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ORIGINAL ARTICLE

Hole characteristics optimization in Nd:YAG laser micro-drilling of zirconium oxide by grey relation analysis

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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, to produce high-quality micro-drills. The Taguchi method coupled with grey relational analysis is therefore used as statistical design of experiment tools for optimization of both the quality characteristics, simultaneously. The optimal result obtained has been verified with the help of an additional confirmatory experiment. This indicates the application feasibility of the grey–Taguchi technique for continuous improvement in product quality in the manufacturing industry.

Keywords Laser micro-drilling · Nd:YAG laser · Grey relational analysis · Taguchi method · Optimization · Zirconium oxide

1 Introduction

Nowadays, laser beam machining is becoming one of the most useful machining tools, especially for micro-machining application. The shortcomings of conventional machining techniques to process a micro-drill on hard-to-machine materials have generated the demand for an efficient technique which employs a pulsed Nd:YAG laser system. The Nd:YAG laser micro-drilling process is advantageous in that it is a non-contact, fast, and flexible process, and it is easy to control and automate. It is applicable to both conductive and non-conductive materials. 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, 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 [1–6]. Taper formation is the most important characteristic during a laser micro-hole percussion drilling operation, as laser machining is based on the interaction of a laser beam with inherent focusing characteristics [7]. In multiple pulse laser percussion drilling, the entry hole diameter is normally larger than the exit hole diameter, and thus, the holes drilled are positively tapered [8]. Also, non-uniform melts ejection erosion to the hole walls and laser power reduction as the beam propagated to the hole can be identified as causes for taper formation [9]. However, it is desirable to drill holes with minimum taper and HAZ width to produce high-quality micro-drills. 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.

Taguchi's philosophy is an efficient tool for the design of a high-quality manufacturing system. Dr. Genichi Taguchi, a Japanese quality management consultant, has developed a method based on orthogonal array experiments, which provides much-reduced variance for the experiment with optimum setting of process control parameters. The traditional Taguchi method was originally designed to optimize a solitary

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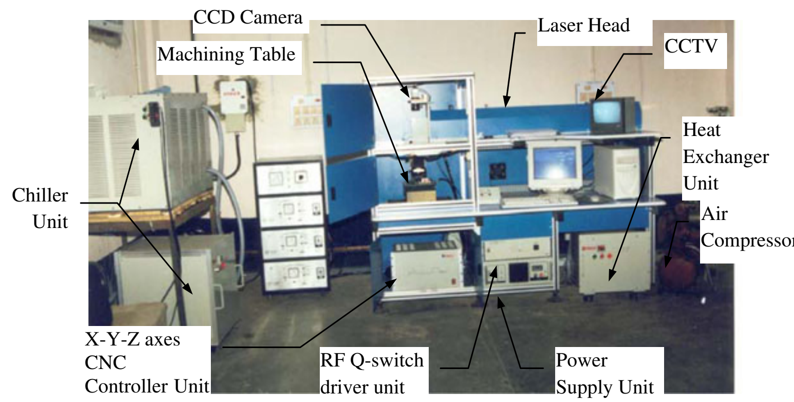

Fig. 1 Photographic view of the CNC pulsed Nd:YAG laser machining system

quality characteristic [10]. Optimization of multiple quality characteristics, however, is much more complicated than the former. Improving a certain quality characteristic might lead to serious degradation of some other critical quality characteristics. The grey theory, first initiated by Dr. Deng in 1982, can provide a solution to a system in which the model is unsure or the information is incomplete [11]. It avoids the inherent shortcomings of conventional statistical methods and requires 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 grey relational analysis based on this theory is applied in different manufacturing processes to effectively solve the complicated interrelationships among multiple quality characteristics and to determine the optimal parameter setting [12–17].

In the present work, an experimental investigation has been performed on pulsed Nd:YAG laser micro-drilling of zirconia. Four independently controllable process variables viz. lamp current, pulse frequency, air pressure, and pulse width are considered as input parameters, while hole taper and HAZ width are considered as the output parameters. The Taguchi method combined with the grey relational analysis is used as a statistical design of the experiment technique to set the optimal process parameters.

