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Definition of Mathematical Models of High-Alloyed Steel 1.4828 in CO_2 Laser Cutting

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Abstract

This paper defines mathematical models of value changes for surface roughness (*Ra*, µm) and heat affected zone width (*HAZ*, mm) during high-alloyed steel 1.4828 laser cutting using oxygen as an assistance gas. For the definition of appropriate mathematical models, multiple linear regression analysis is used, with four independent variables that were varied at five levels. Following parameters are varied: cutting speed (*V*), assist gas pressure (*p*), focus position (*fs*) and stand-off (N_d). In comparison between the model and the experimental results, it can be concluded that the effects of specified parameters on cut quality, productivity and thus the legitimacy of this technology for cutting high-alloyed steels are well described by the obtained mathematical models.

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Keywords: CO_2 laser cutting; high-alloyed steel; mathematical model; heat affected zone (*HAZ*); surface roughness (*Ra*)

1. Introduction

Laser cutting technology can achieve higher accuracy of processing (narrower tolerance measures), better quality (less processed surface roughness), smaller width of cut (material saving), smaller heat affected zone (reduced deformation of materials), increased productivity, etc. However, to achieve this it is necessary to optimize a large number of interconnected nonlinear linked influential parameters for each processed material and processing conditions. The most significant parameters in laser processing are: *parameters of laser beam* (wavelength, laser power, TEM mode, quality and polarization of the laser beam, etc.), *process parameters* (continuous and/or pulse

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laser power oscillation, length and depth of focus, the diameter of focused laser beam, focus position relative to the work piece, type of focusing lens, cutting speed, type and pressure of the assist gas, design and the distance between nozzle and the work piece, etc.) and the *parameters of the processed material* (properties and thickness of the material and the required quality of processing) [1]. Definition of the optimal cutting parameters is a complex task, because laser cutting can be performed by various methods, from cutting by melting with deflating products using assist gas to direct evaporation of materials. Variants of cutting depends on a number of parameters, whose interconnectedness makes material behaviour extremely complex during laser cutting. For example, depending on the material and the desired quality of the processed surface assist gas (oxygen, nitrogen, and air) must be brought into the treatment zone under certain pressure. In order to achieve higher productivity during cutting, especially of steel materials, high purity oxygen is most commonly used (greater than 99.97%). Using oxygen as an assist gas can increase cutting speed by up to 40%, with a linear decrease of the heat affected zone with increasing pressure of assist gas [2]. Oxygen in the reaction with metal creates an exothermic reaction that provides additional heat which results in higher cutting speed. Of course, to maximize the effect of using assist gas, it is necessary to optimize not only the pressure, but also a way of bringing it into the cutting zone as well as diameter, profile and distance between nozzle and the treated material, etc. [3]. What can be concluded, in general sense, is that the researches with the aim of optimizing laser cutting parameters are very extensive and complex due to large number of influencing factors that are in mutual nonlinear interaction. In fact, the productivity of laser systems is usually not optimal only because there is lack of technological basis in a specific production condition. Output parameters that depend on the input, and on the basis of which the quality and justification of its use of this technology are confirmed are: cutting surface roughness - *Ra*, heat affected zone width - *HAZ*, cutting width - *d*, dimensional control of the work piece, the amount of dripping, frequency of stretch marks, microhardness change at HVI, structure change of the base material and other. Cut quality during laser cutting is classified according to EN ISO 9013: 2002 standard (standard for thermal cuts). Apart from that, irregularities in laser cutting can be divided into 5 groups (according to DVS-Merkblatt 3206 that builds on DIN 8518): at the edges, on the cut surface, drips (solidified molten material), cracks on cut surface and other irregularities. The major causes of irregularities are either extremely large submitted energy or wrong cutting parameters (cutting speed, focus position, distance of nozzle, type and pressure of the assist gas, etc.) [4], [5]. The solution is to optimize all influential parameters of cutting for each processed material, material thickness, required cut quality, productivity, and so on. This paper provides a complete analysis of the effects of certain parameters of high-alloy steel laser cutting [6], [7]. Also, optimal cutting parameters were defined with the aim to achieve the desired product quality with maximum savings of the material (reducing the width of cut and heat affected zone). An additional inspection of the material after laser cutting indicates that there is no change in the structure or cutting surface hardness. This increases the justification of high-alloy steel laser cutting technology implementation. Diagram of proposed hypotheses on the basis of which the experiments were performed and are partially presented in this paper as well as the principle of defining the appropriate mathematical models of change indicators of quality of machined surface is presented in Figure 1. [8]. The objective of the researches conducted, which are partially presented in this paper, is the identification, quantification and optimization of cutting parameters in laser cutting of high-alloy steel. Furthermore, the paper outlines sufficiently reliable mathematical models that describe the dependence of input and output parameters for given conditions.

