

## Effect of fiber and CO<sub>2</sub> lasers parameters on the cut surface quality of RVS 1.4301 stainless steel

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**ABSTRACT** – The paper presents the results of experimental research related to the process of cutting of  $t = 3$  mm and  $t = 6$  mm thick RVS 1.4301 (AISI 304, EN X5CrNi18-10) stainless steel using a fiber and CO<sub>2</sub> lasers. The correct selection of technological parameters and the maintenance of the machines in the right technical condition allow obtaining very high quality of the cut edge, which will not require additional mechanical treatment. However, this is a complex issue. Appropriate control of the cutting process requires knowledge about the impact of individual parameters on the process and the quality of the cut edge. The influence of selected parameters and conditions of the laser cutting process on the technological quality of the obtained product was determined. The laser power and cutting speed had a significant influence on the output factors for two cutting techniques. For cutting material with a thickness of  $t = 3$  mm with a CO<sub>2</sub> laser, the highest quality of the cut edge was obtained using the power values  $P = 4200-4300$  W and cutting speed  $v = 2100$  mm/min. For the thickness  $t = 6$  mm, the speed values should be approximately set in range  $v = 1600-1800$  mm/min. The power value should be selected in a range from  $P = 3700$  W to  $P = 4200$  W. For a fiber laser with a material thickness of  $t = 3$  mm, the best results were obtained using speeds in the range  $v = 2000-3300$  mm/min. For the thickness of  $t = 6$  mm, the cutting speed must be higher and in the range  $v = 3500-4000$  mm/min while maintaining the power of about  $P = 4500-4800$  W. The conducted experimental research can be useful on production lines in the aspect of the correct selection of technological parameters of the process due to the adopted energy and quality criteria.

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## INTRODUCTION

The dynamic development of technology, observed in recent years, forces searching for more efficient and precise micromachining processes of materials that will ensure the required quality of the final product, while maintaining the lowest possible costs of its implementation. Laser cutting is currently one of the most modern methods of processing metal materials [1-3]. The biggest advantages of the laser cutting process include high cutting precision, high efficiency, repeatability of the process, limitation of cutting openwork and waste, the possibility of shaping materials with large thicknesses [4, 5]. Laser cutting is fully automated and therefore enables precise processing with a certain repeatability. Such properties are required in many industrial sectors, such as in the automotive, manufacturing and electronics industries. Choosing the right cutting method and then its appropriate application to shape a specific type of material is a difficult task. This is due to the necessity of the correct selection of technological parameters of the process and their control during the process, so as to obtain a product of appropriate technological quality [6-9]. Each of the cutting technologies is currently being developed to achieve greater efficiency and accuracy. Therefore, choosing the right one is a basic problem that bothers entrepreneurs in the metal industry.

The process of cutting stainless steels is a complex issue. This is due to the occurrence of many physical phenomena during the process and the non-linearity of the process [10-12]. Cutting a specific material with different thicknesses results in the creation of a certain technological quality, which in turn ensures the creation of specific functional properties of the product. In the case the main criterion determining the technological quality of the obtained product is its cut surface geometry and the width of the heat zone. Correct selection of the parameters of the cutting process with the use of lasers makes it possible to carry out the process, analyze and evaluate it.

In the current literature, many authors analyze the process of mechanical cutting of various types of metal materials. The research concerns mainly the influence of technological parameters of the processes of blanking, punching, guillotining and trimming on the quality of the sheared edge [10, 13-15]. This is because in the production cycle, mechanical cutting processes can cause cut edge defects in the form of burrs, slivers and edge rollover. Subsequent deburring is required which increases processing time and labor costs. A significant problem is also the increased wear of cutting tools that occurs when cutting stainless steels. The geometry of the cut edge and the punch wear are closely related. Excessive wear of cutting tools causes deviations in the shape of the workpiece [13].

CO<sub>2</sub> lasers are the most widely used lasers in subtractive machining, especially in cutting materials. Recent developments introduce the CO<sub>2</sub> laser cutting option instead of the standard die-cut plates for various materials. Some researchers

analyzed high-power CO<sub>2</sub> laser cutting of steel plates. The effect of the input laser cutting parameters on the cut surface quality was analyzed. An overall optimization was applied to find out the optimal cutting setting that improve the cut surface quality [16]. Work [17] examined the application of the CO<sub>2</sub> laser cutting process to three thermoplastic polymers – polyethylene, polypropylene, polycarbonate – in different thickness ranging from  $t = 2$  to 10 mm.

Fiber lasers are machines with greater efficiency, maximum speed and acceleration. Thanks to the unique capabilities of very fast cutting of thin sheets, they are perfect for cutting as an alternative to turret punching machines, which so far have been considered the cheapest technology for cutting sheet elements. It has been found that in comparison with mechanical cutting, for example, blanking or guillotining fiber lasers cause less stresses in the material and reduce the cut surface defects, for example, burrs and edge waves. The study [18] presents different cutting methods and types of laser, which were used in the examinations in order to achieve a distortion-low and high-quality cutting of the materials in the sintered and unsintered state at high process velocities. Observation of influence of high power (30 kW) of fiber laser on cutting process of very thick plates of carbon steel (300 mm) was carried out in work [19]. The study [20] investigates the effect of fiber laser cutting parameters on the mechanical behavior of laser butt welded joints whose edges were obtained by laser cutting. Analyzing the current state of knowledge, it appears that the greatest problems in production lines result from the necessity of the correct configuration of the parameters of CO<sub>2</sub> and fiber lasers, which is a complex issue.

