Journal of Trends in the Development of Machinery and Associated Technology
Vol. 19, No. 1, 2015, ISSN 2303-4009 (online), p.p. 25-28

DEFINING OF MATHEMATICAL MODELS IN HIGH-ALLOYED STEEL CO2 LASER CUTTING

Ahmet Cekic
Mechanical Engineering Faculty, University of Sarajevo
Vilsonovo setaliste 9, Sarajevo
Bosnia and Herzegovina

Derzija Begic-Hajdarevic
Mechanical Engineering Faculty, University of Sarajevo
Vilsonovo setaliste 9, Sarajevo
Bosnia and Herzegovina

ABSTRACT
This paper defines mathematical models during laser cutting that describe effects of certain processing regime parameters on values for surface roughness - Ra and for width of heat affected zone - HAZ. Cutting of high-alloyed steel 1.4864 (X13CrNiSi35-16), with thickness of s = 3 mm and 1.4541 (X6CrNiTi18-10), with thickness of s = 4 mm was performed by laser cutting using O_2 *and* N_2 *as the 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 most influential cutting parameters were varied: cutting speed (V), assist gas pressure (p), focus position (fs) and stand-off (Nd). It is possible to sufficiently describe the effects of process parameters, with defined models in reliable way, on product quality and also to determine the best parameters of laser cutting of investigated high-alloyed steels.*
Keywords: CO_2 laser cutting, mathematical model, heat affected zone, surface roughness

1. INTRODUCTION
By using laser cutting technology one can accomplish [1, 2] lower material usage, higher accuracy of the product, less heat affected zone width, higher productivity, etc. However, to benefit from advantages of this technology, it is necessary to optimize a large number of mutually connected nonlinear influential process parameters for each processed material (due to the different absorption capacities of laser radiation), thickness, productivity and required processing quality. Influential input parameters for laser cutting [3, 4] are: laser power, the length and depth of focus, focus position relative to the workpiece, cutting speed, type and pressure of the assist gas, design and the distance between nozzle and the workpiece, etc. Output parameters that depend on the input and on the basis of which the application of this technology is justified [5] are (most commonly): cutting surface roughness, cutting width of heat affected zone, cutting width, microhardness changes and changes of the base material structure. This paper defines the mathematical models that describe the dependence of input and output parameters in laser cutting of two high-alloyed steels. Previously conducted experimental research established that the safest laser cutting process optimization of input parameters is done by defining following two (output) parameters: cutting surface roughness - *Ra* and width of heat affected zone - *HAZ*. Criteria for the laser cutting optimization of process parameters are: achieving increased productivity and quality of machined surfaces and reduction of the heat affected zone width. It is important to emphasize that the cutting parameters should be set so that there are no major changes in the structure or the surface hardness from the perspective of possibility of further processing using other technologies. Additionally, the causes of laser cutting irregularities are either

too large inserted energy or incorrect process cutting parameters. So the solution is optimizing the influential parameters for each processed material, thickness, required cut quality and productivity.

2. EXPERIMENTAL SETUP

Sophisticated laser technology laboratory equipment has been used for experimental research at the University of Jena, Germany. Cutting was carried out with different combinations of technological process parameters on CO_2 laser - Rofin DC020 with nominal power of 2000 W. Measuring the width of HAZ was performed on microscope "Stemi 2000 - C ZEISS" with 10x magnification and measurement of surface roughness on the device Taylor Hobson. The measurement of cutting surface microhardness was conducted with Vickers's method, and microscopic metallographic structure recordings of processed materials were carried out on an optical microscope Reichert Microscope Me F3 which provides the ability of magnification up to 400x. Experimental researches of laser cutting processes were performed on two high-alloyed steels 1.4864 and 1.4541. The tested materials in addition to the widespread use are of particular interest for research due to the increased content of Cr which intensely reacts with O_2 forming Cr_2O_3 oxides that have a high melting point. Therefore, experimental investigations of laser cutting were performed using O_2 as an assist gas. However, because better quality of processed surface is achieved by using N_2 as an assist gas, cutting was also performed using said assist gas. Previous experimental research has found that the most important laser cutting parameters of the value of surface roughness (*Ra*) and the width of the heat affected zone (*HAZ*) (depending on variable parameters for mathematical models) are: cutting speed (*V, mm/min*), pressure of the assist gas (*p, bar),* focus position relative to the workpiece surface (*fs*, *mm*) and the nozzle distance (N_d, *mm*).

