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# $CO_2$ Laser Cutting Cost Estimation: Mathematical Model and Application

M. Madić[1,*], M. Radovanović[1], B. Nedić[2] and M. Gostimirović[3]

[1]*Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia*
[2]*Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia*
[3]*Faculty of Technical Science, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia*

Determination of the most suitable cutting regimes for satisfying different dimensional, quality and productivity characteristics while ensuring cutting with the lowest cost is of great importance. In this paper, an attempt has been made to propose comprehensive mathematical model for $CO_2$ laser cutting cost estimation. Based on the comprehensive analysis of the laser cutting process and analysis of number of proposed cost cutting calculation models, influence chart for $CO_2$ laser cutting cost was built upon which the mathematical model was developed. Apart from the previous models, emphasis has been given to assist gas consumption calculation since it represents a considerable percentage share in cost. The calculation of assist gas consumption was based considering technical specifications, recommendations and limitations of the considered $CO_2$ laser cutting machine. The possible application of the proposed model for laser cost calculation in the case of a number of various engineering materials was discussed.

*Keywords: $CO_2$ laser cutting, stainless steel, mild steel, aluminium, operating parameters, cost, mathematical model*

## 1 INTRODUCTION

The technology of laser cutting is based on the use of highly concentrated light energy obtained by laser radiation for cutting materials by the processes of melting and evaporation. The low energy input of laser cutting results in low deformation, a narrow recast layer and a narrow heat affected zone (HAZ) while the high power density enables high cut quality and using high

*Corresponding author: Tel: +381 18500687; E-mail: madic@masfak.ni.ac.rs

cutting speeds, i.e. achieving high productivity [1]. Today the reliability and robustness have put the laser on a par with most other machine tools and the cost of ownership and operation has fallen significantly [2]. Consequently, laser cutting become one of the leading non-conventional cutting technologies used in the industry for contour cutting of different materials.

From a technological point of view, the technology of laser cutting is a very complex process of interactions between the laser beam, assist gas and workpiece material whose performances (quality, productivity, cost and specific process performances such as specific cutting energy, maximal cutting speed for full cut, etc.) are influenced by a large number of factors. In order to achieve the required cut quality, reduce cost, increase productivity or accomplish a certain trade-off between these opposite criteria, it is necessary to quantify the relationships between the process factors and these performances by the use of mathematical models, either analytical or empirical.

Previous reviews [3–6] show that in majority of conducted researches and analysis the effects of process factors on quality including geometrical, surface and metallurgical characteristics were investigated while the cost determination and analysis has been given less attention; however, laser cutting cost is one of the most important criteria for manufacturers using this technology. Cost calculation is a basis for proposing the final price for a given job to potential customers so that all direct (prime) costs and indirect costs are covered while a certain amount of profit is ensured. Due to possible large and strong competition in the market it would be beneficial to calculate these costs as accurately as possible so that one can propose the best competitive price; however, laser cutting cost calculation is complex task considering that one needs to decide which cutting method is to be used for a given workpiece material and its thickness, which performances are to be achieved and finally which set of main factor values, regarding laser power, cutting speed, type and pressure of assist gas, nozzle type and diameter, will be used.

In order to consider laser cutting cost in line with other performances like quality criteria, productivity, etc. it is necessary to consider all constitutive aspects of laser cutting costs through development of a mathematical cost model. In such a way, based on the mathematical model, for a given laser cutting application one can simultaneously analyse different performances including cost and make certain trade-offs ensuring that all requirements are satisfied with the least cost. Although a good number of mathematical models have been developed for analysing cost in laser cutting [7–12], there are certain limitations for their application, and they are concerned with the following issues: (i) the cost of assist gases are taken on average; (ii) some models are very either to specific or very general whereas there is no or negligible difference in cost calculations when different methods of laser cutting (nitrogen or oxygen) are applied; (iii) some models are valid for relatively small experimental hyper-space in which empirical models are developed; (iv) simplified analysis regarding assist gas consumption was performed, etc.

Given that laser cutting costs may vary considerable [1], the present study aims at proposing a mathematical model for $CO_2$ laser cutting cost estimation considering main laser cutting factors such as laser power, cutting speed, assist gas type, and assist gas pressure and nozzle diameter as the main contributors of assist gas consumption in addition to other relevant constitutive costs. The proposed cost model is valid for $CO_2$ laser cutting of mild steel, stainless steel and aluminium using oxygen and nitrogen as assist gasses. The proposed model was developed considering systematization of numerous cost calculations from above mentioned literature. For the purpose of assist gas consumption calculation, technical specifications, recommendations and limitations of the considered $CO_2$ laser cutting machine were taken into account, however, its general form has wider application potential. The possible application for cost calculation in $CO_2$ laser cutting of other engineering materials is discussed considering previous research studies related to modelling and optimization of $CO_2$ laser cutting.