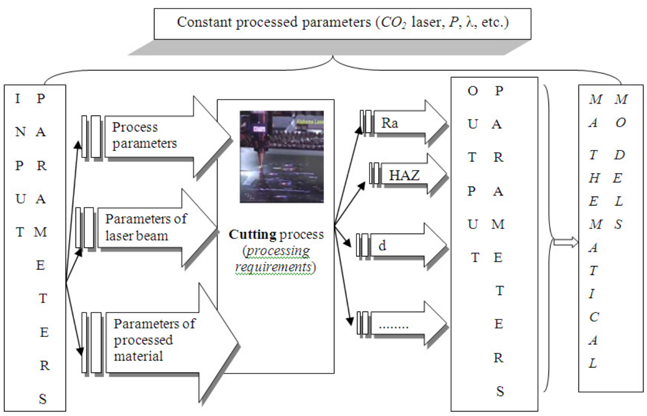

Fig. 1. The general model of experimental studies and used principle in order to define the mathematical models for laser cutting process.

2. Experimental setup

Sophisticated equipment in the laboratory for laser technology at the University of Jena, Germany was used. Bearing in mind that a very large number of processing parameters affects the laser cutting process, following limits were set. Cutting is performed with different combinations of technological parameters on the CO_2 laser with nominal power of 2000 W (Figure 2). Although a number of different types of machining lasers are developed, CO_2 lasers are mainly used because of their greater efficiency and lower investment costs of laser power. Length of focus, wavelength of the laser beam, method of bringing assist gas, movement system of the work piece and the laser beam, etc. are the characteristics of a machining system and can not be used as a variable size during the cutting process.

- nominal laser power: P=2000 W,
- wavelength of the laser beam: λ=10,600 μm,
- laser mode: cw i pw,
- focal length of the lens in order to focus the laser beam on the work piece: f = 127 mm,
- beam quality: M^2=1,063 (K = 0,94),
- relative motion: fixed optics, moving the work piece in the X-Y plane (CNC).

Fig. 2. The appearance and technical characteristics of the CO_2 laser – Rofin DC020 (University of Applied Sciences Jena).

Experimental research of the cutting process were performed on high-alloy steel 1.4828. Hardness, chemical composition and thickness of the material (s = 3 mm) are given in Table 1. This material, due to improved mechanical and fire-resistant characteristics, is becoming more used in various industries, especially in the automotive industry. In fact, taking into account the assessment of relevant institutes that in the future, especially in the automotive industry, there will be further increase in application of alloy steel (increased concentrations of Ni, Cr, etc.), there is an expanding need for research in order to increase the justification degree of the application of laser processing for these materials. The tested material is particularly interesting to study because of the increased content of Cr which intensively reacts with O_2 forming Cr_2O_3 oxides that has a high melting point. Therefore, experimental studies of laser cutting are executed using O_2 as an assist gas.

Table 1. The cemical composition, hardness (HB) and thickness (s) of the material.

Material**: 1.4828** (X15CrNiSi20-12), s = 3 mm								
C ≤	Si	Mn	**Cr**	Ni	P ≤	S ≤	N ≤	HB ≤
0,20	1,5 – 2,5	2,0	**20,0 – 23,0**	11,0 – 13,0	0,045	0,015	0,11	256

Feasibility and process quality of high-alloy steel 1.4828 laser cutting was done on the basis of width of cut measured values (*d*), heat affected zone size (*HAZ* _ lower side), mean arithmetic deviation of profile (*Ra*), as well as measuring the microhardness and metallographic recording of processed surface structure. Geometric shape patterns for cutting and schematic view of work piece parameters during laser cutting is shown in Figure 3.

Measurement of the width of cut and width of *HAZ* were done on the microscope "Stemi 2000 - C ZEISS" with 10x magnification. Measurement of the cutting surface quality was performed on the Taylor Hobson device which operates on the principle of contact method. Measurement of cutting surface microhardness was performed using Vickers method (DIN 50133) on samples where the minimum and maximum *HAZ* width was established. The microhardness was measured on the machine Zwick with load of 5N (HV 0,5). Microscopic metallographic recording of the processed surface structure was performed with an electron microscope.