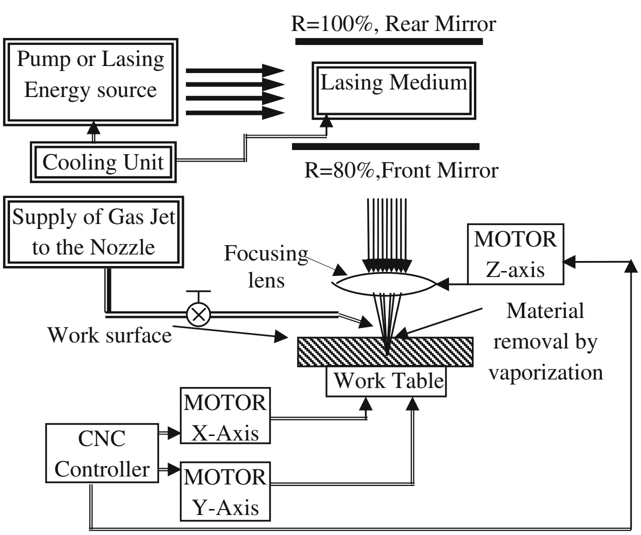

Fig. 2 Schematic representation of CNC Nd:YAG laser machining system

2 Mechanics of material removal in LBM

The basic material removal mechanism involved in laser beam machining is dependent upon the generation of high heat flux that causes melting and vaporization of the material on which the laser beam is focused. A suitable lasing medium is used to get a laser beam of suitable wavelength. The laser beam coming out of a lasing medium has a small diameter. The beam is then focused on the material surface using a good focusing element such as a lens. A laser beam has a well-defined wave front, which is either plane or spherical. When such a beam passes through a lens, it should get focused to a point. As a result, a high energy concentration is obtained at that point. Laser radiation is first absorbed by the material surface where the optical energy is converted into heat. The amount of absorption of laser radiation by a workpiece mainly depends on the wavelength, electrical properties of the workpiece such as conductivity, angle of incidence of the laser beam on the workpiece, and intensity of the focused laser beam.

3 Grey relational analysis

Grey relational analysis is an improved method for identifying and prioritizing key system factors, provides a

Table 1 Variable process parameters and their levels

Parameters	Level				
	1	2	3	4	5
l: Lamp current (amp)	17	19	21	23	25
f: Pulse frequency (kHz)	0.2	1.2	2.2	3.2	4.2
p: Air pressure (kg/cm^2)	0.5	1	1.5	2.0	2.5
w: Pulse width (%)	2	7	12	17	22

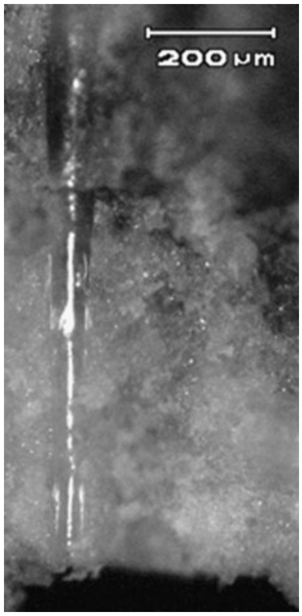

Fig. 3 Cross-sectional view of the drilled micro-hole on zirconia

straightforward mechanism for proposal evaluation, and is useful for variable independence analysis. No information–no solution and all information–unique solution being the extremities, grey systems with incomplete information, in between them, give a variety of feasible solutions. Instead of attempting to find the best solution, grey analysis provides techniques for determining a good solution, an appropriate solution for real-world problems.

In grey relational analysis, the raw experimental data are normalized at first. The normalized results, x_{ij}, for higher-the-better quality characteristic can be expressed as:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \tag{1}$$

For lower-the-better quality characteristic, the normalized results, x_{ij}, can be expressed as:

$$x_{ij} = \frac{\max_j y_{ij} - y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \tag{2}$$

where y_{ij} is the ith quality characteristic in the jth experiment.

Next, a grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient, ξ_{ij}, can be expressed as:

$$\xi_{ij} = \frac{\min_i \min_j |x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|}{|x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|} \tag{3}$$

where x_i^0 is the ideal normalized result for the ith quality characteristics, and ζ is a distinguishing coefficient, which is defined in the range of $0 \leq \zeta \leq 1$.

After obtaining the grey relational coefficient, a weighting method is used to integrate the grey relational coefficients of each experiment into the grey relational grade. The overall evaluation of the multiple quality characteristics is based on the grey relational grade, which is given by:

$$\gamma_j = \frac{1}{m} \sum_{i=1}^{m} w_i \xi_{ij} \tag{4}$$

where γ_j is the grey relational grade for the jth experiment, w_i is the weighting factor for the ith quality characteristic, and m is the number of quality characteristics.

