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GRA APPROACH FOR MULTI-OBJECTIVE OPTIMIZATION OF LASER CUTTING

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Laser cutting is a complex multi-input multi-output machining process. To satisfy different requirements regarding laser cut quality it is necessary to determine optimal laser cutting conditions. This paper demonstrates the application of the grey relational analysis for optimization of different laser cut quality characteristics such as the depth of separation line, drag line separation and burr height. Laser nitrogen cutting of a 3 mm thick AISI 304 stainless steel was performed on a 2.2 kW CO_2 laser cutting system. The laser cutting experiment was planned and conducted according to the Taguchi's L_{27} experimental design. Four cutting parameters such as laser power, cutting speed, assist gas pressure and focus position were considered for multi-objective optimization. The results indicate that optimized and non-optimized laser cutting conditions produce drastically different cut quality characteristics.

Keywords: CO_2 laser cutting, multi-objective optimization, grey relational analysis, cut quality characteristics.

1. Introduction

Laser cutting is a thermal, non-contact, and automated process well suited for various manufacturing industries where a variety of components in large numbers are required to be machined with high dimensional accuracy and surface finish [1]. High cutting speed, superior cut quality and low machining costs made laser cutting to become competitive to existing methods of contour cutting.

Laser cutting is a complex machining process characterized by a number of interacting input parameters which have variable and distinct effect on different performance measures. In laser cutting, for each workpiece material and specimen thickness, they are different laser cutting system and laser process parameters that have to be properly adjusted. Laser cutting system parameters are those related to the type of laser cutting machine (wavelength maximal output power, mode, spatial and temporal distribution of power, power stability), laser beam (diameter of the laser beam, laser beam quality (M2) factor, polarization), cutting head (focusing system) and coordinate work table (table positioning accuracy, precision of movement, spatial mobility). Laser process parameters can be divided into

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changeable, which can be easily controlled during the laser processing operation (laser power, cutting speed and assist gas pressure), and unchangeable such as focus position, type and purity of the assist gas, nozzle diameter and stand-off distance [2]. Performance measures of laser cutting as technological and techno-economical objective functions include different process, quality, productivity and economical categories.

In laser cutting, examination of cut surface provides valuable information about quality performance measures i.e. cut quality characteristics such as surface roughness, striations, grooves, heat affected zone, burr formation and other metallurgical characteristics. It has been widely reported that these cut quality characteristics change drastically with the slight change in laser cutting parameter values. Moreover, it is often the case that the (near) optimal laser cutting parameter values for one cut quality characteristic deteriorate other cut quality characteristics [1].

To satisfy different requirements regarding laser cut quality characteristics necessitates the need for solving multi-objective optimization problems. To this aim there are two general approaches. The first is based on the integration of mathematical models (analytical, empirical or semi-empirical) with classical or modern optimization methods. The second involves the combination of weighed sum method, grey relational analysis (GRA), principal component analysis (PCA) and fuzzy logic with the Taguchi method.