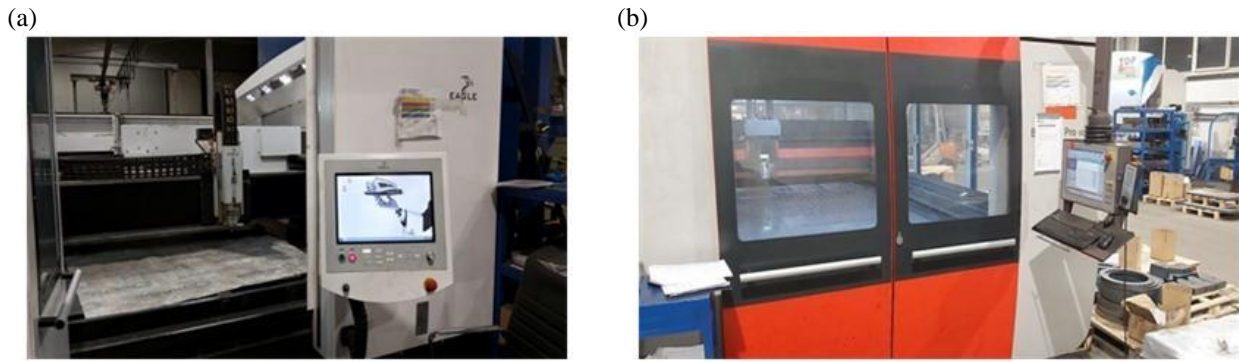
In laser cutting, current research concerns the analysis of physical phenomena occurring during the process. An important physical phenomenon that occurs during the cutting process is laser ablation, as a result of which, under certain conditions of temperature and pressure, there is a transition of a material from a solid to a gas state, omitting the liquid phase. Laser ablation is a sputtering process in which material is removed at the rate of several atomic monolayers per pulse and the surface undergoes structural changes on a mesoscopic scale and in terms of chemical and phase composition [2, 3, 21-23]. Since the temperature in the irradiated micro-areas of the material may temporarily exceed its boiling point, the evaporation process is accompanied by typical hydrodynamic effects, such as the Kundsén layer. This often causes the phenomenon of reverse deposition of the material, e.g. on the surface of the material, expansive transport of the material, as well as the presence of drops of molten material in the generated vapors. These factors may significantly deteriorate the quality of the obtained workpiece [2, 3].

The correct control of the ablation process is a complex issue [24-26]. The number of controllable input variables influencing the laser ablation process and quality of the workpiece is large. The impact of these variables is not fully understood, which means that on production lines they are selected mainly by trial and error combined with experience, which causes workpiece defects in the form of burrs, carbon deposits and wide heat affected zone (HAZ) [27-28].

The aim of the present work is to analyze the influence of laser processing of RVS 1.4301 stainless steel on the quality of the cut edge. Two lasers were used for the research: CO<sub>2</sub> laser and a fiber laser. The tested details were designed in CAD system, and then, using the nesting technology, they were generated in the form of NC code for laser cutting machines. In order to assess the usefulness of two methods of cutting in the technology of manufacturing products, experimental tests were carried out using test stands available at a local manufacturing company dealing in the production of metal products. As a result of the research, the influence of selected parameters and conditions of the laser cutting process on the technological quality of the obtained product was determined. The obtained results enable the appropriate selection of machining parameters in terms of obtaining high-quality products, while maintaining the minimum energy consumption and time-consuming process.

## EXPERIMENTAL PROCEDURE

Before starting the actual experimental researches, preliminary studies were performed to better understand the physical phenomena occurring during cutting and to define the input, output, disruptive and constant factors. The preliminary tests consisted of making details designed in CAD system and made on laser machines for random parameter settings and recommended by the manufacturer. As a result of research, it was possible to determine which factors have the greatest impact on the quality of the cut edge, and which can or should be treated as constant. It was found the relationships between these parameters are not linear. After carrying out the appropriate tests, it will be possible to determine the ranges in which these parameters enable the highest quality of the cut edge of the material to be obtained. After preliminary research the actual experimental tests were carried out - in accordance with the experiment planning theory [29-32]. In the first case, the Eagle iNspire 2040 6 kW laser was used (Figure 1a). In the second case, a Bystronic Bysprint 3015 4.4 kW CO<sub>2</sub> laser was used (Figure 1b).



**Figure 1.** Test stands: a) Laser Eagle iNspire 2040 6 kW and b) Laser Bystronic Bysprint 3015 4.4 kW

RVS 1.4301 (AISI 304, EN X5CrNi18-10) stainless steel with a thickness of  $t = 3$  mm and  $t = 6$  mm was used in research. The mechanical properties and chemical composition are reported in Tables 1 and 2, respectively. Variability for the CO<sub>2</sub> and fiber laser process parameters are presented in Tables 3 and 4.

