

TOPSIS BASED EVALUATION OF LASER CUTTING RESULTS IN CO₂ LASER CUTTING OF 3 MM THICK ALUMINIUM ALLOY

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ABSTRACT: Laser cutting is complex machining process which involves a number of parameters and process performance characteristics. In literature and practice a number of criteria for evaluation of laser cutting results were proposed. In this study, for the purpose of evaluation of laser cutting results obtained in CO₂ laser cutting of 3 mm thick aluminium alloy, a set of criteria proposed by TRUMPF was considered. In order to deal with a number of criteria as well as performance characteristics, both quantitative and qualitative, a multi criteria decision making (MCDM) method was applied, i.e. the technique for order of preference by similarity to ideal solution (TOPSIS). Laser cutting experiment was conducted according to the full factorial experimental design by varying laser power, cutting speed and assist gas pressure at three levels. Based on experimental data the MCDM model with 27 alternatives (laser cuts) and six 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.

KEYWORDS: CO₂ laser cutting, aluminium alloy, TOPSIS, multi criteria decision making

1. INTRODUCTION

Laser cutting is one of the most used non-conventional machining processes in industry for contour cutting of sheets. It is a thermal based machining process in which material removal is obtained by focusing a laser beam on the workpiece surface. By laser cutting, coaxial with the laser beam, assist gas stream is used so as to remove the melted material from the cutting zone.

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 need to be adequately set [1]. Moreover, these input parameters have different and opposite effects on laser cutting performance characteristics.

A number of studies reported in literature consider laser cutting of different materials from specific aspects. For instance, a number of researchers investigated the effects of the main laser cutting parameters - inputs such as laser power, cutting speed, assist gas (type and pressure), nozzle (type and diameter), focus position etc. on specific performance characteristics - outputs such as kerf width, kerf taper, roughness, perpendicularity of cut, heat affected zone, burr, productivity, costs, etc. More specifically, most studies consider up to three inputs or outputs, and only few studies considered several outputs at the same time [2].

Laser cutting is complex process by which specific adjustment of the main laser cutting parameters lead to improvement to a given output, but, as a rule, lead to deterioration in a greater or lesser extent to another output. Therefore, an approach for simulations consideration of multiple outputs based on the use of multi-criteria decision making (MCDM) methods may provide efficient way for process improvement.

In the field of laser cutting previous use of MCDM methods has given less attention although this approach does not require complex calculations, mathematical apparatus and can be easily applied in real production environment by engineers. Madić et al. [1] applied the recent MCDM method, i.e. the weighted aggregated sum product assessment (WASPAS) for analysis of CO₂ laser cutting of stainless steel. Taguchi's L₂₇ experimental design was adopted for experimentation by considering laser power, cutting speed, assist gas pressure and focus position as input parameters. Chakraborty et al. [3] explored the capability of the WASPAS method for parametric optimization of five non-conventional machining processes, including laser cutting process. It was concluded that this method can efficiently determine the optimal parametric combinations of non-conventional machining processes for both single output as well as multi-output optimization problems.

Other common approaches for multi-output optimization of laser cutting processes are mathematical

modelling (RSM, ANN) and optimization, Taguchi method and hybrid approaches. Gadallah and Abdu [4] developed mathematical models for the prediction of kerf taper, surface roughness and heat affected zone by considering laser power, assist gas pressure, frequency and cutting speed in Nd:YAG laser cutting of stainless steel (AISI 316L). By optimization of developed models, the solutions were determined and also compared with Taguchi's optimization solutions. Pandey and Dubey [5] applied hybrid approach by combining Taguchi's methodology and fuzzy logic theory to compute the fuzzy multi-response performance index. This performance index was further used for multi-objective optimization. The same authors proposed also grey-fuzzy methodology for multiple quality optimization in laser cutting [6]. Chaudhary et al. [7] presented a methodology for the simultaneous optimization of multiple quality characteristics in laser cutting process by developing the software 'CATFMO' (Computer Aided Taguchi-Fuzzy Multi-Optimization).

