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MULTI-OBJECTIVE OPTIMIZATION OF ROUNDNESS AND POSITIONAL ERRORS IN CO2 LASER CUTTING OF HOLES IN AISI 316L STAINLESS STEEL

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In laser cutting, there is often a need to determine a compromise cutting conditions with respect to existing different process performance characteristics. This paper is focused on multi-objective optimization of dimensional accuracy characteristics of holes cut in AISI 316L stainless steel by CO_2 laser. Laser cutting experiment, conducted according to 3^2 factorial experimental design, provided a set of data for development of third-order (cubic) polynomials for establishing relationship between process inputs (severance energy and assist gas flow) and outputs (roundness and positional errors). Multi-objective optimization problem was formulated using desirability function approach (DFA) using a novel desirability function, while graphical optimization was used to identify optimum laser cutting conditions. Analysis of contour plot of the overall desirability function revealed that lower assist gas flows and middle to high severance energy levels is beneficial for dimensional accuracy of laser cut holes.

Keywords: CO_2 laser cutting, dimensional accuracy, multi-objective optimization, DFA, AISI 316L.

1. Introduction

Laser cutting is of the most important laser material processing technologies and one of the leading contour cutting technologies in modern industry. Due to numerous advantages and possibilities that this technology offers, such as precision, low heat input, no vibration, minimal distortion, capability to be controlled automatically, great diversity of processed materials, low processing cost, etc. [1, 2], a large number of companies use this technology for cutting of wide spectrum of materials, predominantly stainless steels using nitrogen and mild steels using oxygen as assisting gas.

Like many other manufacturing technologies laser cutting process is characterized by complex and multiple physical phenomena. By altering some of the main process parameters multiple involved physical phenomena, such as, absorption, heat transfer, melting, heating, fluid dynamics, etc. [3], are changed,

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which in turns directly is reflected to a number of process performances from different categories. However, effective application of this technology means finding the best possible solutions, i.e., laser cutting regimes, for a given case study. Therefore, by formulating and solving multi-objective optimization models one would enable companies to get the most out of this technology, with the ultimate aim of better positioning on the market and achieving higher revenues.

A number of different techniques, methods and approaches are applied, being developed and studied with respect to determining the most appropriate laser cutting conditions considering multiple and opposite performance characteristics which may be of different importance. Some of the recent multi-objective optimization studies in laser cutting are summarized in Table 1.

Table 1

Summary of recent multi-objective optimization studies in laser cutting

Reference	Laser technology/method	Sheet material / thickness	Objective functions	Optimization method
[4]	CO_2 / FC	(CFRP) composites / 3, 3.5, 4.5 mm	KT, SR	DFA
[5]	Fiber / FC	SS 304L / 1.5 mm	KW, SR	NSGAII
[6]	Nd:YAG / FC	AA1200 / 1.2 mm	KW, KD, SR, MRR	PSO
[7]	Fiber / FC	SS 304L / 20 mm	SR, KW	TM-GRA
[8]	Fiber / FC	GFRP / 3 mm	KW, KT, SR	NSGA
[9]	Fiber / FC	GFRP / 4.5 mm	KW, KT, HAZ	DFA
[10]	Fiber / FC	Ti6Al4V / 3 mm	MRR, SR, KW, DH	HTS
[11]	CO_2 / FC	SS 304 / 1.5 mm	KW, MRR, H	TM-GRA
[12]	Nd:YAG / FC	BFRP / 1.6 mm	KW, KD, KT	FA
[13]	CO_2 / FC	SS347	MT, HAZ, SR	TOPSIS
[14]	Nd:YAG / FC	SS 304 / 0.8 mm	SR, DE, DH	DFA
[15]	CO_2 / FC	PLA / 4 mm	KT, SR	MOGWO
[16]	CO_2 / FC	PMMA / 4 mm	SR, DA	DFA
[17]	CO_2 / FC	AA AlMg3 / 4 mm	SR, KW	TM-GRA
[18]	CO_2 / FC	AA 6061 / 3 mm	SR, KW, KT	PSO, GA
[19]	Nd:YAG / FC	Hastelloy C276 / 3 mm	KT, MRR, SR	WOA
[20]	Fiber / RC	A653 galvanized steel / 0.5 mm	KW, KD, MRR	DFA

