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Application of Taguchi based Grey Relational Analysis for Evaluating Optimal Parameters of Laser Micro-Drilling Al7075/SiC_p Metal Matrix Composite

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Abstract
The use of the Taguchi method with grey relational analysis, to determine the laser micro-drilling parameters with consideration of multiple quality characteristics, is studied in this paper. The effort has been made to minimize the micro-drilling defects, such as hole taper and heat-affected zone width, spatter and maximize hole circularity to produce high-quality micro-drills on Pulsed Nd: YAG Laser Micro-Drilling (LMD) of Al7075/SiC_p Metal Matrix Composite (MMC). The drilling parameters, namely laser power, pulse frequency, assist gas pressure and pulse width are optimized with respect to circularity, spatter, heat affected zone and taper. Using the Taguchi quality design concept, an L25 Orthogonal Array (OA) table is chosen for the experiments. From the grey analysis, a grey relational grade is obtained and based on this value an optimum level of drilling parameters has been identified. Furthermore, using analysis of variance method, significant contributions of process parameters have been determined. The results of the confirmation experiment show that the optimal laser drilling parameters can be determined successfully so as to perk up numerous quality characteristics through this approach.

Keywords
Laser drilling, Orthogonal Array, Grey Relational Analysis, ANOVA, Optimization

I. Introduction

Metal Matrix Composites (MMC's) are materials which combine tough metallic matrix with a hard ceramic reinforcement with superior properties like high strength to wear ratio, high modulus, superior wear resistance and corrosion resistance. These materials are widely used in various fields like aerospace, automotive, electronics and metallic industries and are very difficult to machine material due to the presence of hard ceramic particle [1–5]. Most of the researches on the machining of Al/SiC_p MMC have focused on turning and facing while drilling has received less attention. Laser-drilling technique has progressed remarkably to become the method of choice for meeting a vast majority of potential industrial requirements for micro hole drilling in diverse components such as watches, turbine blades, circuit boards, etc. [6].

Pulsed Nd: YAG laser micro drilling has progressed remarkably over the years to become an essential tool for micro-hole drilling in many components used in the technologically advanced industries. It is applicable to both conductive and nonconductive materials. During LMD, material is removed by vaporization and physical ejection of molten material based on the absorption of laser energy from a series of laser pulses at the same spot [7]. The use of LMD in manufacturing industry can be attributed to several advantages like high production rate , no mechanical damage or tool wear due to non- contact processing, improved product quality, low material wastage. Due to short wavelength of Nd: YAG (compared with CO_2 lasers), it enables processing of highly reflective materials with less laser power [8].

In spite of the present level of acceptance by the modern industries, due to its several advantages, it does have a number of defects viz. formations of taper, production of non-circular holes Heat-Affected Zone (HAZ), recast layer, etc. A number of studies have been oriented towards the investigation of the effects of laser micro-drilling process parameters on these defects [9-10].

Taper formation and production of non-circular holes are characteristic of the LMD operation, as laser machining is based on the interaction of a laser beam with inherent focusing characteristics [11]. Laser drilled holes are also inherently associated with spatter deposition due to the incomplete expulsion of the ejected material from the drilling site, which subsequently resolidifies and adheres on the material surface around the hole periphery. Therefore it is desirable to make the drilled holes circular and with minimum taper, HAZ width and with minimum spatter to produce high-quality micro-drilled holes.

These qualities, in turn are determined by the process parameters. Thus, it is necessary to find an optimal process condition capable of producing the
desired quality product. However, this optimization is to be performed in such a way that multiple objectives are fulfilled simultaneously. Such an optimization technique is called multi-response optimization.

