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CO_2 Laser Cutting of Alloy Steels using N_2 Assist Gas

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Abstract

Laser beam machining (LBM) is one of the most widely used thermal energy based non-contact type advance machining process which can be applied for almost whole range of materials. This paper defines mathematical models for surface roughness prediction (Ra, µm) and width of heat affected zone (HAZ, mm) during laser cutting of alloy steels 1.4571 and 1.4828 with nitrogen as assist gas. For defining appropriate mathematical models multiple regression analysis is used with four independent variables. Following parameters are varied: cutting speed, focus position, nitrogen assist gas pressure and stand-off. Obtained mathematical models describe dependence of Ra and HAZ from varied process parameters.

Keywords: laser cutting; alloy steel; cut quality; nitrogen assist gas

1. Introduction

With the aim of achieving greater competitiveness on the world market in the metal processing industry, it is necessary to meet the most stringent demands in terms of increased productivity, accuracy, quality of machined surfaces, reducing the consumption of materials and energy. To achieve these objectives, there is a broader use of technology of laser cutting of various materials [1, 2]. Laser cutting is classified as a typical thermal process that has special advantages over other known thermal processes due to the high quality and very smooth cut surface, narrow kerf width, small heat affected zone, small metal deformation, perpendicular and sharp cut sides, square corners of cut edges and little or no oxide layer [3]. To take advantage of this technology it is necessary for each processed material and thickness due to different thermal and structural properties, and different capabilities of absorption of laser radiation parameters to define the best process in terms of productivity and achieving the required quality

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components that are produced by this process [4]. Input parameters that affect product quality and productivity ie the applicability of this technology are: laser type, laser operating mode (continuous and/or pulse oscillation laser power), power/energy and power density of the laser beam, the distribution of power density - TEM mode and the quality of the laser beam, the character of the polarization beam, cutting speed, assist gas for cutting (type, pressure, purity), the type and thickness of the material, surface condition of the workpiece (degree of reflectivity), length and focus position, type and stand off, etc. Output parameters that depend on input and on the basis of which justifies the application of this technology are: cutting surface roughness, dimensional control of the work, frequency of striae, hardness change by HVI, changing the structure of the base material, the width of the HAZ, cutting width, the angle of the cut, the efficiency of the system and others [5]. Most work reviewed in the literature considers only one or two characteristic properties of the laser cut surface to describe quality [6] and [7]. Surface roughness and size of heat affected zone are often used to describe laser cut quality. The assist gas type and pressure have strong influence on the quality of the produced cuts. The effect of laser power, cutting speed and nitrogen assist gas pressure on the cut quality in laser cutting of refractory materials analyzed in [8].

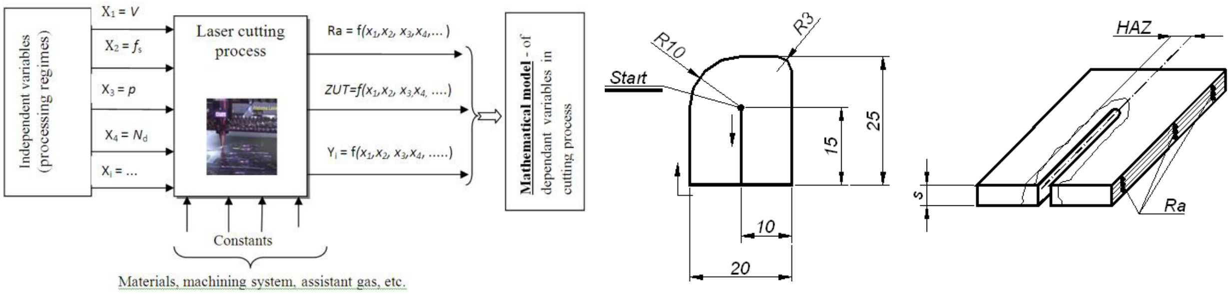
This paper analyzes the process of cutting two different alloyed steel using a CO_2 laser. The research was carried out on steels with increased contents of Cr and Ni, which is increasingly used in the automotive industry. High quality cutting surface is achieved by proper choice of processing parameters and application of appropriate assistant gases. As the laser cutting of steel, using N_2, gets brighter and smoother surface, it is possible to get high-quality and cutting edge (no post processing) to research the laser cutting process carried out with using N_2 as assist gas. The paper presents mathematical models obtained by laser cutting process of two different alloyed steel. Mathematical models are equations that describe the dependence of input ie more independent variables (cutting speed, focus position, stand off, types and assist gas pressure, laser power, etc.) and output parameters, ie dependent variable (kerf width, the width of HAZ, quality of cutting surface, etc.). Mathematical models (equations) are defined by multiple linear regression analysis. So with defined mathematical models, optimal process parameters of laser cutting of related alloy steel are achieved with regard to fulfillment of certain objectives (maximum material saving, higher product quality, etc.).