## 2 $CO_2$ LASER CUTTING COST MATHEMATICAL MODEL

Development of $CO_2$ laser cutting mathematical model for cost estimation needs considering all factors which directly or indirectly influence costs. Apart from investment cost for buying a laser cutting machine, considerable amount make costs of assist gases and electricity costs, followed by cost of laser gases, maintenance costs (cleaning and replacement of lenses, nozzles, guiding mirrors, etc.), labour costs, etc.

Investment costs for buying a laser cutting machine are function of power of the laser, number of cutting axes, coordinate table dimensions, beam quality, accuracy of positioning systems and quality of laser beam and optics installed; however, investment costs primarily depend on the power of the laser because the maximum material thickness that can be cut is in close relationship with power of the laser. Based on the research of laser cutting machine prices one can reach to the conclusion that it takes about 50 EUR *per* watt for two-dimensional (2-D) and 100 EUR *per* watt for three-dimensional (3-D) laser cutting machines. Other above-mentioned costs vary considerably from application to application, such as the type of laser cutting operation (fusion, oxygen, sublimation). This, in combination with selected laser cutting conditions, (laser cutting parameter values (laser power, assist gas pressure, nozzle diameter, cutting speed etc.)) makes estimation of laser cutting costs a complex task. Influence chart for the proposed model of $CO_2$ laser cutting cost estimation is given in Figure 1.

Determination of which assist gas type, gas pressure, nozzle diameter and laser power will be used for specific workpiece/task is a typical decision making situation for process planners and engineers. The selection of these factor values is usually subjective and conservative and it mainly guided by

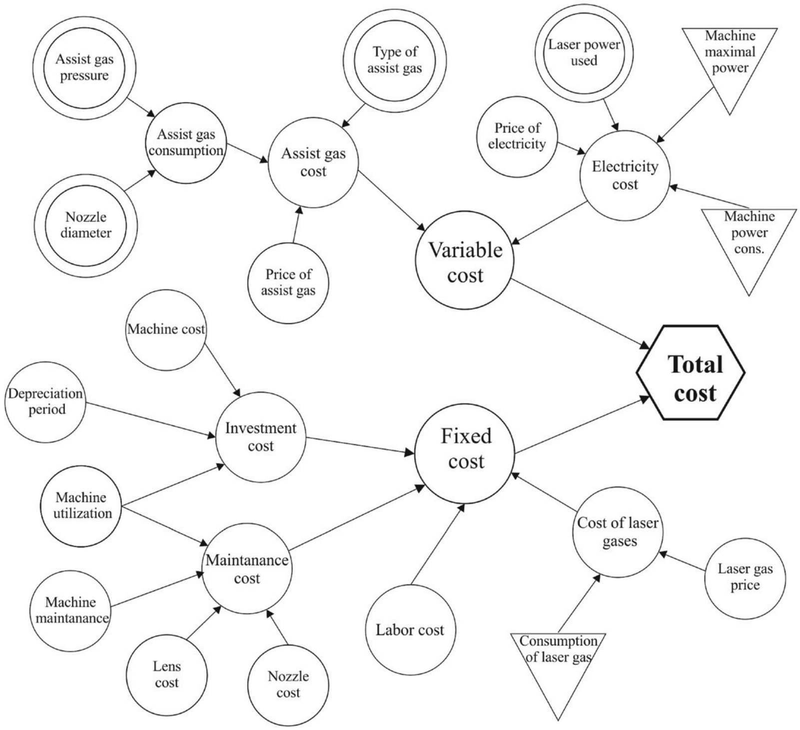



FIGURE 1
Influence chart for $CO_2$ laser cutting cost.

manufacturers recommendations as well as operators past experience and knowledge. Anyway, the final decision about laser cutting parameter values that would define a cutting regime for a given workpiece material and thickness is primarily affected by performance characteristics that should be achieved; for example, if the quality of the cut is not of crucial importance, cutting of stainless steel can be performed using $O_2$ as assist gas. But if superior quality of cut is to be achieved, high pressure laser nitrogen cutting is to be performed. Taking into account the fact that the change intervals for each of these parameters are quite large, it can be said that these parameters can have a decisive influence on the amount of total costs.

According to the basic constitutive cost components (*cf.* Figure 1) the overall $CO_2$ laser cutting cost can be determined using

$$C = C_f + C_v \tag{1}$$

where $C$ (EUR/h) is the overall cost, $C_f$ (EUR/h) is the fixed cost and $C_v$ (EUR/h) is the variable cost. The fixed cost can be determined from

$$C_f = C_i + C_m + C_{lab} + C_{lg} \tag{2}$$

where $C_i$ (EUR/h) is the investment cost of buying a $CO_2$ laser cutting machine, $C_m$ (EUR/h) is the maintenance cost, $C_{lab}$ (EUR/h) is the labour cost and $C_{lg}$ (EUR/h) is the laser gas (mixture of $CO_2$, $H_e$ and $N_2$) cost. The Investment cost of $CO_2$ laser cutting machine consider amortization of laser cutting machine and can be determined from

$$C_i = \frac{C_{lm}}{T_a \cdot L_a} \tag{3}$$

where $C_{lm}$ (EUR) is the buying cost of $CO_2$ laser cutting machine, $T_a$ (year) is the depreciation life of the laser cutting machine and $L_a$ (h/year) is the annual number of working hours of the laser cutting machine.