Motivated by the lack of researches regarding the application of MCDM methods for multi-objective laser cutting process optimization, this study discusses the application of the technique for order of preference by similarity to ideal solution (TOPSIS) method for comprehensive evaluation of laser cutting results in CO₂ laser cutting of 3 mm thick aluminium alloy. Laser cutting experiment, planned according to the full factorial design plan, provided a set of experimental data upon which the MCDM model, consisting of 27 alternatives and six criteria, was developed.

2. EXPERIMENTAL SETUP AND DETAILS

Laser cutting experimentation was conducted in accordance with full factorial design experimental plan where three cutting parameters, i.e. laser power (P), assist gas pressure (p) and cutting speed (v) were varied at three levels:

- P = {3, 3.5, 4} kW;
- p = {6, 8, 10} bar;
- v = {3, 3.25, 3.5} m/min.

The experiment was carried out in real manufacturing environment by using 4 kW Prima Industry laser cutting machine. Laser cuts were performed with a Gaussian distribution beam mode (TEM₀₀) in continuous wave mode on 3 mm thick aluminium alloy (AlMg₃) plate. Focusing lens with a focal length of 127 mm and conical shape nozzle with 2 mm diameter was used. The nozzle-workpiece distance was set at 0.8 mm. During

experimentation the laser beam was focused deep into the bulk of material and nitrogen with purity of 99.95% was used as assist gas.

In the conducted experimental investigation, the laser cutting results were evaluated with respect to criteria as given by TRUMPF [8]. These criteria are: burr height (b), drag line separation (n), pittings (P_i), surface roughness (R_z), perpendicularity (u) and kerf width (K_w). Except pittings, evaluation of cutting results was made by using optical coordinate measuring device Mitutoyo (type: QSL-200Z), stereo microscope (KONUS, Diamond #5420) and SurfTest SJ-301 (Mitutoyo) profilometer. Qualitative assessment of pittings was conducted based on the analysis of cut sample photos by using linguistic terms.

Burr (b). Burr is essentially material that clings to the lower edge of the workpiece and appears as solidified drops after laser cutting [1]. Burr formation depends on the specific adjustment of main laser cutting parameters, however it is mostly affected by the focus position.

Drag line separation (n). 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. The evaluation of drag line separation is carried out on a photo of cut sample with the aid of microscope [8]. This criterion is important in the case when there is a change in direction of cutting, since incomplete cutting may occur if high cutting speeds are used [1].

Pittings (P_i). Pittings are erosions of non-uniform width, depth and form that intercept an otherwise uniform cutting surface [8]. These irregular erosions usually occur at low cutting speeds. The evaluation of pittings on cutting surface is made by visual inspection and described linguistically.

Surface roughness (R_z). Ten-point average roughness is the arithmetic mean of individual roughnesses of five adjacent, representative measuring paths [1]. Surface roughness affects fatigue life, corrosion, thermal conductivity, friction and wear as well as tear of parts. The point of measurement of the R_z depends on the sheet thickness and material type [8].

Perpendicularity (u). 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° [1]. 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 millimetres.

Kerf width (K_w). Kerf width is well recognized advantage of laser cutting technology compared to other technologies of contour cutting. By focusing the laser beam and using coaxial stream of assist gas, workpiece material is heated, melted and eventually removed from the cutting zone which results in the formation of kerf with a certain width. In laser cutting it is common that kerf width from the upper surface becomes narrower to the lower surface of the workpiece material.

3. EXPERIMENTAL RESULTS AND DECISION MATRIX

In accordance with 3^3 full factorial design, 27 experimental trials were conducted and the results were quantitatively and qualitatively evaluated. On the basis of considered criteria for laser cutting results evaluation, the initial decision matrix was developed.

After conversion of linguistic terms for pittings evaluation, by using the 5-point fuzzy scale [9], the final decision matrix having only quantitative data was developed (Table 1). Here it should be noted that all criteria are minimization in nature, i.e. lower attribute values are preferred.