3. MATHEMATICAL MODELING OF SURFACE QUALITY PARAMETERS DURING LASER CUTTING OF TESTED STEELS

In order to define the appropriate mathematical models, multiple linear regression analysis was used for four independent variables that were varied on five levels. The extent of variation of four influential parameters during laser cutting of tested materials is given in Table 1. Sufficiently reliable mathematical models were defined for value change of cutting surface roughness (*Ra*) and the width of HAZ in distinction to cutting regime in order to determine the most appropriate process parameters during cutting of two different alloyed steels. The following conditions during experiments in order to define mathematical models were constant, and they are considered as external factors in the modelling process:

- Basic materials. Laser cutting is performed on two high-alloyed steels 1.4864 (X13CrNiSi35-16), with thickness s = 3 mm and 1.4541 (X6CrNiTi18-10), with thickness s = 4 mm.
- Machining system. Experiments were performed using continuous mode of operation on CO_2 laser - Rofin DC 2000. Focal Length, wavelength of the laser beam, method of assist gas importing, system of workpiece and laser beam movement are the characteristics of machining system and cannot be used as a variable size during the cutting process.
- In order to obtain satisfactory cutting speeds (maximum productivity) experiments have been carried out with maximum laser power of 2000 W.
- Nozzle. Used nozzle diameter was 2 mm and the distance of focus was constant (127 mm).
- The assist gas. The cutting process was performed using O_2 and N_2.

Table 1. Variation levels of influential laser cutting process parameters assisted by O_2 and N_2

Influential parameters		Code values				
		X_{j5}	X_{j2}	X_{j3}	X_{j1}	X_{j4}
		-2	-1	0	1	2
The actual values during laser cutting using O_2 as the assist gas	$X_1 \equiv V$	2000	2875	3750	4625	5500
	$X_2 \equiv f_s$	-2,0	-1,0	0,0	1,0	2,0
	$X_3 \equiv p$	7,5	10,0	12,5	15,0	17,5
	$X_4 \equiv N_d$	0,50	0,75	1,00	1,25	1,50
The actual values during laser cutting using N_2 as the 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
	$X_4 \equiv N_d$	0,50	0,75	1,00	1,25	1,50

4. REGRESSION ANALYSIS AND DISCUSSIONS

Regression models to predict (estimate) values of the parameters *Ra* and *HAZ* during laser cutting of tested steels assisted by O_2 and N_2 after testing the significance of coefficients (coefficients of determination - R^2 of defined models are from 0,86689 to 0,91882) have the form:

a) Model for *Ra* during steel 1.4541 cutting using O_2 as the assist gas is:

$$R_a = 22{,}15 - 0{,}0007 \cdot V - 0{,}59 \cdot f_s - 0{,}23 \cdot p - 21{,}53 \cdot N_d + 8{,}73 \cdot N_d^2 + 0{,}28 \cdot f_s \cdot N_d + 0{,}09 \cdot p \cdot N_d \quad \text{... (1)}$$

b) Model for *HAZ* during steel 1.4541 cutting using O_2 as the assist gas is:

$$HAZ = 2{,}87 - 8 \cdot 10^{-6} \cdot V + 0{,}05 \cdot f_s - 0{,}09 \cdot p - 2{,}99 \cdot N_d + 0{,}02 \cdot f_s^2 + 0{,}98 \cdot N_d^2 + 0{,}07 \cdot p \cdot N_d \quad \text{... (2)}$$

c) Model for *Ra* during steel 1.4541 cutting using N_2 as the assist gas is:

$$Ra = 7{,}95 - 0{,}003 \cdot V - 0{,}59 \cdot f_s - 0{,}35 \cdot p + 1{,}76 \cdot N_d - 3{,}04 \cdot N_d^2 + 0{,}16 \cdot f_s \cdot N_d + 0{,}28 \cdot p \cdot N_d \quad \text{... (3)}$$