FC – fusion cutting, RC – reactive cutting;
CFRP – carbon fiber-reinforced polymer, SS – stainless steel, AA – aluminum alloy, GFRP – glass fiber reinforced plastic, BFRP – basalt fiber reinforced polymer, PLA – polylactide, PMMA – polymethyl methacrylate;
KT – kerf taper, SR – surface roughness, KW – kerf width, KD – kerf deviation, MRR – material removal rate, HAZ – heat affected zone, DH – dross height, H – hardness, MT – machining time, DE – dimensional error, DA – dimensional accuracy;
DFA – desirability function approach, NSGAII – non-dominated sorting genetic algorithm, PSO – particle swarm optimization, TM – Taguchi method, GRA – grey relational analysis, HTS – Heat transfer search algorithm, FA - firefly algorithm, TOPSIS – technique for order of preference by similarity to ideal solution, MOGWO - multi-objective grey wolf optimization algorithm, GA – genetic algorithm, WOA – whale optimization algorithm;

Most of the reviewed multi-objective laser cutting optimization studies considered CO_2 and fiber fusion cutting of metaling materials while considering kerf geometrical and surface quality characteristics with only few research studies addressing the issues of the dimensional accuracy. In order to solve proposed optimization problems different optimization approaches were applied with classical desirability function approach (DFA) and numerous metaheuristic algorithms being the most common.

The laser cutting process capability, defined in terms of dimensional tolerance of a feature, is dependent on several factors, including laser cutting parameters, material thickness and properties, positioning accuracy of the machine, feature size and shape and laser-material interaction phenomena [21]. Given that dimensional accuracy is becoming an important aspect in any manufacturing process, as it indicates how accurate dimensions are achieved compared to nominal dimensions [22], the present study deals with multi-objective optimization of roundness and positional errors of holes cut in AISI 316L stainless steel by CO_2 laser. To model the relationship between process parameters and considered responses third-order (cubic) polynomials were developed while the multi-objective optimization problem was formulated using DFA using a novel desirability function [23, 24]. Graphical optimization was used to identify optimum laser cutting conditions in the covered experimental space.

2. Experimental setup

2.1. Machine, experimental design

A CO_2 laser system developed by Prima Industry (Italy) was used for realization of experiment. The experimental design considered two factors, namely severance energy (E_s) and assist gas flow (Q). In the experiment trials were run based on factorial design 3^2. Severance energy was changed at three levels, E_s=[16, 32, 48] J/mm^2, assist gas flow also at three levels, Q=[10.17, 12.02, 13.87] m^3/h, resulting in total of nine trials with two replicates. The initial process settings were taken as manufacturing recommendations and coincided with middle factor settings. The factors set at constant levels during experiment are workpiece material type and thickness (AISI 316L stainless steel, 2 mm), assist gas type and purity (N_2, 5.0), laser power (2 kW), nozzle diameter (1.5 mm), stand-off distance (0.7 mm), laser beam mode (TEM_{00}) and lens focal length (190.5 mm).

2.2. Performance characteristics and measurement system

The selection of appropriate laser cutting regime, i.e., certain combination of main laser cutting parameter values, has significant multi-impact effect on different cut quality characteristics and other process performances. Unlike majority of previous studies, which were predominantly focused on multi-objective optimization of cut quality characteristics, the present study is focused on multi-objective optimization of hole dimensional accuracy. To this aim, in experimental trials for each laser cut hole two dimensional quality characteristics, i.e., roundness error (y_1) and positional error (y_2), were measured (Figure 1).

