Vol. 37, No. 2 (2015) 236-243

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Multi-Criteria Analysis of Laser Cut Surface Characteristics in CO_2 Laser Cutting of Stainless Steel

M. Madić[a], M. Radovanović[a], D. Petković[a], B. Nedić[b]

[a]*University of Niš, Faculty of Mechanical Engineering, Serbia,*
[b]*University of Kragujevac, Faculty of Engineering, Serbia.*

Keywords:

Multi-Criteria Decision Making
CO_2 Laser Cutting
Laser Cut
Surface Characteristics
WASPAS

Corresponding author:

M. Madić
University of Niš,
Faculty of Mechanical Engineering,
Serbia.
E-mail: madic@masfak.ni.ac.rs

A B S T R A C T

In this paper an approach for multi-criteria analysis of laser cut surface characteristics using multi-criteria decision making (MCDM) approach was presented. Laser cutting experiment was conducted based on Taguchi's L_{27} experimental design by varying laser power, cutting speed, assist gas pressure and focus position at three levels. Multi-criteria analysis was performed by using the weighted aggregated sum product assessment (WASPAS) method while considering burr height, drag line separation, depth of separation line, surface roughness and perpendicularity of the cut as assessment criteria. Based on conducted experimental investigation the MCDM model with 27 alternatives (laser cuts) and five criteria was developed. The relative importance of criteria was determined by using pair-wise comparison matrix and geometric mean method of the analytic hierarchy process (AHP) method.

1. INTRODUCTION

Laser cutting is one the leading technologies for straight and contour cutting of a wide variety of materials and different thicknesses. Although it requires relatively high capital cost of equipment, low operational costs justifies its use for both large batch processing and processing of customized products [1]. Laser cutting technology is well known for its high cut quality and precision, however, achieving superb laser cut quality characteristics is not easy task since for each workpiece material and thickness there are a number of input parameters that are to be adequately set.

Generally, laser cut quality characteristics are in direct relationship with a number of parameters (inputs) such as laser power, cutting speed, assist gas (pressure, type), nozzle (diameter, type), focus position, stand-off distance, etc. What even more complicates determination of input values is the fact that inputs have different and opposite influence on different laser cut quality characteristics, i.e. laser cutting conditions that are the most suitable for minimization of surface roughness may not be even optimal for minimization of kerf width. Thus, in real production environment, for a given workpiece material and thickness, process planners (decision makers) are often faced with the problem of determining the most suitable laser cutting conditions so as to meet a number of requirements which may be in conflict. The most common approaches that can be seen in industry and proposed in literature are trial and error approach, Taguchi method and integration of mathematical modeling and optimization methods. While a number of techniques within the aforementioned categories are applied, the application of multi-criteria decision making (MCDM) methods for solving such type of problems in laser cutting has given less attention, although there exists a number of simple and systematical MCDM methods.

From the literature review [2,3] it can be observed that majority of researches were focused on one, two and three laser cut quality characteristics such as kerf width, surface roughness and heat affected zone. Unlike previous, this study is focused on multi-criteria analysis of different laser cut quality characteristics using MCDM approach in order to determine the most suitable laser cutting conditions. The presented MCDM approach considers determination of the most suitable laser cutting conditions as a MCDM problem whereas laser cut surface characteristics are assessment criteria and laser cuts, obtained in experimental trials at different combinations of laser cutting parameters, are alternatives. Laser cutting experiment, planned according to the Taguchi's L_{27} orthogonal array, provided a set of experimental data upon which the MCDM model was developed. Multi-criteria analysis of laser cut surface characteristics was performed by using the weighted aggregated sum product assessment (WASPAS) method while considering burr height, drag line separation, depth of separation line, surface roughness and perpendicularity of the cut as assessment criteria.