Either for new or used laser cutting machine, regular and preventive maintenance is required in order to ensure reliable and stable working of the laser cutting machine. It is usually performed by system operators and consists of among other things: cleaning and aligning cutting head, cleaning air and supply units, servicing laser module, combined cooling and filtration unit and electronic systems, checking supply lines for leaks, checking travel unit, cleaning and lubricating cutting table, sheet feeder and unloader. Maintenance costs can be roughly determined using

$$C_m = \frac{M}{L_a} + C_l + C_n \tag{4}$$

where $M$ (EUR/year) is the overall maintenance cost of laser cutting machine for one year, $L_a$ (h/year) is the total number of machine working hours for one year, $C_l$ (EUR/h) is the lens cost and $C_n$ (EUR/h) is the nozzle cost. The lens cost can be determined by

$$C_l = \frac{C_l}{T_l} \tag{5}$$

where $c_l$ (EUR) is the price of the lens and $T_l$ (h) is the lens life. The nozzle cost can be determined using

$$C_n = \frac{C_n}{T_n} \tag{6}$$

where $c_n$ (EUR) is the nozzle price and $T_n$ (h) is the nozzle life. In general, labour cost is closely related to the volume of production. They vary from company to company according to the circumstances of each country.

Any $CO_2$ laser cutting machine uses a mixture of gases ($CO_2$, He and $N_2$) for laser cutting operation. Laser gas cost can be determined using

$$C_{\mathrm{lg}} = c_{CO_2} \cdot Q_{CO_2} + c_{He} \cdot Q_{He} + c_{N_2} \cdot Q_{N_2} \tag{7}$$

where $c_{CO2}$, $c_{He}$ and $c_{N2}$ (EUR/m$^3$) are the prices of $CO_2$, He and $N_2$, respectively; and $Q_{CO2}$, $Q_{He}$ and $Q_{N2}$ (m$^3$/h) are consumption rates of $CO_2$, He and $N_2$, respectively.

For a specific laser cutting application, with given workpiece material and its thickness, the nature of laser cutting operation ($O_2$ or $N_2$), as well as selected cutting factors (nozzle diameter, assist gas pressure, cutting speed, laser power), the variable cost consists of laser electrical power cost and assist gas cost:

$$C_v = C_e + C_{ag} \tag{8}$$

where $C_e$ (EUR/h) is the laser electrical power cost and $C_{ag}$ (EUR/h) is assist gas cost. The laser electrical power cost can be determined as the function of the $CO_2$ laser cutting machine electrical power, electricity price and maximal and operational laser power [9]:

$$C_e = 0.8 \cdot c_e \cdot P_E \cdot \frac{P}{P_{\max}} \tag{9}$$

where 0.8 stands for the power factor, $c_e$ (EUR/kWh) is the electricity price, $P_E$ (kW) is the $CO_2$ laser cutting machine electrical power, $P$ (kW) is the laser power and $P_{max}$ (kW) is the maximal laser power.

In $CO_2$ laser cutting, coaxial to the laser beam a stream of assist gas is used in order to remove the melted and evaporated material while ensuring focusing lens protection. Depending on the type of laser cutting operation, workpiece material thickness and required performances (cutting speed, cut quality characteristics, cost, productivity) different assist gas types and pressures can be used. The assist gas cost can be determined from

$$C_{ag} = c_{ag} \cdot Q_{ag} \tag{10}$$

where $c_{ag}$ (EUR/m$^3$) is the price of the assist gas and $Q_{ag}$ (m$^3$/h) is the consumption of the assist gas.

The assist gas consumption is the function of the assist gas pressure and nozzle diameter and can be determined using the developed mathematical models, based on the data provided by Bystronic. Mathematical models for estimation of assist gas consumption, for low pressure (up to 6 bar) and high pressure (from 6 to 20 bar) laser cutting are given, respectively, by

$$Q_{ag} = 4.554 - 5.775 \cdot d_n - 1.513 \cdot p + 2.036 \cdot d_n^2 + 0.046 \cdot p^2 + 1.725 \cdot d_n \cdot p \qquad (11a)$$

$$Q_{ag} = 13.675 - 20.229 \cdot d_n - 0.964 \cdot p + 6.141 \cdot d_n^2 - 0.009 \cdot p^2 + 1.639 \cdot d_n \cdot p \qquad (11b)$$

where $d_n$ (mm) is the nozzle diameter and $p$ (bar) is the assist gas pressure. The accuracy of these developed models was confirmed with coefficient of determination having value of 0.99. The above developed models for assist gas consumption are valid for nozzle diameters of 0.80, 1.00, 1.25, 1.50, 2.00, 2.50 and 3.00 mm.

