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Letter to Editor

Experimental and statistical optimisation of Nd-YAG crystal laser cutting process of INCONEL-718 using grey relational analysis.

Amro M. Yousef[1], Ahmed Saeed[2], Abdel-Monem El-Batahgy[3], Mohamed Sobih[4]

[1]High Institute for Engineering and Technology Alobour, [2]Egyptian Ministry of Defense, [3]Central Metallurgical Research and Development Institute, Cairo, Egypt, [4]Higher Colleges of Technology (HCT), Abu Dhabi, UAE.

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Cutting process optimisation, grey relation analysis, inconel-718 cutting, Laser cutting

Corresponding Author:

Amro M. Yousef, High Institute for Engineering and Technology, Cairo, Egypt, **Tel.:** 01001436154, **Email:** amro.youssef@gmail.com

Abstract

Inconel-718 is one of widely utilized Ni-based superalloysforaerospace enginesapplications. This is due to the superior thermos-mechanical properties and high temperature oxidation resistance.This paper aims to achieve optimal parameterswhile cutting thin sheet of Inconel-718employed pulsed Nd-YAG laser. The Taguchi method will be used to reduce the variation in the process.The overall objective of this work is to obtain trustable optimal cutting parameters by performing smaller numberof experiments aiming to reduce the cost. Kerf width, perpendicularity and number of striations are the parameters under investigation. Grey relational analysis (GRA), is utilised to reach the optimal cutting process parameters.These parameters are traverse feed velocity 350 mm/min, pulse height 80%, pulse duration 1 ms. and pulse frequency 50Hz .Experimental verifications show a good agreement concerning the predicted and the actual cutting process quality measures at the optimal cutting parameters

1. INTRODUCTION

Advanced engineering materials or, aerospace-oriented alloys,areextremely favourable in advanced manufacturing applications.The reason is by the virtue oftheexceptional properties such as;heat resistance, high strength,hot-hardness, oxidation resistance and abrasion resistance. Nearly66% of all the super-alloys fabricated are consumed by the aerospace industries for the manufacturing of gas turbines and aerospace jet propelled engines and their accompaniment accessories[1,2]. Inconel-718, is a Nickel-basedalloy "alloyed by Chromium" with superior thermal resistance, high strength,excellent wear resistance and distinguished oxidationresistance. It showed also favourable welding characterises especially post welding crack-resistance. This alloy is a "Hard-to-Machine Material" owing to its tremendously tough nature.

Laser Beam Machining (LBM),is one of the non-traditional manufacturing operations, most widely used for production ofprecise geometries in almost all metallic materials.Other laser production technologies, such as laser cladding, laser joining, laser drilling/piercing and laser assisted machining, are regularly used to produce mechanical parts[3, 4].

Solid state Nd-YAG, Fiber and CO_2 lasers are used in thin sheet-cutand perforation processesbecause of their;smaller heat affected zone (HAZ), high precision, high power output to input ratio and cutting high speeds. Nd-YAGlaser cutting is an exceptional choice formetal-fabricationoperation because of its; higher laser-beam intensity, low "mean beam" power andflexible focusing characteristics. By virtue of its shorter wave-length (1.06 μm), in comparison to gas lasers which have (10.6 μm)wave length, it is reflected to a lesser extent during cutting, thus enables processing of "highly reflective" materials with fairly less power[5]. The materials thatpossess good thermal conductivity,yieldless than expected "poor"outcomesin the case of the workpiece cutting is handledutilizingGas lasers. The quality resulting from utilizing pulsed Nd-YAG crystall aser is, to high extend, affectedby many controllable cutting processvariables such as; the pulse energy, the pulse height, the pulse frequency andthe pulse width. Also,other cutting process parameter, apart from laser variables, are controllable, such as; traverse feed velocity, type of the assist-gas andassist/cut gas pressure. The appropriatemanipulation of these process variables gives the thought after cut quality. The quality of the cut section resulting from laser cutting of metallic sheets can be assessed by; the κerf width, perpendicularity, HAZ, κerf deviation, number of striations……...etc[6].