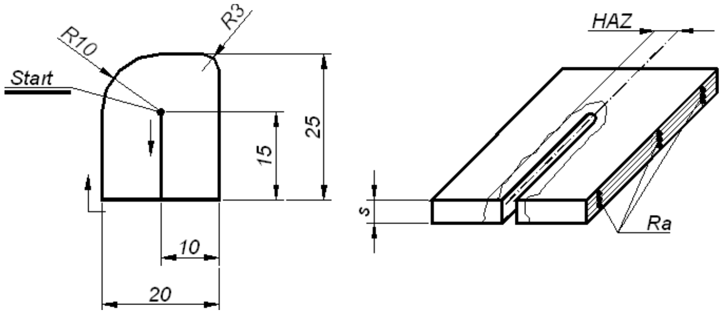

Fig. 3. Geometric shape patterns for cutting and schematic view of work piece parameters during laser cutting.
(•1 - cutting start - hole drilling with laser; s, mm - thickness of the work piece, ↑ - direction of the laser beam)

During the execution of experiments, the following parameters were kept constant:

- continuous laser mode: cw,
- diameter of the laser beam in focus - measured: 0,21 mm,
- nozzle: 2 mm - conical,
- type of assist gas (research was conducted with the use of O_2 with maximum purity),
- assist gas supply: coaxial with the laser beam,
- thickness of the test material (3 mm),
- laser power: (**P = 2000 W**) and
- nozzle distance: (**1 mm**).

Laser cutting of the test material was executed using O_2 as an assist gas by varying the laser power from 500 to 2000 W with increments of 250 W with a wide range of variation in cutting speed, focus position, distance between nozzle and the work piece and gas pressure. Quality of cutting surface was determined by measuring the width of cut and *HAZ* as well as visually inspecting the cut quality. The results of experimental studies have shown that an increase in the radiation power results in higher cutting speeds. As the industry interest is always about achieving maximum productivity, these laser cutting experiments in order to optimize the parameters were performed with maximum power (P = 2000 W). Cutting of the above said steel using O_2 as assist gas was performed in order to determine the optimal nozzle distance. The distance was varied from 0,5 to 2 mm with increments of 0,25 mm. General conclusion of experimental research is, given that with increasing of nozzle distance, width of cut value and *HAZ* also increases, and that by doing so it is not possible to adjust the focus position below the work piece and vice versa, by reducing the distance it is impossible to cut with smaller assist gas pressures and with the focus position over the surface, therefore optimal nozzle distance was determined to be 1 mm.

Experimental results showed that the most important parameters of cutting surface roughness (*Ra*), heat affected zone (*HAZ*) and the width of cut (*d*) are cutting speed (*V*), assist gas pressure (*p*) and focus position relative to the surface of the work piece (f_s). In order to define the optimal parameters of the laser cutting process, a series of experiments were made by which certain acceptable value ranges were specified in terms of achieving a specified target.

On the basis of previous experiments it can be concluded that the cutting speed is the most influential parameter on the quality of cutting surface and productivity. In order to determine the acceptable extent of cutting speed, experiment was performed with varying cutting speeds with a wide range of changes in other process parameters (focus position, the pressure of the assist gas, etc.). Based on the experience gained on the influence of certain parameters on the quality of the cutting surface, general conclusion is that it is necessary for a given material, thickness, and working conditions to firstly define the possible acceptable cutting speed interval, and then to define the scope of other process parameters. Thus, the focus position relative to the surface of the work piece is varied from the maximum down position *fs* = - 1.75 mm to *fs* = + 3 mm with a wide range of variation in the other two important parameters, cutting speed and pressure of the assist gas. Also, the cutting was done with the pressures of O_2 as an assist gas from 2,5 bar up to the maximum (20 bar) with 2,5 bar increments.

By analyzing the data on the change of cut width, HAZ and Ra as well as visual examination of samples, the plan of the experiment, laser cutting of the test material with the following values of variable parameters, was defined:

a) O_2 assist gas pressures: *p* = 12,5 bar, *p* = 15,0 bar. *p* = 17,5 bar,
b) cutting speed: *V* = 2000 mm/min, *V* = 3000 mm/min, *V* = 4000 mm/min,
c) focus position relative to the work piece surface: *fs* = -1 mm, *fs* = 0 mm, *fs* = +1 mm.

Figures 4, 5 and 6 shows the changes in the width of the cut, *HAZ* and *Ra* parameter respectively when cutting the steel 1.4828 with varying cutting speed, focus position and pressure of O_2 as an assist gas. Smaller cutting width is obtained at cutting speeds from 3000 to 4000 mm / min for all combinations of the focus position and the assist gas pressures. Maximum cutting width is determined by the position of the focus of *fs* = + 1 mm and a pressure of 17,5 bar and the minimum at *fs* = - 1 mm and *p* = 12,5 bar. Cutting width is measured on all samples from the inlet side of the laser beam due to the occurrence of dripping on the lower side of the cut.