Madić et al. [3] presented empirical modeling and optimization of surface roughness in CO_2 laser nitrogen cutting of stainless steel using artificial intelligence methods. The surface roughness prediction mathematical model was developed by using the artificial neural network (ANN) trained with gradient descent with momentum algorithm. Statistically assessed as adequate, the ANN model was integrated with simulated annealing algorithm in order to determine optimal laser cutting parameters which minimize surface roughness. Sivarao et al. [4] reported multi-objective optimization of laser cutting process by employing response surface methodology (RSM) with desirability approach. Surface roughness and kerf width were considered as objective functions. Pandey and Dubey [5] applied regression analysis and genetic algorithm for modeling and optimization of kerf taper and surface roughness in laser cutting of titanium alloy. Dubey and Yadava [6] demonstrated hybrid Taguchi method and RSM can be applied to multi-optimization of Nd:YAG laser cutting. Simultaneous optimization of the kerf width and material removal rate (MRR) was based on second-order RSM models. The authors noted that the hybrid approach gives better quality results as compared to only Taguchi method. Dubey and Yadava [7] applied a combined approach based on Taguchi method and PCA for multi-objective optimization of Nd:YAG laser cutting process. Their investigation included the analysis of the laser cutting parameters on the cut quality characteristics such as kerf width, kerf deviation, and kerf taper. Sharma and Yadava [8] applied integrated approach of Taguchi method and GRA coupled with entropy measurement methodology for multi-objective optimization of pulsed Nd:YAG laser cutting of thin aluminum alloy. Surface roughness and taper angle were considered laser cut quality characteristics. The entropy measurement methodology was employed for the calculation of weight corresponding to each quality characteristic. Rao and Yadava [9] presented optimization approach based on Taguchi method and GRA with entropy measurement for determining optimum laser cutting parameters which simultaneously minimize the kerf width, kerf taper, and kerf deviation during pulsed Nd:YAG laser cutting of nickel-based superalloy superni 718. Caydaş and Hasçalik [10] applied the same approach to determine optimum laser cutting parameters (cutting speed and laser power) with multi-performance characteristics (surface roughness, kerf width, and HAZ) during CO_2 laser cutting of mild steel sheet.

This paper demonstrates the application of the GRA approach for optimization of different laser cut quality characteristics such as the depth of separation line, drag line separation and burr height. CO_2 laser cutting experiment of cutting AISI 304 stainless steel with thickness of 3 mm was planned and conducted in accordance with Taguchi's L_{27} experimental design. In solving multi-objective optimization problem, four cutting parameters such as laser power, cutting speed, assist gas pressure and focus position were considered.

2. Material and experimental details

Laser cutting experimental trials were conducted in real manufacturing environment on CO_2 laser cutting machine (Bystronic, ByVention 3015) with a maximal power of 2.2 kW. AISI 304 stainless steel plate with thickness of 3 mm was used as a workpiece. Straight cuts of 60 mm in length each were performed with a Gaussian distribution beam mode (TEM_{00}) in continuous wave mode. In experimentation the following process parameters were constant: lens focal length of 127 mm, nozzle diameter of 2 mm, standoff distance of 1 mm and nitrogen as assist gas with purity of ≥ 99.95 % was used in all experimental trials. By varying the laser power – P, cutting speed – v, assist gas pressure – p, and focus position – f at three levels in accordance with the standard L_{27} (3^{13}) Taguchi's orthogonal array, twenty-seven experimental trials were performed (Table 1).

The quality of the cut surface was assessed by microscopic analysis of laser cut surface patterns by measuring the depth of separation line (d), drag line separation (n) and burr height (b). In general, the laser cut surfaces display two distinct striation patterns: from the top to a depth d where the striations are well formed, distinct and regular; and below a depth d where the flow streams tend to merge and regularity is lost [11]. When laser cutting parameter settings are perfectly adjusted, it is possible to obtain cut with an extremely smooth and flat surface, where drag lines are not readily apparent and the serrations are very shallow. However, in practice, this is very difficult to achieve and drag lines are usually evident to some extent. From the techno-economical point of view, burr formation can be regarded as one of the most important criterion for assessing the laser cutting performance.