Thawari et.al. did disclosed the impact of pulse energy andthe traverse feed velocity on cut edge profile. One-millimetre thick UNS N06002 nickel-chromium-iron-molybdenum alloy has been used. "Cut-quality" measures such as, surface roughness, κerf width and κerf profile were studied and their dependency on the cutting process variables has been discussed. Pulse overlap was optimized to reach a compromise between the speed of cut and the quality of cut surface[7]. While Ahn and Byun have experimentally investigated the influence of cutting process parameters of the Nd-YAG laser cutting of Inconel-718 sheets, including the laser power, cutting feed rate and workpiece thickness,on reaching optimalcut-process quality attributes.These attributes were surface roughness,striation existenceand micro cracks.Also, theyinvestigated the thermal effect of the process on the workpiece material, constructed empirical formulae to forecast the critical cutting power and also estimated optimum conditions with minimum κerf width[8].

Taguchi method was extensively used as a tool for design of experiments in manufacturing processes followed by any optimisation method aiming to find the cutting variables leading to the optimal process characteristics. in laser cutting process. Dubey and Yadavaused single objective optimisation followed by Taguchi method and the method of principal component analysis (PCA), to obtain better cut qualities in machining Aluminium based alloys[9]. The considered experimentally cutting quality parameters were; the κerf width, the κerf deviation, and the κerf taper have been taken also in theinvestigation[10]. The considered input variableswere;the assist-gas pressure, the beam pulse width and frequency, traverse feed velocity. Optimal conditions were obtained and confirmed experimentally[11-14].

The present work utilizes the Taguchi methodto design the experiments. The Grey Relational Analysis is then employed to find the ideal process parameters to be used in the cutting of Inconel-718 sheets. The optimized process quality measures are: the κerf width, perpendicularity, and the number of striations per unit length. While the studied process parameters were;the laser power, the beam pulse width, the pulse frequency, the pulse height (energy) and laser traverse feed velocity.

Table 1: The Taguchi Orthogonal array arrangement

		The "independent" var(s). under investigation								
		2	3	4	5	6	7	8	9	10
The Exp Var. Levels	Two	L_4	L_4	L_8	L_8	L_8	L_8	L_12	L_12	L_12
	Three	L_9	L_9	L_9	L_18	L_18	L_18	L_18	L_27	L_27
	Four	L_16	L_16	L_16	L_16	L_32	L_32	L_32	L_32	L_32
	Five	L_25	L_25	L_25	L_25	L_25	L_50	L_50	L_50	L_50

3. CONSTRUCTION OF EXPERIMENTAL MATRIX

The Taguchi, design of experiment (DOF)method, is a widely acknowledged methodused inminimizing the number of experiments to be performed without the compromise on the accuracy of the outputs. In this method, control factors, which have impact on process outcomes, are taken as input parameters and thenthe experimentsareconstructed as orthogonal array (OA). The appropriate size of (OA) is based on total degrees of freedom (DOF), which is selected from Table 1. In general, the Signal/Noise (S/N) ratio which can be written also as (ηordB) signifies the quality characteristic for the experimental data, mathematically it can be computed as:

$$\eta = -10\ log\ (MSD) \qquad (1)$$

Where,"MSD" is the Mean Square Deviation. It is commonly known as the Quality Loss Function (QLF). Depending on the experimental objectives, (QLF) can be of three types: the lower-the-better (LB), the higher-the-better (HB) and the nominal-the-best (NB) types. In the current study the κerf width and perpendicularity are desirable to have lower values (LB). On the other hand, number of striations needs to follow higher is the better criterion. These (QLF)values in this method are obtained from the next equation as follows:

$$MSD = \left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (2)$$

where,"yi" is, the observed quality measure at the i^th trial and "n" is the number of repetitions at the same trial experiment. The S/N ratio represents the preferred/un-preferred portion. The intentionof using TM analysis is always to maximize this ratio regardless of the nature of the quality characteristics. After obtaining the ranks of theS/N ratio,the most important parameters, having influence on the current process outcomes,ought to be distinguished and optimal sets of process variables canbe obtained.

