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# OPTIMIZATION OF PROCESS PARAMETERS OF ALLOYED STEELS USING CO2 LASERS

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***Abstract:*** *This paper presents results of experimental investigations of influence of process parametars during laser cutting in three different alloyed steel: 1.430 (X15CrNiSi20-12), 1.4571 (X6CrNiMoTi17-12) and 1.4828 (X5CrNi18-10) by using oxygen ($O_2$), nitrogen ($N_2$) and air as assist gas. The set goal is to increase the feasibility of utilization of this technology through optimization of relevant parametars influencing the process. Significant improvements in decreasing the kerf width and width of heat affected zone as well as increasing the quality of the machined surface are achieved.*
***Keywords:*** *CO2 laser cutting, process parameters, heat affected zone, kerf width, surface roughness*

## 1. INTRODUCTION

In order to achieve competitiveness in the global market in the metalworking industry, it is necessary to satisfy any stricter requirements in terms of increased productivity, greater accuracy of the product, quality of machined surface, reduce material consumption, and reduce total costs of treatment. For that reason many new methods of production technology is used every day, which needs to be brought to an enviable level. Cutting materials by laser beam is today the most promising and most used process of application in automotive industry. By using laser cutting technology, one can achieve lower consumption of materials, shorter processing times and greater accuracy of the product. However, in order to exploit the advantages of this technology, it is necessary to optimize each processed material relevant influential parameters. Therefore, the research presented in this paper had the main objective of quantifying and optimizing the process parameters during laser cutting of certain alloy steels. The quality of the product, the maximum possible material saving, productivity and efficiency in laser cutting is primarily dependent on the values of process parameters that are mutually non-linearly related.

The most influential parameters are: laser power, focus position, cutting speed, stand-off distance, nozzle, type and pressure of assist gas [1]. For a complete analysis is necessary to analyze the other process parameters such as: wavelength (selection of appropriate type of lasers), the power density distribution over the cross section of laser beam (TEM mode), quality of laser beam (K) and polarization of the laser beam, focal length and diameter of the focused laser beam [2]. Although laser cutting is contactless method, however, the optimal values of process parameters depend on the characteristics of the material (absorption, surface roughness on which the focused beam is directed and thermal and structural properties) as well as material thickness. The paper [3] investigated the effect of material type and thickness on the kerf width and width of HAZ during laser cutting of two high-strength steels. The presented results in this paper show very different values of optimal process parameters in laser cutting of thick and thin steel sheets.

Taking the assessment of the relevant institutes that further increase of application of alloy steel (higher contents of chemical elements such as Ni and Cr) will be especially in the automotive industry, imposed the need for research to increase the degree of justification for the application of lasers in the treatment of these materials. These steels have enhanced mechanical and heat resistance properties, so using them can reduce the weight of the parts in cars. When processing a directed energy, due to rapid heating and cooling of the material, there may be change of the physical properties of workpiece material in the cutting zone so it is necessary to define these parameters that will not cause a change in the structure, hardness, and the dimensions and shape of the product. Cutting can be performed by various methods, from cutting using melting with deflating products using assist gas to achieve evaporation of material. Different variants of cutting depend on many parameters, whose interconnection makes complex material behaviour during laser cutting.

Because of this, in this paper, attention is focused on $CO_2$ laser cutting of alloy steels for special purposes, because of their increasing use in industry. Because of production of $CO_2$ lasers with increasing output power and laser beam quality, today one can find increased ability to cut thicker materials (up to 50 mm) with achievement of higher cutting speed. The paper [4] analyzes the productivity of application $CO_2$ laser system with a nominal output power of 4 kW during cutting of mild steel thickness of 6 mm.

In this paper, optimal process parameters during laser cutting of alloyed steels are defined with which is possible to minimize the value of HAZ and $K_W$ (material saving) and Ra (increase cut quality). Also, this paper shows that laser machining process can be defined so that no changes in the structure or hardness of cut surface in terms of possible options for further machining by other methods.

