

EVALUATION OF LASER CUTTING CONDITIONS USING THE WASPAS METHOD

Miloš MADIĆ¹, Milan TRIFUNOVIĆ¹,
Dušan PETKOVIĆ¹, Predrag JANKOVIĆ¹

¹⁾ University of Niš, Faculty of Mechanical Engineering in Niš, Niš, Serbia

ORCID iDs: Miloš MADIĆ  <https://orcid.org/0000-0002-2310-2590>
Milan TRIFUNOVIĆ  <https://orcid.org/0000-0002-4653-6957>
Dušan PETKOVIĆ  <https://orcid.org/0000-0002-1871-7144>
Predrag JANKOVIĆ  <https://orcid.org/0000-0001-9951-4500>

Abstract

Selecting the most suitable laser cutting parameters for a specific application is challenging, as it requires balancing numerous techno-technological, quality, productivity, and economic criteria. In this study, a multi-criteria decision-making (MCDM) model was developed to evaluate laser cutting conditions. Experimental data in fiber laser cutting of S235JR steel, obtained from a 2² factorial design, were used to define four alternative cutting conditions. Evaluation and ranking of these alternatives were carried out using the weighted aggregated sum product assessment (WASPAS) method, considering cut perpendicularity, surface roughness, surface productivity, dimensional deviation, and angular deviation as evaluation criteria. The relative importance of these criteria was determined using an analytic hierarchy process (AHP), through a pair-wise comparison matrix and the geometric mean method. The stability of the final ranking was examined with respect to variations in the linear combination coefficient. By analysing the quasilinear model for prediction of the total relative importance of alternatives, it was revealed that the focus position has the utmost importance, followed by the interaction effect of focus position and cutting speed.

Keywords: fiber laser cutting, decision making, S235JR steel, WASPAS, cutting regimes

1 INTRODUCTION

Fiber laser cutting technology has emerged as a key modern manufacturing technology due to its high precision, productivity, flexibility, low operational cost, and reduced service costs in processing a wide range of materials [1-3]. Its significance in industry stems also from the ability to

produce complex cut geometries with thin kerf width, high repeatability, and superior surface quality with limited HAZ [4, 5], especially for thin sheets. The performance of fiber laser cutting is strongly influenced by a number of process parameters, such as focus position, cutting speed, laser power, nozzle diameter, stand-off distance, type and purity of assist gas, which affect process and cut quality performances, including cut geometry characteristics, surface integrity, productivity, cutting costs, time and feature dimensional accuracy. In order to utilize this technology efficiently for plate thickness exceeding 4 mm, it is essential to pay close attention to the cutting process with regard to these input parameters [1]. With adequate selection of process parameters for a given sheet material and thickness, manufacturers can optimize multiple performance criteria simultaneously, achieving efficient, high-quality production, while reducing operational costs. The multi-criteria nature of laser cutting technology highlights the need for systematic decision-making approach to evaluate and rank different laser cutting conditions and identify (near)optimal process windows by balancing trade-offs among conflicting performance criteria.

In recent years, different MCDM methods were proposed for the evaluation of laser cutting conditions. Basar and Der [6] applied CoCoSo, TOPSIS, and VIKOR methods to investigate and rank laser cutting conditions, defined in terms of focal length, power, and cutting speed, in CO₂ laser cutting of polyethylene. Fuzzy AHP was applied to determine the relative importance of criteria, such as surface roughness, kerf width, heat-affected zone (HAZ), and material removal rate (MRR). Der and Basar [7] applied the TOPSIS method to simultaneously optimize multiple cut quality characteristics, such as surface roughness, top kerf width, bottom kerf width, and HAZ. CO₂ laser cutting experiment was performed on PLA plates produced using fused filament fabrication, while the laser cutting conditions were defined in terms of laser power, cutting speed and plate thickness. Der et al. [8] proposed an integrated DEA and SWARA-based CoCoSo approach for the multi-objective optimization of cutting parameters in CO₂ laser cutting of polyethylene. Surface roughness, kerf width, and MRR were considered as evaluation criteria, while sheet thickness, laser power and cutting speed were considered as independent variables used to determine 18 alternative cutting regimes. In the diode laser cutting process, Khalaf et al. [9] applied the MOORA method to identify optimal cutting conditions with respect to emission rate, kerf width, carbonization, and MRR. Stand-off distance, cutting speed, duty cycle and frequency were considered as process parameters. Srinivasan et al. [10] investigated laser cutting of stainless steel SS347 under different combinations of process parameters using Taguchi's L9 orthogonal design for defining alternatives. They applied GRA and TOPSIS methods for deriving decision-making rules for evaluation and ranking. Laser power, cutting speed, assist gas pressure and stand-off distance were considered as process parameters, while surface roughness, machining time, and HAZ were used as criteria. Trifunović et al. [11] applied three fuzzy MCDM methods (fuzzy TOPSIS, fuzzy WASPAS, and fuzzy ARAS) to evaluate and rank different laser cutting conditions, defined in terms of focus position, cutting speed and oxygen pressure. A fiber laser cutting experiment was performed on S235 low-carbon structural steel plates. In the proposed

