Optimization of Nitrogen Use Efficiency in Cutting of Austenitic Stainless Steel by a Fiber Laser

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In metallurgical processes, metal sheet cutting is usually a basic technological operation that needs to be performed. All other technological operations follow the procedure of metal sheet cutting, with the final aim of manufacturing a final product. Machines used for that basic metal cutting operation shall be reliable, efficient, fast, and relatively easy to work with. While working with a laser, the authors noticed the inefficiency of cutting with nitrogen. Nitrogen bottles got empty too quickly, which caused additional costs. Inefficient, i.e., excessive nitrogen consumption requires a more frequent supply of nitrogen. During the COVID-19 pandemic, nitrogen was not always available, as suppliers shifted to manufacture oxygen bottles for medical needs. Therefore, the authors engaged in finding solutions to reduce the consumption of nitrogen at cutting. The mentioned problem was studied within the experiment that focused on the optimization of nitrogen use during fiber laser cutting, the procedure, and results of which are described in this paper. Specimens of different cutting parameters were prepared and cut to measure their roughness and burr height. The collected data were used to create a mathematical model with an ANOVA table. The experiment resulted in the determination of optimal cutting parameters achieved by the lowest possible cutting gas pressure.

Keywords: *cutting parameter optimization, cutting gas pressure, burr height, ANOVA*

1. DESCRIPTION OF A PROBLEM

A fiber laser is applied in cutting metal sheets with nitrogen at an initial operating pressure of p_0 being, 24 bars. Such high operating nitrogen pressure facilitates high-quality cuts at parameters that deviate from optimal ones. However, the disadvantage of high operating nitrogen pressure is slower cutting with the same amount of gas, meaning it is less productive to cut at high operating nitrogen pressure than at reduced operating pressure. In order to get a satisfactory quality cut and to reduce nitrogen consumption, it is necessary to lower the operating pressure of cutting. A quality cut can still be obtained if the operating pressure is reduced by 2 to 3 bars without adjusting other cutting para–meters. Such an approach is simple, but it does not facilitate significant gas savings. While intending to reduce the nitrogen pressure, other cutting parameters have to be adjusted, too, in order to obtain a quality burr-free cut. Parameters are usually adjusted by selec–ting different values for each parameter at which expe–rimental cutting is done. Based on the appearance of cuts, a laser operator decides whether a particular parameter needs further adjustment to achieve the desired effect of cutting [1-3].

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2. INTRODUCTION TO CUTTING PARAMETERS

Metal cutting with fiber laser requires correctly set parameters to make cutting as efficient as possible and get the highest quality cut. The peak cutting power and the laser beam frequency can be adjusted. Yet, those parameters are less important if knowing that the nominal power is sufficient for cutting metal sheets of a certain thickness. Other important parameters refer to nozzle distance from the workpiece, the piercing height and time, and the cutting height.

Figure 1. Example of cutting by fiber laser.

Cutting speed is also an important parameter, which depends on other para–meters, auxiliary gas type, and the kind of processed material. Moreover, cutting is also influenced by the distance of the beam focus from the upper metal surface. The focus distance is measured in millimeters, in positive values if it is above the upper surface of the metal sheet, or in negative values if it is below the upper surface of the metal sheet. Referring to the nozzle parameter, it is important to choose the appropriate type of nozzle, which can be a single nozzle for nitrogen cutting or a double nozzle for oxygen cutting. The nozzle diameter can be larger or smaller, depending on the metal sheet thickness. Before pro–ceeding with laser cutting, it is very important to check the laser beam position and adjust it to the center of the nozzle (Figure 1). Failure to do so may result in poor cuts, uncut workpieces, or in damaged fiber laser parts [4-6].

2.1 Parameters and properties of cutting with auxiliary gases

The type and pressure of auxiliary gas used during cutting are perceived as key cutting parameters. The laser-cutting process is performed with oxygen, air, or nitrogen. Cutting thinner sheets is the fastest with nitro–gen and the slowest with oxygen. Nitrogen used for cutting has to be of a minimum of 99.99% purity. Such high purity of nitrogen prevents changing of cut sheets' color. When cutting with nitrogen, metal is molten only with the laser beam heat [7]. As an inert gas, nitrogen prevents oxidation during cutting and blows away mol–ten metal due to high cutting pressure, which can be between 12 and 25 bars. The higher the nitrogen pres–sure, the more the cutting parameters and properties can deviate from the optimal ones, yet a burr-free quality cut can still be obtained (Figure 2). Higher nitrogen pres–sure also allows for faster-cutting speed, but cutting with nitrogen at lower pressure is more cost-effective [5].

