Research Article/Araştırma Makalesi

GAZİ
JOURNAL OF ENGINEERING SCIENCES

Optimization of laser cutting parameters for improved surface quality in AISI 304 stainless steel

Engin Nas [*a], Sabri Uzuner[b]

Submitted: 18.10.2023 Revised: 13.12.2023 Accepted: 13.12.20223 doi:10.30855/gmbd.0705096

Keywords: Laser, Surface Roughness, Stainless Steel, Top-Bottom Kerf Width, Taguchi, Anova

[a,*] Dr. Engin PAK Cumayeri Vocational School of Higher Education, Duzce University, Turkey
Orcid: 0000-0002-4828-9240
e mail: enginnas@duzce.edu.tr

[b] Mechatronic Engineering, Duzce University, Turkey
Orcid: 0000-0002-9099-1324

[*]Corresponding author: enginnas@duzce.edu.tr

ABSTRACT

In this study, we performed experimental and statistical analysis on the cutting of AISI 304 stainless steel using a commonly utilized laser cutting machine. Three different gas pressures (5.1, 6.4 and 8 bar), three different cutting speeds (2048, 2560 and 3200 mm/min), fixed focal point (-4 mm), fixed frequency (5000 Hz) and fixed gas (Nitrogen) were used as cutting parameters. As a result of the study, it was observed that the surface roughness decreased as the cutting speed increased at all pressure values, and the surface roughness increased as the pressure increased at all cutting speed values. It was determined that the top and bottom kerf width decreased with increasing cutting speed and decreasing gas pressure, and the top and bottom kerf width increased with increasing gas pressure and decreasing cutting speed. When the signal/noise ratios were analyzed as a result of Taguchi analysis, the optimum cutting parameter was calculated as Level 1 (5.1 bar) for pressure and Level 3 (3200 mm/min) for cutting speed. When the variance results were analyzed, it was determined that the important parameter affecting the surface roughness from the pressure and cutting speed factors was determined as cutting speed with 70.74%.

AISI 304 Paslanmaz Çelikte Geliştirilmiş Yüzey Kalitesi için Lazer Kesim Parametrelerinin optimizasyonu

ÖZ

Bu çalışmada, yaygın olarak kullanılan bir lazer kesme makinesi kullanılarak AISI 304 paslanmaz çeliğin kesilmesi üzerine deneysel ve istatistiksel analizler gerçekleştirdik. Kesme parametreleri olarak üç farklı gaz basıncı (5,1, 6,4 ve 8 bar) , üç farklı kesme hızı (2048, 2560 ve 3200 mm/dk), sabit odak noktası (-4 mm), sabit frekans (5000 Hz) ve sabit gaz (Azot) kullanılmıştır. Yapılan çalışmanın sonucunda bütün basınç değerlerinde kesme hızı arttıkça yüzey pürüzlülük değerinin azaldığı, bütün kesme hızı değerlerinde basınç arttıkça yüzey pürüzlülük değerinin arttığı görülmüştür. Kesme hızının artması ve gaz basıncının azalması ile üst ve alt kerf genişliğinin azaldığı, gaz basıncının artması ve kesme hızının azalması ile üst ve alt kerf genişliğinin arttığı belirlenmiştir. Taguchi analizi sonucunda Sinyal/Gürültü oranları incelendiğinde optimum kesme parametresinin basınç için Seviye 1 (5,1 bar) ve kesme hızı için Seviye 3 (3200 mm/dk) olarak hesaplanmıştır. Varyans sonuçları incelendiğinde basınç ve kesme hızı faktörlerinden yüzey pürüzlülüğü değerine etki eden önemli parametrenin %70,74 ile kesme hızı olarak oluştuğu tespit edilmiştir.

Anahtar Kelimeler: Lazer, Yüzey pürüzlülüğü, Paslanmaz Çelik, Alt ve Üst Kerf genişliği,Taguchi, Anova

To cite this article: E. Nas and S. Uzuner, “Optimization of laser cutting parameters for improved surface quality in AISI 304 stainless steel,” *Gazi Journal of Engineering Sciences*, vol.9, no.3, pp. 654-662, 2023. doi:10.30855/gmbd.0705096