In accordance with Equations (2) to (11), the overall $CO_2$ laser cutting cost *per* hour can be represented by the following model:

$$C = C_i + C_m + C_{lab} + C_{\lg} + C_e + C_{ag} \qquad (12)$$

where $C$ is the overall cost in EUR/h.

For a given laser cutting application increased processing speeds decreases the total time required for processing thus, in indirect way, decreases other costs such as labour cost and electricity cost. In that sense by including the cutting speed ($v$ in m/h) in the previous model one obtains mathematical model for estimation of the overall $CO_2$ laser cutting cost *per* meter in the following form:

$$C = \frac{1}{v} \cdot \left( C_i + C_m + C_{lab} + C_{\lg} + C_e + C_{ag} \right) \qquad (13)$$

where $C$ is overall cost *per* meter in EUR/m. While the first, second, third and fourth factors in Equation (12) are primarily dependent on the price of the machine as well as maintenance policy, the fifth and sixth factors are solely dependent on the selected cutting conditions (laser power, assist gas pressure, nozzle diameter, cutting speed) for a given workpiece material thickness as well as cutting method ($O_2$ or $N_2$ cutting).

## 3 ANALYSIS OF $CO_2$ LASER CUTTING COSTS: CASE STUDIES

### 3.1 $CO_2$ laser cutting machine specification

The case study considers the "ByVention" 3015 $CO_2$ laser cutting machine (Bystronic) with a maximal power of $P_{max}$=2.2 kW. Electrical power consumption of this machine is $P_E$=35 kW. For the process of cutting the machine uses laser gas mixture LASERMIX312 and consumes $Q_{N2}$=0.012 m$^3$/h of $N_2$, $Q_{CO2}$=0.0012 m$^3$/h of $CO_2$ and $Q_{He}$=0.025 (m$^3$/h) of He. Other data required for laser cutting cost estimation are given in Table 1.

TABLE 1
Cost data.

| | |
|---|---|
| Unit cost of electrical energy | $c_e = 0.12$ EUR/kWh |
| Overall maintenance cost of $CO_2$ laser cutting machine for one year | $M = 6000$ EUR |
| Annual number of working hours of the laser cutting machine | $L_a = 2000$ h/year |
| Approximate laser cutting machine price | $C_{lm} = 100\,000$ EUR |
| Depreciation life of the laser cutting machine | $T_a = 7$ year |
| Labour cost | $C_{lab} = 5$ EUR/h |
| Average lens price | $c_l = 750$ EUR |
| Average lens life | $T_l = 800$ h |
| Average nozzle price | $c_n = 15$ EUR |
| Average nozzle life | $T_n = 300$ h |
| Average price of $CO_2$ | $c_{CO2} = 15$ EUR/m$^3$ |
| Average price of He | $c_{He} = 20$ EUR/m$^3$ |
| Average price of $N_2$ | $c_{N2} = 6$ EUR/m$^3$ |
| Average price of $O_2$ | $c_{O2} = 1.2$ EUR/m$^3$ |

### 3.2 Customized $CO_2$ laser cutting cost model

Starting from Equation (13) and by using the data from Table 1, laser cutting costs on particular laser cutting machine can be estimated using

$$C = \frac{1}{v} \cdot \left(16.72 + 1.527 \cdot P + c_{ag} \cdot Q_{ag}\right) \tag{14}$$

where $C$ is overall cost *per* meter (EUR/m), $v$ is the cutting speed, $P$ is the laser power, $c_{ag}$ is the price of the assist gas (EUR/m$^3$)and $Q_{ag}$ is the consumption of the assist gas.

### 3.3 Application of the developed model for estimation of $CO_2$ laser cutting costs

This section further discusses the application of the proposed mathematical model for estimation of laser costs in the case of oxygen and nitrogen cutting of mild steel, stainless steel and aluminium using the cutting conditions (cutting speed, assist gas pressure, type of assist gas, laser power and nozzle diameter) as recommended by manufacturers, machine tool producers and previous experimental practice and industrial applications.

Given the fundamental differences in the nature of the cutting process mechanism during oxygen and nitrogen cutting, the calculation considers also the cutting speed, therefore laser cutting cost is expressed in EUR/m.