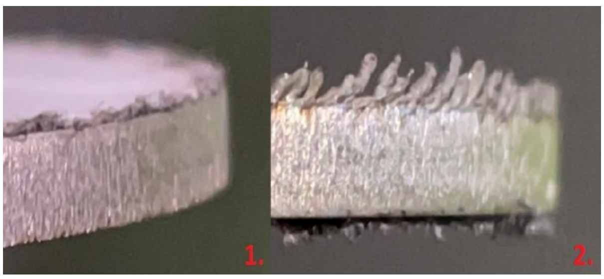

Figure 2. Cutting with nitrogen at sufficient and insufficient pressure; 1 - Appearance of the cut workpiece at sufficient nitrogen pressure; 2 - Appearance of the cut workpiece at insufficient nitrogen pressure.

Compared to nitrogen cutting, it is 3 to 5 times slower. Oxygen cutting pressure can usually range from 0,6 to 1,5 bars. When the laser beam heats the metal to the ignition temperature, an exothermic reaction occurs and burns the metal. Oxygen facilitates a 3 kW laser cutting up to 20 millimeter-thick metal sheets. The success of oxygen or nitrogen cutting depends on the focus distance, which needs to be well adjusted to the upper surface of the metal sheet. On Figure 3 could be seen when cutting with oxygen, the focus must be above the upper surface of the sheet, and when cutting with nitrogen, the focus must be on or slightly above the lower surface of the sheet [8,9].

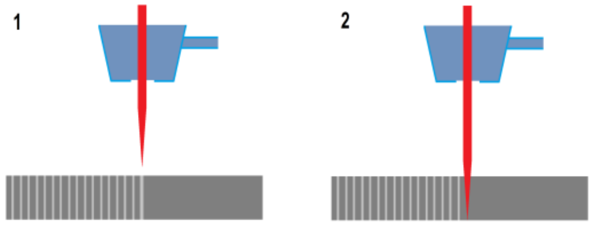

Figure 3. Position of focus depending on the auxiliary cutting gas; 1 – Position of focus at oxygen cutting; 2 – Position of focus at nitrogen cutting.

2.2 Experiment description

Aiming to obtain a good burr-free cut at the lowest possible operating gas pressure, this experiment deter–mined the interdependence of certain parameters on specimens cut out of the X5 CrNi 18-10 polished stain–less austenitic steel sheet with a protective foil. The sheet was 3 millimeters thick, 1250 millimeters wide, and 2500 millimeters long. Various cutting parameters (cutting frequency, peak power) affect the final cut quality, yet examining all aspects of their interde–pendence would be complex and superfluous for this research. Therefore, three cutting parameters were selected and examined in terms of their optimization effects on final cuts, while the remaining parameters were set to a fixed value. The parameters to be opti–mized were:
- focus distance from the upper surface of metal sheet f, mm
- operating nitrogen pressure p, bar
- nozzle height measured from the specimen surface h, mm.

Twenty sets of parameters were determined and applied on twenty workpieces to obtain data, i.e., measures of the arithmetic mean deviation of the profile Ra, the maximum roughness height Rz, the mean square deviation of the measured profile Rq, and the burr height hs. The above-stated parameters were assigned with different values, as determined by the Design-Expert software. The interdependence of parameters resulting from the measured values was used to determine the minimum nitrogen-cutting pressure at which burr-free cuts can be obtained [10].

The Design-Expert software was used to determine the values of cutting parameters for each of the twenty specimens.

Table 1. Parameters defined for the experiment.