One of the most important steps in solving any MCDM problem is the determination of the criteria relative significance. In most cases this is represented with weight coefficients, ranging from 0 to 1, whereas sum of all weight coefficients must be

1, and higher weight coefficient value means greater significance of the given criterion. In this study importance of considered criteria was determined by using geometric mean method of the AHP method. The Saaty's 9-point preference scale [10] was adopted for constructing the pair-wise comparison matrix based on the experience of the authors (Table 2).

Table 2. Pair-wise comparison of considered criteria

	b	n	P_t	R_z	u	K_w
b	1	7	7	3	3	5
n	0.143	1	1	0.111	0.143	0.2
P_t	0.143	1	1	0.111	0.143	0.2
R_z	0.333	9	9	1	3	5
u	0.333	7	7	0.333	1	3
K_w	0.2	5	5	0.2	0.333	1

By calculation of the geometric means of rows and after its normalization the weight coefficients of criteria were obtained as $w=[0.39, 0.03, 0.03, 0.29, 0.17, 0.09]$. From the analysis of criteria weight coefficients it is clear that the ability to produce burr free, perpendicular, high quality cuts is of the greatest importance. In order to ensure the accuracy of calculation, a consistency check was conducted. For six criteria, i.e. for random index of 1.24, consistency index and consistency ratio values of 0.097 and 0.079 were obtained, respectively. These values show that the estimation of criteria weight coefficients is reasonable.

Table 1. Experimental trials with associated laser cutting parameter values (decision matrix)

Experimental trial	P [kW]	p [bar]	v [m/min]	b [mm]	n [mm]	P_t	R_z [μ m]	u [mm]	K_w [mm]
1	3	6	3	1.28	0.69	0.495	20.5	0.10	0.41
2	3	6	3.25	1.89	1.32	0.295	22.6	0.16	0.40
3	3	6	3.5	1.50	0.73	0.115	35.3	0.13	0.40
...
9	3	10	3.5	3.33	3.17	0.115	32.6	0.12	0.47
10	3.5	6	3	0.00	0.67	0.895	19.0	0.15	0.41
11	3.5	6	3.25	0.00	0.42	0.895	21.9	0.15	0.44
...
17	3.5	10	3.25	3.27	2.03	0.495	27.3	0.16	0.51
18	3.5	10	3.5	3.03	1.82	0.495	31.5	0.20	0.47
19	4	6	3	0.00	0.37	0.695	19.4	0.08	0.39
...
25	4	10	3	1.24	1.33	0.695	34.7	0.16	0.54
26	4	10	3.25	0.00	1.63	0.695	30.8	0.16	0.53
27	4	10	3.5	0.00	1.08	0.695	35.4	0.09	0.42

4. TOPSIS METHOD

TOPSIS method was proposed by Hwang and Yoon in 1981 [11]. This method is based on the concept which assumes that the optimal alternative should have a minimum Euclidean distance from the positive-ideal solution and the greatest to the negative-ideal solution. Positive-ideal solution is a hypothetical solution where all attribute values correspond to the most desirable alternative attribute values with respect to all criteria. On the other hand, the negative-ideal solution is a hypothetical solution where all the attribute values correspond to the most undesirable attribute values with respect to all criteria. Therefore, the solution determined by the TOPSIS method is "the nearest" to the hypothetical positive-ideal solution and, at the same time, "the farthest" from the hypothetical negative-ideal solution. The basic procedure of the TOPSIS method application can be summarized in the following steps [9, 11, 12].

Step 1. Develop decision matrix X :

$$X = [x_{ij}] = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (1)$$

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

Step 2. Develop normalized decision matrix which elements are calculated as:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (2)$$

Step 3. Determine relative significance of considered criteria by calculation of criteria weight coefficients.

Step 4. Determine weighted normalized decision matrix which elements are calculated as:

$$v_{ij} = r_{ij} \cdot w_j \quad (3)$$

Step 5. Determine positive-ideal and negative-ideal attribute values with respect to each criterion. Positive-ideal and negative-ideal attribute values can be represented as:

$$V^+ = \begin{cases} \max(v_{ij}) \text{ for } j \in J \\ \min(v_{ij}) \text{ for } j \in J' \end{cases} = \{V_1^+, \dots, V_n^+\} \quad (4a)$$

$$V^- = \begin{cases} \min(v_{ij}) \text{ for } j \in J \\ \max(v_{ij}) \text{ for } j \in J' \end{cases} = \{V_1^-, \dots, V_n^-\} \quad (4b)$$

where J is the set of maximization criteria, and J' is the set of minimization criteria.