2. EXPERIMENTAL PROCEDURE AND LASER CUT SURFACE CHARACTERISTICS

Laser cutting experiment was performed in real industrial environment by using ByVention 3015 (Bystronic) CO_2 laser cutting machine delivering a maximum output power of 2.2 kW at a wavelength of 10.6 μm. Laser cuts were performed in a continuous wave operating mode with Gaussian distribution beam mode (TEM_{00}) on a 3 mm thick AISI 304 stainless steel plate. Nitrogen gas with a purity of 99.95 % was used as assist gas. A focusing lens with a focal length of 5 in. (127 mm) was used to perform the cut. The conical shape nozzle (HK20) with 2 mm nozzle diameter was used. The nozzle–workpiece stand-off distance was controlled at 1 mm. Twenty-seven experimental trials with different combination of laser cutting parameters (laser power, cutting speed, assist gas pressure and focus position) were conducted in accordance with the standard L_{27} Taguchi's orthogonal array [1].

The multi-criteria analysis considered the following laser cut surface characteristics: burr height (b), drag line separation (n), depth of separation line (d), surface roughness (R_a) (Fig. 1). As perpendicularity of the cut (u) is one of the most important criterions for assessing the quality of laser cuts as per DIN EN ISO 9013 standard, it has been included in the multi-criteria analysis. Among these, DIN EN ISO 9013 standard proposes also the analysis of the melting of the top edge by characterizing the form of the upper edge of the cut.

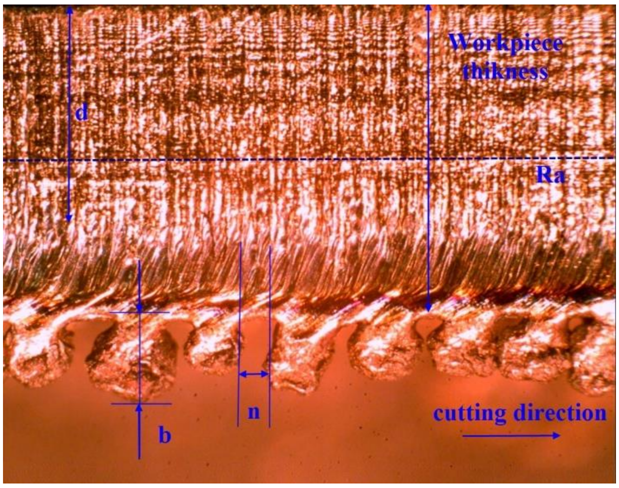


Fig. 1. Laser cut surface characteristics considered in the multi-criteria analysis.

Burr. Burr is essentially material that clings to the lower edge of the workpiece and appears as solidified drops after laser cutting. Burr formation depends on the surface tension and viscosity of the molten material [4]. From the techno-economical point of view, burr formation can be regarded as one of the most important criterion since a highly adhesive burr cannot be removed without post processing. Also, burr formation is undesirable as it causes the release of energy back to the metal leading to increased heat affected zone. Depending on assist gas used, workpiece material being cut, focus position and other related laser cutting parameters, in laser cutting one can obtain drop-like burr, crumb-like burr or sharp-edged burr.

Drag line separation. When cutting the contours using the laser beam, perpendicular drag lines are formed on the surfaces of the cut. Drag line separation indicates the greatest distance between the two drag lines in the cutting direction. At low cutting speeds, the grooves run almost parallel to the laser beam. As the cutting speed increases, the grooves bend away from the direction of cutting [5]. Therefore, drag line separation (groove lags) are important in the case when there is a change of direction cutting, since incomplete cutting may occur if high cutting speeds are used.

Depth of separation line. In laser cutting the presence of periodic striations along the cut surface is common. On the laser cut surface two distinct patterns exists. One pattern, closer to the upper surface of the workpiece, is characterized with relatively fine striations. The other pattern, closer to the lower cut surface, has relatively coarse striations. The two patterns are separated by a distinct line (separation line) that is almost parallel to the workpiece surface. The two striation patterns result from the temperature distribution in the molten layer in the vertical direction, being higher in the upper portion compared to the lower portion [4].

Surface roughness. The factors leading to surface roughness formation in laser cutting are complex. The mechanism behind surface roughness formation is further complicated considering interaction effects between laser beam, process parameters, and workpiece properties. Also, the order of magnitude of a given parameter on surface roughness is dependent on the values of other parameters and their interactions [6]. There are several ways to describe surface roughness among which the average surface roughness, which is often represented with the R_a symbol, and ten-point mean roughness R_z are one of the most used. R_a is defined as the arithmetic value of the departure of the profile from the centerline along sampling length. R_z is the arithmetic mean of individual roughnesses of five adjacent, representative measuring paths [5]. It is well known that surface roughness affects fatigue life, corrosion, thermal conductivity, friction and wear and tear of parts.