2. Experimental setup

Parameter modelling of laser cutting process aims to reach most favourable values of cutting parameters using mathematical method with which to achieve minimum surface roughness (maximum quality) and to achieve maximum savings of the material. General scheme of the laser cutting process model by which outlines appropriate mathematical models is shown in figure 1a. This paper defines two mathematical models that describe the change in surface roughness of - Ra and HAZ width as a function of the most influential processing parameters. Following parameters with most influence during laser cutting of alloy steels are: cutting speed (V, mm/min), focus position (fs, mm), assist gas pressure (p, bar) and stand-off (Nd, mm).

The controlled parameters have been the width of heat affected zone and surface roughness. Figure 1b shows examples of the measurements taken. Surface roughness of the cut edge was measured in terms of the average roughness Ra, using a Taylor-Hobson stylus instrument. Roughness was measured along the length of cut at approximately medium of thickness. The size of heat affected zone was measured using a Stemi microscope fitted with a video camera and a zoom lens. For defining mathematical model experiments were made with following constant conditions:

- Basic materials. Mathematical modelling process of laser cutting is made on two high-alloyed steels: 1.4571 and 1.4828. Table 1 presents the mechanical properties, chemical composition and thickness (s) of tested steels.
- Machining system. Experiments were performed at steady-state CO_2 laser ROFIN DC020 (quality laser beam is K = 0.94). In order to achieve maximum productivity, experiments to define mathematical models have been carried out with maximum laser power of 2000 W. During cutting nozzle with 2 mm diameter was used. Focus distance was constant value (127 mm).
- Assist gas. The cutting of these steels is performed using N_2 as assist gas. Assist gas in the process of cutting the maximum quality is brought to the work piece through a nozzle coaxially with the laser beam.



a) b)

Fig. 1. a) Input and output parameters for identification of machining processes during laser cutting; b) The measured quality characteristics.

Table 1. Chemical composition, hardness (HB) and the thickness (s) of the analyzed materials.

Material: 1.4828 (X15CrNiSi20-12), s = 3 mm							
C	Si	Mn	Cr	Ni	P	S	HB
0.20	2.5	2.0	21	13,0	0.05	0.015	230
Material: 1.4571 (X6CrNiMoTi17-12-2), s = 4 mm							
C	Si	Mn	Cr	Ni	P	S	HB
0,08	1,0	2,0	18,5	13,5	0,05	0,015	215

Physical values of the influential parameters are varied in five levels. In table 2 the real and coded parameter values were given at levels according to which plan of experiments was defined when cutting both examined steels using N_2 as assist gas.

Since the experiment was performed with four factors, then the total number of experiments is:

$$N = n_k + n_\alpha + n_0 = 2^k + 2 \cdot k' + n_0 = 2^4 + 2 \cdot 4 + 7 = 31 \tag{1}$$

where: N – total number of experiments,
k – number of varying basic factors (k = 4),
n_k – number of points of first plan order $n_k = 2k$,
n_α – number of points of plan on central axes, $n_\alpha = 2k = 8$ and
n_0 – number of central points of the plan, $n_0 = 7$.