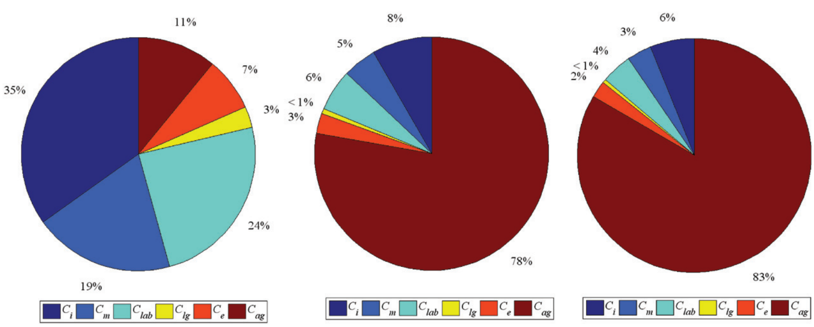
According to manufacturer's specification, the $CO_2$ laser cutting machine is able to cut mild steel using oxygen as assist gas up to 8 mm in thickness, stainless steel using nitrogen as assist gas up to 6 mm in thickness and aluminium using nitrogen as assist gas up to 4 mm in thickness. To this aim, when cutting with oxygen, normal pressure nozzles with inner diameters from 1.0 to 1.7 mm are used and in the case of nitrogen cutting, high pressure nozzles with inner diameters from 1.0 to 3.0 mm are used.

For the purpose of comparative analysis of the share of the constitutive costs as well as the total variable cost for cutting workpiece material with thickness of 2 mm, the proposed cost model is applied taking into account the recommended cutting conditions. Summary results are presented in Table 2.

Parsing down into component factors one obtains percentage share of costs for cutting mild steel, stainless steel and aluminium for a workpiece material with a thickness of 2 mm (see Figure 2). Based on the presented data, it can be seen that, in the case of oxygen cutting, the cost of the assist gas is about above 50% of the total variable costs, while in the case of nitrogen cutting, the cost of the assist gas account for more than 98%. This is due

TABLE 2
Laser cutting cost.

| Workpiece Material | Assist Gas | Cutting Conditions | | | | Laser Costs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $P$ (kW) | $v$ (m/min) | $p$ (bar) | $d_n$ (mm) | $C_f$ (EUR/h) | $C_e$ (EUR/h) | $C_{ag}$ (EUR/h) | $C$ (EUR/h) | $C$ (EUR/m) |
| Mild steel | $O_2$ | 1.0 | 7.0 | 3 | 1.0 | 16.72 | 1.53 | 2.24 | 20.49 | 0.049 |
| Stainless steel | $N_2$ | 1.6 | 4.0 | 10 | 1.5 | 16.72 | 2.44 | 67.16 | 86.32 | 0.360 |
| Aluminium | $N_2$ | 1.8 | 2.5 | 14 | 1.5 | 16.72 | 2.75 | 97.85 | 117.32 | 0.780 |




(a) (b) (c)

FIGURE 2
Pie charts showing the percentage share of individual costs in laser cutting of (a) mild steel, (b) stainless steel and (c) aluminium.

significantly lower cutting speeds, higher assist gas pressures which results in much higher gas consumption.

The calculation of the total cost of laser cutting for different thicknesses with appropriate cutting regimes is shown in Figure 3. In addition to the

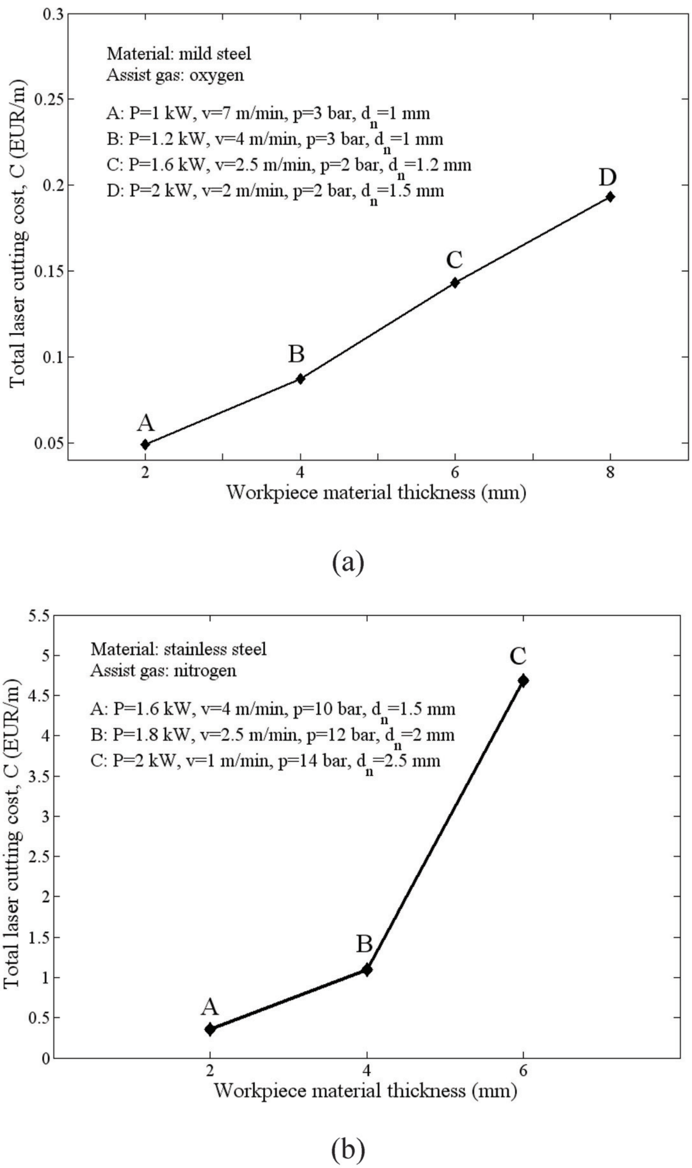



FIGURE 3
Graphs showing the total laser cost *versus* workpiece material thickness for (a) mild steel, (b) stainless steel and (c) aluminium.