Step 6. Calculate distances from positive-ideal and negative-ideal attribute values with respect to each criterion using the following equations:

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - V_j^+)^2} \quad (5a)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - V_j^-)^2} \quad (5b)$$

Step 7. Determine the relative closeness to the ideal solution (P_i) using the following equation:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (6)$$

Step 8. On the basis of P_i values one need to determine the complete ranking of alternatives. The values of the relative closeness to the ideal solution (P_i) are in the range $[0,1]$.

5. RESULTS AND DISCUSSION

Computational details of the TOPSIS method for assessment of laser cutting results are given in Table 3.

Table 3. Computational details of the TOPSIS method

Experimental trial (Alternative)	S^+	S^-	P_i
1	0.003905	0.107696	0.965011
2	0.00879	0.073223	0.892826
3	0.006658	0.121062	0.94787
...
9	0.027328	0.075496	0.734225
10	0.00025	0.170902	0.998539
11	0.000324	0.172759	0.99813
...
17	0.02596	0.069906	0.729204
18	0.023081	0.082492	0.781372
19	3.18E-05	0.169081	0.999812
...
25	0.005149	0.132108	0.962486
26	0.001045	0.179228	0.994201
27	0.001258	0.180137	0.993064

Based on P_i values the complete ranking of alternatives, i.e. experimental trials with accompanied laser cutting parameter values was

obtained as follows: 19-20-10-11-23-14-12-21-24-22-15-26-27-13-16-4-1-25-3-5-6-2-7-8-18-9-17. In other word experimental trial 19, which is performed by using laser power of 4 kW, cutting speed of 3 m/min and assist gas pressure of 6 bar, is determined as the best alternative, i.e. these laser cutting conditions produce the best laser cutting results. It is revealed that experimental trial 20 is determined as the second best alternative. On the other hand, experimental trial 17, which is performed by using laser power of 3.5 kW, cutting speed of 3.25 m/min and assist gas pressure of 10 bar, is determined as the least preferred trial, i.e. laser cutting conditions which should be avoided with respect to the considered criteria.

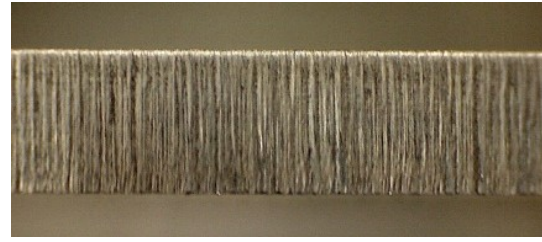
Regarding the obtained complete ranking of the experimental trials one has to note that in the case of the first fourteen experimental trials (19-20-10-11-23-14-12-21-24-22-15-26-27-13) there is negligible difference in P_i values (about 0.99), so one can choose the appropriate cutting conditions by taking into account also other criteria. Experimental trials (16-4-1-25-3-5-6-2-7) have P_i values ranging from 0.85 to 0.98, and finally experimental trials (8-18-9-17) have P_i values ranging from 0.73 to 0.81. The final selection of the best laser cutting conditions was based on the following facts:

- it is beneficial to use up to 80% of available power and that laser cutting process is less stable at lower laser power levels,
- less assist gas pressure implies less gas consumption, i.e. costs, and
- higher cutting speeds ensure higher productivity.

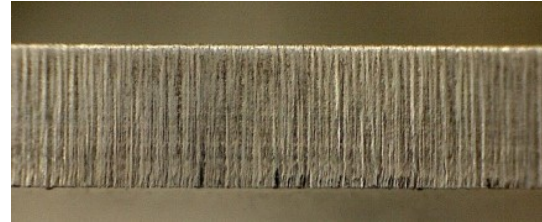
For the covered experimental hyperspace, considered criteria, and aforementioned facts one can recommend CO₂ laser cutting of 3 mm thick aluminium alloy sheet using cutting speed of 3.5 m/min, laser power of 3.5 kW and assist gas pressure of 6 bar (experimental trial 11).