Kuar et al. [12] experimentally investigated the influence of laser machining parameters on the heat affected zone thickness and phenomena of tapering during CNC-pulsed Nd: YAG laser micro-drilling of zirconium oxide (ZrO_2) and performed parametric analysis through response surface methodology (RSM). Ghoreishi et al. [13] employed a statistical model to analyze and compare hole taper and circularity in laser percussion drilling on stainless steel and mild steel. Yilbas [14] conducted drilling experiments on three materials, stainless steel, nickel, and titanium, using single pulsed laser beam. It has been shown that the extent of taper formation during laser percussion drilling of thin sections can be significantly reduced by suitable control of laser variables. His work has further revealed that optimization of parameters like focal position, pulse energy, pulse width and pulse frequency can effectively control recast layer formation inside the drilled hole. In this context, it can be suggested that the required peak power should be preferably obtained by appropriate control of pulse energy and pulse duration. French et al. [15] used two level factors in Nd: YAG laser percussion drilling to find the significant factors from a list of 17 factors. The main effects of factors and first- and second order interactions were analyzed, and it was found that pulse shape, energy, peak power, focal position, gas pressure, and Nd: YAG laser rod were the most significant influences on the hole taper and circularity. In order to prevent spatter, Low et al. [16] performed spatter-free laser percussion drilling closely spaced array holes. Sharp et al. [17] applied another anti spatter technique for laser micro drilling.

The Taguchi Method (TM) is a statistical approach for the purpose of designing and improving product quality. It uses orthogonal array to set up the experiment for the advantage of less number of experiments, and optimizes the process parameters by the analysis of signal-to-noise ratio response table and response graph. The optimal process parameters can improve the robustness of products, so the Taguchi method is also called parameter design.

In recent years, the TM has become a powerful tool for improving the productivity during research and development stage so that quality products can be produced quickly and at low cost. Some researchers have concentrated on achieving multiple quality characteristic at a time as a function of different appropriate level of input parameter settings.

Dubey et al. [18-20] applied TM, orthogonal array with principle component analysis and TM, and RSM to optimize multiple quality characteristics during pulsed Nd: YAG laser cutting of different thin sheets. Some researchers also tried to solve the problem with multiple quality characteristics by the grey relational analysis (GRA). In 1982, Deng first proposed grey relational analysis to fulfill the crucial mathematical criteria for dealing with a poor, incomplete, and uncertain system [21].

In GRA, black represents having no information and white represents having all information. A grey system has a level of information between black and white. It avoids the inherent shortcomings of conventional, statistical methods and only requires a limited data to estimate the behavior of an uncertain system. It also provides an efficient solution to the uncertain, multi-input, and discrete data problem. The main function of the GRA is to indicate the relational degree between two sequences by using discrete measurement method the distance. GRA can be effectively recommended as a method for optimizing the complicated interrelationships among multiple performance characteristics [22-23].

In the present study, experimental details using the Taguchi method of parameter design have been employed for optimizing multiple performance characteristics such as Circularity, Spatter, HAZ and Taper for LMD of Al7075/10%SiC_p metal matrix composite. Grey relational analysis has been considered for optimization of multiple response characteristics. Finally analysis of variance (ANOVA) and confirmation test have been conducted to validate the test result.

II. Experimental Procedure

In this wok Aluminum alloy 7075 (Si-0.4%, Fe-0.5%, Cu-1.6%, Mn-0.3%, Mg-2.5%, Cr-0.15%, Zn-5.5%, Ti-0.2%, Al-88.9%) reinforced with silicon carbide particulates of size 50 μm with 10% volume fractions manufactured through stir casting route is used for experimentation.

The experimental laser micro-drilling tests were carried out using an optical fibre delivered pulsed Nd: YAG laser beam system (Model: JK300D) with a maximum power rating of 16 kW. Five levels of each control factor have been selected without considering the interaction effect. The control factors taken were Pulse Power (PP), Pulse Frequency (PF), Assist Gas Pressure (GP) and Pulse Width (PW). The numerical values of control factors at different levels were shown in Table 1. An exhaustive pilot experimentation has been conducted to decide the parameter range for micro-drilling of Al7075/10%SiC_p composite of 2mm thickness.

In multi objective optimization, the loss in some quality characteristics is always expected as compared to a single objective optimization but the overall quality always improves.

Laser micro-drilling is used, especially when very small dimension diameter hole have to be obtained. The materials can be of various types like: hard or extra-hard, very thin foils, glass, composites, etc. The quality characteristic of drilled hole mainly depends on HAZ (a thin region on hole walls), hole taper which was formed with the entrance end being enlarged, hole circularity (which determines regularity of hole circle) and spatter (resolidified material normally found at the entrance and exit of the hole). The appropriate selection of different input parameters and their levels that affect these quality characteristics can improve hole characteristics.