MCDM model, four criteria were considered (kerf width on a straight and curved cut, surface roughness, and surface productivity). Das and Chakraborty [12] proposed the use of the superiority and inferiority ranking (SIR) method to identify optimal parameter combinations for Nd:YAG and pulsed CO₂ laser cutting. Assist gas pressure, pulse width, pulse frequency and cutting speed were considered as process parameters, while kerf width, kerf deviation, and kerf taper angle were used as criteria. Lukić et al. [13] applied a grey fuzzy approach to select the most suitable non-conventional contour cutting method (plasma arc machining, laser beam machining, abrasive water jet machining). As evaluation criteria, machining time, dimensional accuracy, kerf width, and surface roughness were considered. To compare technologies, a special nine-point experimental design was used. Khan and Maity [14] demonstrated the application of the TOPSIS method to optimize multiple quality characteristics of several modern manufacturing processes, including non-conventional processes, such as laser cutting, EDM, and water-jet machining.

The aim of the present study is to evaluate different laser cutting regimes in fiber laser cutting of S235JR steel. The proposed MCDM model incorporates five criteria: cut perpendicularity, surface roughness, surface productivity, dimensional deviation, and angular deviation, capturing essential aspects of cut quality, dimensional accuracy, and process productivity. Four alternative cutting conditions were defined based on a 2² factorial design by varying focus position and cutting speed at two levels. The decision rule for evaluating and ranking these laser cutting conditions was developed using the WASPAS method, while the AHP approach was employed to determine the relative importance of the criteria. The stability of the final ranking was examined with respect to variations in the linear combination coefficient. Additionally, a quasilinear model was developed to reveal the significance of laser cutting parameters on alternative rankings.

2 EXPERIMENTAL SETUP

The experiment was conducted in a manufacturing environment using an HGTECH 3015 fiber laser-cutting machine with a Raycus fiber laser source and a maximum power of 6 kW. Laser cutting was performed on 4 mm thick low-carbon S235JR steel sheet. The laser beam was focused by the Raytools cutting head. A conical nozzle with a 1.2 mm diameter was positioned at a distance of 0.8 mm from the plate, supplying oxygen with a purity of 99.95% (grade 3.5) as the assist gas to ensure clean cuts. During the experiment, the laser power was set constant at 3.2 kW, and the assist gas

pressure was kept at 0.65 bar. To define the alternatives, four laser cutting trials were conducted in accordance with standard 2² factorial design by varying focus position (f) and cutting speed (v): A1 ($f = 1.2$ mm, $v = 3$ m/min), A2 ($f = 1.6$ mm, $v = 3$ m/min), A3 ($f = 1.2$ mm, $v = 3.6$ m/min) and A4 ($f = 1.6$ mm, $v = 3.6$ m/min).

In previous studies, related to the application of MCDM methods in laser cutting, researchers considered a variety of process outputs as criteria, including kerf width, kerf width on a curved cut, kerf taper, material removal rate, surface productivity, surface roughness, heat-affected zone, machining time, as well as emission rate and carbonization [6, 9-12]. In the present study, the multi-criteria analysis of the fiber laser cutting process considered the following evaluation criteria: cut perpendicularity (C1), surface roughness (C2), surface productivity (C3), dimensional deviation when cutting a 10 mm diameter hole (C4), and angular deviation when cutting at a 45° angle (C5). The selected criteria represent important quality and performance indicators in fiber laser cutting, influencing the dimensional accuracy, surface integrity, and overall process productivity.