The overall evaluation of the multiple quality characteristics is based on the grey relational grade. The optimal level of the process parameters is the level with the highest grey relational grade.

4 Experimentation

A pulsed Nd:YAG laser-based CNC machining system, manufactured by M/s Sahajanand Laser Technology, India, is used for the experimental study, with subsystems such as the laser source and beam delivery unit, power supply unit, radio frequency Q-switch driver unit, cooling unit, compressed air supply unit, and a CNC controller for X-, Y-, and Z-axis movements. The photographic view of the CNC pulsed Nd: YAG laser machining system is shown in Fig. 1. The radiation coming out from the laser is directed to the workpiece using a beam delivery system that first bends the laser beam at right angles and then focuses it on the work spot through the focusing lens. The cooling unit, consisting of a three-phase

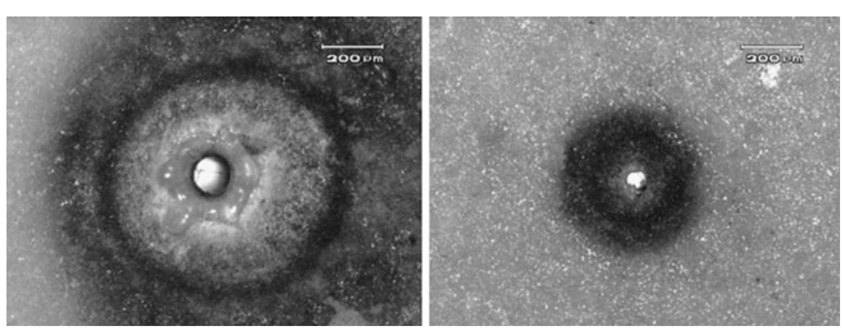

Fig. 4 Microscopic views (*top* and *bottom* surfaces, respectively) of the drilled hole showing a large taper on zirconia (ZrO_2)

chiller unit and a pump, cools the system by circulating chilled water to avoid thermal damage of the laser cavity, lamp, Nd: YAG rod, and the Q switch. A compressed air supply unit is designed, in which compressed air is used as an assist gas for removing debris from the working zone. The CNC controller consists of an *X–Y–Z* translation work table and a control unit. Each of the axes of the work table is attached with a stepper motor and is connected to the control unit. The *Z*-axis controller controls the *Z*-axis movement of the focusing lens. Figure 2 shows the schematic representation of the CNC Nd: YAG laser machining system.

The following independently controllable process parameters are identified to carry out the experiments: lamp current, pulse frequency, assist air pressure, and pulse width. The ranges of these parameters are selected on the basis of trial experiments conducted by using a one-factor-at-a-time approach. The working range is decided by inspecting the workpiece for a through micro-hole of acceptable quality as observed through naked eye. The selected process parameters and their levels, units, and symbols are given in Table 1. Other process parameters like focal length of the focus lens and types of assist gas are kept constant. The focal length is considered as zero, and only compressed air is used as assisted gas.

Zirconium oxide (ZrO_2) ceramic is used as work material. The workpiece thickness is measured by a digital vernier caliper having a least count of 0.001 mm, and is found 1 mm. The workpiece is held on the CNC work table using a specially designed fixture. A CCD camera is used for viewing the location of the workpiece and also for checking the laser beam focusing on the workpiece surface. Air pressure is varied with the help of a pressure regulating system. Other process parameters are varied through the machining setup.

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.

After the micro-drilling operation, the safety shutter is closed, and the workpiece is removed from the fixture. The top and bottom diameters of the micro-holes are measured at ×10 magnification with the help of an optical measuring microscope (Olympus STM6). Microscopic views of the holes are also captured for further analyses.