In metal cutting field, the classicalstatistical methodologies may not analyse those intertwined metal cutting, forming, or welding systems in afavourable or dependableway without the use of large data sets to satisfy certain statistical criteria. The Gre Relation Analysis theory, conversely, can deal with both in-complete information and un-clear problems in a precise manner[10]. GRA theory, defines situations with no information as “lack”, and the situation with perfect and complete information as “white”. Therefore, a “Grey” system means that the system has a part of the available information and part of information is unavailable. A variety of available different scenarios can be obtained by Grey systems outputs. It does not claim to present challenge and find the only best solutions[15-17].On the contrary, it does provide,in a precise way, practices for shaping a good solution. It is presented as follows;

The higher is better

$$x_i^*(k.) = \frac{x_i^0(k.) - min.x_i^0(k.)}{max.x_i^0(k.) - min.x_i^0(k.)} \tag{3}$$

The lower is better

$$x_i^*(k.) = \frac{max.\,x_i^0(k.) - x_i^0(k.)}{max.x_i^0(k.) - min.x_i^0(k.)} \tag{4}$$

A desired value x^0

$$x_i^*(k.) = 1 - \frac{\left|x_i^0(k.) - x^0\right|}{max.x_i^0(k.) - x^0} \tag{5}$$

Where:

x_i^* (κ).The generation value of GRA

The GR coefficients ξ_i (κ)., and GR gradγ_i was evaluated using equations(8) and (12).

$$x_0(\kappa) = \{(x_0(1)\&x_0(2)\&\&x_0(\kappa.)\} \tag{6}$$

$$x_i(\kappa) = \{(x_i(1)\&x_i(2)\&\&x_i(\kappa.)\} \in X \tag{7}$$

where: i= 1,2,….,m. κ= 1,2,….,ЄN

The Grey relation coefficient is calculated as following:

$$\xi_{0i}(\kappa) = \frac{\Delta_{min} + \mathcal{E}.\Delta_{max}}{\Delta_{0,i}(\kappa) + \mathcal{E}.\Delta_{max}} \tag{8}$$

where: i= 1,2,….,m. k= 1, 2,…., ,n.

and Ɛ means; The distinctive (identification) coefficient, where:ƐЄ[0,1], Ɛ = 0.5 is commonly used,Δ0,i (k.) representing the deviations sequence from a reference sequencex $_0$(k), x_i(k);

$$\Delta_{0,i}(k) = |x_0(k) - x_i(k)| \tag{9}$$

$$\Delta_{min} = \forall j^{min} \in i\forall\, k^{min}|x_0(k) - x_j(k)| \tag{10}$$

$$\Delta_{max} = \forall j^{max} \in i\forall\, k^{max}|x_0(k) - x_j(k)| \tag{11}$$

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}(\xi_{0i}(k)) \tag{12}$$

4. EXPERIMENTAL PROCEDURES

The material used in this workis1 mm thick sheetof Inconel-718 with the chemical composition was measuredusingmaterial spectrometerType PMI-Master Pro by Oxford Instruments and tabulated in Table 2.