Perpendicularity of the cut. Perpendicularity is defined as the distance between two parallel straight lines, which limit the upper and lower boundaries of the cut surface profile at the theoretically correct angle of 90^{o}. For achieving high cut quality with close dimensional tolerances, it is important to obtain accurate perpendicularity of cut edge, especially when using sheet thickness over several millimeters. The perpendicularity of the cut and slant tolerance encompasses the deviation from both straightness and flatness [5]. For defining quality classes of laser cuts as per DIN EN ISO 9013 standard, perpendicularity of the cut is considered in relation to workpiece thickness.

Measurements of drag line separation (n), depth of separation line (d) and burr height (b) were carried out on a photos of each laser cut sample with the aid of stereo microscope (KONUS, Diamond #5420, magnification 40 X). The measurements were made at five equally distanced positions along the photo of cut sample and the average values were calculated and stored. Surface roughness, given in terms of the average surface roughness (R_a), was measured using Surftest SJ-301 (Mitutoyo) profilometer along the cut at approximately the middle of the thickness and the measurements were repeated three times to obtain averaged values. Perpendicularity of the cut (u) for each workpiece was calculated considering top and bottom kerf widths.

3. MCDM MODEL

Based on the measured laser cut surface characteristics, the MCDM model was developed (Table 1). In the MCDM framework, the experimental trials with specific combination of laser cutting parameter values (P, v, p and f) represent alternatives, whereas measured laser cut surface characteristics represent criteria for assessment of alternatives, i.e. laser cuts. Here it should be noted that except depth of separation line (n), all other criteria are minimization in nature, i.e. lower attribute values of alternatives are preferred.

Table 1. Experimental design and measured laser cut surface characteristics.

Trial	*P* [Kw]	*v* [m/min]	*p* [bar]	*f* [mm]	*b* [mm]	*n* [mm]	*d* [mm]	R_a [µm]	*u* [mm]
1	1.6	2	9	−2.5	0.07	0.19	2.58	1.84	0.06
2	1.6	2	10.5	−1.5	1.53	0.15	2.54	1.98	0.03
3	1.6	2	12	−0.5	1.25	0.21	1.95	2.17	0.32
4	1.6	2.5	9	−1.5	1.42	0.23	2	2.34	0.04
5	1.6	2.5	10.5	−0.5	1.37	0.1	1.78	2.08	0.19
6	1.6	2.5	12	−2.5	0.05	0.05	1.14	1.67	0.08
7	1.6	3	9	−0.5	1.05	0.21	1.56	2.20	0.21
8	1.6	3	10.5	−2.5	0.11	0.21	1.1	1.83	0.11
9	1.6	3	12	−1.5	0.65	0.14	1.92	2.30	0.03
10	1.8	2	9	−1.5	1.37	0.31	2.05	1.71	0.23
11	1.8	2	10.5	−0.5	1.22	0.01	3	1.96	0.26
12	1.8	2	12	−2.5	0.08	0.05	1.91	2.20	0.07
13	1.8	2.5	9	−0.5	1.38	0.01	3	1.70	0.30
14	1.8	2.5	10.5	−2.5	0.13	0.1	1.03	1.77	0.07
15	1.8	2.5	12	−1.5	1.35	0.1	2.22	1.69	0.16
16	1.8	3	9	−2.5	0.06	0.14	1.08	2.09	0.08
17	1.8	3	10.5	−1.5	1.11	0.17	1.82	2.15	0.16
18	1.8	3	12	−0.5	1.64	0.21	1.69	1.91	0.21
19	2	2	9	−0.5	1.58	0.01	3	1.89	0.27
20	2	2	10.5	−2.5	1.23	0.21	2.54	3.02	0.06
21	2	2	12	−1.5	1.45	0.37	2.34	1.83	0.29
22	2	2.5	9	−2.5	0.96	0.22	1.63	2.294	0.02
23	2	2.5	10.5	−1.5	1.19	0.3	2.23	1.47	0.28
24	2	2.5	12	−0.5	1.46	0.01	3	2.16	0.31
25	2	3	9	−1.5	1.3	0.18	1.88	1.60	0.25
26	2	3	10.5	−0.5	1.61	0.05	1.79	2.21	0.34
27	2	3	12	−2.5	0.06	0.07	1.5	1.93	0.06

Regarding the assessment of laser cut quality, laser cut surface characteristics do not have the same importance. For example, it is clear that burr formation is more important criterion that drag line separation. In the context of MCDM framework, the relative importance of criteria is represented by assigning them a certain criteria weights.