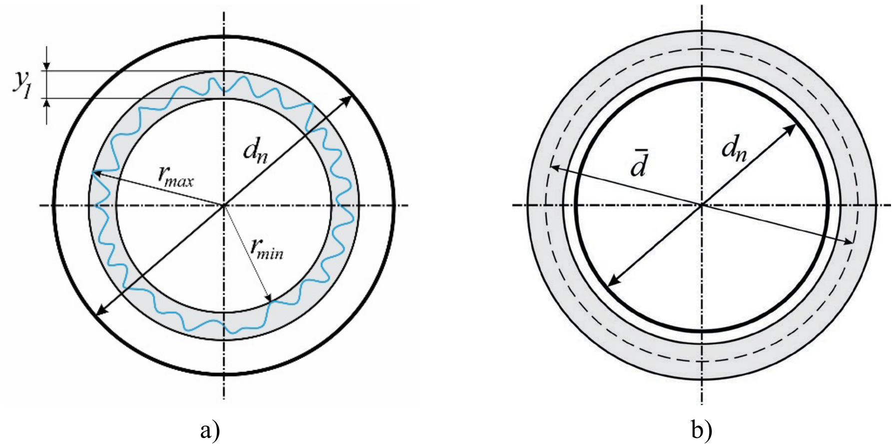


Fig. 1. Experimental setup: a) roundness error, b) positional error

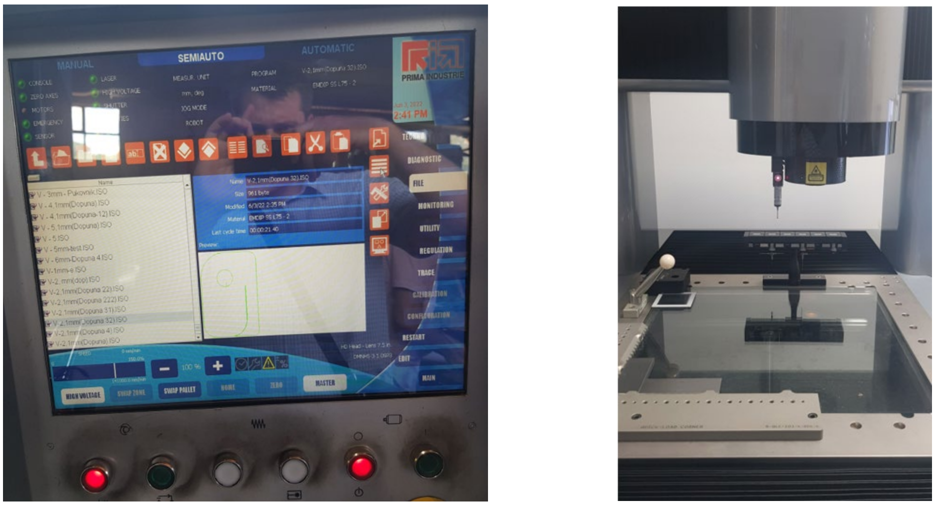
In terms of mathematical models these hole dimensional quality characteristics can be estimated as:

$$y_1 = \frac{(d_{\max} - d_{\min})}{2} = r_{\max} - r_{\min} \tag{1}$$

$$y_2 = \frac{\bar{d}}{d_n} \tag{2}$$

where r_{max} and r_{min} are radii of the two coaxial circles (circumscribed and inscribed) that enclose all of the measurements, $\bar{d}$ is the mean measured hole diameter and d_n is the nominal hole diameter.

As given in equation 1, the minimum zone circle method is used for assessment of roundness error [25]. An optical coordinate measuring machine (CMM) DeMeet 443 was used as a reference measurement system. It has a measuring range of 400 mm × 400 mm × 100 mm and LED based illumination (backlight, coaxial light and segmented ring light) [26] and resolution of 0.1 μm. The optical CMM measuring principle is based on measuring on the picture which is digitized into an array containing information of the light intensity of each pixel [27]. Laser cutting and measurement experimental setup is given in Figure 2.



a) b)

Fig. 2. Experimental setup: a) operator console with specimen design, b) DeMeet 443 CMM

2.3. Data preprocessing

In this work, the experimental data indicate that the considered laser hole dimensional quality characteristics are within the following intervals: $y_1 \in [0.12, 0.25]$ (mm); $y_2 \in [1.006, 1.008]$. For initial parameter settings, i.e., central point in the experiment, measured roundness and positional errors were $y_1 = 0.154$ mm and $y_2 = 1.008$. It should be noted that, as individual desirability function, roundness error belongs to the category smaller-the-better (STB). On the other hand, positional error belongs to the category nominal-the-best (NTB), i.e., the goal is that the ratio of the mean measured hole diameter and nominal hole diameter is equal to 1.

The bounds (and targets) of each response should be determined in advance to define individual desirability functions. These bounds may be chosen arbitrarily in a different way, for instance, on the basis of product/process operating limits, the decision maker's subjective choice, consensus of experts, etc. [24]. In the present study the adopted bounds for both dimensional quality characteristics are given in Table 2.

Table 2

Specification of responses for DFA

Dimensional quality characteristic (response)	Type	y_{min}	Target value, T	y_{max}
Roundness error, y_1	STB	0.05	0.05	0.2
Positional error, y_2	NTB	0.99	1	1.01