Analysis of *HAZ* was performed according to measured values at the output side of the laser beam from the work piece due to higher values obtained in relation to the input side of the cut. It is important to emphasize that there are similar changes in *HAZ* of cut upper and lower side as a function of cutting process major parameters (*V, fs, p*). At the focus position *fs* = - 1 mm increasing of the cutting speed reduces the HAZ and even more so at lower gas pressure. With the focus position on and above the work piece there is an increase in the *HAZ* with increase of cutting speeds for all combinations of gas pressure. The maximum change in the width of the *HAZ* for the varied cutting parameters is 0,318 mm.

The maximum value of *Ra = 5,938* µm is achieved using O_2 as an assist gas at a pressure of 17,5 bar, focus position of *fs* = – *1* mm and a cutting speed of 2000 mm/min. The minimum value of *Ra = 2,634* µm is achieved at a pressure of O_2 as an assist gas of 12,5 bar and the focus position of *fs* = + *1* mm.

Requirements to obtain increased accuracy of dimensions and shapes of the product, productivity and cost-effectiveness of the process with maximum material savings are research imperative. Previous experimental research shows that apart from distance between nozzle and the work piece most important parameters of the laser cutting process of high-alloy steel which affect the value of surface roughness of cutting (*Ra*), the width of the heat affected zone (HAZ) and the width of cut (*d*) are cutting speed (*V*), assist gas pressure (*p*) and focus position relative to the work piece surface (*fs*). However, for a comprehensive approach to optimization of process parameters other parameters must be analyzed, such as the characteristics of the working system, laser power, assist gas, material and the thickness of the work piece, work piece surface condition, etc. Only by optimization of all process parameters it is possible to minimize the maximum value of the *HAZ*, *d*, *Ra*, etc. and thereby increase the degree of justification of the application of this procedure in the process of high-alloy steel cutting.

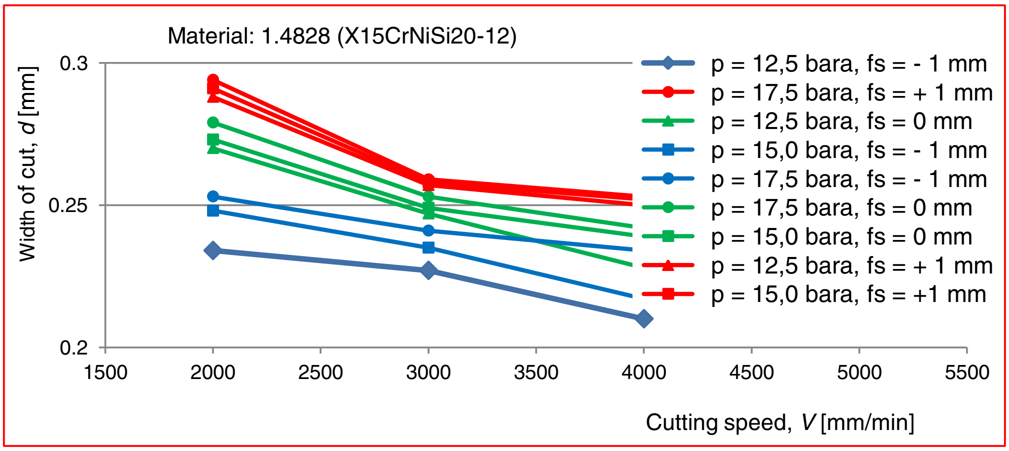

Fig. 4. Change of the width of cut during laser cutting of steel 1.4828 with O_2 as an assist gas.