Relative importance of laser cut quality surface characteristics is determined by using geometric mean method of the AHP method. The Saaty nine-point preference scale [7] is adopted for constructing the pair-wise comparison matrix based on the experience of the authors. A criteria compared with itself is always assigned value 1, so the main diagonal of the pair-wise comparison matrix contains values 1 (Table 2).

Table 2. Comparison matrix of criteria.

	b	n	d	Ra	u
b	1	5	5	3	3
n	0.2	1	1	0.33	0.33
d	0.2	1	1	0.33	0.33
R_a	0.33	3	3	1	3
u	0.33	3	3	0.33	1

Relative significance of each criterion was determined by using the the geometric mean method [8]:

$$\mathrm{GM_i} = \left(\prod_{j=1}^{n} b_{ij} \right)^{1/n} . \quad (1)$$

$$w_j = \mathrm{GM}_i / \sum_{j=1}^{n} \mathrm{GM}_i . \quad (2)$$

Using above-mentioned equations criteria weights were obtained as w = [0.46, 0.07, 0.07, 0.24, 0.15]. Therefore, bur formation followed by surface roughness and perpendicularity of the cut are criteria with the greatest importance, respectively. Although this is subjective approach for determination of the relative importance of criteria, consistency check of determined criteria weights was performed. For five considered criteria i.e. for random index (RI) of 1.11, consistency index (CI) and consistency ratio (CR) values of 0.048 and 0.043 were obtained, respectively. CI and CR values show that determination of criteria weights is reasonable.

4. WASPAS METHOD

In this paper, determination of decision rule for multi-criteria analysis of laser cut surface characteristics was performed using the recently developed MCDM method, i.e. the WASPAS method. This MCDM method was proposed by Zavadskas et al. [9]. In essence this method represents a unique combination of two well known MCDM methods, i.e. weighted sum method (WSM) and weighted product method (WPM). The main procedure of the method for solving MCDM problems includes several steps [8-10]:

Step 1. Set the initial decision matrix:

$$X = \left[x_{ij} \right]_{m \times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}. \quad (3)$$

where x_{ij} is the assessment value of the i-th alternative with respect to the j-th criterion, m is the number of alternatives and n is the number of criteria.

Step 2. Normalization of the decision matrix by using following equations:

- for maximization criteria:

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}}. \quad (4a)$$

- for minimization criteria:

$$\bar{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}}. \quad (4b)$$

Step 3. The total relative importance of i-th alternative, based on weighted sum method (WSM), is calculated as follows [10]:

$$Q_i^{(1)} = \sum_{j=1}^{n} \bar{x}_{ij} \cdot w_j . \quad (5)$$

where w_j is criteria weight which represents relative importance or significance of the j-th criterion.

Step 4. The total relative importance of i-th alternative, based on weighted product method (WPM), is calculated as follows:

$$Q_i^{(2)} = \prod_{j=1}^{n} \bar{x}_{ij}^{\,w_j} . \quad (6)$$

Step 5. In order to have increased ranking accuracy and effectiveness of the decision making process, in the WASPAS method, a more generalized equation for determining the total relative importance of alternatives is developed [9]:

$$Q_i = \lambda \cdot Q_i^{(1)} + (1-\lambda) \cdot Q_i^{(2)}, \ \lambda = 0,\ 0.1,\ \ldots,1. \quad (7)$$

Finally, the competitive alternatives are ranked based on the Q values, i.e. the best alternative would be the one having the highest Q value.

Till date, the WASPAS method has very limited application for solving real manufacturing decision making problems [10-12]. Regarding the application of the WASPAS method it should be noted that coefficient of linear combination (λ) usually takes value of 0.5. By varying values of λ one can observe the change in values of total relative importance of alternatives as well as rankings of alternatives.