Table 2: Inconel-718 Chemical composition

Element.	Composition. (wt.%)
Ni.	53.700
Fe.	18.300
Cr.	17.400
Nb.	4.960
Mo.	2.850
Ti.	0.890
Al.	0.710
Cu.	0.0386
Co.	0.374
V.	0.0362
C.	0.314
Mn.	0.268
W.	0.225
Si.	0.0917
Mg.	0.0039
Zr.	0.001

The cutting experiments areexecutedby means of a pulsed Nd-YAG lasermodel “JK 700 Lumonics”. The machine has a maximum output power of 400 W emitted at 1.06 µm. Laser beam is delivered through a cutting Nozzle and head that contains the necessary optics and utilized conical assist gas nozzle with 1.5mm in diameter. In these experiments the pulseenergy is calculated as follows:

$$E = h^2cw \quad \text{(j/pulse)} \tag{13}$$

and Pulse frequency to calculate power

$$p = h^2cw\,r \quad \text{(j)} \tag{14}$$

Where:

w is the laser power.

r is the beam pulse frequency.

c is a power conversion factor (Laser power to pulse height) equals 0.0009 for the used laser head.

h is the beam pulse height

The attainable process parameter ranges are listed in Table 3.During these experiments, three levels have been assigned for each one of the controlled process variables, Table 4. The values used for this stage represent the attainable range based on the laser source employed during these experiments.

Table 3: Laser parameters range

Laser power. (w.)	0-400
Pulsed frequency. (Hz.)	30 – 50
Pulsed height.	60% - 80%
Pulse waveduration. (ms.)	0.6 - 1
Traverse feed velocity. (mm/min.)	300-500
OperationMode.	Pulsed
Assistgas.	Air
Gaspressure. (bar.)	5
Nozzle diameter. (mm.)	1.5
Nozzlestandoff(mm.)	1
Focallens (mm.)	140
Focusposition	At the Surface
Focalspotsize (mm)	0.6

Taguchi analysis method is applied to design the experiment (four variables and three levels) as L9OA using Minitab® with the values listed in table 4. The table also presents the results of the experimental cuts using these process parameters. It can be seen that only two conditions are sufficient for preforming the cut, thus a modified matrix was created as shown Table 6. These values ensure that all experiments would yield a cutting path and thus a second stage of experiments is necessary using the new modified range.

Table 7 lists the values and the results used in the second stage of experiments. It can be seen that all levels successfully performed a cutting path.

Table 4: Controlfactors and experimental parameters levels

Symbol	Factor	Unit	Level 1	Level 2	Level 3
A.	Pulse height.	%	60	70	80
B.	Pulse duration.	Ms.	6.00E-01	8.00E-01	one
C.	Pulse frequency.	Hz.	30	40	50
D.	Traverse feed velocity.	mm/min.	300	400	500

Table 5: L_9OA parameters

1	h (%)	w (ms)	E(j/Pulse)	r (Hz.)	f (mm/min)	Power (Watt)	Ct result
2	80	1.0	6.311	50	500	300	True
3	80	0.8	5.04	40	400	185	False
4	80	0.6	3.78	30	300	100	False
5	70	1.0	4.83	40	300	185	False
6	70	0.8	3.86	30	500	113	False
7	70	0.6	2.9	50	400	145	False
8	60	1.0	3.55	30	400	115	False
9	60	0.8	2.84	50	300	160	True
	60	0.6	2.13	40	500	95	False

Engineering Science and Military Technologies
Volume (9) - Issue (1) - March 2025

Table 6: Modified process parameters

Symbol	Factor	Unit	Level 1.	Level 2.	Level 3.
A.	Pulse height.	%	75	77.5	80
B.	Pulse duration.	Ms.	0.8	0.9	1
C.	Pulse frequency.	Hz.	40	45	50
D.	Traverse feed velocity.	mm/min.	300	350	400

Table 7: Modified L_9OA parameters and experimental results

	h (%)	W (ms)	E (j/pulse)	r (Hz.)	f (mm/min)	Power (Watt)	Cut result
1	80	1	50	400	6.311	310	True
2	80	0.9	45	350	5.68	250	True
3	80	0.8	40	300	5.049	198	True
4	77.5	1	45	300	5.92	268	True
5	77.5	0.9	40	400	5.33	213	True
6	77.5	0.8	50	350	4.73	236	True
7	75	1	40	350	5.54	229	True
8	75	0.9	50	300	4.992	253	True
9	75	0.8	45	400	4.437	200	True