**Table 1.** Mechanical properties of the adopted material

Properties	values	units
Density	7900	(kg/m <sup>3</sup> )
Young's modulus	193-200	(GPa)
Yield strength (at 0.2%)	185	(MPa)
Elongation (at 50 mm)	45	(%)
Tensile strength	490-685	(MPa)
Brinell Hardness	170-360	-
Specific heat	480	(J/kg K)
Thermal conductivity	16	(W/m K)

**Table 2.** Chemical composition of the adopted material

C /max	Si /max	Mn /max	P /max	S /max	N /max	Cr	Ni
0.07	1.00	2.00	0.045	0.030	0.10	17.50÷19.50	8.0÷10.5

**Table 3.** Variability for the fiber laser process parameters

Laser power P [W]	Cutting speed v [mm/min]	Wavelength $\lambda$ [ $\mu$ m]	Frequency f [kHz]
4000-5000	2000-11000	1.07	5

**Table 4.** Variability for the CO<sub>2</sub> laser process parameters

Laser power P [W]	Cutting speed v [mm/min]	Nozzle distance h [mm]	Gas pressure p [MPa]
3500-4500	1100-2100	0.7	1.5

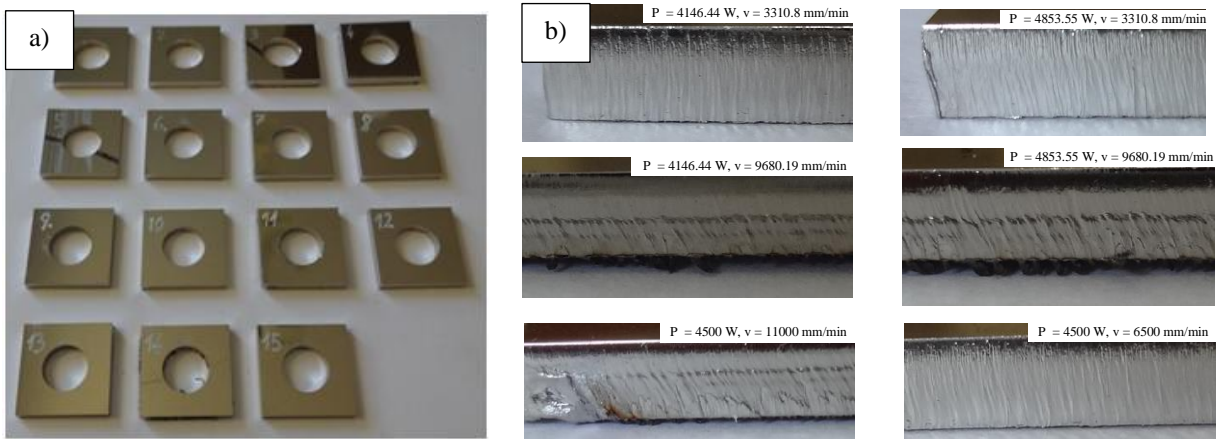
Experiments were conducted based on the classical experimental design method, with the use of five-level rotatable plan of experiment with the use of the E-Planner program [33]. The tests were carried out for three replications for each plan level. The quality of the cut surface was assessed using two methods: the height of the burrs and the size of HAZ. The evaluation of selected features of the cut edge was made on the basis of observation and microscopic measurements of the cut surface. The evaluation of the cut surface characteristic features after the sheet metal cutting process was carried out on a measuring microscope by Kestler - Vision Engineering Dynascope with the ND 1300 Quadra-Chek measuring system.

## EXPERIMENTAL RESULTS

### Fiber Laser

After the cutting process, for each of the samples, an initial inspection was made to assess whether it was possible to obtain complete separation of material and whether there are leading defects of the cut edge. Examples of the cut details for the fiber laser are shown in Figures 2, 4 and 5 for the tested sheet thicknesses. After the initial inspection of the

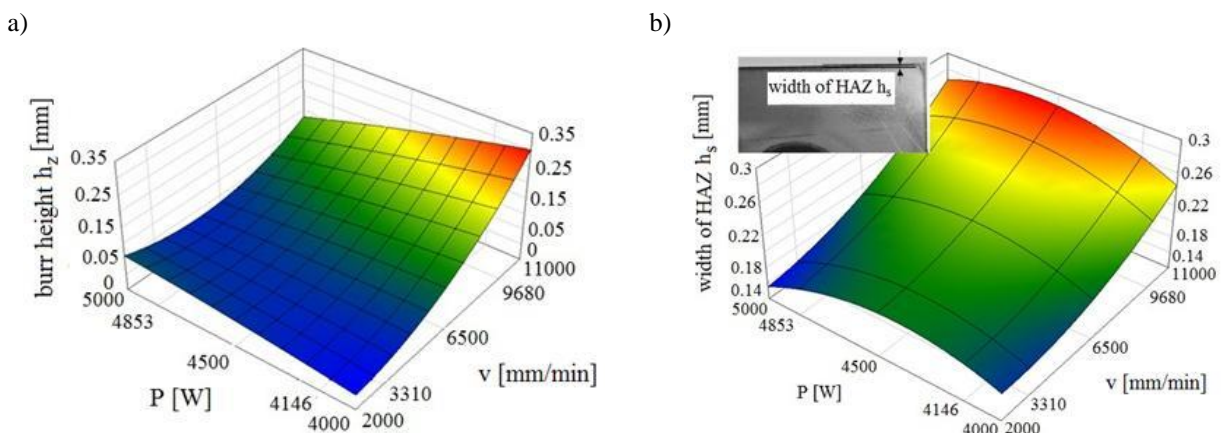
samples, it was possible to state that the smooth zone on the cut edge in some configurations can be obtained. In a few cases, however, defects such as burrs and effects of the heat affected zone are visible.