. Table 2. Varying levels of influential process parameters during laser cutting of examined steels.

Influential parameters during laser cutting		Coded values				
		X_{j5}	X_{j5}	X_{j5}	X_{j5}	X_{j5}
		-2	-2	-2	-2	-2
Real cutting values with N_2 as assist gas	$X_1 \equiv V$	550	725	900	1075	1250
	$X_2 \equiv f_s$	- 2,0	-1,0	0,0	1,0	2,0
	$X_3 \equiv p$	7,5	10,0	12,5	15,0	17,5
	$X_4 \equiv N_d$	0,5	0,75	1,0	1,25	1,50

For modeling the cutting process of examined alloy steels following two dependent variable parameters were selected: Ra and HAZ. In fact, based on these two indicators one can accurately reach a conclusion about the feasibility of the laser cutting technology.

Since four influential cutting parameters (*V*, *fs*, *p*, *Nd*) were chosen, adequate model for the four variables that quite satisfactorily describes technological laser cutting process was applied:

$$\overline{Y_i} = b_0 X_0 + \sum_{i=1}^{4} b_i X_i + \sum_{i=1}^{4} b_{ii} X^2 + \sum_{1 \le i \angle j}^{4} b_{ij} X_i X_j + \sum_{1 \le i \angle j \angle k}^{4} b_{ijk} X_i X_j X_k \quad (2)$$

where: Yi - quality control parameters,
b_0, b_i, b_j, b_k - coefficients of the model (2) which is set after the implementation of the experiment and
Xi - variables.

3. Parameters modeling of cut quality in laser cutting

Modeling of parameters of machining regimes in laser cutting steel 1.4571 and 1.4828 using N_2 as assist gas was performed using regression analysis based on the measured values of the parameter Ra and HAZ width for proper independent variable Xi (table 2). Used model was based on multi-factor experiment plans. With mathematical model (1) and applying the rotatable central compositional plan of the experiment (N=31) change in the parameter of roughness Ra ($X_1 = V$, $X_2 = fs$, $X_3 = p$, $X_4 = Nd$) or HAZ ($X_1 = V$, $X_2 = fs$, $X_3 = p$, $X_4 = Nd$) variation of all factors on five levels was defined. As regression analysis accepts the 17 variables for defining the regression coefficients and the proposed model (equation 1) is composed of 18, several iterations eliminated one parameter that had a minimum value of significance. Rating significance of calculated coefficients of mathematical model was based on the Student t – criteria for the condition, $t_{ri} > t_{(f_{E,\alpha})}$ where $f_E = n_0 - 1 = 7 - 1 = 6$ and the degree of significance $\alpha = 0{,}05$. Checking the adequacy of the model (equation 1) was performed according to the Fisher criteria for a condition that is $F_\alpha < F_{tf\alpha,f_E)} = F_{T/14,6)}$ the degree of significance $\alpha = 0{,}01$.

Regression models after testing the significance of the proposed model coefficients for predicting (estimate) the value of Ra and HAZ width in examined laser cutting steel with using N_2 as an assist gas have following form:

a) Model for *Ra* when cutting steel 1.4571 using N_2 (coefficient of determination of the model is $R^2 = 0{,}86689$).

$$R_a = 7{,}95 - 0{,}01 \cdot V - 0{,}59 \cdot f_s - 0{,}35 \cdot p + 1{,}76 \cdot N_d - 3{,}04 \cdot N_d^2 + 0{,}16 \cdot f_s N_d + 0{,}28 \cdot pN_d \quad (3)$$

b) Model for *HAZ* when cutting steel 1.4571 using N_2 (coefficient of determination of the model is $R^2 = 0{,}86967$).