Specimen Ord. No.	Focus *f*, mm	Nitrogen pressure *p*, bar	Nozzle height *h*, mm
1	-1.4054	22.3649	0.401349
2	-3	18.5	0.55
3	-1.4054	14.6351	0.698651
4	-2.5946	14.6351	0.401349
5	-2	12	0.55
6	-1	18.5	0.55
7	-2	18.5	0.55
8	-2	18.5	0.55
9	-2	18.5	0.55
10	-2	18.5	0.3

11	-2	18.5	0.8
12	-2.5946	14.6351	0.698651
13	-2.5946	22.3649	0.698651
14	-2	18.5	0.55
15	-2	25	0.55
16	-1.4054	22.3649	0.698651
17	-2	18.5	0.55
18	-2	18.5	0.55
19	-1.4054	14.6351	0.401349
20	-2.5946	22.3649	0.401349

Laser cutting was run by the CypCut software, in which values of the cutting parameters can be set to one decimal place. Therefore, the parameters listed in the Table 1 had to be rounded to the values presented in Table 2.

Table 2. Parameters applied to specimen cutting.

Specimen Ord. No.	Focus *f*, mm	Nitrogen pressure *p*, bar	Nozzle height *h*, mm
1	-1.4	22	0.4
2	-3	19	0.6
3	-1.4	15	0.7
4	-2.6	15	0.4
5	-2	12	0.6
6	-1	19	0.6
7	-2	19	0.6
8	-2	19	0.6
9	-2	19	0.6
10	-2	19	0.3
11	-2	19	0.8
12	-2.6	15	0.7
13	-2.6	22	0.7
14	-2	19	0.6
15	-2	25	0.6
16	-1.4	22	0.7
17	-2	19	0.6
18	-2	19	0.6
19	-1.4	15	0.4
20	-2.6	22	0.4

Cutting at the set parameters was done by using a single nozzle with a diameter of 2 millimeters. At a cut–ting pressure of 24 bar with a single 2.0 nozzle, the best cut appeared burr-free on the lower edge. The cutting speed was constant at 3 m/min. The laser beam power was 3 kW, and the frequency was 5 kHz (Figure 4).

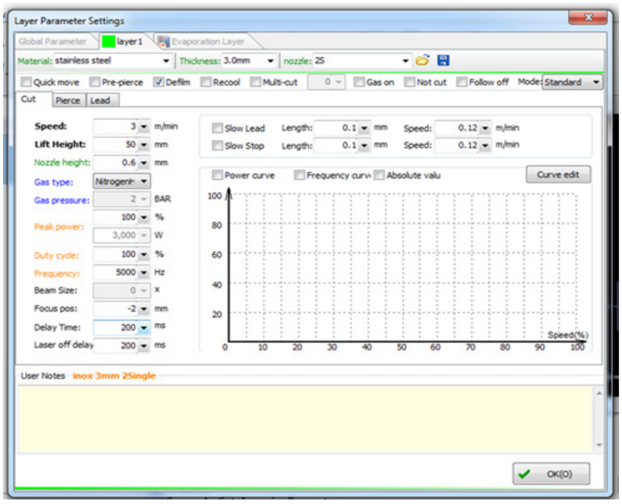

Figure 4. Set-up of parameters in the CypCut software [7].

Before starting the cutting process, the selected nozzle was checked, and the laser beam was positioned to the center of the nozzle to avoid the laser beam's in–correct position from affecting the quality of the specimens' cut. Specimens were 40 millimeters wide and 60 millimeters long. In the CypCut software, the path layer was planned, and the piercing position was placed on the outside contour at a length of 2 milli–meters to obtain a full rectangular cross-section without holes. Cutting was done outside the contour to avoid possible burrs or roughness on the cut. The cutting parameters did not cause roughness; it rather occurred because of high heat input, melting, and blowing of the material around the piercing spot [11, 12]. Specimens had a protective foil on their upper surface, so the cutting surface was protected from accidental damage. In certain cases, the protective foil significantly affects the quality of the cut; therefore, the process of cutting the specimens included the removal of protective foil with a laser beam along the cutting path (Figure 5).