**Figure 2.** Selected samples cut on fiber laser ( $t = 3$  mm): a) view of selected samples, b) view of sheared edges of selected samples

On the basis of microscopic images, it can be concluded that obtaining a complete material separation was possible for each level of the test plan for a thickness of  $t = 3$  mm. Due to the complexity of the ablation process, it was decided to conduct straight line cutting tests and curvilinear cutting tests in the form of the hole edge (Figure 2a). This made it possible to assess not only the quality of the cut edge depending on the machining parameters, but also to check the correct operation of the control modules. Visible defects in the form of edge burns and burrs occur for the following parameter settings for a sheet with a thickness of  $t = 3$  mm:  $P = 4146.44$  W,  $v = 9680.19$  mm/min;  $P = 4853.55$  W,  $v = 9680.19$  mm/min;  $P = 4500$  W,  $v = 11000$  mm/min (Figure 2b).

The specificity of a fiber laser is, among others the fact that when cutting thin sheets it is possible to use even several times higher speeds compared to  $CO_2$  machines, thanks to a much higher energy density or physical differences of the laser beam. As the tests carried out showed, the quality of the edges directly depends on the cutting speed, the power of the laser used and the thickness of the cut materials. For the lower ranges of the cutting speed, the laser power parameter is less sensitive for the tested sheet thickness than for high speeds (Figure 3). Increasing the cutting speed requires increasing the power. The problem is to find a power limit that will ensure high quality cutting at high speeds. For the tested sheet thickness, from the point of view of the quality criteria and the application of the detail, the burr height should not exceed  $h_z = 5\%$  g. This means that the maximum allowable burr height can be obtained for a cutting speed of approx.  $v \leq 6500$  mm/min while using the minimum power (Figure 3a). Cutting at maximum speed requires the use of power above  $P = 4700$  W. The influence of the tested parameters of the cutting process on the width of the heat-affected zone is shown in Figure 3b. The heat-affected zone is visible at the bottom of the samples, where the effects of the ablation process accumulate, visible in the form of the so-called lumber. The width of the heat zone influence for all cases is negligible and ranges from  $h_s = 0.05 - 0.28$  mm. The smallest width of the HAZ zone was obtained using cutting speeds in the range  $v = 2000 - 3300$  mm/min.

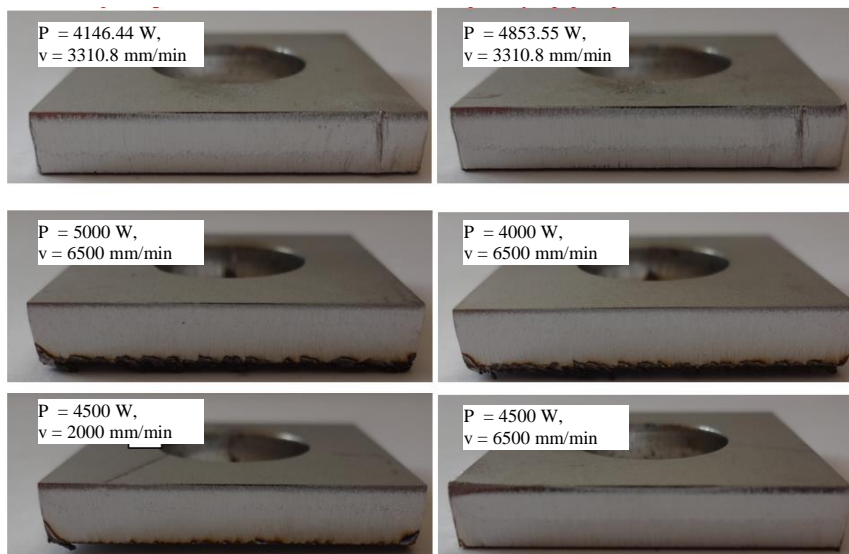


**Figure 3.** a) the influence of laser power and cutting speed on burr height, b) the influence of laser power and cutting speed on width of heat-affected zone ( $t = 3$  mm)