5. RESULTS AND DISCUSSION

Computational details of the WASPAS method for multi-criteria analysis of laser cut surface characteristics are given in Table 3.

The application of the WASPAS method for multi-criteria analysis of laser cut surface characteristics starts with normalization of the decision matrix (Table 1) using Eqs. 4a and 4b. Normalization of attributes with respect to each criterion is necessary step since it represents a logical basis for decision making.

Table 3. Computational details of the WASPAS method for multi-criteria analysis of laser cut surface characteristics.

Trial	*Normalized decision matrix*					$Q_i^{(1)}$	$Q_i^{(2)}$	Q_i	Rank
1	0.7143	0.0526	0.8600	0.7973	0.2966	0.6283	0.5444	0.5863	3
2	0.0327	0.0667	0.8467	0.7402	0.5833	0.3441	0.1454	0.2448	12
3	0.0400	0.0476	0.6500	0.6767	0.0579	0.2383	0.1059	0.1721	26
4	0.0352	0.0435	0.6667	0.6259	0.4217	0.2794	0.1314	0.2054	18
5	0.0365	0.1000	0.5933	0.7039	0.0963	0.2487	0.1158	0.1823	23
6	1.0000	0.2000	0.3800	0.8800	0.2397	0.7478	0.6536	0.7007	1
7	0.0476	0.0476	0.5200	0.6656	0.0859	0.2343	0.1194	0.1768	25
8	0.4545	0.0476	0.3667	0.7999	0.1690	0.4554	0.3805	0.4180	7
9	0.0769	0.0714	0.6400	0.6370	0.6863	0.3410	0.2100	0.2755	8
10	0.0365	0.0323	0.6833	0.8569	0.0783	0.2843	0.1098	0.1970	19
11	0.0410	1.0000	1.0000	0.7492	0.0708	0.3493	0.1443	0.2468	11
12	0.6250	0.2000	0.6367	0.6662	0.2611	0.5451	0.5172	0.5312	5
13	0.0362	1.0000	1.0000	0.8609	0.0620	0.3726	0.1382	0.2554	10
14	0.3846	0.1000	0.3433	0.8283	0.2755	0.4481	0.4009	0.4245	6
15	0.0370	0.1000	0.7400	0.8640	0.1121	0.3000	0.1272	0.2136	16
16	0.8333	0.0714	0.3600	0.7022	0.2333	0.6171	0.5256	0.5713	4
17	0.0450	0.0588	0.6067	0.6826	0.1132	0.2481	0.1252	0.1867	21
18	0.0305	0.0476	0.5633	0.7673	0.0871	0.2540	0.1014	0.1777	24
19	0.0316	1.0000	1.0000	0.7766	0.0690	0.3513	0.1287	0.2400	13
20	0.0407	0.0476	0.8467	0.4866	0.3043	0.2437	0.1288	0.1863	22
21	0.0345	0.0270	0.7800	0.8003	0.0626	0.2738	0.1015	0.1876	20
22	0.0521	0.0455	0.5433	0.6395	1.0000	0.3687	0.1781	0.2734	9
23	0.0420	0.0333	0.7433	1.0000	0.0665	0.3237	0.1196	0.2216	15
24	0.0342	1.0000	1.0000	0.6807	0.0586	0.3279	0.1262	0.2271	14
25	0.0385	0.0556	0.6267	0.9146	0.0721	0.2958	0.1165	0.2062	17
26	0.0311	0.2000	0.5967	0.6653	0.0537	0.2378	0.1020	0.1699	27
27	0.8333	0.1429	0.5000	0.7617	0.3153	0.6584	0.6023	0.6303	2

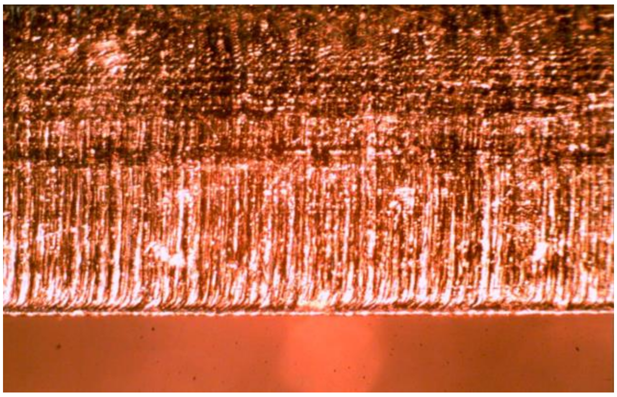
Subsequently, total relative importance of alternatives as per WSM ($Q_i^{(1)}$) and WPM ($Q_i^{(2)}$) are calculated by Eqs. 5 and 6, respectively. Finally, joint criterion of optimality of the WASPAS method is calculated by using Eq. 7.