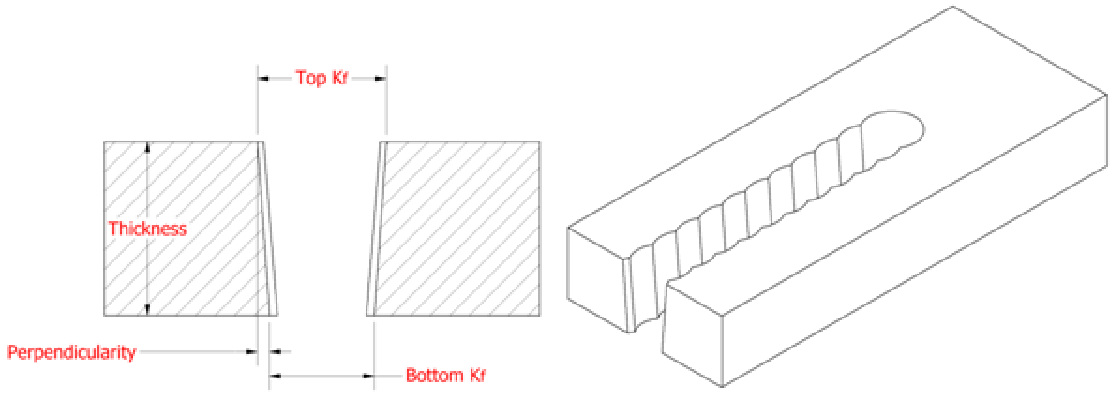


Fig. 1: Schematic of various cut quality attributes

5. RESULTS AND DISCUSSIONS

The quality characteristics analysed are;top and bottomkerf widths, perpendicularity and number of striations per unit length.These parameters are shown in Figure 1.

5.1. MEASUREMENT OF THE KERF WIDTH AND PERPENDICULARITY

Each cutting path isset to 30 mm. The top kerf width and the bottom kerf width are measured with Toolmaker microscope Mitutoyo TM-510 with 15 X magnification. The average of five readings is taken along the top and bottom cutsurfaces. The readings and average kerf width and perpendicularity are listed in Table 8.

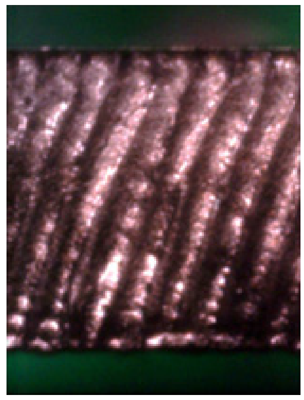
5.2. MEASUREMENT THE NUMBER OF STRIATION/1 MM.

The specimen is placed under the microscope using a special fixture. Figure 2, shows the striations perpendicular to the cut edge. The number of striations was measured taking six readings and calculating the average number of striations. The results and average number of striations is listed in Table 9.

5.3. OPTIMISATION OF PROCESS PARAMETERS

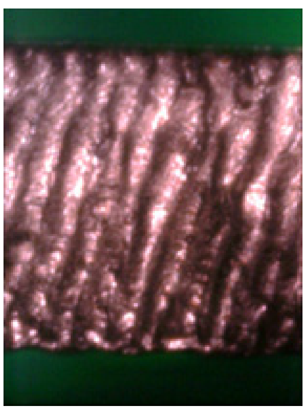
After performing the experiments and measurements, GRA is used to obtain the optimal cutting parameters leading to minimum κerf width, minimum deviation from perpendicularity and maximum number of striation per unit length. The experimental result can be normalised based on equation 8. The next stage is to use GRA to calculate$\Delta_{0,i}(k)$(deviation sequence). Table 10, shows the deviations sequence for the investigated quality measures

1- Stration photo for experment LBM.