## 2. EXPERIMENTAL SETUP

Experimental investigations were conducted at the University of Applied Sciences Jena in Germany. Bearing in mind that a large number of process parameters effect on laser cutting process, following is set:

a. The experiments were conducted on three alloyed steel. The first is 1.4828 (X15CrNiSi20-12), 3 mm thick, which is increasingly used in automotive industry, and the other two 4 mm thick (for comparability of results) are: 1.4571 (X6CrNiMoTi17-12) and 1.4301 (X5CrNi18-10). These are alloy steels with different chemical composition which are due to improved mechanical and fire-resistant characteristics increasingly applied in various industries. Materials that are also examined are of interest for research because of the increased content of various alloying elements, especially Cr, which intensively reacted with $O_2$ forming $Cr_2O_3$ oxides with high melting point.
b. Cutting was carried out with different combinations of technological parameters of the $CO_2$ laser - Rofin DC020 by using oxygen, nitrogen and air as assist gas.
c. Laser output power - 2000 W, wavelength of laser beam - 10600 nm, laser beam quality - K = 0,94, mode of operation - cw, focal length of lens - 127 mm, nozzle diameter - 2 mm as well as system of moving the material and laser beam are characteristics of this system and are constants during the cutting process.

Measurement the quality parameters of analyzed cutting steel is performed on the appropriate equipment. Following values that are measured are:

a. kerf width (Kw, mm) and width of heat affected zone (HAZ, mm) -microscope Stemi 2000 - CZEISS,
b. roughness (Ra, μm) - Taylor Hobson device,
c. cutting surface microhardness (Vickers - method) and
d. structure of the tested material recorded before and after treatment (optical Reichert Microscope Me F3, enlargement up to 400x).

During cutting of tested material with all three type of assist gases ($O_2$, $N_2$ and air) most influential three process parameters were varied: the position of focus ($f_S$, mm), assist gas pressure (p, bar) and cutting speed (V, mm/min). The values of the parameters that were varied during the execution of experiments are shown in Table 1.

Industries interests are achieving the maximum productivity, so experiments to optimize the parameters in laser cutting of the tested materials are done with the maximum output power of 2000 W. Also, in order to determine the optimal stand-off distance, experiments were conducted by using $O_2$, $N_2$ and air as assist gases [5]. Distance was varied from 0.5 to 2 mm with 0.25 mm increments. The conclusion, optimal distance is 1 mm, because it allows varying the focus position, cutting speed and the assist gas pressure in a larger range.

| Process parameters | Assist gas | Varied values | | |
|---|---|---|---|---|
| V (mm/min) | $O_2$ | 2000 | 3000 | 4000 |
| | $N_2$ | 500 | 750 | 1000 |
| | Air | 1250 | 1750 | 2250 |
| $f_s$ (mm) | $O_2$ | -1 | 0 | +1 |
| | $N_2$ | | | |
| | Air | | | |
| p (bar) | $O_2$ | 12,5 | 15,0 | 17,5 |
| | $N_2$ | 10,0 | 12,5 | 15,0 |
| | Air | 7,5 | 10,0 | 12,5 |

Tab. 1. Plan of experiments

## 3. RESULTS AND DISCUSSION

Figure 1 shows the minimum and maximum kerf width that are obtained during cutting of tested steel for the specified range of varied parameters by using $O_2$ as assist gas.

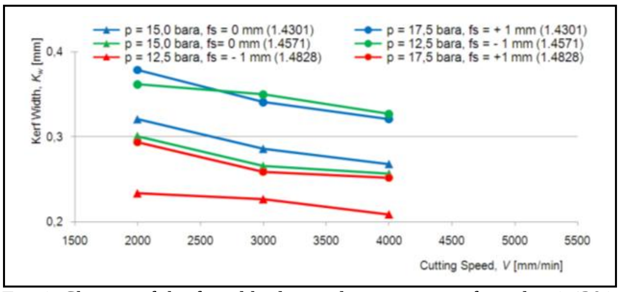


Fig. 1. Change of kerf width during laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) and 1.4828 (s = 3 mm) by using $O_2$ as assist gas

Although the kerf width primarily depends on the quality of laser beams, it is still directly dependent on the values of other process parameters. It may be noted that it is generally smaller, in order to obtain smaller kerf width (material saving) during laser cutting of steels 1.4301 and 1.4571 with cutting speed of 4000 mm/min, the focus position of 0 mm ($f_s$= 0mm) and the gas pressure of 15 bar. However, when cutting steel 1.4828, it is evident that kerf width is smaller than the in the previous two steels. This is due to less material thickness (s = 3 mm), and if the process parameters such that: V = 4000 mm/min, $f_s$ = –1 mm and p = 12,5 bar. This confirms that the thickness of the material is one of the influential parameters on the laser cutting conditions, ie. one of the important factors that should be taken into account in the analysis of other process parameters.