$$HAZ = 0{,}47 - 0{,}01 \cdot V + 0{,}08 \cdot f_S + 0{,}03 \cdot p + 1{,}22 \cdot N_d + 0{,}08 \cdot f_S^2 - 0{,}32 \cdot N_d^2 - 0{,}05 \cdot f_S N_d - 0{,}04 \cdot pN_d \quad (4)$$

c) Model for *Ra* when cutting steel 1.4828 using N_2 (coefficient of determination of the model is $R^2 = 0{,}8735$).

$$R_a = 8{,}49 - 0{,}01 \cdot V + 0{,}22 \cdot f_s + 0{,}01 \cdot p - 4{,}41 \cdot N_d + 0{,}64 \cdot N_d^2 - 0{,}37 \cdot f_s N_d + 0{,}09 \cdot pN_d \quad (5)$$

d) Model for *HAZ* when cutting steel 1.4828 using N_2 (coefficient of determination of the model is $R^2 = 0{,}88466$).

$$HAZ = 0{,}89 - 0{,}01 \cdot V - 0{,}11 \cdot f_s - 0{,}07 \cdot p + 1{,}58 \cdot N_d + 0{,}03 \cdot f_s^2 - 0{,}97 \cdot N_d^2 + 0{,}04 \cdot f_s N_d + 0{,}04 \cdot pN_d \quad (6)$$

The coefficient of determination show good mutual dependence of variable Xi and roughness parameters Ra and HAZ in laser cutting the examined steels within the interval covered by the experiment.

4. Results and discussion

Figures 2, 3, 4 and 5 presents the comparison of the experimental and model parameter values Ra and HAZ of steel 1.4571 (models 3 and 4) and 1.4828 (models 5 and 6) which are cut with N_2 gas as an assist gas, respectively. It should be noted that the diagrams are made for certain parameters and for clarity any variations of the parameters are not shown because in this case the diagrammatic representation would be overloaded, which would significantly reduce the visibility patterns and matching. On all diagrams a combination of parameters cutting regime at which receives the minimum or maximum value of the surface roughness of cutting (Ra) and the minimum and maximum value of the width of the heat affected zone (HAZ) is shown.

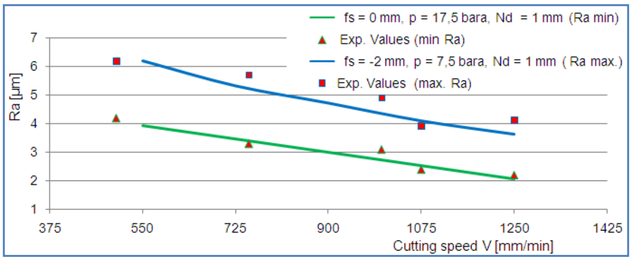


Fig. 2. Comparison of model and experimental values of the parameter Ra (cutting of steel 1.4571 using N_2 as assist gas - (3)).

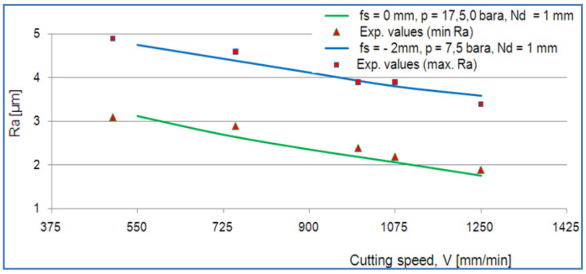


Fig. 3. Comparison of model and experimental values of the parameter Ra (cutting of steel 1.4828 using N_2 as assist gas - (5)).

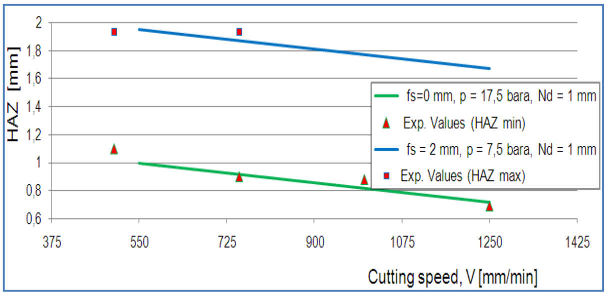


Fig. 4. Comparison of model and experimental values of HAZ width (cutting of steel 1.4571 using N_2 as assist gas - (4)).