The quality characteristics analyzed were circularity, spatter, HAZ and taper. Holes were drilled at spot size of 180μm in each experimental run. The Measurement of diameters for circularity, HAZ, taper and spatter were calculated using optical measuring microscope OLYMPUS STM6 on cut sectioned hole sample. The methodology of Taguchi for four factors at five levels is used for the implementation of the plan of orthogonal array experiments. An L25 orthogonal array with 4 columns and 25 rows is employed in this work. The experiments are carried out according to the arrangement of the orthogonal array and the response values obtained are given in Table 2.

III. Multi Objective Optimization Using Grey Relational Analysis

Step 1 Signal to Noise (S/N) ratio: To be used as procedures of the effect of noise factors on target characteristics, Taguchi anticipated the notion of a signal-to-noise (S/N, φ) ratios. In this study, spatter, HAZ and taper are the performance characteristic of the smaller- the- better, whilst on the other hand, circularity is that of the Larger-the-better.

The S/N ratios can be premeditated as:

$$(\varphi) = -10\log_{10}\left(\frac{1}{k}\right)\sum_{a=1}^{k}\frac{1}{y_a^2} \quad (1)$$

This is applied for problem where maximization of the quality characteristic of interest is sought after.

$$(\varphi) = -10\log_{10}\left(\frac{1}{k}\right)\sum_{a=1}^{k}y_a^2 \quad (2)$$

where y_a is the assessment indicator value of the observed response values measured to the a^{th} time and k is the number of repeated experiment, in this case k=5. This is applied for problem where minimization of the quality characteristic of interest is sought.

Step 2 In grey relational analysis, the step performed to normalize the random grey data with different measurement units to transform them to dimensionless parameters is the data pre-processing is Thus, data pre-processing converts the original sequences to a set of comparable sequences depending upon the quality characteristics of the original data. Different methods are employed to pre-process grey data. The original reference sequence and pre-processed data (comparability sequence) are represented by $y_0^{(0)}(k)$ and $y_a^{(0)}(k)$, where a=1, 2,…m; k=1,2,…,n respectively, where m is the number of experiments and n is the total number of observations of data.

Table 1 Control Factors and their levels

S.No	Control Factor	Symbol for coded factor	Levels				
			1	2	3	4	5
1	Pulse-Power(W)	x_1	210	220	230	240	250
2	Pulse-Frequency(Hz)	x_2	210	220	230	240	250
3	Assist Gas Pressure(kg/cm^2)	x_3	8	9	10	11	12
4	Pulse-Width(ms)	x_4	0.2	0.3	0.4	0.5	0.6

Depending upon the quality characteristics, the main categories for normalizing the original sequence are identified as follows:

'Larger-the-better':

$$y_a^*(k) = \frac{y_a^{(0)}(k) - miny_a^{(0)}(k)}{maxy_a^{(0)}(k) - miny_a^{(0)}(k)} \quad (3)$$

'Smaller-the-better':

$$y_a^*(k) = \frac{maxy_a^{(0)}(k) - y_a^{(0)}(k)}{maxy_a^{(0)}(k) - miny_a^{(0)}(k)} \quad (4)$$

Where $maxy_a^{(0)}(k)$ and $miny_a^{(0)}(k)$ are the maximum and minimum values respectively of the original sequence $y_a^{(0)}(k)$ Comparable sequence $y_a^*(k)$ is the normalized sequence of original data.

Table 2: Experimental Layout Using L_{25} Orthogonal Array and Multi Performance Results