In Figure 2 are shown minimum and maximum values of the kerf width that are obtained during cutting of the tested steel for the specified range of varied process parameters by using $N_2$ as assist gas. The smaller kerf width is obtained during cutting of steels 1.4301 and 1.4571 with the following parameters: focus position of 0 mm ($f_s$ = 0 mm) and assist gas pressure of 15 bar. While the maximum kerf width is obtained at $f_s$ = - 1.0 mm and assist gas pressure of 10 bar. It is important to note that at cutting speeds greater than 750 mm/min, pressure of 15 bar and the focus position of 1 mm ($f_s$ = + 1mm) leads to the interruption of continuous cutting process. With these parameters cutting of steel 1.4828 can be done, but then the maximum kerf width is result. This is caused by lower material thickness.

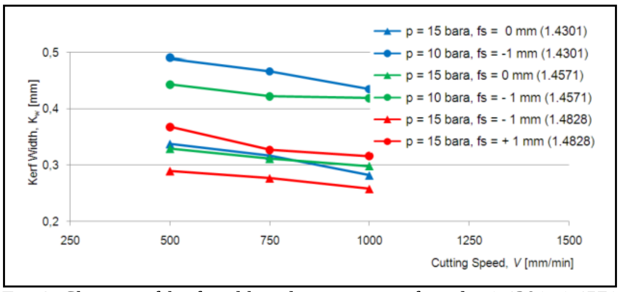


Fig. 2. Changes of kerf width in laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) and 1.4828 (s = 3 mm) by using $N_2$ as assist gas

Figure 3 shows the minimum and maximum kerf width that are obtained when cutting the tested steel for the specified range of varied process parameters by using air as assist gas. It may be noted that when cutting steels 1.4301 and 1.4571 one can obtain a minimum kerf width at the focus position of 0 mm ($f_s$ = 0 mm) but with different assist gas pressures. When cutting steel 1.4828 at the focus position $f_s$ = -1 mm and a pressure of 12.5 bar one can get smaller kerf width. To obtain the minimum kerf width (maximum material saving, optimum cutting speed is the interval from 1750 to 2250 mm/min for all three steels).

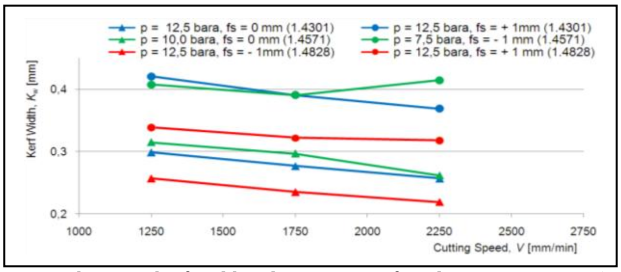


Fig. 3. Change in kerf width in laser cutting of steels: 1.4301, 1.4571 (s = 4mm) and 1.4828 (s = 3 mm) by using air as assist gas

Figure 4. shows the minimum and maximum values of HAZ that is obtained during cutting of tested steel for the specified range of varied cutting parameters by using $O_2$ as assist gas. It may be observed that in order to obtain minimum HAZ during the laser cutting process of steel 1.4828 (s = 3 mm), the first acceptable cutting speed is 4000 mm/min while for the other two steels is 3000 mm/min. Although minimum HAZ is obtained during cutting of tested steels at different focus position and assist gas pressure, however, one may adopt the following parameter values that results in smaller HAZ: p = 12.5 bar, and $f_s$ = - 1 mm. The difference between values of HAZ in laser cutting of steels 1.4301 and 1.4571 at the pressure of 12.5 and 15 bar is small, from an economic point of recommended pressure of 12.5 bar.

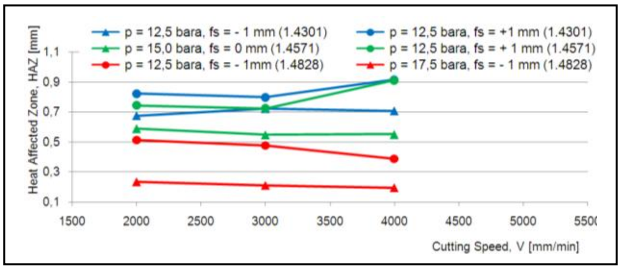


Fig. 4. Change in width of HAZ in laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) and 1.4828 (s = 3 mm) by using $O_2$ as assist gas

Figure 5 shows the minimum and maximum values of HAZ that are obtained during cutting of tested steel for the specified range of varied parameters by using $N_2$ as assist gas. To obtain smaller values of HAZ in all three steels it is necessary to choose the gas pressure p = 15 bar and minimal cutting speed V = 750 mm/min and to set the focus position above the surface of the workpiece, ie. $f_s$ = + 1 mm. It is important to note that to achieve higher cutting speed should be set the focus position of 0 mm ie. $f_s$ =0 mm. The difference in width of the HAZ, at focus position $f_s$ = +1 mm and $f_s$ = 0 mm and cutting speed of 1000 mm (min. is 0.026 mm (1.4301) and 0.040 mm (1.4828)) which is a negligible difference between the witdh of HAZ.