Laser cut surface patterns of the top, middle and worst ranked experimental trials (alternatives) are given in Figure 1. As could be clearly observed from Figures 1a and 1b at low assist gas pressure (up to 6 bar) it is possible to burr free cut with an smooth and flat surface where drag separation lines are not apparent. On the other hand, combinations of lower power levels and high assist gas pressure of 10 bar at moderate to high cutting speeds (3.25-3.5 m/min) produce coarse cut surface at the laser beam exit in approximately in the lower half of the cut. This is also accompanied with clearly pronounced drag line

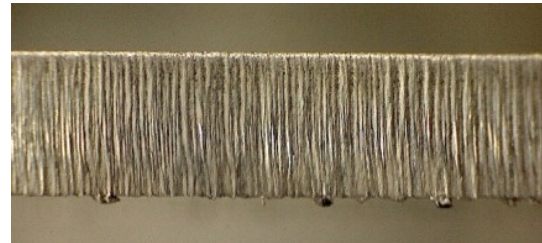
separation and formation of sharp-edged burr (Figures 1e, 1f).



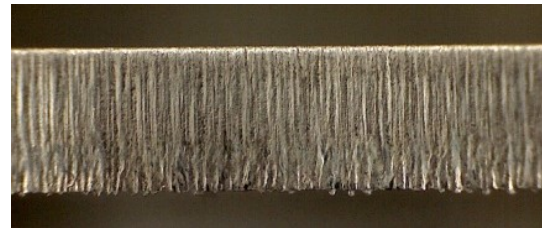
a) experimental trial 11 (P=3.5 kW, p=6 bar, v=3.25 m/min)



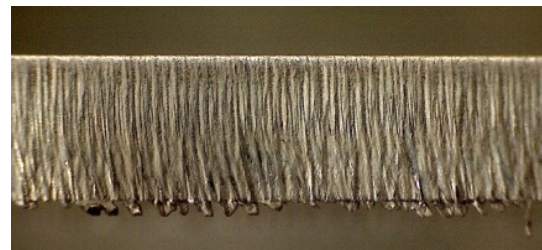
b) experimental trial 19 (P=4 kW, p=6 bar, v=3 m/min)



c) experimental trial 16 (P=3.5 kW, p=10 bar, v=3 m/min)



d) experimental trial 1 (P=3 kW, p=6 bar, v=3 m/min)



e) experimental trial 8 (P=3 kW, p=10 bar, v=3.25 m/min)



f) experimental trial 18 (P=3.5 kW, p=10 bar, v=3.5 m/min)

Figure 1. Laser cut surface cuts obtained in experimental trials

6. CONCLUSIONS

This paper presented the TOPSIS based evaluation of laser cutting results in CO₂ laser cutting of 3 mm thick aluminium alloy. The presented approach can be efficiently used for multi-objective optimization of laser cutting process in situations when there are both quantitative and qualitative assessments of laser cutting results. Based on conducted analysis all experimental trials were classified into three groups: top ranked experimental trials (19-20-10-11-23-14-12-21-24-22-15-26-27-13), middle ranked experimental trials (16-4-1-25-3-5-6-2-7) and worst ranked experimental trials (8-18-9-17). Regarding the covered experimental hyperspace and considered criteria it can be concluded that it is not beneficial to use combination of high assist gas pressure and high cutting speed with power levels up to 3.5 kW. It is revealed that cutting speed of 3.5 m/min, laser power of 3.5 kW and assist gas pressure of 6 bar produces acceptable results in CO₂ laser cutting of 5 mm thick aluminium alloy. Since in real production environment there often exists opposite requirements, the presented methodology may be useful for determination of suitable laser cutting conditions, when there is a set of already conducted experimental trials.

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