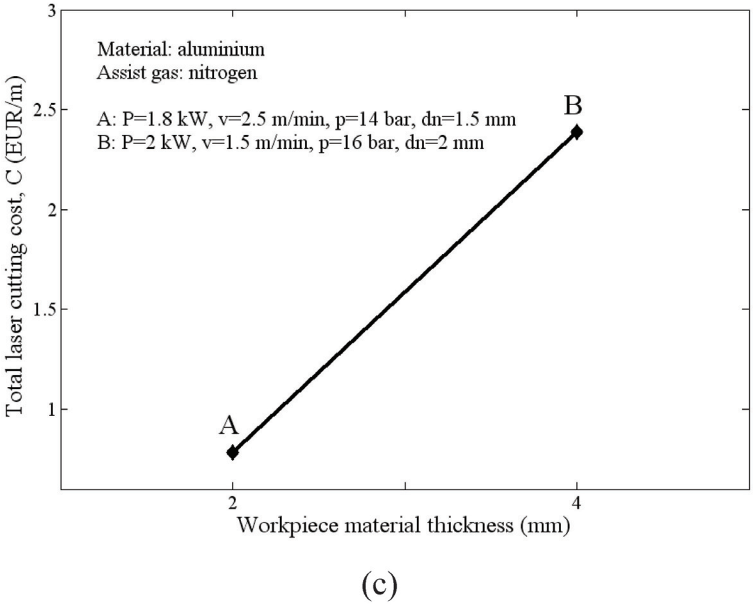



FIGURE 3, cont'd

previously given results, the proposed model was used to analyse the laser cutting cost of other materials according to the techno-technological capabilities of the considered $CO_2$ laser cutting machine. Using the available literature data, as well as the experiences of the researchers in the field of $CO_2$ laser cutting, related to the choice of the relevant cutting regimes, the proposed model was used to calculate the $CO_2$ laser cutting cost of various engineering materials, which are given in Table 3. The results of cost calculation are based upon the previously adopted cutting regimes considering different optimization criteria used by previous researchers.

## 4 CONCLUSIONS

For comprehensive analysis of a given laser cutting operation among different quality characteristics and productivity, one needs to consider also estimation of laser cutting cost. In this way, the conditions for more efficient use of laser cutting technology are created allowing achievement of required dimensional tolerances, surface finish and production rates at minimal cost. Moreover, having in mind the possibility of cost calculation one can easily make economical comparison of laser cutting with other conventional and nonconventional cutting techniques for a given part and cutting contour.

TABLE 3
Calculated $CO_2$ laser cutting cost based on the proposed cost model.

| Reference | Workpiece Material | WMT (mm) | *P* (kW) | *v* (m/min) | *p* (bar) | $d_n$ (mm) | Assist gas | OC | *C* (EUR/h) | *C* (EUR/m) |
|---|---|---|---|---|---|---|---|---|---|---|
| 13 | MDF | 4 | 0.15 | 5 | 3 | 1.5 | compressed air | Cost | 17.13 | 0.057 |
| | | 6 | 0.27 | 5 | 4 | 1.5 | | | 17.27 | 0.058 |
| | | 9 | 0.375 | 5 | 4 | 1.5 | | | 17.43 | 0.058 |
| 14 | AA 5083 | 2 | 1.8 | 3 | 14 | 1.5 | $N_2$ | SR | 117.32 | 0.652 |
| 15 | Kevlar-49 composite | 1 | 0.8 | 30 | 16 | 0.8 | $N_2$ | KW, KT, D | 45.98 | 0.026 |
| 16 | PMMA | 3 | 0.4 | 0.4 | 3 | 0.8 | compressed air | SR | 17.36 | 0.723 |
| 17 | PMMA | 6 | 0.65 | 2 | 0.5 | 0.8 | $N_2$ | SR | 24.81 | 0.207 |
| 18 | PTFE | 3 | 0.9 | 5 | 4.5 | 0.8 | compressed air | SR | 18.16 | 0.061 |
| 19 | PE | 3 | 0.5 | 2.7 | 3 | 0.8 | compressed air | SR | 17.54 | 0.108 |
| | | 5 | 0.5 | 1.1 | 3 | 0.8 | | | 17.54 | 0.266 |
| | PC | 3 | 0.6 | 8.2 | 3 | 0.8 | | | 17.7 | 0.036 |
| | | 5 | 1.2 | 7.2 | 3 | 0.8 | | | 18.61 | 0.043 |
| | PP | 3 | 1 | 9 | 3 | 0.8 | | | 18.31 | 0.034 |
| | | 5 | 1.2 | 5.3 | 3 | 0.8 | | | 18.61 | 0.059 |
| 20 | AISI-309 | 3 | 2 | 1.25 | 15 | 2 | $N_2$ | SR | 263.09 | 3.51 |
| 21 | AHSS | 0.7 | 0.3 | 7 | 6 | 1 | $O_2$ | SR | 21.67 | 0.052 |
| | | 1.5 | 0.5 | 2.5 | 4 | 1 | | | 20.36 | 0.136 |
| 22 | Galvabond | 1 | 0.7 | 5 | 2 | 1.7 | $O_2$ | KW, HAZ, D | 22.16 | 0.074 |
| 23 | Incoloy | 1 | 2 | 2 | 11 | 1 | $N_2$ | SR, D | 55.31 | 0.461 |