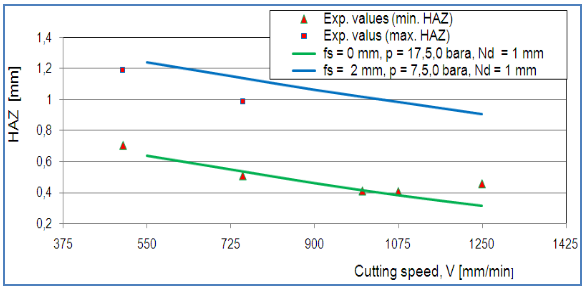


Fig. 5. Comparison of model and experimental values of HAZ width (cutting of steel 1.4828 using N_2 as assist gas - (6)).

Comparing the results of the parameter value Ra and HAZ obtained by the corresponding regression models with experimental values shows quite good matching and especially in terms of cutting with which better quality is obtained. When cutting steel 1.4828 (s = 3 mm) using N_2 as assist gas lower values of the parameter Ra are obtained. This confirms the fact that the thickness of the material is one of the important factors that should be taken into account in the analysis of other process parameters.

One can notice a reduction of HAZ width with increasing of cutting speed. It can also be noticed that smaller width of HAZ is obtained during laser cutting of high alloy steel 1.4828 (s = 3 mm).

5. Conclusion

For optimal design of technology, we need to know the model of the technological process and the effects of all relevant parameters on the product quality, material savings, etc. The obtained mathematical models represent a direct contribution to more comprehensive qualification process of laser cutting of examined and related materials. Also, the obtained mathematical models describe good dependence of HAZ and cutting surface roughness Ra of treatment regime during cutting high alloyed steel. It is evident that a change in laws of parameters Ra and HAZ in both steel are similar. With this may be concluded that the ability to draw conclusions about the most favorable cutting parameters for a group of related steel is possible on the basis of the presented indicators.

With this may be concluded that the ability to draw conclusions about the most favorable cutting parameters for a group of related steel is possible on the basis of the presented indicators. With this, approach for determining the optimal technological process for laser cutting of materials from wider group alloy steels has been greatly simplified. It is important to point out the following conclusions:

- When you require better quality cutting surface then the solution is the use of N_2 as assist gas. We obtained surface integrity N4.
- To obtain smaller values of the parameter Ra one should aim greatest possible cutting speed with focus position

above the surface of the work piece. Minimum values of Ra = 1.627 μm was obtained during cutting high alloy steel 1.4828 (s = 3 mm) using N_2 pressure 15.0 bar, and the position of focus fs = + 1 mm and cutting speed of 1000 mm/min.

- Due to the negligible difference between the value of Ra that are obtained with increasing pressure of assist gas and the cost of the process is proposed to use the least possible pressure of assist gas.
- Optimization of parameters of the cutting process must be done for each type of the material and thickness as well as the required quality and productivity.
- Due to adhesion and high viscosity of molten material on the underside of the work piece drip water appears.
- Small variation of assist gas pressure has no significant influence on the cutting process.
- Cutting speed is inversely proportional to the thickness of the material. As the tested materials had thickness 3 mm and 4 mm, percentage decrease of maximum acceptable cutting speed is determined by 6%. Better quality and wider range of cutting speed can be achieved during cutting smaller material thickness.

Directions for future research include**:**

- Based on these parameters the most favourable for the tested steels may be concluded that further research should be based on cutting a wider range of material thicknesses from related groups alloy steel.
- With the consideration of various forms of composite materials it would be very interesting to perform additional tests of cutting curved surfaces (pipes) and different thicknesses.
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