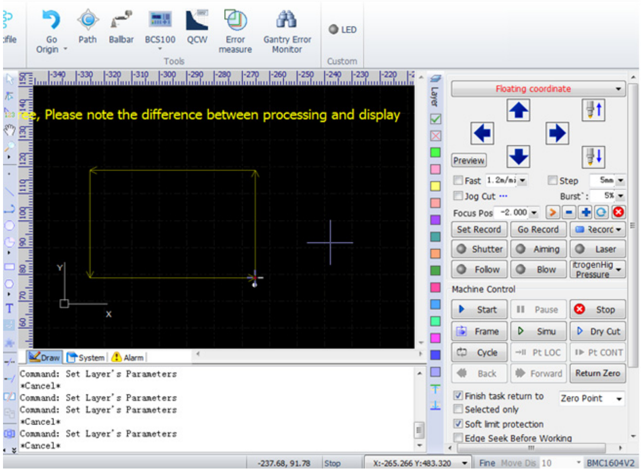

Figure 5. Path layer planning for cutting of specimens by the CypCut.

The parameters of focus f, pressure p, and height h were adjusted for cutting specimens at the appropriate pressure. Before starting the cutting process, the ope–rating pressure was set to the lowest defined value of 12 bars. After cutting all samples at a common value of the pressure parameter p, the pressure was increased to a certain value, and the procedure was repeated until reaching the pressure value of 25 bar. The cut speci–mens were labeled with a predetermined ordinal number and stored.

3. MEASUREMENT OF SPECIMENS AND DESC–RIPTION OF MEASURED VALUES

The cut specimens were measured to obtain the arith–metic mean deviation of the profile Ra, the maximum roughness height Rz, the mean square deviation of the measured profile Rq, and the burr height hs. The surface roughness of specimens was measured with a measuring device equipped with a gauge. Roughness of specimens was measured on the 60-millimeter-long side can be seen in Figure 6. Roughness was measured at a reference length *lr* of 12,5 mm with a profile sample length λc of 2,5 mm. The number of measuring sample lengths N was 5.

Figure 6. Measurement of specimen roughness.

Burr height *hsc* was calculated by subtracting the value of material thickness t, which was 3 mm, from the measured value referring to the minimum distance dmin. The distance was measured with a Vernier scale, i.e., nonius, that facilitates measuring up to five-hundredths of a millimeter. After measuring the distance dmin, the value of material thickness t was subtracted, and the value of the burr height *hs* was obtained (Figure 7). That value was entered into the table of measured values. The following expression was used for the calculation of the burr height:

$$h_s = d_{\min} t \quad (1)$$

where:

- *hs* – measured burr height, mm
- *dmin*- the minimum distance between the speci–men's upper surfaces and the measured burr peak, mm
- *t* – specimen thickness, mm

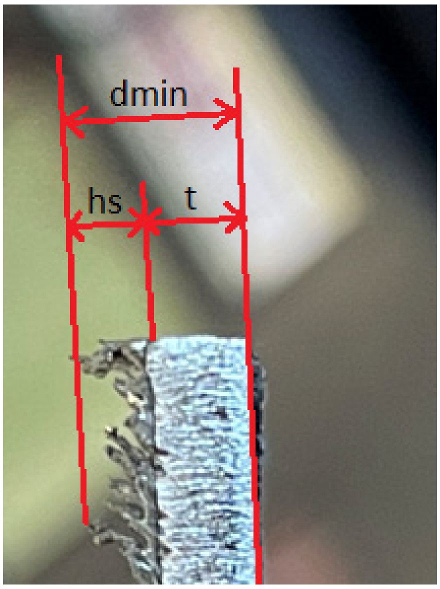

Figure 7. Measuring of specimen's burr height.

After completing the measurement procedure, Table 3 was created to overview the measured values for each specimen.

Table 3. Measured values of specimens' roughness and burr height *hs*.