As could be seen from Table 3 by applying the WASPAS method for multi-criteria analysis of laser cut surface characteristics, the complete ranking of laser cuts, obtained at different combinations of laser cutting parameter values, is obtained. It can be observed that laser cut obtained in trial 6 is determined as the best cut. It is revealed that laser cut obtained in trial 27 is the second best choice, and that laser cut obtained in trial 1 is the third choice. Laser cuts obtained in trials 3, 7 and 26 are the least preferred laser cuts.

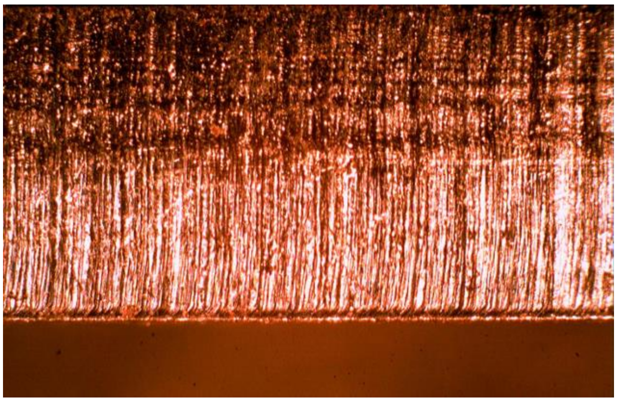
From Table 3 one can also notice that there exists a drastic difference between laser cuts obtained in different experimental trials regarding the values of the total relative importance of alternatives. Only few alternatives have total relative importance values higher than 0.5, whereas the majority have total relative importance values between 0.17 and 0.3.

Laser cut surface patterns of the two top ranked laser cuts (alternatives) are shown in Fig. 2.

In any MCDM analysis it is beneficial to check the stability of the obtained complete ranking of alternatives. This is usually accomplished by varying the values of criteria weights or by applying other MCDM methods for assessment of alternatives. In this study the stability of obtained rankings of the three best laser cuts as well as the least preferred was checked by varying values of coefficient of linear combination (λ) (Fig. 3).



a)



b)

Fig. 2. Laser cut surface patterns obtained in trial 6 (a) and trial 27 (b).

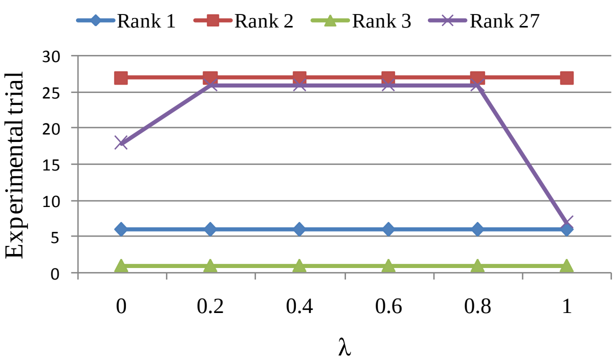


Fig. 3. Rankings of the most and least preferable laser cuts with respect to λ.

From Fig. 3 it can be observed that that the obtained rankings of the top three laser cuts are stable to perturbations of λ values. On the other hand, one can notice that when λ=0, i.e. when the WASPAS method behaves like the WPM, the least preferred is laser cut obtained in experimental trial 18. Also, when λ=1, i.e. when the WASPAS method behaves like the WSM, the least preferred is laser cut obtained in experimental trial 7.