Figure 3 shows the cross-sectional view of a micro-drilled hole on zirconia. Figure 4 shows the top and bottom surface of the hole, respectively. Taper of the drilled hole has been calculated considering the straight taper profile, as follows:

$$\text{Taper} = \frac{(\text{Hole\_Dia}_{\text{top}} - \text{hole\_Dia}_{\text{bottom}})}{2 \times \text{thickness}} \tag{5}$$

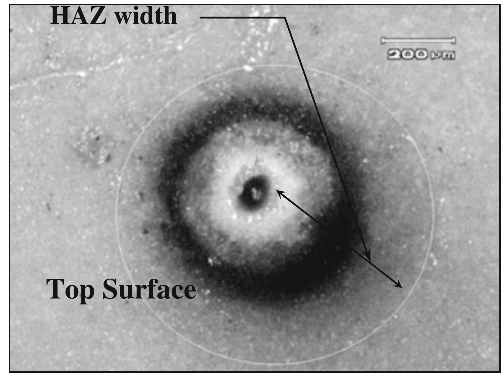

Fig. 5 Top surface of the micro-drilled hole showing the HAZ width

The HAZ width has been measured from the top surface only and shown in Fig. 5. The HAZ width has been determined as:

$$\text{HAZ width} = \frac{\text{HAZ\_Dia}_{\text{top}} - \text{hole\_Dia}_{\text{top}}}{2} \tag{6}$$

Table 2 Experimental assignments and results

Experiment no.	Process parameters				Quality characteristics	
	l (amp)	*f* (kHz)	*p* (kg/cm^2)	*w* (%)	Hole taper (rad)	HAZ width (mm)
1	1	1	1	1	0.0788	0.3366
2	1	2	2	2	0.0698	0.2946
3	1	3	3	3	0.0663	0.3536
4	1	4	4	4	0.0700	0.3271
5	1	5	5	5	0.0780	0.3667
6	2	1	2	3	0.0727	0.5125
7	2	2	3	4	0.0451	0.4925
8	2	3	4	5	0.0714	0.3485
9	2	4	5	1	0.0686	0.3915
10	2	5	1	2	0.0737	0.3509
11	3	1	3	5	0.0651	0.4580
12	3	2	4	1	0.0556	0.4558
13	3	3	5	2	0.0658	0.4288
14	3	4	1	3	0.0937	0.4529
15	3	5	2	4	0.0899	0.3827
16	4	1	4	2	0.0733	0.6102
17	4	2	5	3	0.0841	0.6282
18	4	3	1	4	0.1220	0.7849
19	4	4	2	5	0.1284	0.5265
20	4	5	3	1	0.1182	0.4850
21	5	1	5	4	0.0927	0.6023
22	5	2	1	5	0.0801	0.5692
23	5	3	2	1	0.0972	0.6506
24	5	4	3	2	0.1116	0.4643
25	5	5	4	3	0.0897	0.4452

Table 3 Results of the ANOVA for hole taper

Source	Degrees of freedom	Sum of squares	Mean squares	*F* value	Prob>*F*	Contribution (%)
l	4	0.0054317	0.0013579	11.33	0.002	58.53
f	4	0.0023992	0.0005998	5.00	0.026	25.82
p	4	0.0013379	0.0003345	2.79	0.101	14.41
w	4	0.0001135	0.0000284	0.24	0.910	1.24
Error	8	0.0009590	0.0001199			
Total	24	0.0102413				

The experimental layout for the laser micro-drilling parameters using the L25 orthogonal array and the experimental results are presented in Table 2.

5 Influence of process parameters on process quality

The purpose of the analysis of variance is to investigate which micro-drilling parameter significantly affects the quality characteristics. This is accomplished by separating the total variability of the response, which is measured by the sum of squared deviations from the total mean of the response, into contributions by each micro-drilling process parameter and the error. The ANOVA results furnished in Tables 3 and 4 have been obtained by using statistical software MINITAB® 15. The same table shows the percentage contribution of each process parameter to the total variation, indicating their degree of influence on the responses.

According to Table 3, the lamp current has the most dominant effect on hole taper, and it is followed by pulse frequency, air pressure, and pulse width. The energy of the laser beam depends mainly on the lamp current. A higher lamp current generates high thermal energy, which produces a large taper. The low energy of the laser beam generates a small taper. A high-energy laser beam with a small incident time removes the material from the top surface almost instantly; therefore, thermal spalling as well as melting and vaporization occur at the top surface during the laser micro-drilling which increases the tapering effect. At very high pulse frequency, a small taper is observed, but at low pulse frequency, a large taper is generated. At very low pulse frequency, comparatively high beam energy is generated, which results in the high tapered hole. Again, at higher pulse frequency, less energy beam generates a small taper of micro-hole. Lower assisted air pressure is unable to compensate for the excess heat generated at the drilling zone as well as unable to assist the removal of ejected material at the bottom zone; therefore, the top hole diameter increases. This phenomenon causes a large taper. However, at a higher level of assist air pressure, some amount of excess heat has been removed rapidly and also helps to eject the molten material; as a result, a low taper is observed. The pulse width has positive effect on taper, and the taper increases with pulse width. At lower pulse widths, high concentrated beam energy causes quick penetration in the workpiece, compared to the higher pulse widths; as a result, a large taper is formed at higher pulse widths.