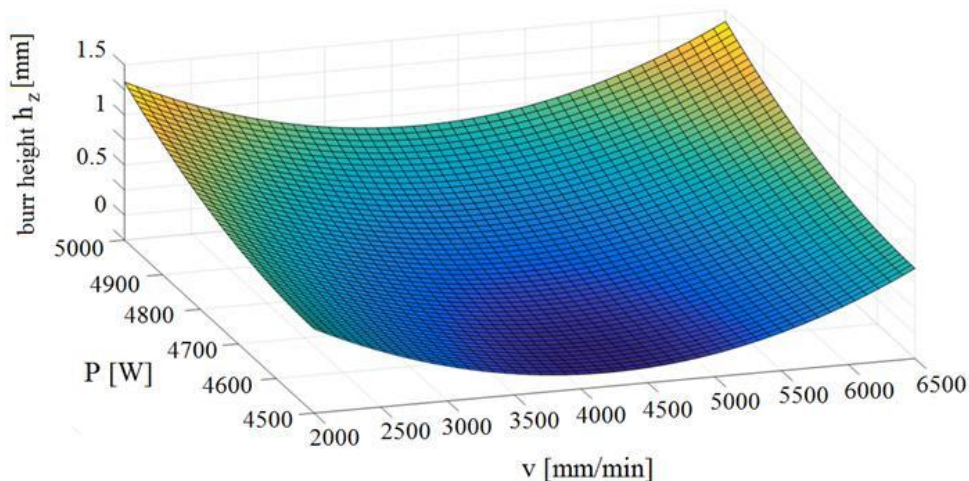
Examples of the cut details cut on fiber laser for the  $t = 6$  mm are shown in Figure 4. The view of the cut surfaces of the selected samples is shown in the Figure 5. The use of high cutting speeds above  $v = 6500$  mm/min was particularly disadvantageous. The highest quality of the cut edge was obtained with the power  $P = 4500 - 4800$  W and the speed  $v = 3500 - 4000$  mm/min (Figures 6 and 7).



**Figure 4.** Selected samples cut on fiber laser ( $t = 6$  mm)

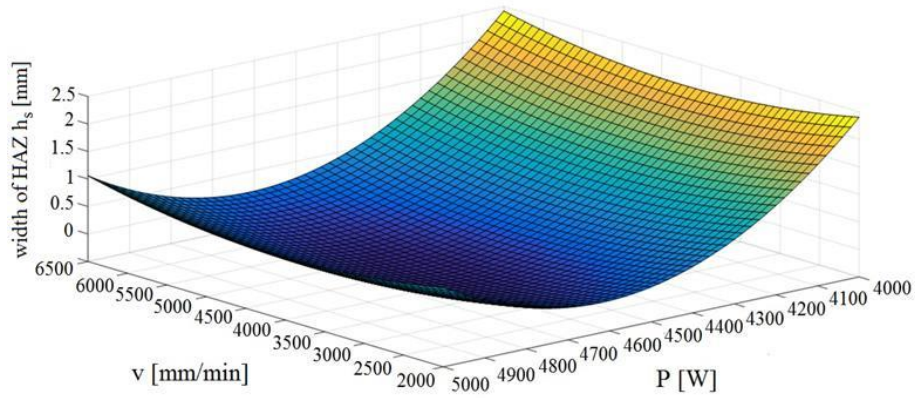


**Figure 5.** View of sheared edges of selected samples cut on fiber laser ( $t = 6$  mm)



**Figure 6.** The influence of laser power and cutting speed on burr height ( $t = 6$  mm)

Due to the thickness of the beam, cutting thick sheets is more cumbersome as opposed to  $\text{CO}_2$  lasers, however, with the appropriate selection of processing parameters, it provides a higher quality of the cut edge, as shown by the obtained results.



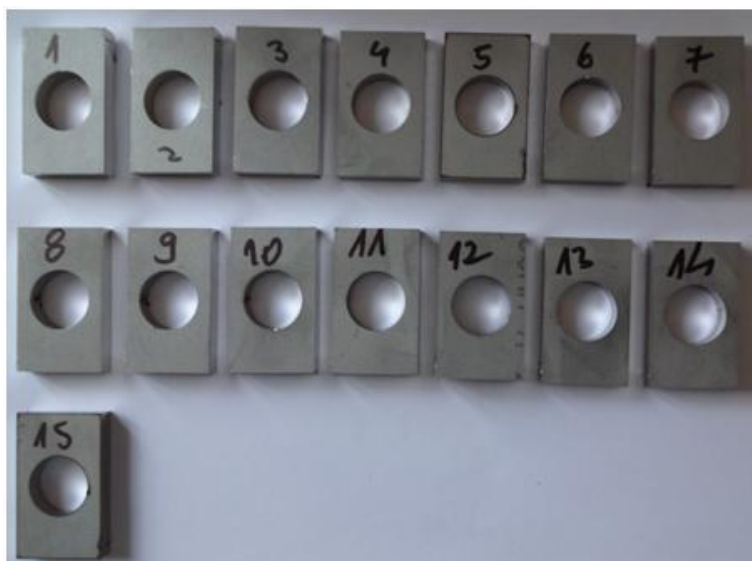
**Figure 7.** The influence of laser power and cutting speed on width of heat-affected zone ( $t = 6 \text{ mm}$ )

### CO<sub>2</sub> Laser

The view of the selected cut details with using CO<sub>2</sub> laser is shown in Figures 8 and 9. Figures 10 and 11 show the view of the cut edges depending on the set values of the cutting process parameters. During the cutting process with a CO<sub>2</sub> laser, it is very important, among others adequate support of the cut parts. Lack of proper support can disturb the cut line as the part being cut deviates. It is also important to avoid overheating in the final phase - care should be taken that the heat delivered by the beam approaching the edge can be absorbed by the surrounding material without causing an excessive increase in temperature. The condition for obtaining good cutting quality and maintaining the tolerance of the dimensions of the cut structural elements is the precise guidance of the cutting stream in the joint with a good, stable cutting machine with high vibration resistance and good repeatability of working movements.