6. CONCLUSION

This study was focused on multi-criteria analysis of laser cut surface characteristics using MCDM approach. Laser cutting experiment, planned as per Taguchi's L_{27} orthogonal array, considering laser power, cutting speed, assist gas pressure and focus position, provided a set of experimental data upon which the MCDM model was developed. In the MCDM framework, the experimental trials with specific combination of laser cutting parameter values were considered as alternatives, whereas measured laser cut surface characteristics were considered as criteria for assessment of alternatives, i.e. laser cuts. Relative importance of criteria was determined by using pair-wise comparison matrix and geometric mean method of the AHP method. Subsequently, determination of decision rule regarding the multi-criteria analysis of laser cut surface characteristics was obtained by the application of the WASPAS method.

The obtained results suggested that the laser cuts obtained in experimental trials 1, 6 and 27 are the most preferred laser cuts, whereas laser cuts obtained in experimental trials 3, 7 and 26 are the least preferred laser cuts. Regarding the laser cutting parameter values used in these experimental trials one can conclude that it is beneficial to focus the laser beam deep into the bulk of material (-2.5 mm). On the other hand, the least preferred laser cut surface characteristics are obtained in experimental trials where laser beam was focused close to workpiece top surface (-0.5 mm). From a more detailed analysis one can conclude that focus position has the dominant influence on laser cut surface characteristics, whereas the influence of other laser cutting parameters are less pronounced.

Since in real production environment there often exists a need to satisfy opposite requirements, the presented methodology for multi-criteria analysis of laser cut surface characteristics using MCDM approach may be useful for determination of suitable laser cutting conditions. In essence, MCDM approach allows for discrete multi-objective optimization whereas the solutions (alternatives) are known in advance.

Finally it should be noted that the presented MCDM approach can be efficiently used for solving other types of decision making problems, i.e. multi-objective optimization problems in engineering domain.

Acknowledgement

This work was carried out within the project TR 35034 financially supported by the Ministry of Science and Technological Development of the Republic of Serbia.

REFERENCES

[1] M. Madić, M. Radovanović and B. Nedić, 'Modeling and simulation annealing optimization of surface roughness in CO2 laser nitrogen cutting of stainless steel', *Tribology in Industry*, vol. 35, no. 3, pp. 167-176, 2013.

[2] P. Parandoush and A. Hossain, 'A review of modeling and simulation of laser beam machining', *International Journal of Machine Tools and Manufacture*, vol. 85, pp. 135-145, 2014.

[3] Sivarao, K.M. Robert, D. Sivakumar, Taufik, Yuhazri, C.F. Tan, I. Haery, Alif and S.L. Tin, 'An exploratory study - critical laser processing of composite materials', *International Journal of Engineering Research and Technology*, vol. 1, no. 10, pp. 1-8, 2012.

[4] E.K. Asibu, *Principles of Laser Material Processing*. Wiley, New Jersey, 2009.

[5] www.trumpf-laser.com

[6] M. Madić, M. Radovanović and B. Nedić, 'Correlation between surface roughness characteristics in CO_2 laser cutting of mild steel', *Tribology in Industry*, vol. 34, no. 4, pp. 232-238, 2012.

[7] T.L. Saaty, *The Analytic Hierarchy Process*. McGraw-Hill, 1980.

[8] M. Madić, B. Nedić and M. Radovanović, *Business and Engineering Decision Making by Using Multi-Criteria Decision Making Methods*, Faculty of Engineering, University of Kragujevac, 2015.

[9] E.K. Zavadskas, Z. Turskis, J. Antucheviciene and A. Zakarevicius, 'Optimization of weighted aggregated sum product assessment', *Electronics and Electrical Engineering*, vol. 122, pp. 3-6, 2012.

[10] S. Chakraborty and E.K. Zavadskas, 'Applications of WASPAS method in manufacturing decision making', *Informatica*, vol. 25, no. 1, pp. 1-20, 2014.

[11] S. Chakraborty, O. Bhattacharyya, E.K. Zavadskas and J. Antucheviciene, 'Application of WASPAS method as an optimization tool in non-traditional machining processes', *Information Technology and Control*, vol. 44, no.1, pp. 77-88, 2015.

[12] S. Chakraborty, E.K. Zavadskas and J. Antucheviciene, 'Applications of WASPAS method as a multi-criteria decision-making tool', *Economic Computation and Economic Cybernetics Studies and Research*, vol. 49, no. 1, pp. 5-22, 2015.