d) Model for *HAZ* during steel 1.4541 cutting using N_2 as the assist gas is:

$$HAZ = 0{,}47 - 0{,}0004 \cdot V + 0{,}08 \cdot f_s + 0{,}03 \cdot p + 1{,}22 \cdot N_d + 0{,}08 \cdot f_s^2 - 0{,}32 \cdot N_d^2 - 0{,}05 \cdot f_s \cdot N_d - 0{,}04 \cdot p \cdot N_d \quad \text{... (4)}$$

e) Model for *Ra* during steel 1.4864 cutting using O_2 as the assist gas is:

$$R_a = 8{,}49 - 0{,}0005 \cdot V + 0{,}23 \cdot f_s + 0{,}9 \cdot p - 4{,}41 \cdot N_d + 0{,}65 \cdot N_d^2 - 0{,}37 \cdot f_s \cdot N_d + 0{,}09 \cdot p \cdot N_d \quad \text{... (5)}$$

f) Model for *HAZ* during steel 1.4864 cutting using O_2 as the assist gas is:

$$HAZ = 0{,}67 - 0{,}00001 \cdot V - 0{,}04 \cdot f_s - 0{,}01 \cdot p - 0{,}82 \cdot N_d + 0{,}06 \cdot f_s^2 + 0{,}44 \cdot N_d^2 + 0{,}01 \cdot p \cdot N_d \quad \text{... (6)}$$

g) Model for *Ra* during steel 1.4864 cutting using N_2 as the assist gas is:

$$Ra = 8{,}78 - 0{,}002 \cdot V - 0{,}67 \cdot f_s - 0{,}24 \cdot p - 3{,}99 \cdot N_d + 0{,}88 \cdot N_d^2 + 0{,}17 \cdot f_s \cdot N_d + 0{,}14 \cdot p \cdot N_d \quad \text{... (7)}$$

h) Model for *HAZ* during steel 1.4864 cutting using N_2 as the assist gas is:

$$HAZ = 0{,}89 - 0{,}0005 \cdot V - 0{,}12 \cdot f_s - 0{,}07 \cdot p + 1{,}58 \cdot N_d + 0{,}03 \cdot f_s^2 - 0{,}98 \cdot N_d^2 - 0{,}04 \cdot f_s \cdot N_d + 0{,}04 \cdot p \cdot N_d \quad \text{... (8)}$$

Figures 1, 2, 3 and 4 demonstrate the comparison of model and experimental values of the parameters *Ra* (models 1 and 3) and HAZ (models 2 and 4) during steel 1.4541 cutting using O_2 or N_2 as the assist gas, respectively. Considering the comprehensibility of the presentation, the diagrams do not show every variation of parameters, because in that case the diagram representations would be overloaded, which would significantly reduce the transparency and legality of the matching.

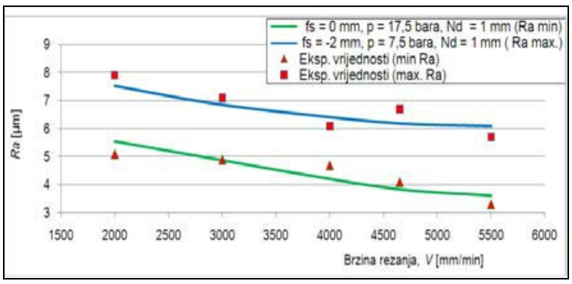

Figure 1. Comparison of model and experimental values of the parameter Ra (steel 1.4541 cut using O_2 as the assist gas).

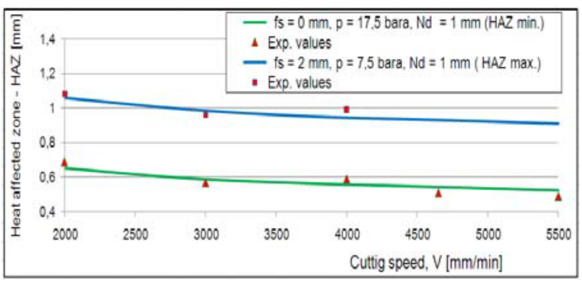

Figure 2. Comparison of model and experimental values of the parameter HAZ (steel 1.4541 cut using O_2 as the assist gas).