**Figure 8.** Selected samples cut on a CO<sub>2</sub> laser for  $t = 3 \text{ mm}$



**Figure 9.** Selected samples cut on a CO<sub>2</sub> laser for  $t = 6 \text{ mm}$

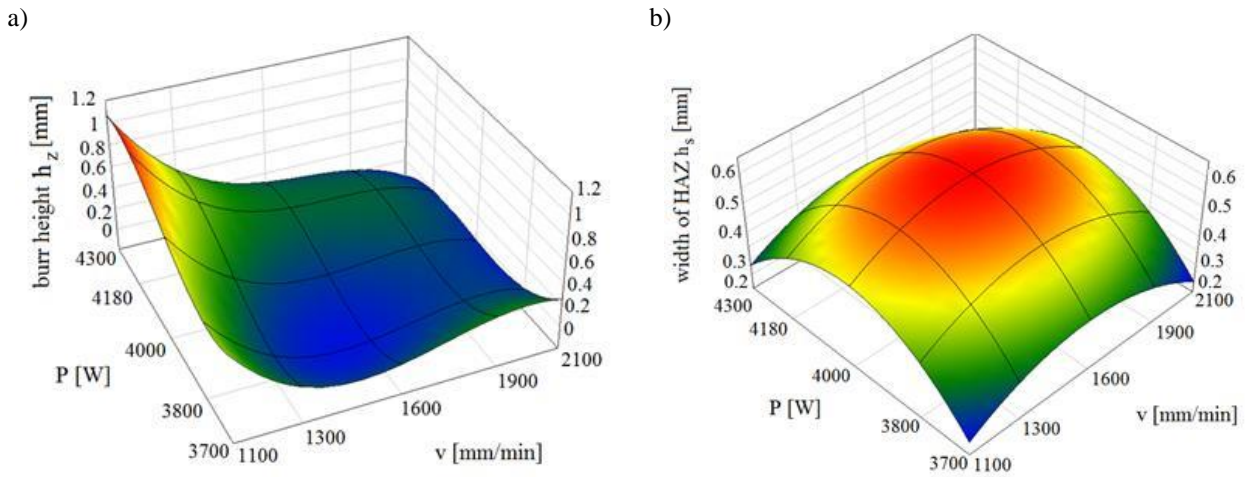
Visible damage and defects in the form of edge burns and burrs occur for the following parameter settings for a sheet with a thickness of  $t = 3 \text{ mm}$ :  $P = 4300 \text{ W}$ ,  $v = 1400 \text{ mm/min}$ ;  $P = 4000 \text{ W}$ ,  $v = 1100 \text{ mm/min}$  (Figure 10). This settings also cause burns to the surface inside the hole. The  $\text{CO}_2$  laser is characterized by a much slower cutting speed compared to a fiber laser. Based on the research, it can be seen that the cutting speed must be increased with increasing power. The sample cut with the settings of  $P = 3700 \text{ W}$ ,  $v = 1400 \text{ mm/min}$  is of sufficient quality with a small burr (Figure 10). For samples cut with  $P = 4300 \text{ W}$ ,  $v = 1400 \text{ mm/min}$  the power was increased by  $600 \text{ W}$ , which resulted in damage to the quality of the cut edge and the formation of a sharp burr. Increase the cutting speed to  $v = 1850 \text{ mm/min}$  using the power value settings  $P = 3700 \text{ W}$  and  $P = 4300 \text{ W}$  improved edge quality. The beam power control within the limits of  $P = 3500\text{-}4500 \text{ W}$  at a speed of  $v = 1700 \text{ mm/min}$  did not cause a difference in the quality of the edges. However, when the speed is lower and is set at  $v = 1100 \text{ mm/min}$  with power of  $P = 4000 \text{ W}$  scorched edges and an irregular burr was obtained on sample.

Due to technological criteria, the burr height should not exceed  $h_z = 10\%t$ . The greatest burr heights were obtained using cutting speeds in the range of  $v = 1100\text{-}1300 \text{ mm/min}$  and power values above  $P = 4200 \text{ W}$ . The lowest burr height was obtained using the power values from the range of  $P = 3800\text{-}4000 \text{ W}$  and the cutting speed  $v > 1300 \text{ mm/min}$  (Figure 11a).

Figure 11b shows the influence of the tested parameters of the cutting process on the width of the heat-affected zone. The research results show that controlling the width of the HAZ zone is difficult due to the lack of wide ranges of variability of the tested input factors in which the width of this zone would be minimal. The largest width of the HAZ zone was obtained using cutting speeds in the range of  $v = 1500\text{-}1700 \text{ mm/min}$ . In these cutting speed ranges it is not preferred to use the power values in the range of  $P = 3900\text{-}4100 \text{ W}$ .