Ord. No.	Ra, µm	Rz, µm	Rq, µm	Burr height h_{sm}, mm
1	6.27	39.59	7.81	0.3
2	5.25	27.44	6.34	0.35
3	5.01	27.64	6.20	2.00
4	5.03	28.85	6.19	0.15
5	6.61	35.53	8.03	2.80
6	5.60	33.39	6.97	2.10
7	5.80	33.14	7.03	0.10
8	5.83	31.45	6.91	0.10
9	6.42	36.93	7.73	0.10
10	6.77	37.31	8.47	0.05
11	7.31	41.27	8.89	0.90
12	6.62	41.00	8.37	0.80
13	7.27	42.94	9.01	0.05
14	6.32	40.31	8.01	0.20
15	9.56	44.65	11.05	0.15
16	5.08	31.71	6.36	1.80
17	7.41	38.96	8.91	0.05
18	7.17	37.42	8.68	0.15
19	4.95	32.97	6.29	1.75
20	5.72	35.23	7.17	0.10

4. OPTIMIZATION OF NITROGEN CONSUMPTION

Optimization of nitrogen use is performed in the Design-Expert software. The measured values were entered into the software. The measured roughness values did not provide a response based on which the interactions between the parameters could be deter–mined. There was no response because the roughness of the cut surface was mostly affected by the cutting speed parameter, which was sufficient to achieve satisfactory roughness. The burr height values gave a response based on which the interaction between the given parameters was determined. The burr height was the most affected by the gas pressure p. The lower the gas pressure, the higher the burr height, and vice versa. In Table 4, the quadratic model was applied to establish interactions between the parameters.

Table 4. ANOVA table for the quadratic model of burr height.

Source	Sum of square	df	Mean square	F - value	p - value	
Model	13,09	9	1,45	9,86	0,0007	significant
A - Focus	4,33	1	4,33	29,38	0,0003	
B - Nitrogen pressure	3,49	1	3,49	23,68	0,0007	
C - Nozzle height	1,05	1	1,05	7,09	0,0238	
AB	0,0903	1	0,0903	0,6123	0,4521	
AC	0,1653	1	0,1653	1,12	0,3147	
BC	0,0378	1	0,0378	0,2563	0,6236	
A^2	1,66	1	1,66	11,28	0,0073	
B^2	2,64	1	2,64	17,91	0,0017	
C^2	0,0803	1	0,0803	0,5441	0,477	
Residual	1,48	10	0,1475			
Lack of fit	1,46	5	0,2923	1,98	0,1674	
Pure Error	0,0133	5	0,0027	0,01		
Cor Total	14,57	19				

Values presented in the ANOVA table 4 were obtained by measuring specimens and by processing the obtained data. The final formula for the model was also obtained:

$$\begin{aligned} h_{sc} &= 19.23194 + 4.75255 \cdot f - 1.34973 \cdot p - \\ &-0.814426 \cdot h - 0.046234 \cdot f \cdot p + 1.62635 \cdot h \cdot f + \\ &+0.119664 \cdot p \cdot h + 0.961083 \cdot f^2 + 0.028665 \cdot p^2 + \\ &+3.37734 \cdot h^2 \end{aligned} \quad (2)$$

Expression 2 shows the regression model of the burr height of the machined surface of corrosion-resistant AISI steel on the cutting parameters, focus (factor A), nitrogen pressure (factor B), and nozzle height (factor C) with the actual values of the factors.

where:

- h_{sc}–calculated burr height, mm
- f - focus, mm
- p - operating nitrogen pressure, bar
- h - nozzle height, mm

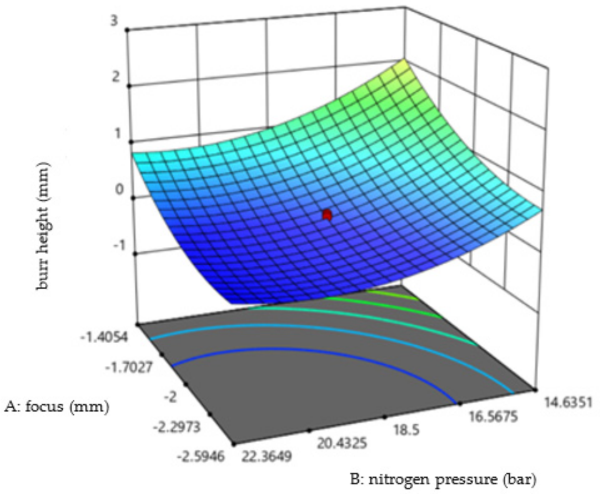

Figure 8. Interaction between burr height hs, focus f, and nitrogen pressure p - quadratic model

Figure 8 shows the interaction between burr height, focus, and nitrogen pressure; burr height decreases as the focus penetrates deeper into the material; it can also be seen in equation 2 that f^2 is positive, indicating the possibility of finding the smallest burr height for certain parameter values. The focus curve has an extremum (minimum = second derivative greater than zero) at the point where the first derivative equals zero. The local minimum burr height is at a focus distance of –2,5 mm.

