2500 | 0.4031 |
| 11 | 0.4484 | 0.0700 | 0.2154 |
| 12 | 0.2057 | 0.6700 | 0.8077 |
| 13 | 0.2037 | 0.3100 | 0.4192 |
| 14 | 0.9926 | 0.4085 | 0.5154 |
| 15 | 0.6176 | 0.5800 | 0.7308 |
| 16 | 0.6765 | 0.2800 | 0.4846 |
| 17 | 0.9926 | 0.4075 | 0.4846 |
| 18 | 0.2794 | 0.6300 | 0.7538 |
| 19 | 0.0000 | 0.3300 | 0.6462 |
| 20 | 0.7647 | 0.6200 | 0.8846 |
| 21 | 0.9926 | 0.3850 | 0.5308 |
| 22 | 0.9926 | 0.6950 | 0.7615 |
| 23 | 0.2868 | 0.5450 | 0.6669 |
| 24 | 0.6250 | 0.3150 | 0.5385 |
| 25 | 0.7353 | 0.2950 | 0.6231 |

The response table of Taguchi method was employed here to calculate the average grey relational grade for each factor level. The procedure was to group the relational grades firstly by factor level for each column in the orthogonal array, and then to average them [30] and table 7 shows the response table.

Since the grey relational grades represented the level of correlation between the reference and the comparability sequences, the larger grey relational grade means the comparability sequence exhibits a stronger correlation with the reference sequence. Therefore, the comparability sequence has a larger value of grey relational grade for the surface roughness, top kerf width and width of HAZ. Based on this premise, this study selects the level that provides the largest average response In Table 7, A5, B3,C5 and D5 show the largest value of grey relational grade for factors A, B, C and D respectively. Therefore, A5B3C5D5 is the condition for the optimal parameter combination of the laser cutting process.

**Table 6: Deviation sequences**

| | Grey relational coefficient | | | Grey grade |
|---|---|---|---|---|
| | wt(mm) | Ra(mm) | HAZ (mm) | |
| 1 | 1.456 | 1.550 | 1.808 | 1.605 |
| 2 | 1.135 | 1.535 | 1.900 | 1.523 |
| 3 | 1.993 | 1.451 | 1.523 | 1.656 |
| 4 | 1.206 | 1.308 | 1.469 | 1.328 |
| 5 | 1.346 | 1.560 | 1.608 | 1.082 |
| 6 | 1.993 | 1.409 | 1.548 | 1.650 |
| 7 | 1.588 | 1.490 | 1.598 | 1.559 |
| 8 | 1.956 | 1.775 | 1.985 | 1.905 |
| 9 | 1.000 | 1.455 | 1.577 | 1.344 |
| 10 | 1.610 | 1.250 | 1.403 | 1.421 |
| 11 | 1.448 | 1.070 | 1.215 | 1.245 |
| 12 | 1.206 | 1.670 | 1.808 | 1.561 |
| 13 | 1.204 | 1.310 | 1.419 | 1.311 |
| 14 | 1.993 | 1.409 | 1.515 | 1.639 |
| 15 | 1.618 | 1.580 | 1.731 | 1.643 |
| 16 | 1.676 | 1.280 | 1.485 | 1.480 |
| 17 | 1.993 | 1.408 | 1.485 | 1.628 |
| 18 | 1.279 | 1.630 | 1.754 | 1.554 |
| 19 | 1.000 | 1.330 | 1.646 | 1.325 |
| 20 | 1.765 | 1.620 | 1.885 | 1.756 |
| 21 | 1.993 | 1.385 | 1.531 | 1.636 |
| 22 | 1.993 | 1.695 | 1.762 | 1.816 |
| 23 | 1.287 | 1.545 | 1.667 | 1.500 |
| 24 | 1.625 | 1.315 | 1.538 | 1.493 |
| 25 | 1.735 | 1.295 | 1.623 | 1.551 |

When the last column of Table 7 was compared, it is observed that the difference between the maximum and minimum value of the grey relational grade for factor D is bigger than other factors. This indicates that the pulse width has stronger effect on the multi-performance characteristics. If the number of machining parameters increases, the importance of the controllable factors on the multi-performance characteristics will be determined by ordering max–min grade relational values.

**Table 7: Response Table**

| Cutting parameters | Average grey relational grade | | | | | |
|---|---|---|---|---|---|---|
| | Levels | | | | | |
| | 1 | 2 | 3 | 4 | 5 | Max-Min |
| A | 1.43 | 1.34 | 1.51 | 1.61 | 1.81 | 0.38 |
| B | 1.37 | 1.45 | 1.53 | 1.5 | 1.5 | 0.16 |
| C | 1.5 | 1.26 | 1.51 | 1.48 | 1.65 | 0.39 |
| D | 1.49 | 1.07 | 1.51 | 1.48 | 1.53 | 0.46 |
| *optimum level | | | | | | |

## 5. CONCLUSIONS

To optimize the laser cutting process with the multiple-performance characteristics, use of the grey relational analysis has been reported in this article. A grey relational analysis of the work piece surface roughness, top kerf width and width of HAZ obtained from the Taguchi method can convert optimization of the multiple-performance characteristics into optimization of a single performance characteristic called the grey relational grade. As a result, optimization of convoluted multiple-performance characteristics can be greatly cut down through this approach. It is shown that the performance characteristics of the laser cutting process such as surface roughness, top kerf width and width of HAZ are improved together by using the method projected by this study.

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