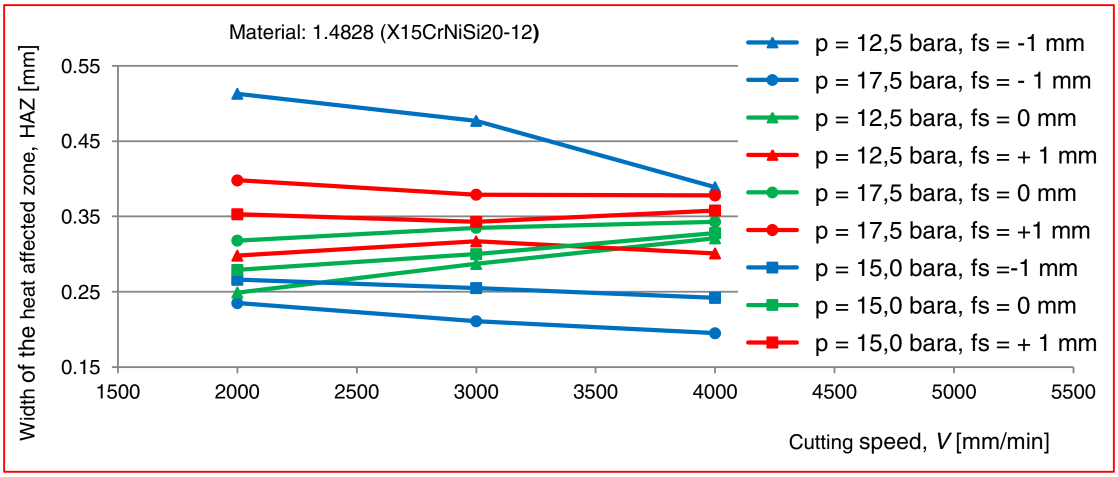

Fig. 5. Change of the width of HAZ during laser cutting of steel 1.4828 with O_2 as an assist gas.

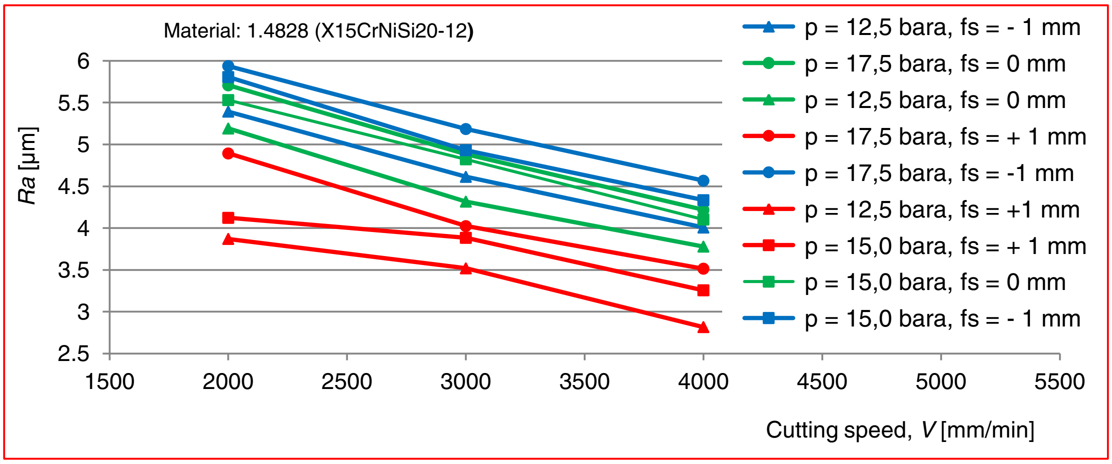

Fig. 6. Change of Ra during laser cutting of steel 1.4828 with O_2 as an assist gas.

3. Mathematical modeling of processed surface parameters during laser cutting of the examined steel

Parameter modelling of laser cutting process quality requires the use of mathematical method in order to find the most favorable values of cutting parameters with which to achieve the minimum surface roughness, maximum productivity and maximum savings of the material with the proper planning of experiments, using the regression analysis based on the measured values of the cut quality parameters. Overall scheme of the laser cutting process model which outlines the appropriate mathematical models is shown in *Figure 7*.

Selection of the influential parameters for definition of the mathematical models is determined on the basis of literature data on this process as well as the experience gained during the implementation of preparatory experiments. Following four parameters were selected as the most influential in terms of the justification of the use of laser cutting technology:

- cutting speed – *V*, mm/mi
- focus position – *fs*, mm
- assist gas pressure– *p*, bar and distance between nozzle and the work piece – N_d, mm.

Other conditions during the experiments were constant and are considered as an external factors for modeling process. Experiments that were conducted in order to define the mathematical models were performed under the following conditions:

- *The base material.* Mathematical modeling was performed for the cutting of high-alloy steel for special purposes: 1.4828. Table 2 shows the mechanical properties, chemical composition and thickness of the investigated steel.
- *Machining system*. Experiments were performed under steady-state regime on CO_2 laser - Rofin DC020. Technical characteristics are given in Figure 2. In order to achieve greater acceptable cutting speed (maximum productivity) experiments were carried out with a maximum laser output power of 2000 W.
- *Nozzle*. Used nozzle diameter during cutting was 2 mm. Focus distance was constant (127 mm).
- *The assist gas*. Cutting process is performed using O_2 as an assist gas. Additional gas of maximum quality for cutting process is brought to the workpiece in a unique way, through a nozzle coaxially with the laser beam.