*Calculation based on the price of compressed air of 0.025 EUR/$m^3$
MDF - Medium density fibreboard, PMMA - Polymethyl methacrylate, PTFE - Polytetrafluoroethylene, PE - Polyethylene, PC - Polycarbonate, PP - Polypropylene, AHSS - Advanced high strength steel, GFRP - Glass fiber reinforced polymer;
SR – surface roughness, KW – kerf width, KT – kerf taper, D – dross, HAZ – heat affected zone
WMT – workpiece material thickness, OC – optimization criterion

Based on a comprehensive analysis of the $CO_2$ laser cutting process, in this study a mathematical model for the $CO_2$ laser cutting cost estimation is proposed. The conducted analysis of using 2.2 kW laser machine for cutting mild steel, stainless steel and aluminium revealed that laser cutting cost are mostly influenced by the choice of assist gas, followed by workpiece material thickness, where for greater thicknesses, in the case of nitrogen cutting, higher assist gas pressures are needed which results in higher cost, particularly when using nozzles of larger diameters. The developed model has a general application potential, and for the given case study it requires knowledge of laser cutting machine specification, as well as specified cutting regimes, that is, nozzle diameter, assist gas (type and pressure), laser power and cutting speed. By entering these information, one can obtain a clear view of the laser cutting cost structure and percentage share of each single constitutive costs.

## NOMENCLATURE

| | |
|---|---|
| $C$ | Overall cost (EUR/h) |
| $c_{ag}$ | Price of the assist gas (EUR/m$^3$) |
| $C_{ag}$ | Assist gas cost (EUR/h) |
| $c_{CO2}$ | Price of carbon-dioxide (EUR/m$^3$) |
| $c_e$ | Electricity price (EUR/kWh) |
| $C_e$ | Laser electrical power cost (EUR/h) |
| $C_f$ | Fixed cost (EUR/h) |
| $c_{He}$ | Price of helium (EUR/m$^3$) |
| $C_i$ | Investment cost (EUR/h) |
| $c_l$ | Price of the lens (EUR) |
| $C_l$ | Lens cost (EUR/h) |
| $C_{lab}$ | Labour cost (EUR/h) |
| $C_{lg}$ | Laser gas cost (EUR/h) |
| $C_{lm}$ | Cost of $CO_2$ laser cutting machine (EUR) |
| $C_m$ | Maintenance cost (EUR/h) |
| $c_n$ | Nozzle price (EUR) |
| $C_n$ | Nozzle cost (EUR/h) |
| $c_{N2}$ | Price of nitrogen (EUR/m$^3$) |
| $C_v$ | Variable cost (EUR/h) |
| $d_n$ | Nozzle diameter (mm) |
| $L_a$ | Annual number of working hours of the laser cutting machine (h/year) |
| $M$ | Overall maintenance cost of laser cutting machine (EUR/year) |
| $p$ | Assist gas pressure (bar) |
| $P$ | Laser power (kW) |
| $P_E$ | $CO_2$ laser cutting machine electrical power (kW) |
| $P_{max}$ | Maximal laser power (kW) |
| $Q_{ag}$ | Consumption of the assist gas (m$^3$/h) |
| $Q_{CO2}$ | Consumption of carbon-dioxide (m$^3$/h) |
| $Q_{He}$ | Consumption of helium (m$^3$/h) |
| $Q_{N2}$ | Consumption of nitrogen (m$^3$/h) |
| $T_a$ | Depreciation life of the laser cutting machine (year) |
| $T_l$ | Lens life (h) |
| $T_n$ | Nozzle life (h) |
| $v$ | Cutting speed (m/min) |

## REFERENCES

[1] Ion J. *Laser Processing of Engineering Materials: Principles, Procedure and Industrial Application*. Oxford: Butterworth-Heinemann. 2005.