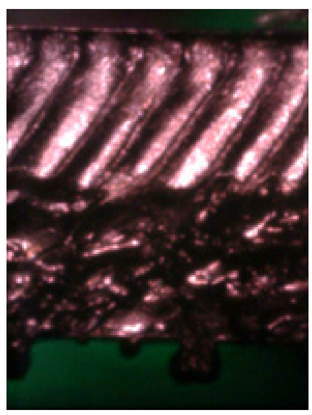


2- Stration photo for experment LBM

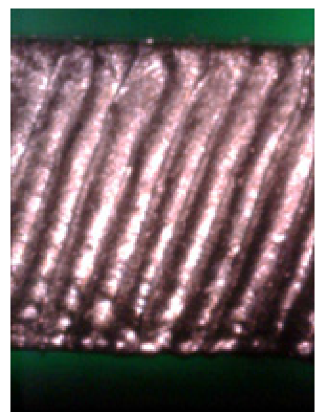
3- Stration photo for experment LBM



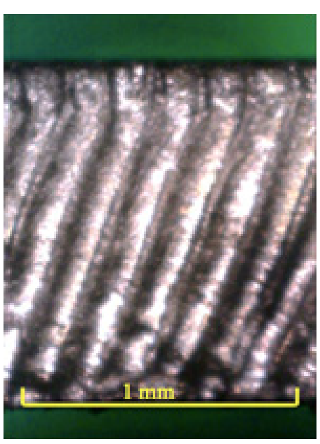
4- Stration photo for experment LBM.



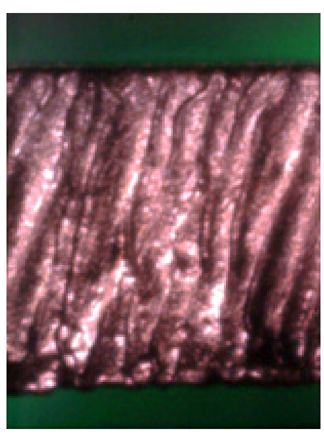
5- Stration photo for experment LBM.



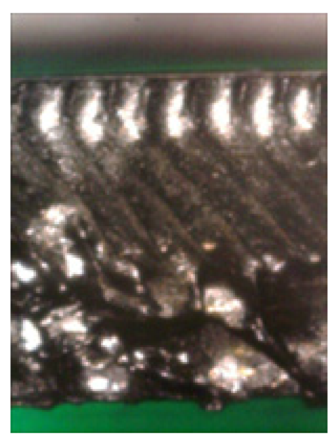
6- Stration photo for experment LBM.



7- Stration photo for experment LBM



8- Stration photo for experment LBM.



9- Stration photo for experment LBM

Fig. 2: Striation at the cut edge

From the Grey relation analysis, it can be seen from Table 11, showing the calculated results of Grey relation coefficient ξ_{0i} for the κerf width, perpendicularity and number of striation/ mm. and Grey relation grad γ. According to the performed experiment design, it can be observed from the same table and also from Figure 4, that the cutting process variables setting of experiment no.7, 9 has the highest GR grade.