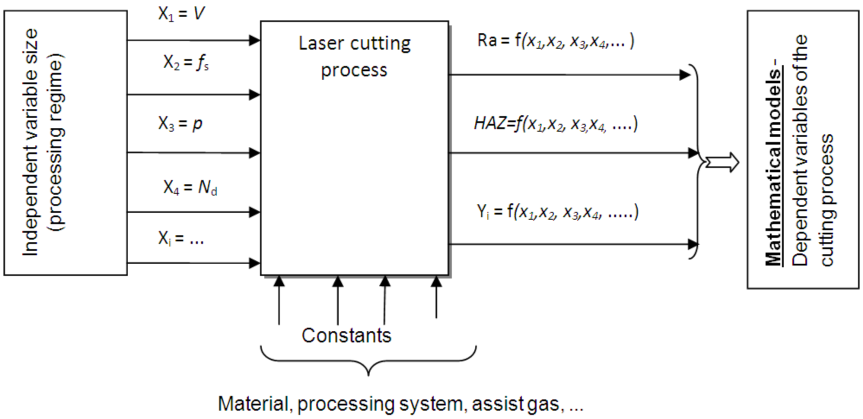

Fig. 7. Input and output parameters of processing identification in laser cutting.

Mathematical modeling of machining parameters during cutting of steel 1.4828 using O_2 as an assist gas was performed by using regression analysis based on the measured values of the parameters *Ra* and the width of the *HAZ* for the corresponding independent variable *Xi*. Specifically, based on the previously conducted experimental research whose results are presented in the first part of this paper, for cutting process modeling of tested high-alloy steel, following two dependent variable parameters were selected, *Ra* and width of the *HAZ*. Based on these two indicators one can usually reach a conclusion about the justification for applying the technology of laser cutting. Physical values of the influential parameters are varied in five levels. Table 2 shows the real and coded values of the parameters by levels according to which the plan for cutting experiments of tested steel using O_2 as an assist gas was defined. We used a model based on several factors. Namely, the mathematical model (1) and using the central compositional rotary experiment plan (N = 31) a change of parameter values of roughness *Ra* was defined ($X_1 = V$, $X_2 = fs$, $X_3 = p$, $X_4 = N_d$), respectively *HAZ* ($X_1 = V$, $X_2 = fs$, $X_3 = p$, $X_4 = N_d$), by variation of all factors (independent variables) on five levels. As four influential technological parameters were selected (*V, fs, p, Nd*), adequate model was applied for four variables that sufficiently describe the technological laser cutting process:

$$\widehat{Y_i} = b_0 x_0 + \sum_{i=1}^{4} b_i x_i + \sum_{i=1}^{4} b_{ii} x_i^2 + \sum_{1 \le i < j}^{4} b_{ij} x_i x_j + \sum_{1 \le i < j < k}^{4} b_{i\,j\,k}\, x_i x_j x_k \quad (1)$$

and equation (1a):

$$Y_i = b_0 X_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 + b_{44} X_4^2 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{14} X_1 X_4 + b_{23} X_2 X_3 + b_{24} X_2 X_4 + b_{34} X_3 X_4 + b_{123} X_1 X_2 X_3 + b_{134} X_1 X_3 X_4 + b_{234} X_2 X_3 X_4 \quad (1a)$$

where: Yi – quality control parameters (*HAZ* or *Ra*)

b_0, b_i, $b_{(ij)}$ $b_{(ii)}$,b_{ijk}…. coefficients of the model (1 or 1a), which are defined after conducting an experiment

Xi, ... variables

Table 2. The levels of variation of influential process parameters of laser cutting.

Influential parameters		Coded values				
		X_{j5}	X_{j2}	X_{j3}	X_{j1}	X_{j4}
		-2	-1	0	1	2
The actual values of laser cutting using O_2 as assist gas	X_1=V	2000	2875	3750	4625	5500
	X_2=fs	-2,0	-1,0	0,0	+1,0	+2,0
	X_3=p	7,5	10,0	12,5	15,0	17,5
	X_4=Nd	0,50	0,75	1,00	1,25	1,50

As regression analysis accepts 17 variables for defining the regression coefficients and the proposed model (equation 1) consists of 18, after several iterations one parameter that showed the lowest value of significance was eliminated. Coefficients significance rating of mathematical models was made based on the Student t - criteria for the condition $t_{ri} \rangle t_{(f_E,\alpha)}$, where $f_E = n_0 - 1 = 7 - 1 = 6$ and for the significance level of $\alpha = 0{,}05$. Adequacy check of the model (equation 1) was performed according to the Fisher criteria for the condition $F_a \langle F_{t(f_a,f_E)} = F_{T(14,6)}$ and for the level of significance of $\alpha = 0{,}01$.