Table 1

Experimental design and measured responses

Exp. trial	Natural factor				Coded factor				Experimental results		
	P	*v*	*p*	*f*	A	B	C	D	Burr height, *b*	Drag line separation, *n*	Depth of separation line, *d*
	(kW)	(m/min)	(bar)	(mm)					(mm)	(mm)	(mm)
1	1.6	2	9	-2.5	1	1	1	1	0.07	0.19	2.58
2	1.6	2	10.5	-1.5	1	1	2	2	1.53	0.15	2.54
3	1.6	2	12	-0.5	1	1	3	3	1.25	0.21	1.95
4	1.6	2.5	9	-1.5	1	2	1	2	1.42	0.23	2.00
5	1.6	2.5	10.5	-0.5	1	2	2	3	1.37	0.10	1.78
6	1.6	2.5	12	-2.5	1	2	3	1	0.05	0.05	1.14
7	1.6	3	9	-0.5	1	3	1	3	1.05	0.21	1.56
8	1.6	3	10.5	-2.5	1	3	2	1	0.11	0.21	1.10
9	1.6	3	12	-1.5	1	3	3	2	0.65	0.14	1.92
10	1.8	2	9	-1.5	2	1	1	2	1.37	0.31	2.05
11	1.8	2	10.5	-0.5	2	1	2	3	1.22	0.01	3.00
12	1.8	2	12	-2.5	2	1	3	1	0.08	0.05	1.91
13	1.8	2.5	9	-0.5	2	2	1	3	1.38	0.01	3.00
14	1.8	2.5	10.5	-2.5	2	2	2	1	0.13	0.10	1.03
15	1.8	2.5	12	-1.5	2	2	3	2	1.35	0.10	2.22
16	1.8	3	9	-2.5	2	3	1	1	0.06	0.14	1.08
17	1.8	3	10.5	-1.5	2	3	2	2	1.11	0.17	1.82
18	1.8	3	12	-0.5	2	3	3	3	1.64	0.21	1.69
19	2	2	9	-0.5	3	1	1	3	1.58	0.01	3.00
20	2	2	10.5	-2.5	3	1	2	1	1.23	0.21	2.54
21	2	2	12	-1.5	3	1	3	2	1.45	0.37	2.34
22	2	2.5	9	-2.5	3	2	1	1	0.96	0.22	1.63
23	2	2.5	10.5	-1.5	3	2	2	2	1.19	0.30	2.23
24	2	2.5	12	-0.5	3	2	3	3	1.46	0.01	3.00
25	2	3	9	-1.5	3	3	1	2	1.30	0.18	1.88
26	2	3	10.5	-0.5	3	3	2	3	1.61	0.05	1.79
27	2	3	12	-2.5	3	3	3	1	0.06	0.07	1.50

The depth of separation line (d), drag line separation (n) and burr height (b) evaluation was carried out on a photo of each cut sample with the aid of stereo microscope (KONUS, Diamond #5420, magnification 40 X) (Fig. 1). The measurements were made at five equally distanced positions along the photo of cut sample and the average values were calculated and stored.

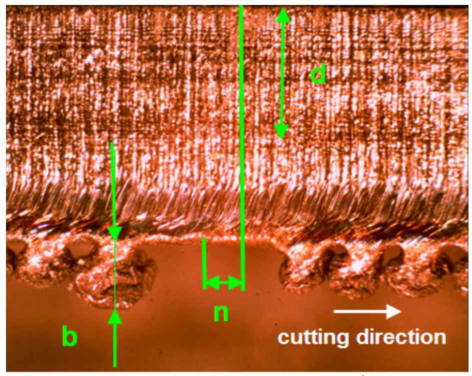


Fig. 1. Cut quality characteristics obtained in the 21st experimental trial

The data points at which measurements were made are displayed in Fig. 2. As could be observed points are scattered in experimental space which necessitates the multi-objective optimization of cut quality characteristics.

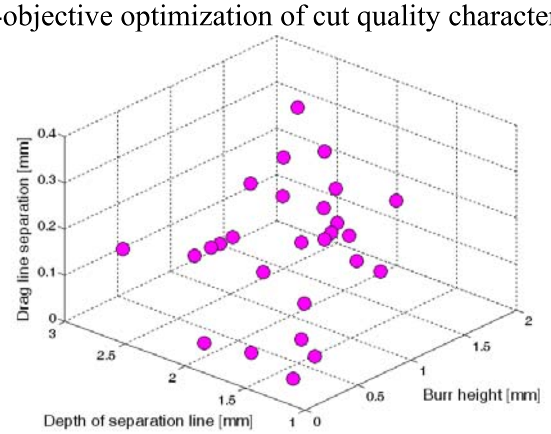


Fig. 2. Correlation between multiple cut quality characteristics based on experimental measurements

3. Grey relational analysis

The grey relational analysis (GRA), based on grey system theory proposed by Deng [12], represents an effective and powerful tool for the analysis of processes/systems which are characterized by multiple performance characteristics. Application of GRA consists of the three basic steps: (1) data pre-processing, (2) calculation of the grey relational coefficients and (3) calculation of the overall grey relational grade (GRG) by using the weighting coefficient for the performance characteristics (responses).