3. Mathematical and optimization models

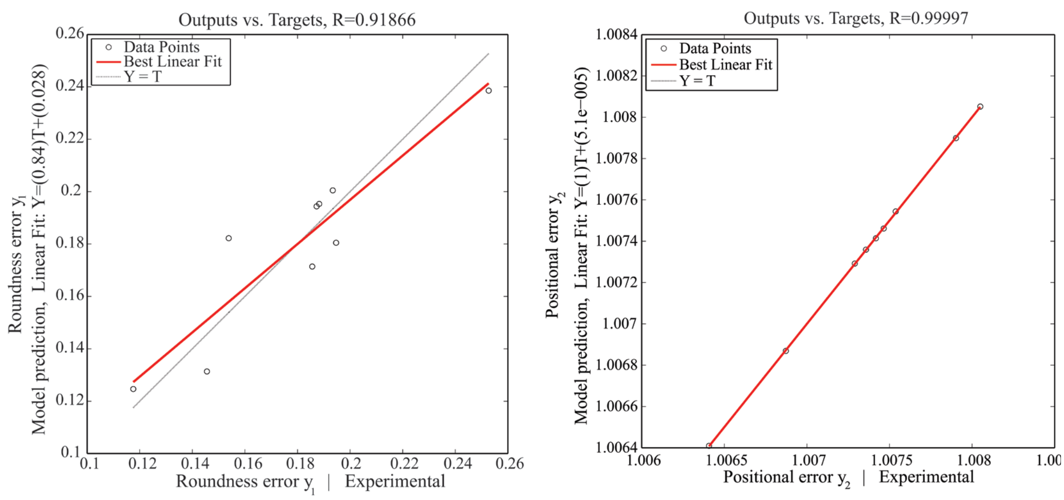
3.1. Empirical mathematical models

Based on conducted experimental research and application of measurement system two third-order (cubic) polynomial empirical mathematical models for relating process factors and considered responses were developed in the following form:

$$y_1 = 0.182 - 0.029E_S + 0.02Q + 0.019E_SQ + 0.027E_S^2 - \\ - 0.031Q^2 + 0.01E_SQ^2 - 0.004E_S^2Q \quad (3)$$

$$y_2 = 1.008 + 0.0005Q - 0.00011E_S^2 - 0.00016Q^2 + \\ + 0.0004E_SQ^2 - 0.00012E_S^2Q \quad (4)$$

For accuracy assessment of the developed prediction models Pearson's correlation coefficient was used as it represents one of the most widely used statistics. In this case, this coefficient measures the strength of correlation between actual versus predicted values of roundness errors and positional errors. As could be observed from Figure 3 the developed empirical models for prediction of roundness and positional errors have high prediction accuracy given their very high correlation coefficient values.



a) b)

Fig. 3. The prediction performance of developed empirical models for prediction of a) roundness error, b) positional error

3.2. Multi-objective optimization model

Once statistically assessed as adequate these empirical models can be used for independent analysis of the main and interaction effects of the severance energy and assist gas flow on resulting roundness and positional errors within the covered experimental space. However, the main focus of the present study is to determine the laser cutting conditions so that roundness and positional errors are simultaneously minimized. In the present study DFA was applied to formulate this multi-objective optimization problem. This methodology is an attractive, easy-to-use, and well-established approach [23] which is based on the combination of desirability functions into overall desirability function using the geometric mean method. In the DFA framework, the following multi-objective laser cutting optimization problem was formulated:

$$\begin{aligned}&\textit{Determine } E_S, Q_a\\&\textit{Maximize } D[d(y_1, y_2)]\\&\textit{subject to}: 0.05 \le y_1 \le 0.2, \quad 0.99 \le y_2 \le 1.01\\&16 \le E_S \le 48[J/mm^2], \quad 10.17 \le Q \le 13.87[m^3/h]\end{aligned} \tag{5}$$

where D is overall desirability and d is the individual desirability function calculated as recommended in recent study [23]. It has to noted that default shape parameter value of r_j=2.5 was used in the formulation of the DFA multi-objective problem for both desirability functions which were considered of equal importance.

4. Results and discussion

There is a number of traditional and metaheuristic algorithms for solving multi-objective optimization problems. Given that in the present experimental research figure only two variables, i.e., severance energy and assist gas flow, graphical optimization represents cost effective solution. Contour plots provide the best graphical representation of the optimization problem defined in terms of two variables [28]. They depict the response surface over the covered two-dimensional experimental space wherein the points on any curve (contour) have the same value of the function. Thus, these plots enhance the examination and visual inspection of the problem at hand. Figure 4 shows a contour plot of the overall desirability function for several contours from which one can easily identify the direction of the maximum.