Figure 6 shows the minimum and maximum values of HAZ that are obtained during cutting of tested steel for the specified range of varied parameters by using air as assist gas. The optimum focus position for all three steels is $f_s$ = - 1 mm and assist gas pressure of 10 bar.

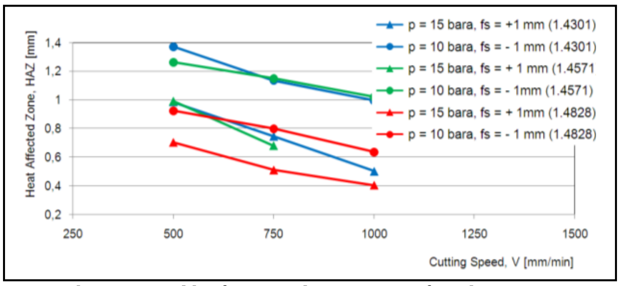


Fig. 5. Change in width of HAZ in laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) i 1.4828 (s = 3 mm) by using $N_2$ as assist gas

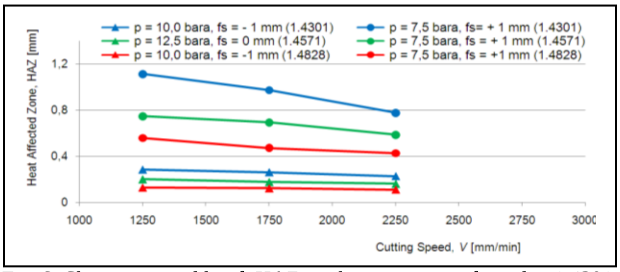


Fig. 6. Change in width of HAZ in laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) i 1.4828 (s = 3 mm) by using air as assist gas

In Figure 7 photographs of samples with maximum and minimum width of the HAZ obtained during cutting of tested steel by using $O_2$, $N_2$ and air as assist gases are given, respectively.

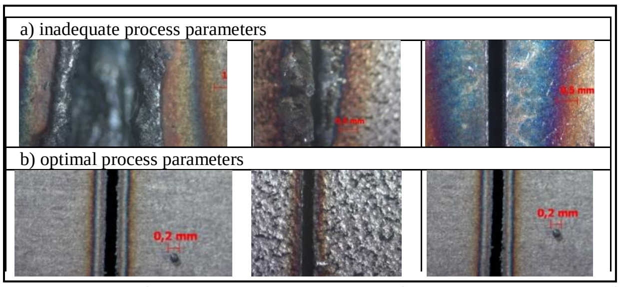


Fig. 7. Photos of samples that shows width of HAZ in laser cutting of tested steel by using $O_2$, $N_2$ and air as assist gas

In the diagrams given in Figures 8, 9 and 10 are shown the minimum and maximum values of roughness parameter Ra that is obtained in cutting of tested steels for the specified range of varied parameters by using $O_2$, $N_2$ and air as assist gases, respectively.

Type of assist gas, cutting speed and focus position have a significant impact on the value of Ra. The lowest surface roughness was obtained by using $N_2$ as assist gas, and then use the air, while the highest roughness was obtained when using $O_2$ as assist gas during laser cutting of tested steels. At higher speeds smaller values of the parameter Ra were obtained. The optimum focus position to obtain lower surface roughness depends of the type of assist gas. Specifically, during cutting by using $O_2$ and $N_2$ as assist agses the focus position is 1 mm ie. $f_s$ = + 1 mm while the $f_s$ = 0 mm by using air as assist gas.

It is important to note that for a certain focus position, values of the parameter Ra are in interval that belongs to the same class of roughness regardless of variation of cutting speed and assist gas pressure at a certain extent.