Ex No	x_1	x_2	x_3	x_4	PP	PF	GP	PW	Circularity (mm)	Spatter (mm)	HAZ (mm)	Taper (deg)
1	1	1	1	1	210	210	8	0.2	0.9000	0.045	0.065	4.100
2	1	2	2	2	210	220	9	0.3	0.9305	0.044	0.067	3.815
3	1	3	3	3	210	230	10	0.4	0.9610	0.040	0.069	3.580
4	1	4	4	4	210	240	11	0.5	0.9615	0.045	0.075	3.307
5	1	5	5	5	210	250	12	0.6	0.9820	0.044	0.080	3.170
6	1	1	2	3	220	210	9	0.4	0.9305	0.059	0.088	3.622
7	2	2	3	4	220	220	10	0.5	0.9510	0.059	0.094	3.315
8	2	3	4	5	220	230	11	0.6	0.9615	0.057	0.089	3.277
9	2	4	5	1	220	240	12	0.2	0.8820	0.050	0.081	4.120
10	2	5	1	2	220	250	8	0.3	0.8900	0.074	0.102	3.962
11	3	1	3	5	230	210	10	0.6	0.9610	0.049	0.078	3.305
12	3	2	4	1	230	220	11	0.2	0.8915	0.045	0.066	4.160
13	3	3	5	2	230	230	12	0.3	0.9220	0.041	0.068	3.925
14	3	4	1	3	230	240	8	0.4	0.9200	0.071	0.099	3.702
15	3	5	2	4	230	250	9	0.5	0.9405	0.074	0.105	3.380
16	4	1	4	2	240	210	11	0.3	0.8915	0.047	0.071	3.985
17	4	2	5	3	240	220	12	0.4	0.9220	0.042	0.073	3.775
18	4	3	1	4	240	230	8	0.5	0.9500	0.070	0.100	3.505
19	4	4	2	5	240	240	9	0.6	0.9505	0.072	0.105	3.322
20	4	5	3	1	240	250	10	0.2	0.8710	0.066	0.097	4.135
21	5	1	5	4	250	210	12	0.5	0.9220	0.046	0.078	3.570
22	5	2	1	5	250	220	8	0.6	0.9500	0.075	0.104	3.435
23	5	3	2	1	250	230	9	0.2	0.8805	0.068	0.092	4.245
24	5	4	3	2	250	240	10	0.3	0.8810	0.067	0.098	3.967
25	5	5	4	3	250	250	11	0.4	0.9015	0.072	0.104	3.755
PP-Pulse-power, PF-Pulse-frequency, GP-Assist gas pressure, PW-Pulse-width												

Step 3: A weighting method is then used to integrate the grey relational coefficients of each experiment into the grey relational grade.

Calculate the grey relational co-efficient for the normalized S/N ratio values [24]:

$$\aleph(y_0(n), y_a(n)) = \frac{\Delta min + \gamma \Delta max}{\Delta_{ob}(n) + \gamma \Delta max} \quad (5)$$

Where

1. b=1, 2…k; n=1, 2….m, k is the experimental data items and m is the number of responses.
2. $y_o(n)$ is the reference sequence ($y_o(n)$=1, n=1,2,…m); $y_b(n)$ is the specific comparison sequence
3. Δ_{ob} is the deviation sequence of the reference sequence y_0 and tha compatibility sequence y_b i.e., $\Delta_{ob}=\|y_0(n)-y_b(n)\|$ = The absolute value of the difference between
4. $\Delta min=min_{\forall b \in a} min_{\forall n}\|y_0(n)-y_b(n)\|$ is the smallest value of $y_b(n)$ and $\Delta max=max_{\forall b \in a} max_{\forall n}\|y_0(n)-y_b(n)\|$ is the largest value of $y_b(n)$
5. γ is the distinguishing coefficient, which is defined in the range 0≤ γ ≤1 (the value may adjusted based on the practical needs of the system)

Step 4 The overall evaluation of the multiple performance characteristics is based on the Grey Relational Grade i.e.,

$$\widetilde{\gamma_b} = \frac{1}{n}\sum_{a=1}^{m}\gamma_{ab} \quad (6)$$

Where $\tilde{\gamma_b}$ is the grey relational grade for the b[th] experiment and n is the number of performance characteristics.

Step 5 Determine the optimal factor and its level combination. The higher grey relational grade implies the better product quality; therefore, on the basis of grey relational grade, the factor effect can be estimated and the optimal level for each controllable factor can also be determined.

Step 6 ANOVA is a standard statistical technique to interpret the experimental results. It is extensively used to identify the performance of a group of parameters under investigation. The purpose of ANOVA is to investigate the parameters whose combination to total variation is significant. It separates the total variability of response (sum of squared deviations about the grand mean) into contributions rendered by each of the parameter/ factor and the error.

Thus

$$SS_T = SS_F + SS_E \quad (7)$$

Where $SS_T = \sum_{j=1}^{p}(\alpha_j - \alpha_m)^2$ - Total sum of squared deviations about the mean

α_j - Mean response for jth experiment

α_m - Grand mean of the response

SS_F - Sum of squared deviations due to each factor

SS_E - Sum of squared deviations due to error

In ANOVA table mean square deviation is defined as:

$$MS = \frac{sum\ of\ squared\ deviation}{Degree\ of\ freedom}$$

F-value is defined as: $F = \frac{MS\ for\ a\ term}{MS\ for\ the\ error\ term}$

Percentage contribution (ρ) of each of the design parameters is given by the following equation

$\rho = SS_j/SS_T$ (8)

Where SS_j is sum of squared deviations for each design parameter.