After GRG has been calculated, subsequent analysis includes: (*i*) Analysis of variance (ANOVA) using calculated GRG values in order to find which parameters and their interactions significantly affect the multiple performance characteristics, (*ii*) Selection of the optimal combination of parameter levels so as to yield higher GRG, and (*iii*) Conducting confirmation experiment trials in order to verify the optimal combination of parameter levels.

The first step in GRA is the data pre-processing. Data pre-processing is the process of transforming the original sequence to a comparable sequence [13]. Data preprocessing is normally required since the range and unit in one data sequence may differ from the others [8]. A set of original experimental results for multiple quality characteristics are thus normalized between zero and one in the process called grey relational generation. Depending on the nature of the quality characteristic different types of data normalization exists.

When the aim is to make the response as small as possible (e.g. surface roughness, cost), then the original sequence should be normalized as follows:

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

If the goal is "larger-the-better" (e.g. material removal rate), then the original sequence is normalized as follows:

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

where i=1,...,n, k=1,...,m, where n is the total number of experiment trials, m is the number of quality characteristics considered, $x_i^*(k)$ is the normalized value of the k^{th} response in the i^{th} sequence, $min\, x_i(k)$ is the smallest value of $x_i(k)$ for the k^{th} response, and $max\, x_i(k)$ is the largest value of $x_i(k)$ for the k^{th} response.

Following grey relational generation, a grey relational coefficient is calculated to express the relationship between the ideal sequence $x_0^*(k)$ and actual normalized experimental results. The grey relational coefficients can be calculated using the following equation [13]:

$$\gamma_{0,i}(k) = \frac{\Delta_{\min} + \zeta \cdot \Delta_{\max}}{\Delta_{0,i}(k) + \zeta \cdot \Delta_{\max}}, \quad 0 \le \gamma_{0,i}(k) \le 1, \; i = 1,...n, \; k = 1,...m. \tag{3}$$

where $\Delta_{0,i}(k)$is the difference of the absolute values of $x_0^*(k)$ and $x_i^*(k)$ i.e.: $\Delta_{0,i} = \left\| x_0^*(k) - x_i^*(k) \right\|$, $\Delta_{max} = \max_i \max_k \left\| x_0^*(k) - x_i^*(k) \right\|$, $\Delta_{\min} = \min_i \min_k \left\| x_0^*(k) - x_i^*(k) \right\|$, where $\zeta \in [0,1]$ is the distinguishing or identification coefficient which is used to adjust the difference of the relational coefficient [12].

After obtaining the grey relational coefficients, for computing the GRG, it is usual to adopt the average value of grey relational coefficients. However, in real engineering system the importance of each quality characteristic may be different [7]. Thus, GRG can be represented as a weighted sum of the grey relational coefficients:

$$\Gamma_i = \sum_{i=1}^{n} w_k \cdot \gamma_{0,i}(k), \sum_{k=1}^{m} w_k = 1, i = 1,...n, k = 1,...m. \quad (4)$$

where w_k is the weighting coefficient of the k^{th} response (quality characteristic).

Higher the GRG, the corresponding parameter combination is closer to the optimal. The parameter combination which yields the highest GRG is assigned a rank of 1, while the other parameter combinations, based on GRG, can be ranked in descending order.