Figure 9 shows the interaction between burr height, focus, and nozzle height. The nozzle height curve has an extremum (minimum = second derivative greater than zero) at the point where the first derivative equals zero. The local minimum burr height is at a nozzle height of 0,4 mm. The burr height decreases when the nozzle height decreases, it can also be seen in equation 2 that h^2 is positive, indicating the possibility of finding the smallest burr height value for certain parameter values.

Figure 10 shows the interaction between burr height, nozzle height, and nitrogen pressure. The burr height decreases when the nozzle height is smaller; the nozzle height recommended by the machine manufacturer is *0.8-1 mm*; from Figure 10, it can be seen that reducing the nozzle height can also reduce the nitrogen pressure, which affects the nitrogen consumption and cost reduction. In equation 2, it can also be seen that p^2 is positive, indicating the possibility of finding the smal–lest burr height value for certain parameter values. The nitrogen pressure curve has an extremum (minimum = second derivative greater than zero) at the point where the first derivative equals zero. The local minimum burr height is at a nitrogen pressure of 19 bars.

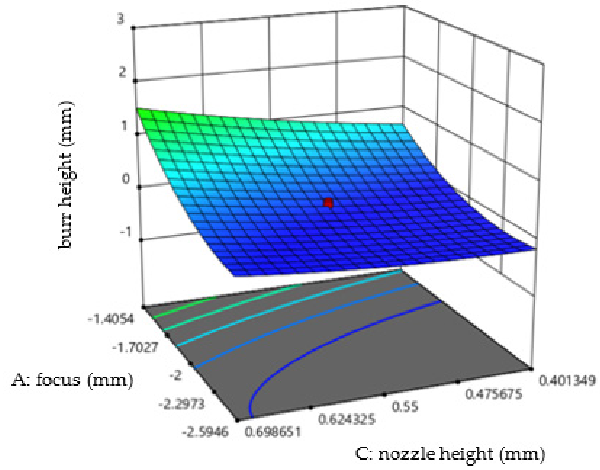

Figure 9. Interaction between burr height hs, focus f, and nozzle height h.

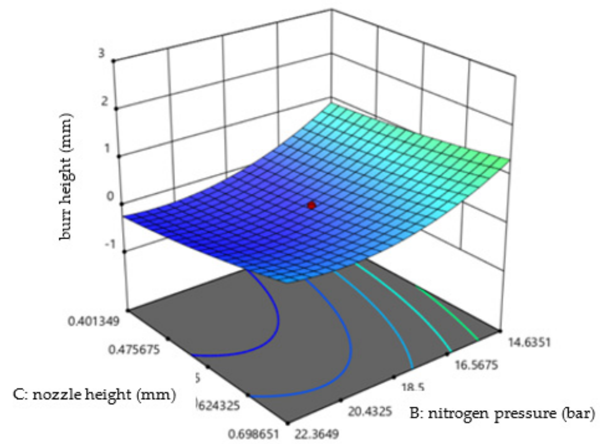

Figure 10. Interaction between burr height *hs*, nozzle height *h*, and nitrogen pressure *p*

In the production of metal sheets, manufacturers need to pay particular attention to sheets' thickness since this parameter is important for further processing of metal sheets into final products. When working with a fiber laser, an operator has to be informed about the power re–quired to cut a specific type of material. How–ever, laser power and frequency are not the only key cutting para–meters that need to be properly adjusted. They are usually always set to their highest values to facilitate fast cutting. Cutting speed is a very important cutting parameter. Yet, other parameters, such as the focus distance from the sheet metal upper surface, the nozzle height, and the operating gas pressure, influence it. Therefore, those parameters must also be correctly set [13-16].