Step 7 Calculate the predicted optimum condition. Once the optimal level of the design parameters has been selected, the final step is to predict and verify the quality characteristic using the optimal level of the design parameters.

$$\hat{\tau} = \tau_m + \sum_{a=1}^{q}(\overline{\tau_a} - \tau_m) \quad (9)$$

where

$\hat{\tau}$ is the grey relational grade for predicting the optimal laser micro-drilling parameters

τ_m is the average grey relational grade

τ_a is the average grey relational grade of the optimal level of a certain significant factor

q is the number of significant factors

IV. Implementation of the Solution Methodology

Step 1 Calculate the S/N ratios for a given response and predicted S/N ratios of the starting conditions using the Eqs. (1) and (2) depending upon the type of quality characteristics. The computed S/N ratios for each quality characteristic are shown in Table 3.

Step 2 Normalize the S/N ratio values by Eqs. (3). and (4). The results are given in Table 3. Experimental data have been normalized first (Grey relational generation). The normalized data for each of the parameters of circularity, HAZ, spatter and taper have been furnished in Table 4.

Table 3: S/N Ratios and Normalized S/N Ratios

No	S/N ratios				Normalized S/N ratios			
	Circularity	Spatter	HAZ	Taper	Circularity	Spatter	HAZ	Taper
1	-0.9151	26.9357	23.7417	-12.2557	0.2731	0.1874	0.0000	0.881
2	-0.6257	27.1309	23.4785	-11.6299	0.5509	0.1516	0.0632	0.6342
3	-0.3455	27.9588	23.223	-11.0777	0.8198	0.0000	0.1245	0.4165
4	-0.341	26.9357	22.4988	-10.3887	0.8241	0.1874	0.2984	0.1449
5	-0.1578	27.1309	21.9382	-10.0212	1.0000	0.1516	0.4330	0.0000
6	-0.6257	24.5830	21.1103	-11.1790	0.5509	0.6183	0.6317	0.4565
7	-0.4364	24.5830	20.5374	-10.4097	0.7326	0.6183	0.7692	0.1532
8	-0.3410	24.8825	21.0122	-10.3095	0.8241	0.5634	0.6553	0.1137
9	-1.0906	26.0206	21.8303	-12.2979	0.1046	0.3550	0.4589	0.8976

10	-1.0122	22.6154	19.828	-11.9583	0.1799	0.9786	0.9396	0.7637
11	-0.3455	26.1961	22.1581	-10.3834	0.8198	0.3228	0.3802	0.1428
12	-0.9976	26.9357	23.6091	-12.3819	0.1939	0.1874	0.0318	0.9307
13	-0.7054	27.7443	23.3498	-11.8768	0.4744	0.0393	0.0941	0.7316
14	-0.7242	22.9748	20.0873	-11.3687	0.4563	0.9128	0.8773	0.5313
15	-0.5328	22.6154	19.5762	-10.5783	0.6400	0.9786	1.0000	0.2197
16	-0.9976	26.5580	22.9748	-12.0086	0.1939	0.2565	0.1841	0.7835
17	-0.7054	27.5350	22.7335	-11.5383	0.4744	0.0776	0.2420	0.5982
18	-0.4455	23.0980	20.0000	-10.8938	0.7238	0.8902	0.8983	0.3440
19	-0.4410	22.8534	19.5762	-10.4280	0.7282	0.9351	1.0000	0.1604
20	-1.1996	23.6091	20.2646	-12.3295	0.0000	0.7966	0.8347	0.9101
21	-0.7054	26.7448	22.1581	-11.0534	0.4744	0.2223	0.3802	0.4069
22	-0.4455	22.4988	19.6593	-10.7185	0.7238	1.0000	0.9800	0.2749
23	-1.1054	23.3498	20.7242	-12.5576	0.0904	0.8441	0.7244	1.0000
24	-1.1005	23.4785	20.1755	-11.9692	0.0952	0.8206	0.8561	0.7680
25	-0.9007	22.8534	19.6593	-11.4922	0.2869	0.9351	0.9800	0.5800