4. Results and discussion

In the present study, burr height, drag line separation and depth of separation line were measured for different combinations of laser cutting parameter values. It is desired to minimize burr height and drag line separation and maximize depth of separation line. Therefore, the data sequences have a “smaller-the-better” characteristic for burr height and drag line separation and “larger-the-better” characteristics for depth of separation line. Table 2 lists all of the sequences following data pre-processing using Eq. 1 for burr height and drag line separation and Eq. 2 for depth of separation line. The results for all $\Delta_{0,i}(k)$ values i.e. deviation sequences are also given in this table.

Grey relational coefficients and overall GRG for each experimental trial were calculated by applying Equations. 3 and 4 and are given in Table 3. Thereby, considering that the burr height is of prime importance, weighting coefficients of 0.25 were used for drag line separation and depth of separation line, and weighting coefficient of 0.5 was used for burr height in Eq. 4.

The results from Table 3 indicate that the laser cutting condition that corresponds to experimental trial 12 has the highest overall GRG.

To calculate main effects of each parameter on the GRG, the analysis of means (ANOM) was employed [14]. The effect of parameter C at level l can be calculated using the following equation:

$$\overline{\Gamma}_{C_l} = \frac{1}{n_{C_l}} \cdot \sum_{i=1}^{n_{C_l}} \left[\Gamma_{C_l}\right]_i \quad (5)$$

where n_{C_l} is the number of appearances of parameter C at level l in the experimental plan and Γ_{C_l} is the GRG related to parameter C at level l.

Table 2

Grey relational generation of cut quality characteristics and $\Delta_{0,i}(k)$ deviation sequences

Exp. trial no.	Burr height, *b*	Drag line separation, *n*	Depth of separation line, *d*	$\Delta_{0,i}(1)$	$\Delta_{0,i}(2)$	$\Delta_{0,i}(3)$
Reference sequence	Ideal sequence					
	1	1	1			
1	0.987	0.491	0.787	0.013	0.509	0.213
2	0.069	0.598	0.766	0.931	0.402	0.234
3	0.245	0.440	0.467	0.755	0.560	0.533
4	0.138	0.376	0.492	0.862	0.624	0.508
5	0.170	0.743	0.381	0.830	0.257	0.619
6	1.000	0.892	0.056	0.000	0.108	0.944
7	0.371	0.437	0.269	0.629	0.563	0.731
8	0.962	0.436	0.036	0.038	0.564	0.964
9	0.623	0.627	0.452	0.377	0.373	0.548
10	0.170	0.160	0.518	0.830	0.840	0.482
11	0.264	1.000	1.000	0.736	0.000	0.000
12	0.981	0.901	0.447	0.019	0.099	0.553
13	0.164	1.000	1.000	0.836	0.000	0.000
14	0.950	0.741	0.000	0.050	0.259	1.000
15	0.182	0.746	0.604	0.818	0.254	0.396
16	0.994	0.636	0.025	0.006	0.364	0.975
17	0.333	0.544	0.401	0.667	0.456	0.599
18	0.000	0.438	0.335	1.000	0.562	0.665
19	0.038	1.000	1.000	0.962	0.000	0.000
20	0.258	0.443	0.766	0.742	0.557	0.234
21	0.119	0.000	0.665	0.881	1.000	0.335
22	0.428	0.405	0.305	0.572	0.595	0.695
23	0.283	0.198	0.609	0.717	0.802	0.391
24	0.113	1.000	1.000	0.887	0.000	0.000
25	0.214	0.524	0.431	0.786	0.476	0.569
26	0.019	0.887	0.386	0.981	0.113	0.614
27	0.994	0.839	0.239	0.006	0.161	0.761

For example, the GRG for factor A at level 1 can be calculated as follows:

$$\overline{\Gamma}_{A_1} = \frac{1}{9}(0.787 + 0.484 + 0.438 + 0.419 + 0.465 + 0.792 + 0.411 + 0.668 + 0.547) = 0.56$$

Using the same method, calculations were performed for other parameters at each level and response graph was generated as shown in Figure 3.