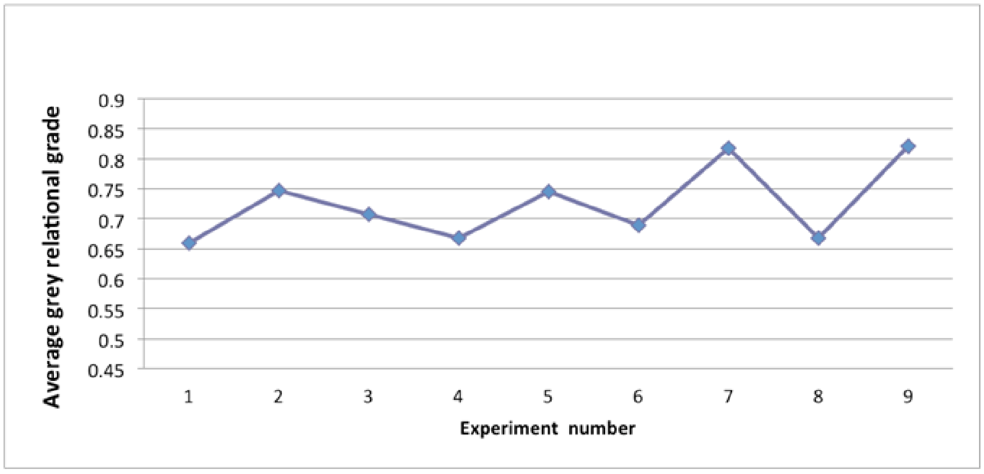


Fig. 4: Grey relational grade

Table 8: Kerf width and perpendicularity results

Exp. No.	Top Kf.	Bottom Kf.	Perpendicularity.
1.	1.0268	0.6958	0.1655
2.	0.952	0.6722	0.1399
3.	0.9678	0.6874	0.1402
4.	1.0378	0.6776	0.1801
5.	0.9882	0.6612	0.1635
6.	1.007	0.6416	0.1827
7.	1.0042	0.6526	0.1758
8.	1.0152	0.678	0.1686
9	0.997	0.6484	0.1743

Table 9: Average number of striations

Exp. No.	Average width of striation.	Striation / 1 mm.
1.	0.137167	7.290401
2.	0.133833	7.47198
3.	0.143167	6.984866
4.	0.115	8.695652
5.	0.170833	5.853659
6.	0.120167	8.321775
7.	0.150333	6.651885
8.	0.107	9.345794
9	0.141	7.092199

Table 10: Deviations sequence.

Exp. No.	Deviation sequence		
	Kf.	Perp.	s/mm.
1.	0.88677	0.236369	6.878969
2.	0.048	0.8601	7.008552
3.	0.149609	0.852791	6.660925
4.	1.039	0.119352	7.881822
5.	0.404092	0.285098	5.853659
6.	0.639184	0.1827	7.615006
7.	0.604	0.014585	6.423294
8.	0.741437	0.160839	8.345794
9	0.494241	0.021962	6.737523

Table 11: Grey relation coefficient ξ0i and Grey relation grad γ

Exp. No.	Deviation sequence			Grey relation grad γ
	Kf.	Prep.	s/mm	
1.	0.40355	0.66720	0.90723	0.659325807
2.	1	0.34464	0.89671	0.747117232
3.	0.848143	0.34660	0.92549	0.706743658
4.	0.364132	0.80931	0.83175	0.6683975
5.	0.614449	0.62174	1.00000	0.745395719
6.	0.48978	0.72564	0.85058	0.688666154
7.	0.505118	1	0.94624	0.817119787
8.	0.450062	0.75248	0.80093	0.667824547
9	0.559807	0.98368	0.91899	0.820825602

It is possible to separate the effect of each of the process variables on GR grade at different levels. This can be calculated by obtaining the average of the GR gradefor theexperiments where that certain parameter level has been executed. Table11presents the resulting output effect of the input processvariables on GR grade. The parameter level, that leads to desired values of the process performance measures, is the level of maximum grade of the Grey analysis.The impact of all the individual cutting variable can be further clearly demonstrated by presenting theirGrey relational grade graphin Figure 4. It highlights the variation in the output response, in relation to the factors change from level one to level three. In this figure, the greater the values of the grade give the better value of the parameter under optimisation.

The highest grade in the Grey relation response of Table 12,the optimal cutting parametersare highlighted. The corresponding process values are traverse feed velocity at 350mm/min, pulse height at 80%, pulse duration at 1 ms. and pulse frequency at 50Hz.