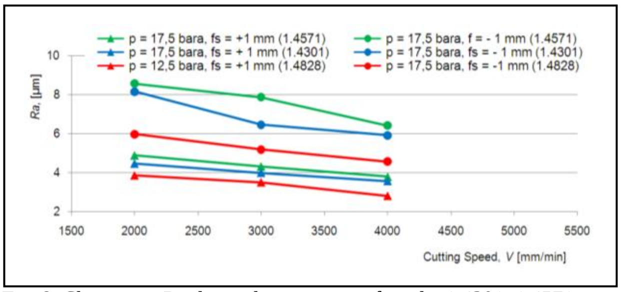


Fig. 8. Changes in Ra during laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) and 1.4828 (s = 3 mm) by using $O_2$ as assist gas

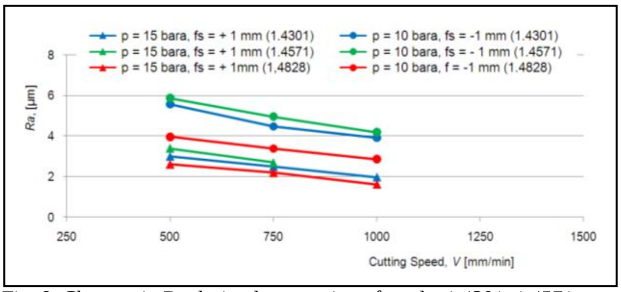


Fig. 9. Changes in Ra during laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) and 1.4828 (s = 3 mm) by using $N_2$ as assist gas

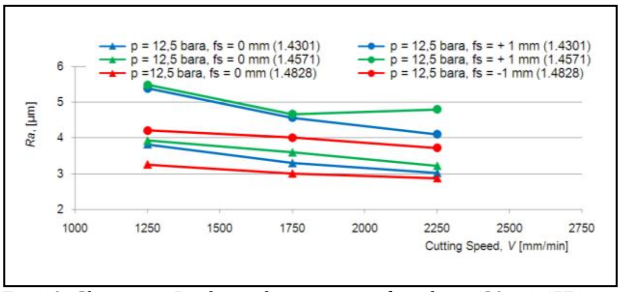


Fig. 10. Changes in Ra during laser cutting of steels: 1.4301, 1.4571 (s = 4 mm) and 1.4828 (s = 3 mm) by using air as assist gas

Although process of laser cutting is intended to be final technology in making products, it is necessary in specific circumstances to apply a different procedure for cutting of any corrections (removal of dross, HAZ, etc.).

Because of that, metallographic examination of unprocessed and processed materials was done, and the measured distribution of cutting surface microhardness was also done. Metallographic tests were performed on samples with a maximum size of the HAZ of each material for all three assist gases. Samples for metallographic examination were prepared by mechanical polishing and etching the surface with 2-3% $HNO_3$. The basic structure of the investigated steel is austenitic and has recorded significant changes in the structure of the investigated materials.

Testing the hardness distribution on the surface of the cutting was performed on samples with minimum and maximum size of the HAZ. Measurement was performed according to EN ISO 6506-1/2001 standards. The difference of minimum and maximum measured hardness is 37 HV 0.5 so that for such a small load, such as HV 0.5 the differences were not significant, which in principle can be considered a satisfactory result. Specifically, no significant change in hardness of the material is noted after processing by laser cutting in the investigated range of variation of parameters.

## 4. CONCLUSION

In this paper, the complete analysis of the influence process parameters on the laser cutting process was done and the optimal values of these parameters are defined with the aim of achieving the required product quality (achieving lower values of Ra) and productivity (the maximum possible cutting speed) with a maximum saving of the material (the minimum of kerf width and heat affected zone). This increases the validity of application of technology of laser cutting alloyed steels. Higher cutting speeds are possible during laser cutting of steels by using $O_2$ as assist gas. However, since Cr has the highest affinity with oxygen and it is forming an oxide layer that does not evaporate, but materials form a layer that restricts the exothermic reaction that causes a problem when cutting, especially in the upper part of the cutting surface. This is the cause of the dross and creating a rougher surface. The oxide layer on the surface of the cutting has more Cr than the base material, and melted part has less Cr. Using $N_2$ as assist gas in laser cutting of tested steels, results that are achieved high cut quality (does not require post processing), and brighter and smoother surface compared to the use of active gases ($O_2$), but the cutting speed is smaller. However, due to adhesion and high viscosity of the dissolved material on the underside of the workpiece dross can be seen.

The authors of this paper defined directions of further research, namely:

a. further study should be based on cutting various thicknesses of material from related groups of alloy steels,
b. In addition to consideration of various forms of composite materials, it would be very interesting to perform additional tests of cutting curved surfaces (pipes) and different thickness and
c. In addition define adequate mathematical models for change of quality parameters with the aim of quickly defining optimal process parameters. The experimental results show different effects of individual process parameters, but show that one can define a common model that will be valid for a certain material thickness and approximately similar chemical composition, and for a certain interval of variation of variable parameters.

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