[2] Steen W.M. ‘Light’ industry: An introduction to laser processing and its industrial applications. in Lawrence J., Pou J., Low D.K.Y. and Toyserkani E. (Eds.) *Advances in Laser Materials Processing: Technology, Research and Application*. Cambridge: Woodhead Publishing Limited. 2010.

[3] Meijer J. Laser beam machining (LBM), state of the art and new opportunities. *Journal of Materials Processing Technology* **149**(1–3) (2004), 2–17.

[4] Dubey A. and Yadava V. Laser beam machining - A review. *International Journal of Machine Tools and Manufacture* **48**(6) (2008), 609–628.

[5] Radovanović M. and Madić M. Experimental investigations of $CO_2$ laser cut quality: A review. *Nonconventional Technologies Review* **15**(4) (2011), 35–42.

[6] Parandoush P. and Hossain A. A review of modeling and simulation of laser beam machining. *International Journal of Machine Tools and Manufacture* **85**(1) (2014), 135–145.

[7] Radovanović M. and Dašić P. Cost analysis of laser cutting. *Annals of the University of Petrosani* **8**(1) (2006), 5–14.

[8] Ready J.F. and Farson D.F. *LIA Handbook of Laser Materials Processing*. Orlando: Laser Institute of America. 2001.

[9] Eltawahni H.A. Hagino M. Benyounis K.Y. Inoue T. and Olabi A.G. Effect of $CO_2$ laser cutting process parameters on edge quality and operating cost of AISI316L. *Optics & Laser Technology* **44**(4) (2012), 1068–1082.

[10] Brinke E. Costing Support and Cost Control in Manufacturing. A Cost Estimation Tool Applied in the Sheet Metal Domain. PhD thesis, University of Twente. 2002.

[11] Harničárová M. Valíček J. Zajac J. Hloch S. Čep R. Džubáková I. Tofil S. Hlaváček P. Klich J and Čepová L. Techno-economical comparison of cutting material by laser, plasma and oxygen. *Technical Gazette* **19**(4) (2012), 813–817.

[12] Nedić B. Erić M. and Aleksijević M. Calculation of laser cutting costs. *International Journal for Quality Research* **10**(3) (2016), 487–494.

[13] Eltawahni H.A. Olabi A.G. and Benyounis K.Y. Investigating the $CO_2$ laser cutting parameters of MDF wood composite material. *Optics & Laser Technology* **44**(3) (2011), 648–659.

[14] Stournaras A. Stavropoulos P. Salonitis K. and Chryssolouris G. An investigation of quality in $CO_2$ laser cutting of aluminum. *CIRP Journal of Manufacturing Science and Technology* **2**(1) (2009), 61–69.

[15] El-Taweel T.A. Abdel-Maaboud A.M. Azzam B.S. and Mohammad A.E. Parametric studies on the $CO_2$ laser cutting of Kevlar-49 composite. *The International Journal of Advanced Manufacturing Technology* **40**(9–10) (2009), 907–917.

[16] Choudhury I.A. and Shirley S. Laser cutting of polymeric materials: an experimental investigation. *Optics & Laser Technology* **42**(3) (2010), 503–508.

[17] Davim J.P. Oliveira C. Barricas N. and Conceição M. Evaluation of cutting quality of PMMA using $CO_2$ lasers. *The International Journal of Advanced Manufacturing Technology* **35**(9–10) (2008), 875–879.

[18] Kurt M. Kaynak Y. Bagci E. Demirer H. and Kurt M. Dimensional analyses and surface quality of the laser cutting process for engineering plastics. *The International Journal of Advanced Manufacturing Technology* **41**(3–4) (2009), 259–267.

[19] Caiazzo F. Curcio F. Daurelio G. and Minutolo F.M.C. Laser cutting of different polymeric plastics (PE, PP and PC) by a $CO_2$ laser beam. *Journal of Materials Processing Technology* **159**(3) (2005), 279–285.

[20] Cekic A. Begic-Hajdarevic D. Kulenovic M. and Omerspahic A. $CO_2$ laser cutting of alloy steels using $N_2$ assist gas. *Procedia Engineering* **69**(1) (2014), 310–315.

[21] Lamikiz A. De Lacalle L.L. Sanchez J.A. Del Pozo D. Etayo J.M. and Lopez J.M. $CO_2$ laser cutting of advanced high strength steels (AHSS). *Applied Surface Science* **242**(3–4) (2005), 362–368.
[22] Wang J. and Wong W.C.K. $CO_2$ laser cutting of metallic coated sheet steels. *Journal of Materials Processing Technology* **95**(1–3) (1999), 164–168.
[23] Syn C.Z. Mokhtar M. Feng C.J. and Manurung Y.H. Approach to prediction of laser cutting quality by employing fuzzy expert system. *Expert Systems with Applications* **38**(6) (2011), 7558–7568.