Table 4: Data Preprocessing (Grey Relational Generation)

Ex No	Circularity	Spatter	HAZ	Taper
Ideal Sequence	1	1	1	1
1	0.727	0.813	1.000	0.119
2	0.449	0.848	0.937	0.366
3	0.180	1.000	0.875	0.583
4	0.176	0.813	0.702	0.855
5	0.000	0.848	0.567	1.000
6	0.449	0.382	0.368	0.544
7	0.267	0.382	0.231	0.847
8	0.176	0.437	0.345	0.886
9	0.895	0.645	0.541	0.102
10	0.820	0.021	0.060	0.236
11	0.180	0.677	0.620	0.857
12	0.806	0.813	0.968	0.069
13	0.526	0.961	0.906	0.268
14	0.544	0.087	0.123	0.469
15	0.360	0.021	0.000	0.780
16	0.806	0.743	0.816	0.216
17	0.526	0.922	0.758	0.402
18	0.276	0.110	0.102	0.656
19	0.272	0.065	0.000	0.840
20	1.000	0.203	0.165	0.090
21	0.526	0.778	0.620	0.593
22	0.276	0.000	0.020	0.725
23	0.910	0.156	0.276	0.000
24	0.905	0.179	0.144	0.232
25	0.713	0.065	0.020	0.420

Step 3 Perform the grey relational analysis. From the data in Table 3, calculate the grey relational co-efficient for the normalized S/N ratio values by using Eq. (5). The value for is taken as 0.5 in Eq. (5). Since all the process parameters are of equal weighting [25]. The results are given in Table 5.

Step 4 Next, the grey relational grade can be computed by Eq. (6). Finally, the grades are considered for optimizing the multi response parameter design problem. The results are given in the Table 5.

Step 5 From the value of grey relational grade in Table 5, the main effects are tabulated in Table 6. In other words, optimization of the complicated multiple performance characteristics can be converted into the optimization of a single grey relational grade [26].

The effect of laser micro-drilling process parameter on the grey relational grade at different levels can be independent because the experimental design is orthogonal.

In addition, the total mean of the grey relational grade for the 25 experiments is calculated and listed in Table 6.

Table 5: Grey Relational Co-Efficient and Grey Grade Values

	Grey Relational coefficient				Grey Grade
Ex No	Circularity	Spatter	HAZ	Taper	
1	0.408	0.381	0.333	0.808	0.482
2	0.527	0.371	0.348	0.578	0.456
3	0.735	0.333	0.364	0.461	0.473
4	0.740	0.381	0.416	0.369	0.476
5	1.000	0.371	0.469	0.333	0.543
6	0.527	0.567	0.576	0.479	0.537
7	0.652	0.567	0.684	0.371	0.569
8	0.740	0.534	0.592	0.361	0.557
9	0.358	0.437	0.480	0.830	0.526
10	0.379	0.959	0.892	0.679	0.727
11	0.735	0.425	0.446	0.368	0.494
12	0.383	0.381	0.341	0.878	0.496
13	0.488	0.342	0.356	0.651	0.459
14	0.479	0.852	0.803	0.516	0.662
15	0.581	0.959	1.000	0.391	0.733
16	0.383	0.402	0.380	0.698	0.466
17	0.488	0.352	0.397	0.554	0.448
18	0.644	0.820	0.831	0.433	0.682
19	0.648	0.885	1.000	0.373	0.727
20	0.333	0.711	0.752	0.848	0.661
21	0.488	0.391	0.446	0.457	0.446
22	0.644	1.000	0.962	0.408	0.753
23	0.355	0.762	0.645	1.000	0.690
24	0.356	0.736	0.777	0.683	0.638
25	0.412	0.885	0.962	0.543	0.701

Basically the larger the grey relational grade, the better the multiple performance characteristics. However, the relative importance among the laser micro-drilling process parameters for the multiple performance characteristics still needs to be known so that the optimal combination of the laser micro-drilling process parameter levels can be determined more accurately [27]. Considering maximization of grade values, we can obtain the optimal parameter conditions PP5PF5GP1PW5

Step 6 The ANOVA analysis in Table 7 indicate that the assist gas pressure (35.36%) is the most significant process parameter followed by pulse frequency (35%), pulse power (23.93%) and pulse width (4.29%).