It can be found from Table 4 that the lamp current has the most dominant effect on HAZ width, and it is followed by pulse frequency, pulse width, and assist air pressure. HAZ width increases with the lamp current. It is due to the fact that the energy of the laser beam mainly depends on the lamp current. The high lamp current generates high thermal energy, which produces high HAZ width. The observed HAZ width varies nonlinearly with the pulse frequency. At very low pulse frequency, the laser beam usually penetrates a greater depth, but the time between two subsequent laser pulses during micro-drilling is sufficient to dissipate the heat from the surface as assisted air is supplied. As a result, the thickness of the heat-affected zone becomes less. However, at higher pulse frequency, less energy beam generates a small HAZ width. But at the middle value of the pulse

Table 4 Results of the ANOVA for HAZ width

Source	Degrees of freedom	Sum of squares	Mean squares	*F* value	Prob>*F*	Contribution (%)
l	4	0.231848	0.057962	11.98	0.002	74.83
f	4	0.044174	0.011043	2.28	0.149	14.24
p	4	0.012299	0.003075	0.64	0.651	4.00
w	4	0.021391	0.005348	1.11	0.417	6.93
Error	8	0.038700	0.004837			
Total	24	0.348412				

frequency, a relatively high-energy beam is applied with lesser time between pulses, which causes a large value of the HAZ width during micro-machining. A lower assisted air pressure is unable to compensate for the excess heat generated at the drilling zone as well as unable to assist the removal of ejected material. As a result, the thickness of the heat-affected zone becomes large. However, at a higher level of assist air pressure, some amount of excess heat is removed rapidly. Higher air pressure also helps to eject the molten material; as a result, a low HAZ width is observed. At lower pulse widths, less heat-affected zone is generated, than that of higher pulse widths.

6 Determination of optimal process parameters

6.1 Normalizing the experimental data

In grey relational analysis, the dimensions of factors considered are usually different, and their magnitude difference is large. Therefore, the original data are normalized to make the magnitude of the original data of order one and dimensionless. Table 5 presents the normalized results for both the quality characteristics. Larger normalized results correspond to better quality, and the best-normalized result should be equal to 1.

6.2 Grey relational coefficient calculation

Table 6 presents grey relational coefficients for each experiment of the L25 orthogonal array. In this study, the value of ζ is taken as 0.5 for calculating the grey relational coefficients.

6.3 Determination of grey relational grades

The results of the grey relational grades are tabulated in Table 7. In calculating the grey relational grades, the weighting ratio for both the quality characteristics is set as 1:1, i.e., each characteristic has equal importance or relative weighting. The higher the grey relational grade, the closer the experimental result is to the ideally normalized value.

Table 5 Data preprocessing of the experimental results

Experiment no.	Data normalizing	
	Hole taper	HAZ width
1	0.5948	0.9143
2	0.7314	1.0000
3	0.7688	0.9214
4	0.7011	0.9337
5	0.5976	0.8360
6	0.6507	0.5331
7	1.0000	0.5965
8	0.6683	0.8776
9	0.7360	0.7973
10	0.6569	0.8853
11	0.7596	0.6667
12	0.8737	0.6713
13	0.7640	0.7569
14	0.4229	0.6976
15	0.4742	0.8612
16	0.6704	0.3661
17	0.5176	0.2951
18	0.0762	0.0000
19	0.0000	0.5270
20	0.0990	0.5965
21	0.4286	0.3724
22	0.5860	0.4552
23	0.3688	0.3046
24	0.1901	0.6080
25	0.4642	0.6929