The angular and hole dimensions were measured in three parallel planes, near the upper surface of the plate, at the mid-thickness, and near the lower surface of the plate. All measurements were performed using a DeMeet 443 coordinate measuring machine (CMM). Surface roughness, expressed as the average height of the profile (R_z), was measured three times along the cut edge at mid-thickness using a Marsurf XR 1 surface roughness tester. Surface productivity is defined as the amount of cut surface area generated per unit time. It can be estimated by multiplying the sheet thickness by cutting speed, providing a practical measure of the effective material removal rate.

3 MCDM MODEL

Based on the conducted fiber laser cutting experiment, the measured and estimated attribute values with respect to each of the five selected criteria, the MCDM model for fiber laser cutting of S235JR steel was developed (Table 1). Within the MCDM framework, each experimental trial, defined by a specific combination of focus position (f) and cutting speed (v), represents an alternative. On the other hand, evaluation criteria include cut perpendicularity (u), surface roughness (R_z), surface productivity (R), dimensional deviation when cutting a 10 mm diameter hole (Δ_h), and angular deviation when cutting at a 45° angle (Δ_a). It should be noted that surface productivity is the only maximization criterion, whereas all other criteria are of the minimization type, meaning that lower attribute values are preferred.

Table 1 MCDM model for fiber laser cutting of S235JR steel

Alternative	f (mm)	v (m/min)	u (mm)	R_z (μ m)	R (mm ² /min)	Δ_h (mm)	Δ_a (°)
1	1.2	3	0.011	2.58	12000	0.035	0.01
2	1.6	3	0.050	1.77	12000	0.104	0.08
3	1.2	3.6	0.029	2.48	14400	0.063	0.21
4	1.6	3.6	0.032	2.36	14400	0.101	0.11

The relative significance of the criteria in the proposed MCDM model was determined using the geometric mean method of the AHP in combination with Saaty's nine-point preference scale [15]. The overarching objective was to

achieve superior cut quality and dimensional accuracy. The resulting criteria weights were obtained as: $w_1 = 0.291$, $w_2 = 0.187$, $w_3 = 0.091$, $w_4 = 0.215$ and $w_5 = 0.215$. Accordingly,

cut perpendicularity, as well as dimensional and angular deviations were assigned the highest importance. Given the subjective nature of pairwise comparisons, a consistency check of the criteria evaluations was conducted. For the five criteria considered (with a corresponding random index, $RI = 1.12$), the calculated consistency ratio (CR) was 0.039, indicating high logical coherence of the judgments and confirming that the derived criteria weights are reliable.

4 RESULTS AND DISCUSSION

The WASPAS (Weighted Aggregated Sum Product Assessment) method, originally proposed by Zavadskas and co-authors in 2012 [16], was applied to derive the decision rule for evaluating alternatives within the proposed MCDM model. WASPAS represents a hybrid MCDM method that integrates two well-established methods, i.e., the weighted sum method (WSM) and the weighted product method (WPM). By combining the additive nature of WSM with the

multiplicative assessment of WPM, WASPAS enhances the robustness and reliability of the decision-making process, allowing it to capture both absolute performance differences and proportional relationships among alternatives.

The main computational procedure of the WASPAS method consists of several systematic steps, including data normalization, weighted aggregation, calculation of partial WSM and WPM indices, and determination of the total importance of alternatives using a joint criterion with a coefficient of linear combination, i.e., aggregation parameter (λ). Detailed descriptions of the computational steps of the WASPAS method can be found in the reference literature [16, 17].

Initially, the evaluation of alternatives was performed using a coefficient of linear combination of $\lambda = 0.5$. To assess the stability of the alternative rankings, values of the coefficient of linear combination (λ) were varied across the full range [0,1], and the resulting rankings of alternatives are presented in Fig. 1.