Based on the above discussion, the optimal laser drilling process parameters are pulse power (250W) at level 5, pulse frequency (250Hz) at level 5, assist gas pressure (8kg/cm^2) at level 1 and pulse width (0.6ms) at level 5. Therefore, experiment 22 shown in Table 2 fits the optimal process conditions.

Step 7 Confirmation tests: The optimal laser drilling process parameter revealed through the Taguchi orthogonal array from the experiments was PP5PF5GP1PW5 (250W, 250W, 8kg/cm^2 and 0.6ms) which was then employed to predict the grey relation that represents the laser micro-drilling of Al7075/10%SiC$_p$ MMCs. Only the effects of more significant factors i.e., GP, PF and PP are taken into account for prediction of grey relational grade of the optimal laser drilling parameters. Factor PW is excluded in the prediction computation due to its minimal effect. Therefore the effect of PP5PF5GP1 is included.

Table 6 Main Effects on Grey Grade

Symbol	Levels				
	1	2	3	4	5
x_1	0.486	0.583	0.569	0.597	0.645[a]
x_2	0.485	0.544	0.572	0.606	0.672[a]
x_3	0.661[a]	0.629	0.567	0.539	0.484
x_4	0.571	0.549	0.564	0.581	0.614[a]
a Optimum level					

Computation of the grey relational grade for predicting the optimal laser micro-drilling parameters is as follows:

Finally, the confirmation experiment is conducted via the optimal laser drilling parameter combination of $PP_5PF_5GP_1PW_5$. The evaluation points obtained for circularity, spatter, HAZ and taper are 0.9503mm, 0.075mm, 0.104mm and 4.03^0. The S/N ratios of the above parameters were determined as −0.44279, 22.498, 19.647 and -12.1241 respectively. The computational value of the grey grade is 0.841. Comparisons of the laser drilling between the initial laser drilling parameter and the optimal laser drilling parameter combinations are shown in Table 8. It is found that utilization of the optimal laser drilling parameter combination enhances the grey relation of laser drilling qualities between the of laser drilling quality from 0.727 to 0.841 by 15.5%.

Table 7: Results of ANOVA on Grey Grade

Symbol	DOF	Sum of squares	Mean Squares	F calculated	Contribution (%)
x_1	4	0.067	0.017	5.98	23.93
x_2	4	0.098	0.025	8.75	35.00
x_3	4	0.099	0.025	8.84	35.36
x_4	4	0.012	0.003	1.07	4.29
Error	8	0.005	0.000		1.78
Total	24	0.28			100

Table 8: Comparison Between the Initial and Optimal Process Parameters

Level	Raw	Optimal laser drilling parameters	
		Prediction	Experiment
	$PP_5PF_5GP_1PW_5$	$PP_5PF_5GP_1PW_5$	$PP_5PF_5GP_1PW_5$
Circularity (mm)	0.89		0.950
Spatter (mm)	0.074		0.075
HAZ (mm)	0.102		0.104
Taper (deg)	3.962		4.03
Grey relational grade	0.727	0.8259	0.841
Percentage of improvement of the grey relational grade = 15.55%			

V. Conclusions

Laser micro-drilling experiments were carried out using an optical fibre delivered pulsed Nd: YAG laser beam system and Al7075/10%SiCp metal matrix composites as work material. The circularity, spatter, HAZ and taper were collected under different conditions for various combinations of drilling parameters. The following conclusions were drawn:

- Grey relational analysis in the Taguchi method for the optimization of multi response problems is a very useful tool for predicting the circularity, spatter, HAZ and taper in the laser micro-drilling of Al7075/10%SiC$_p$ MMCs.
- From this analysis, it is revealed that the gas pressure (35.36%) is the most significant process parameter followed by pulse frequency (35%), pulse power (23.93%) and pulse width (4.29%) which affects the laser micro-drilling of Al7075/10%SiC$_p$ MMCs. The machining parameters set at their optimum levels can make certain considerable enhancement in the process parameters
- The best performance characteristics was obtained with pulse power of 250W, pulse-frequency of 250Hz, assist gas pressure of 8kg/cm^2 and pulse width 0.6ms
- By a combination of optimal laser micro-drilling parameters, significant improvement in grey relation can be accomplished

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