The response graphs show the change in the response when a given parameter goes from lower level to higher level. From these graphs one can assume the optimal combination of process parameters. Fig. 3 clearly suggests a dominant influence, in a quantitative sense, of focus position on the GRG.

Table 3

Grey relational coefficients and overall grey relational grade

Exp. trial no.	Burr height, *b*	Drag line separation, *n*	Depth of separation line, *d*	Grey relational grade, $\Gamma_{o,i}$	Rank
	Grey relational coefficients				
1	0.975	0.496	0.701	0.787	3
2	0.349	0.554	0.682	0.484	16
3	0.398	0.472	0.484	0.438	23
4	0.367	0.445	0.496	0.419	24
5	0.376	0.661	0.447	0.465	17
6	1.000	0.823	0.346	0.792	2
7	0.443	0.470	0.406	0.441	21
8	0.930	0.470	0.341	0.668	11
9	0.570	0.573	0.477	0.547	12
10	0.376	0.373	0.509	0.408	26
11	0.405	1.000	1.000	0.702	6
12	0.964	0.835	0.475	**0.809**	**1**
13	0.374	1.000	1.000	0.687	8
14	0.909	0.659	0.333	0.702	7
15	0.379	0.663	0.558	0.495	13
16	0.988	0.579	0.339	*0.723*	*5*
17	0.429	0.523	0.455	0.459	18
18	0.333	0.471	0.429	**0.392**	**27**
19	0.342	1.000	1.000	0.671	10
20	0.403	0.473	0.682	0.490	14
21	0.362	0.333	0.599	0.414	25
22	0.466	0.456	0.418	0.452	19
23	0.411	0.384	0.561	0.442	20
24	0.361	1.000	1.000	0.680	9
25	0.389	0.512	0.468	0.439	22
26	0.338	0.816	0.449	0.485	15
27	0.988	0.756	0.396	0.782	4

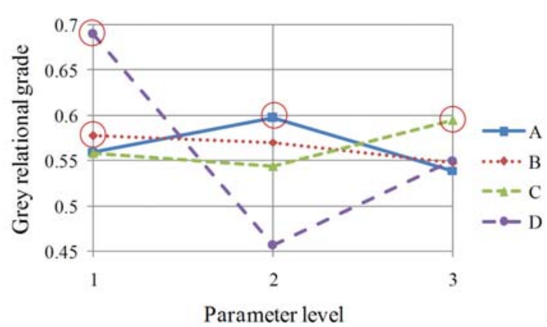


Fig. 3. Effects of laser cutting parameters on multiple cut quality characteristics

The optimum level for a parameter is the level that gives the highest value GRG. From Fig. 3, levels 2, 1, 3 and 1 have the highest value of GRG for parameters A, B, C and D, respectively. Therefore, $A_2B_1C_3D_1$ represents the optimal parameter level combination for the laser cutting process in satisfying multiple cut quality characteristics. In terms of natural values, the optimal laser cutting parameter values corresponding to maximal value of GRG are: laser power of 1.8 kW, cutting speed of 2 m/min, assist gas pressure of 12 bar and focus position of -2.5 mm.

In order to find the relative contribution of each laser cutting parameter on the GRG and estimate the error variance, the statistical analysis through ANOVA was performed. The results of ANOVA are shown in Table 4.