Regression models, after testing the coefficients significance of the proposed model for the prediction (estimate) of the values of Ra and the width of the HAZ during laser cutting of examined steel with O_2 as the assist gas, are:

a) Ra model for steel 1.4828 cutting using O_2 (determination model of the coefficient is $R^2 = 0{,}8735$):

$$Ra=8{,}4915-0{,}0005\cdot V+0{,}2224\cdot fs+0{,}0087\cdot p-4{,}4036\cdot N_d+0{,}6442\cdot N_d^2-0{,}366 f_s N_d+0{,}0867\, pNd \tag{2}$$

b) HAZ model for steel 1.4828 cutting using O_2 (determination model of the coefficient is $R^2 = 0{,}91882$.)

$$HAZ= 0{,}6713-0{,}00001\cdot V-0{,}0339\cdot fs-0{,}0044\cdot p- 0{,}8128\cdot Nd+0{,}0609\cdot f_s^2+0{,}4379\cdot N_{d2}+0{,}0003\cdot pNd \tag{3}$$

4. Results and discussion

Figures 8 and 9 present the comparison of experimental and model parameter values of *Ra* (Equation 2) and *HAZ* (Equation 3) respectively for steel 1.4828 cutting, using O_2 as an assist gas. It should be noted that the diagrams are made for certain parameters and for clarity not all the variations of parameters are shown because in that case diagram representations would be overloaded, which would significantly reduce the visibility of legality and matching. The Figures shows the combination of cutting parameters at which the minimum or maximum value of the surface roughness of cutting (*Ra*) and minimum or maximum values of the width of heat affected zone (*HAZ*) are obtained.

By comparing the results of the parameters *Ra* or *HAZ* obtained by the corresponding regression models with measured values one can notice a good agreement especially in terms of cutting at which better quality is obtained (Figure 8) or the smaller width of the heat affected zone (Figure 9). It is important to note that at the focus position above the entrance side of the laser beam into the work piece, *Ra* decreases during the cutting of the examined steel. However, in these conditions, there is a reduction of the maximum acceptable cutting speeds. The decreasing trend in cutting speeds would continue with focus increase which is opposed to the desirability to achieve greater productivity (black line in Figure 8). The values of surface roughness of cutting (*Ra*) with focus position *fs = 0* mm and *fs = 2* mm are in the range that belongs to the same class of roughness. The Reduction of the width of HAZ is noticeable with increasing cutting speeds.

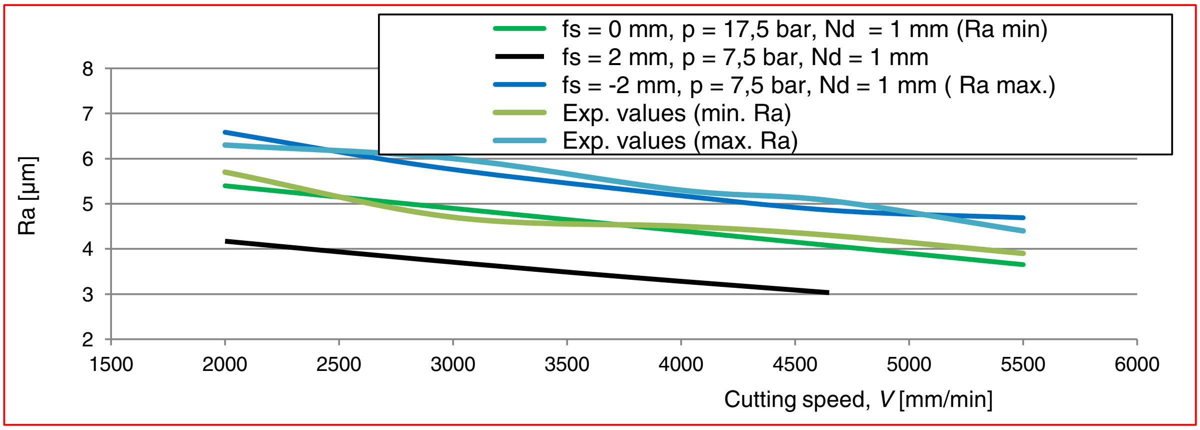

Fig. 8. Comparison of model and experimental values of the Ra parameter (Steel 1.4828 cut with laser using O_2 as an assist gas).