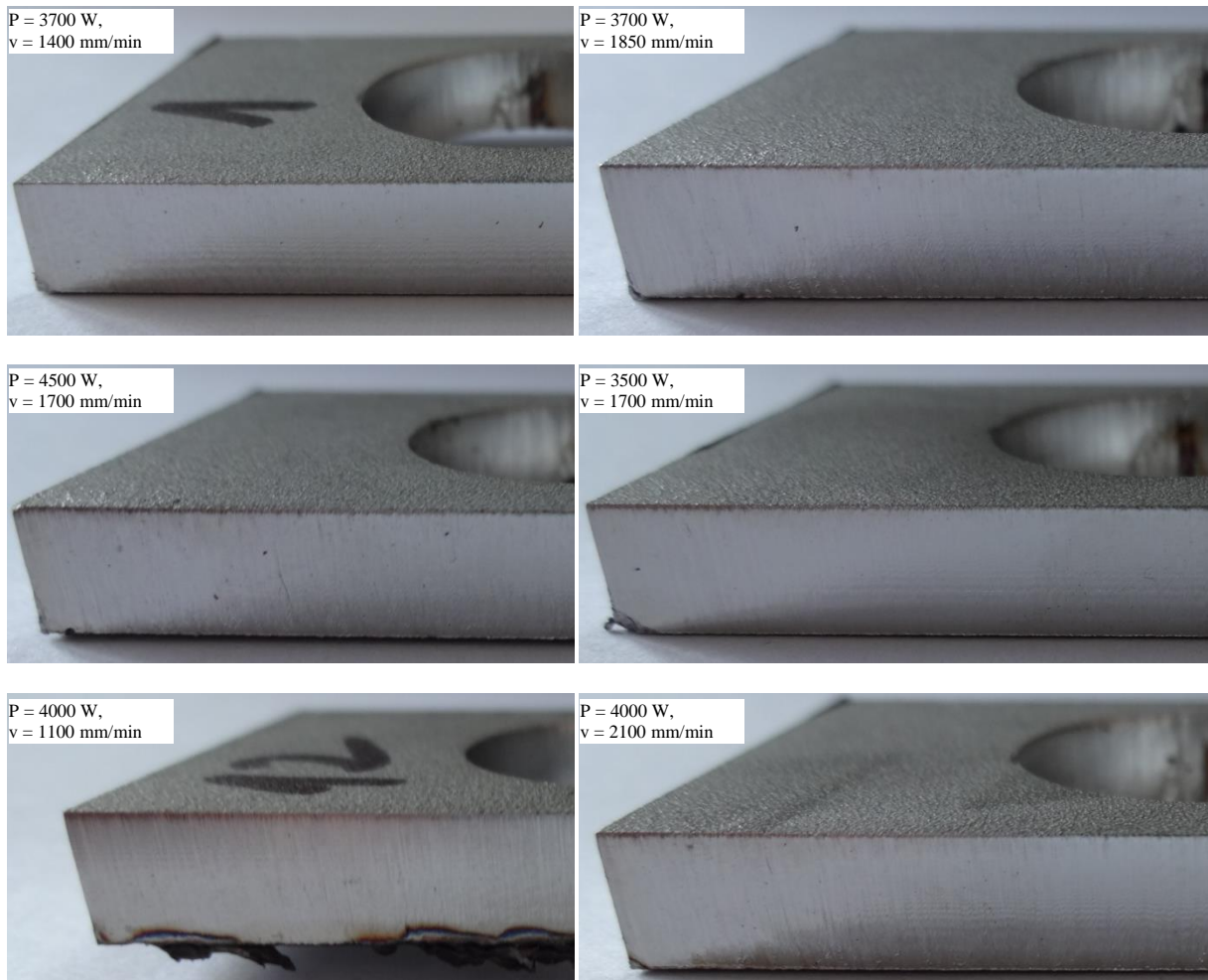
**Figure 10.** View of sheared edges of selected samples cut on  $\text{CO}_2$  laser ( $t = 3 \text{ mm}$ )



**Figure 11.** a) the influence of laser power and cutting speed on burr height, b) the influence of laser power and cutting speed on width of heat-affected zone ( $t = 3 \text{ mm}$ )

The minimum value of the width of HAZ zone can be obtained by using four variants of setting the input parameters:  $P = 3700 \text{ W}$ ,  $v = 1100 \text{ mm/min}$ ;  $P = 3700 \text{ W}$ ,  $v = 2100 \text{ mm/min}$ ;  $P = 4300 \text{ W}$ ,  $v = 1100 \text{ mm/min}$ ;  $P = 4300 \text{ W}$ ,  $v = 2100 \text{ mm/min}$ . It should be noted that applying the setting of  $P = 4300 \text{ W}$  and  $v = 1100 \text{ mm/min}$  will increase burr height (Figure 11a). Therefore, it will be very important to precisely control the cutting process and to limit the impact of interferences, because even small deviations from these parameter values will result in an increase in the width of the HAZ zone (Figure 11b).

Figure 12 shows view of cut edges of selected samples cut from sheet of  $t = 6 \text{ mm}$  thick. In each sample cut, it was possible to achieve complete separation of the material.