Table 6 The calculated grey relational coefficients

Experiment no.	Grey relational coefficient	
	Hole taper	HAZ width
1	0.5524	0.8537
2	0.6506	1.0000
3	0.6838	0.8641
4	0.6258	0.8829
5	0.5541	0.7530
6	0.5888	0.5171
7	1.0000	0.5534
8	0.6012	0.8034
9	0.6545	0.7115
10	0.5930	0.8134
11	0.6753	0.6000
12	0.7983	0.6034
13	0.6793	0.6728
14	0.4642	0.6232
15	0.4874	0.7827
16	0.6027	0.4410
17	0.5090	0.4150
18	0.3512	0.3333
19	0.3333	0.5139
20	0.3569	0.5534
21	0.4667	0.4434
22	0.5471	0.4786
23	0.4420	0.4183
24	0.3817	0.5605
25	0.4827	0.6195

Table 7 Grey relational grade and its order

Experiment no.	Grey relational grade	Order
1	0.7031	6
2	0.8253	1
3	0.7740	3
4	0.7544	4
5	0.6536	11
6	0.5529	14
7	0.7767	2
8	0.7023	7
9	0.6830	9
10	0.7032	5
11	0.6377	12
12	0.7009	8
13	0.6761	10
14	0.5437	16
15	0.6351	13
16	0.5218	17
17	0.4620	20
18	0.3423	25
19	0.4236	24
20	0.4551	21
21	0.4550	22
22	0.5128	18
23	0.4301	23
24	0.4711	19
25	0.5511	15

6.4 Calculating the response table for grey relational grades

The effect of each machining parameter on the grey relational grade at different levels can be separated out because the experimental design is orthogonal. The mean of the grey relational grade for the lamp current at levels 1, 2, 3, 4, and 5 is calculated by averaging the grey relational grade for experiments 1 to 5, 6 to 10, 11 to 15, 16 to 20, and 21 to 25, respectively. Similarly, it is calculated for the respective levels for pulse frequency, air pressure, and pulse width and is summarized in Table 8. The total mean value of the grey relational grade is found to be 0.5979. The lamp current has been found to have maximum effect on the responses.

6.5 Selecting optimal factor levels

The optimal values of Nd:YAG laser micro-drilling process parameters for zirconium oxide are identified from Table 8. Based on this response table, the optimal process parameters setting is to maintain the lamp current at level 1 (l=17.0 amp), pulse frequency at level 2 (f=1.2 kHz), air pressure at level 4 (p=2.0 kg/cm^2), and pulse width at level 2 (w=7.0%) for minimizing hole taper and HAZ width, simultaneously.

Table 9 Result of confirmation experiment

	Initial parameter setting	Optimal parameters	
		Prediction	Experiment
Level	$l_1f_4p_4w_4$	$l_1f_2p_4w_2$	$l_1f_2p_4w_2$
Hole taper (rad)	0.0700		0.0586
HAZ width (mm)	0.3271		0.2984
Grey relational grade	0.7544	0.8896	0.8697
Improvement of the grey relational grade=0.1153			

7 Confirmation tests

The confirmatory experiment is carried out to verify the feasibility and reproducibility of the proposed method. The results obtained thereby are tabulated in Table 9. The improvement in grey relational grade at the optimum level is found to be 0.1153. As shown in Table 9, both the hole taper and HAZ width are decreased simultaneously from 0.0700 to 0.0586 rad and 0.3271 to 0.2984 mm, respectively. The results show that adoption of the grey-based Taguchi method leads to effective improvement of product quality in Nd:YAG laser micro-drilling of zirconium oxide.

Table 8 Response table for grey relational grade

Machining parameters	Grey relational grade						
	Level 1	Level 2	Level 3	Level 4	Level 5	Delta	Rank
Lamp current, l	*0.7421*	0.6836	0.6387	0.4410	0.4841	0.3011	1
Pulse frequency, f	0.5741	*0.6555*	0.5849	0.5752	0.5996	0.0814	3
Air pressure, p	0.5610	0.5734	0.6229	*0.6461*	0.5859	0.0851	2
Pulse width, w	0.5944	*0.6395*	0.5767	0.5927	0.5860	0.0628	4
Total mean value of the grey relational grade=*0.5979*							

8 Conclusions

A multi-response optimization technique has been adopted in the search for an optimal parametric combination to yield a favorable hole geometry during Nd:YAG laser micro-drilling of zirconium oxide ceramics. The hole taper and the HAZ width, which greatly influence the quality and feature characteristics of a drilled hole, are the responses considered for study. The improvement of hole taper and the HAZ width from the initial condition to optimal condition is 16.29 and 8.77%, respectively, which validates the effectiveness of the optimization method proposed in this study.

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