Cutting parameters required for optimized nitrogen use had the following values:

- focus f=-2,5 mm
- nozzle height h=0,55 mm

- operating nitrogen pressure p_1= *1,9 MPa*

Final reduction of the pressure Δp is calculated as:

$$\Delta p = \left(1-\frac{p_1}{p_0}\right)\cdot 100 = \left(1-\frac{1.9}{2.4}\right)\cdot 100 = 22.9\% \qquad (3)$$

where:

- Δp - the percentage of operating pressure reduc– tion, %
- p_0 - initial operating pressure, MPa
- p^1 - optimized operating pressure, MPa

The nozzle height *h*=0,55 mm was chosen as the optimal parameter since, at this height, the burr height is close to zero and does not cause any technological problems during cutting (frequent touching of the workpiece).

By optimizing the operating pressure of nitrogen both for constant and optimized cutting parameters, the operating pressure was reduced by 22,9%.

5. CONCLUSION

It was determined that the burr height *hs* depended on the cutting parameters. The burr height got lower when the value of the nozzle height h and the focus value f were reduced, i.e., when the focus value was theo– retically nearly ideal, which, in this case, was *hs=-3 mm*. The burr height *hs* decreased as the nitrogen pressure p increased. When selecting the condition at which the burr height *hs=0* mm and nitrogen pressure *p* was minimal, the parameters of focus f and nozzle height h resulted in a burr-free cut obtained at the lowest value of nitrogen pressure. Such selection confirmed that the mentioned three cutting parameters provided satisfactory cuts.

Although optimization of cutting requires more material, detailed measurement, and modeling, it provi– des better cutting results and final savings. When the operating gas pressure is higher than the optimal value, other cutting parameters do not have to be ideally set, yet the cutting shall still result in good cuts. In this experiment, when cutting stainless steel, instead of following an iterative procedure, the cutting parameters were optimized on cut and examined specimens. Within the described experiment performed on metal sheet specimens, measurements and modeling resulted in a reduction of operating gas pressure by 22.9%. It is possible to improve further this procedure applied to fiber laser cutting. Testing the cutting speed parameter for optimization of nitrogen consumption would potentially result in a determination of parameter values that facilitate faster and more cost-effective cutting of stainless steel with a fiber laser.

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NOMENCLATURE

h_s	measured burr height, mm
dmin	the minimum distance between the specimen's upper surfaces and the measured burr peak, mm
t	specimen thickness, mm
h_{sc}	calculated burr height, mm
f	focus, mm
p	operating nitrogen pressure, bar
Δp	the percentage of operating pressure reduction, %
p_0	initial operating pressure, MPa
p_1	optimized operating pressure, MPa

ОПТИМИЗАЦИЈА ЕФИКАСНОСТИ УПОТРЕБЕ АЗОТА У РЕЗАЊУ АУСТЕНИТНОГ НЕРЂАЈУЋЕГ ЧЕЛИКА ЛАСЕРОМ СА ВЛАКНИМА

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У металуршким процесима, сечење лимова је најчешће основна технолошка операција коју је потребно извршити. Све остале технолошке опера–ције одвијају се по поступку сечења лимова, са крај–њим циљем израде финалног производа. Машине које се користе за ту основну операцију сечења метала морају бити поуздане, ефикасне, брзе и релативно лаке за рад. Током рада са ласером, аутори су приметили неефикасност сечења азотом. Боце азота су се пребрзо испразниле, што је изаз–вало додатне трошкове. Неефикасна, односно прекомерна потрошња азота захтева чешће снаб–девање азотом.

Током пандемије ЦОВИД-19, азот није увек био доступан, пошто су се добављачи пребацили на производњу боца са кисеоником за медицинске потребе. Стога су се аутори ангажовали на проналажењу решења за смањење потрошње азота при сечењу. Поменути проблем је проучаван у оквиру експеримента који се фокусирао на оптимизацију употребе азота при ласерском резању влакана, чији су поступак и резултати описани у овом раду. Узорци различитих параметара сечења су припремљени и исечени да би се измерила њихова храпавост и висина ивица. Прикупљени подаци су коришћени за креирање математичког модела са АНОВА табелом. Експеримент је резултирао одре–ђивањем оптималних параметара резања постиг–нутих најнижим могућим притиском резног гаса.