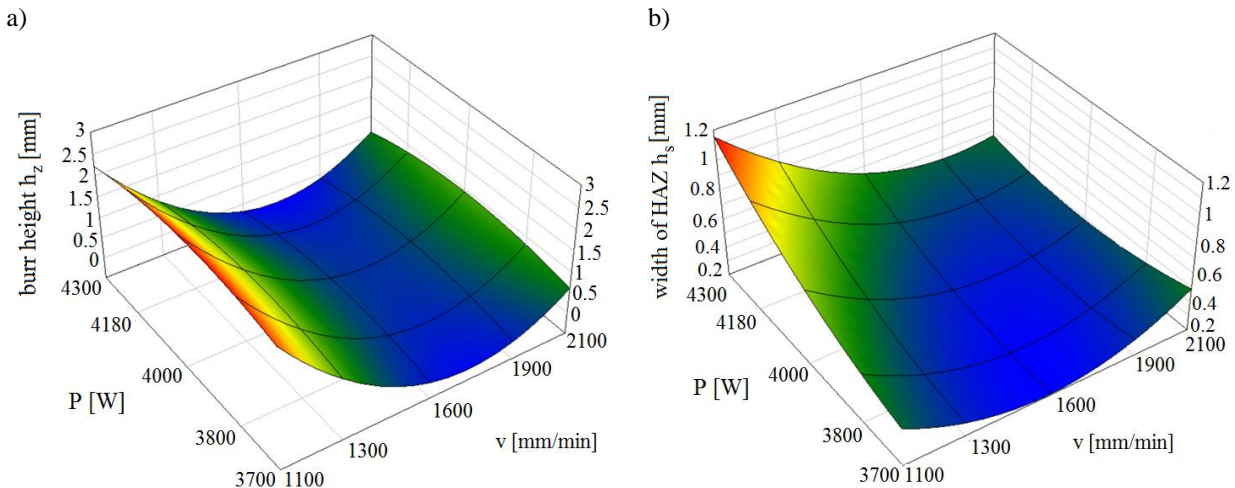


**Figure 12.** View of sheared edges of selected samples cut on  $\text{CO}_2$  laser ( $t = 6 \text{ mm}$ )



The mechanisms of the burr formation process are similar to those in the case of  $t = 3$  mm sheet. It is not appropriate to use cutting speeds below  $v = 1300$  mm/min. In this case, for each power value, a significant burr height of about 30% of the sheet thickness is obtained (Figures 12 and 13a). Setting the power within the limits  $P = 3700$ - $4300$  W and the cutting speed  $v = 1600$  mm/min allows to obtain a burr height of about  $h_z = 10\%t$ . Increasing the cutting speed above this value increases the size of the burr and may result in the cut edge not melting.

The diagram (Figure 13b) shows that the linear increase in cutting power causes a significant increase in the heat affected zone when using low cutting speeds. The results show that in order to reduce the HAZ width for sheets of significant thickness, different recommendations must be followed than for thin sheets. However, the range of permissible settings is greater than in the case of thickness  $t = 3$  mm. Consequently, fewer edge burns were recorded both on the edges of the side details and in the holes. As with the burr height analysis, the optimal HAZ reduction results can be obtained using speeds of about  $v = 1600$ - $1800$  mm/min. The power value can be selected in a wide range from  $P = 3700$  W to  $4200$  W. The use of higher powers gives the increase in the HAZ, especially when using speeds below  $1200$  mm/min.



**Figure 13.** a) the influence of laser power and cutting speed on burr height, b) the influence of laser power and cutting speed on width of heat-affected zone ( $t = 6$  mm)

## CONCLUSION

The results of experimental research confirm the possibility of using the CO<sub>2</sub> laser cutting technique and the fiber type to shape stainless steels with a high-quality cut edge. It was found that the laser power and cutting speed had a significant influence on the output factors for two cutting techniques. These parameters must be selected very precisely depending on the given material thickness. When using a fiber laser, there are power ranges in which the material has not been completely separated. The burr height and the heat affected zone depends on the cutting speed. It is especially visible when processing thin sheets. Reducing or increasing the power causes significant changes in the width of the HAZ for thin sheets at low cutting speeds.

Based on the experimental research carried out on CO<sub>2</sub> laser, the following conclusions can be drawn:

- the quality of cutting thicker sheets, after developing appropriate setting guidelines, gives similar results as in the case of a fiber laser, but the range of optimal parameters is smaller than it is during fiber laser cutting,
- CO<sub>2</sub> lasers do not have a minimum and maximum P-beam power limitation, their operation is cheaper and the head is less susceptible to dirt. They are larger than fiber lasers and less efficient, and the use of shielding gases of inadequate purity can damage the mirrors,
- For  $t = 3$  mm the lowest burr height and HAZ was obtained using the power value of  $P = 4200$ - $4300$  W and the cutting speed  $v = 2100$  mm/min. For  $t = 6$  mm the minimum HAZ can be obtained using speeds of about  $v = 1600$ - $1800$  mm/min. The power value should be selected in a range from  $P = 3700$  W to  $4200$  W.

Based on the experimental research carried out on fiber laser, the following conclusions can be drawn:

- fiber lasers are delicate and susceptible to dirt, even minimal wear or contamination of the optics may make it impossible to cut material,
- due to the thickness of the beam, cutting thick sheets is more difficult as opposed to CO<sub>2</sub> lasers, however, with the appropriate selection of processing parameters, it provides a higher quality of the cut edge,
- fiber lasers are machines especially recommended for the processing of thin sheets due to their high efficiency and the quality of the product edges, which was confirmed by the conducted tests,
- the burr height and the heat-affected zone in thin sheets depends mainly on the cutting speed. Reducing or increasing the power in the tested ranges of variability intervals had less impact on the quality of the cut edge. The

smallest width of the HAZ zone and burr height for  $t = 3$  mm was obtained using cutting speeds in the range of  $v = 2000 - 3300$  mm/min. For  $t = 6$  mm the highest quality of the cut edge was obtained with the power  $P = 4500 - 4800$  W and the speed  $v = 3500 - 4000$  mm/min.

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