5.4. RESULTS VERIFICATION

Experimental verification was carried out using the updated parameters. The results of the verification tests were measured and are listed in Table 13. It can be seen from these results that the Grey relation analysis was successful in obtaining better results for the quality measure under investigation compared with the values for the first stage.

5.5. Conclusions

1. In this work Taguchi method was utilized to minimise the number of experiments required for the optimisationof the output inNd-YAG Crystal laser cutting operation of Inconel-718 super alloy.
2. Grey relation analysis was employed to find the optimal values of the process variables for improving multi-process measures.
3. The optimized values were verified experimentally and the measures under investigation were improved using the recommended values.

4. The optimal cutting parameters were; atraverse feed velocity at 350mm/min., pulse height at 80%, pulse duration at 1 ms. and the pulse frequency at 50Hz. This led to minimum κerf width, perpendicularity and maximum number of striation/ mm.

5. The same methodology can be used to optimize more aspects of the same process and other configurations of workpieces.

Table 12: Grey relational grade response table

Parameter.	Deviation sequence		
	Level 1.	Level 2.	Level 3.
Pulse height.	0.70440	0.70082	0.768589979
Pulse duration.	0.71495	0.72011	0.738745138
Pulse frequency.	0.67194	0.74545	0.756419722
Traverse feed velocity.	0.74185	0.75097	0.680988568

Table 13: Experimental results of the verification test

Kf.	Perp.	Striation /mm.
0.906	0.137	13.61

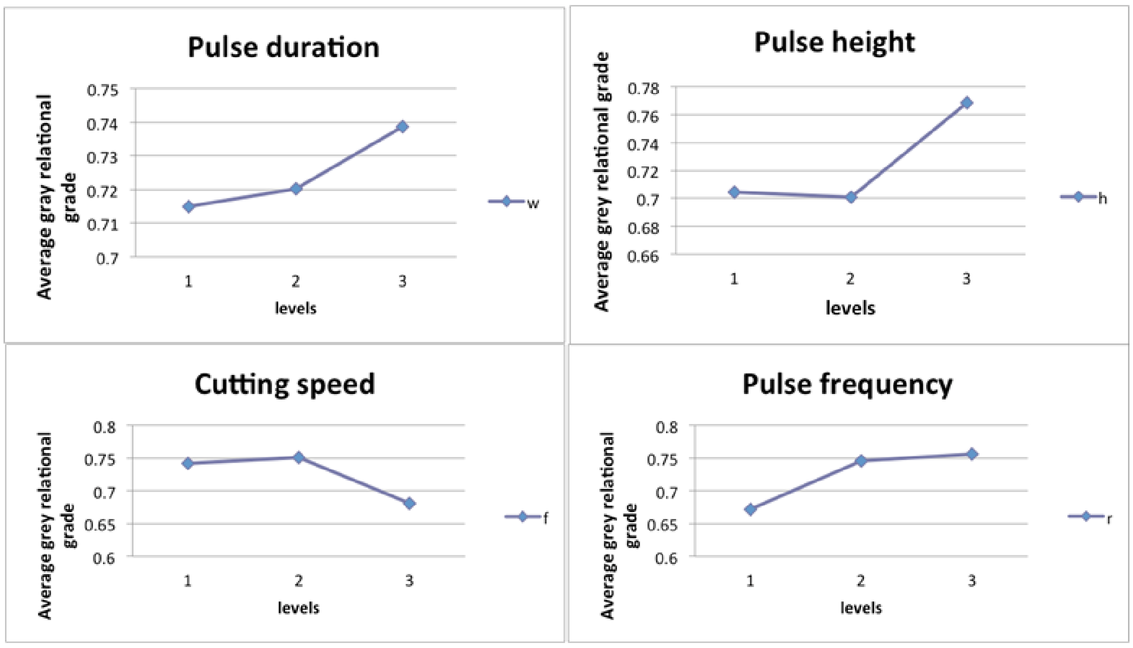


Fig.5: Grey relational grade graphs for laser cutting parameters

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