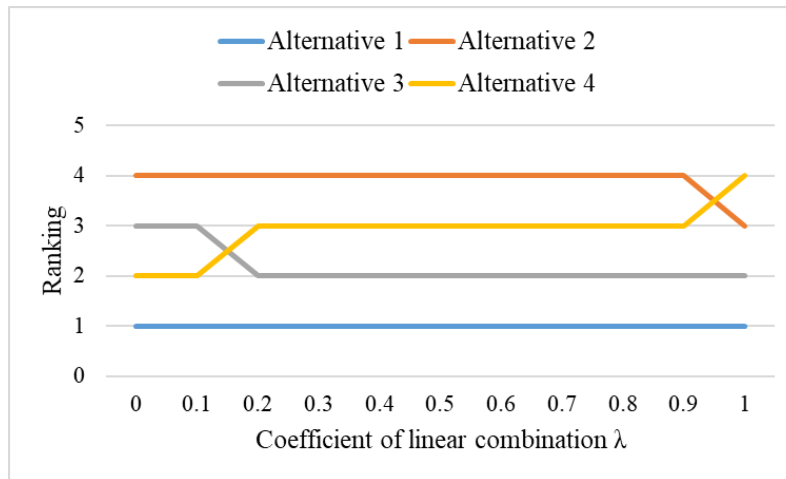


Fig. 1 Ranking results of alternative laser cutting conditions with respect to λ

Alternative 1 consistently holds the highest ranking, demonstrating clear superiority and robust performance regardless of the values of the coefficient of linear combination. Alternatives 2, 3, and 4 fluctuate between the second, third, and fourth positions, with notable changes occurring at both low and high values of the coefficient of linear combination. Overall, Fig. 1 highlights that while alternative 1 is consistently the best choice, alternative 2 is generally the least preferred.

The ranking pattern indicates that a lower focus position is crucial to yield better overall alternative's performance, since this parameter significantly affects kerf geometry characteristics and resulting perpendicularity and dimensional deviations, which dominate the ranking due to higher criteria weights. On the other hand, cutting speed mainly influences productivity.

By developing the quasilinear model for the prediction of the mean total relative importance of alternatives for all values of the coefficient of linear combination within [0,1] range, it can be shown that focus position has a strong negative correlation with the total relative importance of alternatives. There also exists a negative correlation between cutting speed and the total relative importance of alternatives. However, the effect is much less pronounced. Also, there is a

strong positive interaction of the focus position and the cutting speed.

In the scenario where surface productivity is assigned to be of the highest importance ($w_1 = 0.251$, $w_2 = 0.162$, $w_3 = 0.324$, $w_4 = 0.149$ and $w_5 = 0.113$), it can be shown that alternative 1 would consistently retain the highest ranking, whereas alternative 2 would remain the least preferred across all values of the coefficient of linear combination.

5 CONCLUSION

The present study applied the AHP-WASPAS approach for the evaluation of alternative cutting conditions in fiber laser cutting of S235JR steel. The analysis of results revealed that the focus position is the most significant parameter, as lowering consistently improves all quality criteria and criteria related to dimensional accuracy, driving the ranking outcomes more strongly than changes in cutting speed. Even when surface productivity is given top priority, the consistently superior balance of considered criteria is achieved in laser cutting conditions with low focus positions. These observations were confirmed by developing and analysing a quasilinear model for the prediction of the total

relative importance of alternatives. In addition, it was revealed that a notable effect comes from interaction of the cutting speed and focus position. Therefore, a coordinated adjustment of these parameters, rather than treating these parameters independently, is essential to achieve optimal cut quality or productivity. For future study, one should investigate a process window defined by moderate cutting speeds and lower focus positions in order to achieve the optimal trade-off between cut quality, dimensional accuracy, productivity, given their relative significance. The applied MCDM framework allows manufacturers to quantitatively evaluate trade-offs among multiple quality and productivity criteria, facilitating data-driven decision-making for process optimization, setup planning, and quality assurance in laser cutting operations.

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Contact address:
Miloš Madić
University of Niš
Faculty of Mechanical Engineering in Niš
18104 Niš
Aleksandra Medvedeva 14
E-mail: milos.madic@masfak.ni.ac.rs