Table 4

Results of ANOVA for grey relational grade

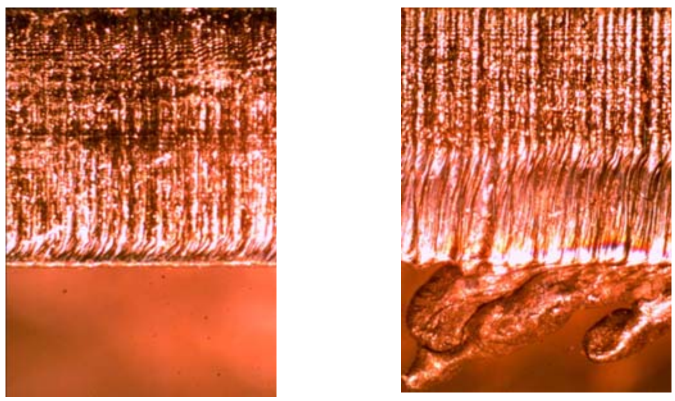
Source of variation	DOF	Sum of squares (SS)	Mean square (MS)	F	p	Percentage contribution
A	2	0.015632	0.007816	1.17	0.373	2.9
B	2	0.0043	0.00215	0.32	0.737	0.8
C	2	0.012133	0.006066	0.91	0.453	1.12
D	2	0.247261	0.123631	18.49	0.003	45.84
A×D	4	0.09642	0.024105	3.61	0.079	17.88
B×D	4	0.064375	0.016094	2.41	0.161	11.94
C×D	4	0.059178	0.014795	2.21	0.184	10.97
Error	6	0.04011	0.006685			7.44
Total	26	0.53941				

The percentage contributions of each parameter to the total variance are focus position 45.84%, laser power 2.9%, assist gas pressure 1.12% and cutting speed 0.8%. It can be also observed that the ANOVA has resulted in around 7.44% of error contribution due to other interaction effects (not included in the analysis) and noise (uncontrollable) effects. Although the main effects of laser power, cutting speed and assist gas pressure can be almost neglected, it can be observed that their interaction effects with the focus position are much more pronounced resulting in around ~~of~~ 41% of total contribution. These interactions indicate that the overall effects of laser power, cutting speed and assist gas pressure on the multiple cut quality characteristics are primary dependent on the focus position. Strong influence of interaction effects on the GRG is due to the fact that laser cutting parameters differently affect cut quality characteristics and that the laser cutting process is sensitive to slight change in independent input parameter values.

The optimal laser cutting conditions have to be verified through conducting a confirmation experimental trial to see if the error caused by the interaction among the laser cutting parameters is within an acceptable tolerance.

However, in this study it can be found that the optimal combination of laser cutting parameter levels ($A_2B_1C_3D_1$) is already included in the experimental matrix and corresponds to the experimental trial no. 12 in Table 1.

It is possible to see the drastic difference in the surface patterns produced at the optimal combination of laser cutting parameter levels (with the highest GRG of Γ = 0.809) and the one which yields the smallest GRG of Γ = 0.392 (experimental trial no. 18) in Figure 4.



a) P=1.8 kW, v=2 m/min, p=12 bar, f=-2.5 mm b) P=1.8 kW, v=3 m/min, p=12 bar, f=-0.5 mm

Fig. 4. Comparison of laser cut surface patterns with optimized and non-optimized cutting conditions

5. Conclusions

This study presents the microscopic analysis of laser cut surface characteristics and GRA based multi-objective optimization of CO_2 laser cutting process. On the basis of the experimental and optimization results and derived analysis the following conclusions were drawn:

- focus position has the most dominant effect on the grey relational grade, as a summary measure for assessing the burr height, depth of separation line and drag line separation. The effects of laser power, assist gas pressure and cutting speed are not significant; however its interaction effects with focus position are statistically significant,
- based on GRA results it is beneficial to focus laser beam deep into the bulk of material (-2.5 mm) while using the combination of the highest level of assist gas pressure (12 bar), intermediate level of laser power (1.8 kW) and lowest level of cutting speed (2 m/min),
- considering economic reasons and productivity, the optimal combination of laser cutting parameters is: laser power P = 1. 8 kW, cutting speed v = 3 m/min, assist gas pressure p = 9 bar, and focus position f = -2.5 mm.

In mass production application of laser cutting technology, where the complexity of laser machining process requires taking into account various process parameters and process performance measures at the same time as well as their optimization, the application of grey relational analysis provides a systematic, easy-to-use approach that can be readily implemented in real manufacturing environment.

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