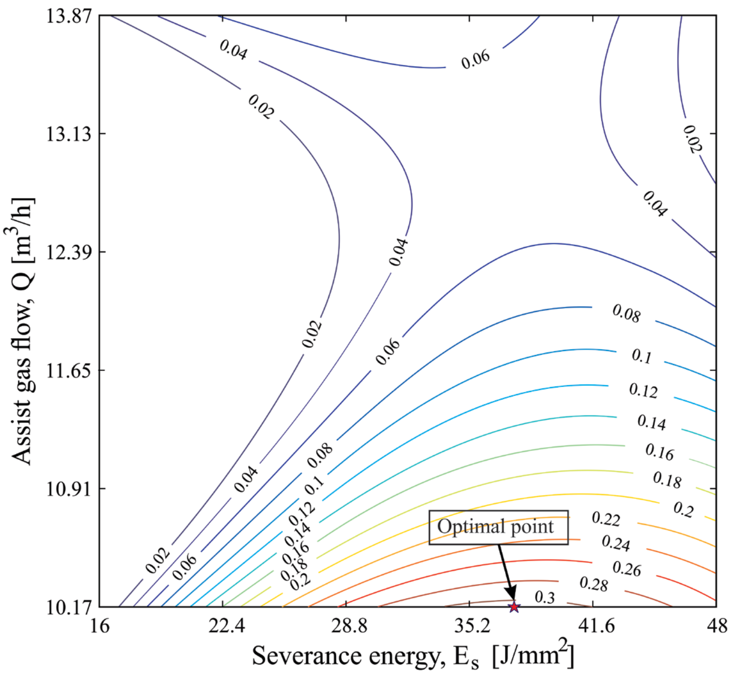


Fig. 4. Contour plot of the overall desirability function

Based on contour lines given in Figure 4, one can observe that combinations of middle to higher severance energy levels and lower assist gas flow rate are beneficial for minimization of roundness and positional error. Actually, having in mind design points used for covering experimental space, it is clear that combination of highest severance energy and lowest assist gas flow (E_s= 48 J/mm^2, Q=10.17 m^3/h, point in the lower right corner in Figure 4) yields highest overall desirability (D=0.264). However, optimization solution with less severance energy of E_s=37.54 J/mm^2 and the same assist gas flow yields a slightly better solution, i.e., within the covered experimental space the maximum overall desirability of D=0.307. Having in mind constant factor values used in the experiment it can be said that combination of factor values: laser power = 3.2 kW, cutting speed = 2.56 m/min, nozzle diameter = 1.5 mm and assist gas pressure = 10 bar, represents the best optimization solution with respect to multi-objective optimization of roundness and positional errors of laser cut holes. Under this cutting regime predicted roundness error is y_1=0.122 mm and positional error y_2=1.007.

The comparison of the obtained results, in terms of considered responses with initial process factor settings which usually overlaps with central point in experimental design, is given in Table 3.

Table 3

Comparison of responses for different laser cutting conditions

	Process inputs				Process outputs		Overall desirability
	P (kW)	v (m/min)	d_n (mm)	p (bar)	y_1 (mm)	y_2	D
Initial process settings	3.2	3	1.5	12	0.154	1.008	0.054
Optimized process settings	3.2	2.56	1.5	10	0.122	1.007	0.307

The results from Table 3 suggest that notably improvement in terms of overall desirability value can be achieved by solving the proposed multi-objective laser cutting optimization problem. However, the greatest benefit is reflected in significant minimization of the roundness error, that is the width of the field in which the actual hole diameter lies, whereas only minor improvement is made considering the minimization of the positional error. Here it should be noted that the search for other possible multi-objective optimization solutions can consider adjustment of weighting factors of individual desirability functions and/or changing default shape parameter value.

In referential literature high sensitivity of the cutting process to small variations in the chemical composition of the material in CO_2 laser reactive cutting of low alloyed steel is documented [29]. Given that stainless steels have higher alloying content than mild steel one could expect different cutting results regarding dimensional accuracy for the same covered experimental hyper-space. Since there are only general cutting laser cutting regime recommendations for the entire group of stainless steels, future research could be in that direction.

5. Conclusions

Dimensional accuracy depends not only on the cutting process itself but also on the laser cutting machine and its CNC control capabilities, the laser cutting method, the thickness and type of material being cut, the effects of thermal distortion during the cutting process but also on laser cutting settings. The present study was focused on multi-objective optimization of roundness and positional errors in CO_2 laser cutting of holes in AISI 316L stainless steel. The research methodology integrated development of third-order (cubic) polynomials for process modeling, DFA for formulation of multi-objective optimization problem and graphical optimization for determining optimized process conditions.

The obtained results showed that it is possible to obtain significant improvement in terms of overall desirability which was obtained thanks to a significant reduction in the roundness error (around 22%), whereas only minor improvement was made with respect to the positional error. It was observed that lower assist gas flows and middle to high severance energy levels promotes higher dimensional accuracy of laser cut holes. Based on the contour plot of the overall desirability function one can identify potential change intervals of severance energy and assist gas flow for future research.

The proposed mathematical models for functional representation of laser hole dimensional quality characteristics can be used together with other important performances such as HAZ, MRR, surface quality characteristics, etc. for formulation of comprehensive multi-objective laser cutting optimization models, and that is the direction of further research.

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