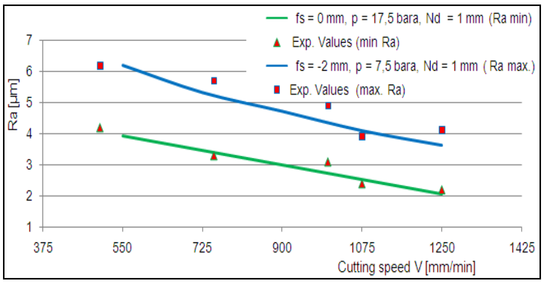

Figure 3. Comparison of model and experimental values of the parameter Ra (steel 1.4541 cut using N_2 as the assist gas).

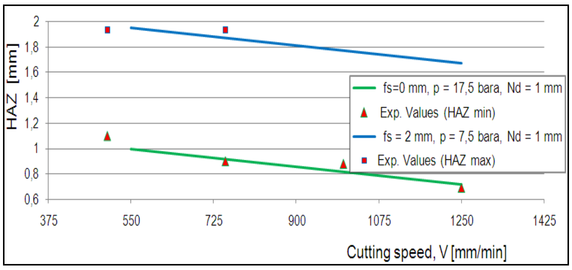

Figure 4. Comparison of model and experimental values of the parameter HAZ (steel 1.4541 cut using N_2 as the assist gas).

Comparing the results of the values of parameters Ra and HAZ obtained by the corresponding regression models with measured values shows the adequately good consistency and in particular in terms of cutting that gives better quality. It is important to note that when cutting steel 1.864 (s=3 mm) using O_2 and N_2 as assist gas similar principle is obtained, but with smaller values of parameters of both *Ra* and *HAZ*. This confirms the fact that the thickness of the material is one of important factors which must be taken into account in the analysis of other process parameters.

5. CONCLUSION

Presented mathematical models can sufficiently, in a reliable way, describe the effects of relevant parameters on product quality, productivity and justification of the use of this technology. It is important to point out that the aditional analysis of processed materials was caried and laser cutting with optimal parameters does not change the structure or the hardness of the cutting surface. Main conclusions are:

- When higher productivity is required, O_2 assist gas should be used and when the imperative is better cutting surface quality, the solution is use of N_2 as the assist gas.
- Although the tested materials had various thicknesses, to obtain smaller values of parameter Ra one should strive towards higher cutting speed with the focus position above the surface of the workpiece.
- Due to the insignificant difference between the values of *Ra* obtained from increasing the assist gas pressure, and to improve efficiency of the process, it is proposed to use the least possible assist gas pressure if the quality is not a priority for the workpiece.
- Change of the Ra and *HAZ* legality in both steels is similar. This concludes the possibility of drawing conclusions about the optimum cutting parameters for a group of related steels on the basis of the presented indicators. It greatly simplifies the approach to determine the optimal technological process of materials from the wider group of alloyed steels.

6. REFERENCES

[1] Avanish K.D. & Vinod Y.: Laser beam machining – A review. International Journal of Machine Tools & Manufacture, 48, pp. 609-628, ISSN: 0890-6955, 2008,
[2] Radonić S., Kovač P., Mitrović A.: Defining new processing parameters in laser cutting, 16th international Research/Expert Conference ”Trends in the Development of Machinery and Associated Technology”, Dubai; UAE, pp. 47 - 50, TMT 2012,
[3] Čekić A.: Contribution to the optimization of process parameters in laser cutting of special purpose alloy steels, Ph.D. Dissertation, Department of Mechanical Engineering, University of Sarajevo, Bosnia and Herzegovina, 2010,
[4] Čekić A., Begić-Hajdarević Đ., Kulenović M., Omerspahić A.: CO2 Laser Cutting of Alloy Steels using N2 Assist Gas, Procedia Engineering, Vol. 69, pp. 310–315, Elsevier, (Web of Science)., 2014,
[5] Lamikiz A., Lacalle L.N.L., Sanchez, J.A., Pozo D., Etayo J.M. & Lopez J.M.: CO2 laser cutting of advanced high strength steels (AHSS), Applied Surface Science, 242, pp.362–368, ISSN: 0169-4332. 2005.