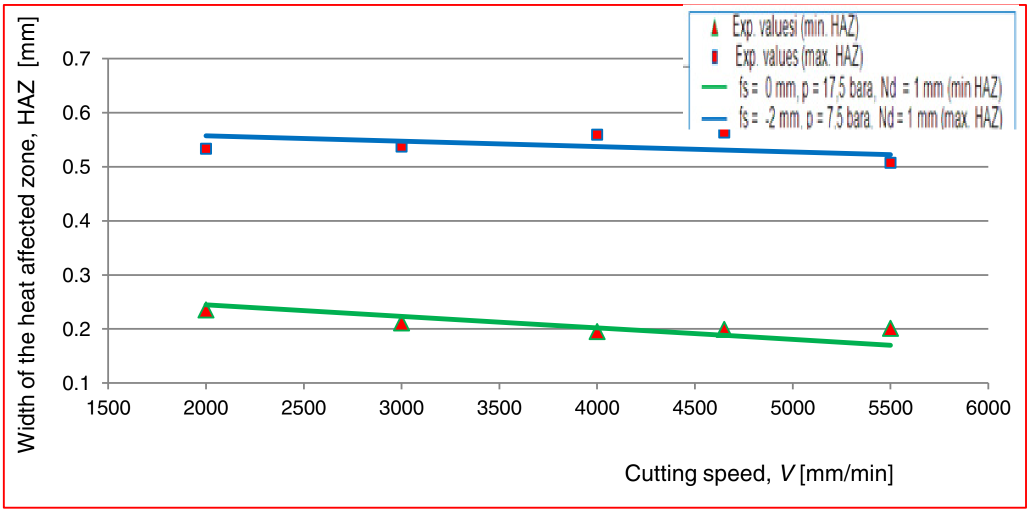

Fig. 9. Comparison of model and experimental values of the HAZ parameter (Steel 1.4828 cut with laser using O_2 as an assist gas).

Conclusion

Of particular importance in the application of laser cutting technology is to increase productivity, quality of cutting surface and material savings. The experimental studies have shown that, to achieve these goals it is necessary to optimize a large number of influential parameters (cutting speed, focus position, assist gas pressure, nozzle distance, power and characteristics of the laser, thickness and properties of the material, etc.) that are in a multiple mutual nonlinear interaction. Although from the literature review it can be concluded that the laser cutting technology can be applied in almost all materials, however, due to different thermal and structural properties and different abilities of laser radiation absorption for each type of material one must define the most suitable processing parameters. In fact, for optimal design of technology, it is necessary to know the model of technological processes and impacts of all relevant parameters on the productivity of the process, product quality, material saving, etc. Systematic experimental measurements of the parameters controlling the quality of the cut surface condition are the requirement for forming of the mathematical models. Criteria for optimization of process parameters in laser cutting are: achieving minimal surface roughness of cut, minimum width of cut, minimum width of the heat affected zone, maximum cutting speed, etc.

Defined models that are presented in this paper describe in a sufficiently reliable manner the effects of relevant parameters on product quality and productivity, i.e. justification of high alloyed steel technology laser cutting use. The presented study results, laser cutting of high-alloy steel for special purposes, will enable the achievement of major techno-economic effects of application of this technology.

It is important to point out the following conclusions:

- to assess the quality of laser cutting it is necessary to analyze many parameters, such as: cutting width, slope and taper of the cut, *HAZ* influence, surface roughness, dripping height, "stretch marks" phenomenon, hardness and structure change, etc.
- on the basis of the experimental data and mathematical models, optimum parameters of cutting high-alloy steel 1.4828 with thickness of 3 mm with CO_2 laser with the assistance of O_2 as an assist gas in order of achieving a minimum width of cut, *HAZ*, as well as optimal surface roughness are: P = 2000 W, $fs = -1$ mm, $p = 12{,}5$ bar, $N_d = 1$ mm with cutting speed of $V = 4625$ mm/min.
- to obtain smaller values of the *Ra* parameter, one should strive as much possible towards higher cutting speed with a focus position above the work piece surface.
- because of the unsubstantial difference between the values of *Ra*, which are obtained with increasing the assist gas pressure and the economy of the process, it is recommended to use the least possible assist gas pressure if the quality is not a priority for the work piece. Specifically, the experimental research determined that a small variation in assist gas pressure receives no significant change in the quality of cutting surface. In particular, the assist gas pressure should be viewed as a function of the other parameters of the process, primarily: laser power, cutting speed, nozzle distance and focus position.

The direction of future research should be:

- Based on presented most suitable parameters for examined steel, it can be concluded that further research should be based on cutting different thickness of material from related groups of high alloyed steel at higher laser power with the use of other assist gases (nitrogen, air).
- With the consideration of various sheet-like materials it would be very interesting to perform additional cutting tests on curved surfaces (pipes) of different thicknesses.

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