1. Introduction

Laser technology is one field that has shown significant developments in recent years with the developing technology and is widely used in the manufacturing sector. The laser cutting method is widely used in many areas of the manufacturing industry due to its ease of use, processing precision, low cost, surface quality of the produced part, high processing speed and minimal material waste [1]. This method has a wide range of applications, especially in military applications, machinery and electronics, aerospace, healthcare, and manufacturing industries [1, 2]. When the laser cutting method is analyzed in terms of engineering science, laser radiation affects an important area in welding, cutting, and drilling processes. One of the major advantages is the processing of brittle materials, non-conductive materials, and materials that are difficult to cut without contact [1]. During laser cutting, the workpiece is exposed to high temperatures. The cutting zones exposed to high temperatures show excessive thermal variations, resulting in deterioration of the surface quality of the workpiece [3]. The laser beam focused along the material's surface to be cut causes the material to melt, and a high-pressure gas is required to remove the molten material from the area. Meanwhile, a narrow kerf is formed in the cutting area [4]. The kerf width indicates the waste material removed from the workpiece and is always desired to be small. The kerf width is analyzed in two parts: top and bottom of kerf width. In addition, the lower kerf width has a smaller dimension than the upper kerf width. [5]. In laser cutting, many parameters such as focus, gas pressure, cutting speeds and frekans have a significant impact on the performance of the cutting process. Having more than one processing parameter is the goal of manufacturers in this sector to minimize productivity, part quality and production cost. These goals are achieved by correctly selecting the cutting parameters and at the most optimal values [6, 7].

In laser-cutting machines, the workpiece is cut from the sheet by moving the laser-cutting head on the sheet to the desired dimensions. A capacitive height control system ensures that the distance between the nozzle tip and the cut sheet remains constant. The distance in the Z-axis between the nozzle tip and the sheet metal is adjusted according to the material thickness. The quality of the surface cut can be influenced by raising the focal point just above or below the sheet surface [8]. In laser cutting, the power density must first be focused into a small spot for the laser light to cut the material. The focusing distance of the lens determines the size of the focal spot and the depth of focus for satisfactory cutting [9]. The focal ability of laser light was shown in Figure 1. "Z" refers to the depth of focus (Rayleigh length). Equation 1 shows the parameters that determine the focal spot size (df).

$$df = \frac{4\lambda}{\pi} . \frac{f}{D} . M^2 \quad (1)$$

Where "f" is the distance between the lens and the smallest focal spot, "D" is the unfocused raw laser beam diameter, "λ" is the laser beam wavelength, and “M^2” is the beam quality factor. The focal distance also depends on similar parameters, such as focal spot size. A small focal diameter is typically associated with a short focal distance [9].

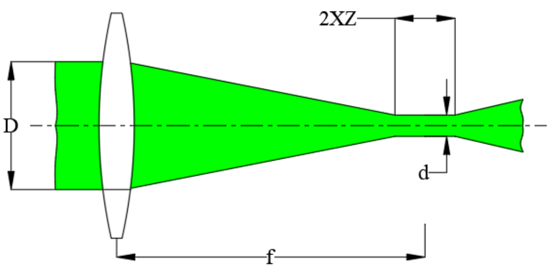


Figure 1. Focusing the laser light [9]

Extensive research has been conducted to investigate the effect of laser-cutting parameters on various output parameters to improve part quality in the laser-cutting process. Cebeci et al. focused on investigating the influence of cutting parameters on surface roughness, kerf width and burr height when laser cutting AISI 304 stainless steel sheets. Parameters such as gas pressure, cutting speed and frequency were investigated. The study revealed that higher cutting speed reduced surface roughness, kerf width, and burr height. In addition, varying the frequency affected these parameters differently, decreasing surface roughness and burr height but increasing kerf width [10]. In another study, Işık et al. conducted an experimental and statistical analysis of the effects of cutting parameters on surface roughness (Ra) and kerf width (kW) during laser cutting of St-37 material. They used a Taguchi L32 (2×4×4) orthogonal design to determine the cutting parameters, which included frequency, gas pressure, and cutting speed. Optimal values for surface roughness and kerf width were identified through data analysis. Analysis of variance highlighted that frequency and gas pressure were the most influential parameters, accounting for 55.78% and 54.26% of the effects, respectively [1]. Mert et al. investigated the effects of cutting parameters on the cutting process of AISI 304 stainless steel sheet material using CO2 laser machines. Parameters such as power, speed, focus distance, pressure, and using nitrogen (N2) as an assist gas were considered. The study concluded that "increasing pressure, decreasing cutting power, and decreasing feed rate resulted in a decrease in surface roughness [2].

The objective of this study was to investigate and optimize laser cutting parameters for cutting AISI 304 stainless steel sheet material, with a focus on achieving improved surface finish and minimizing kerf width. The results of the study may provide the most effective combination of parameters that would result in improved part quality, higher productivity, and cost efficiency in the manufacturing industry.

2. Material and Method

2.1. Material

Stainless steels are widely available materials, are easy to shape and weld, and have high corrosion resistance [11]. In this study, AISI 304 stainless steel material measuring 210 × 297 mm and having a thickness of 4 mm was employed. The chemical structure and mechanical properties of AISI 304 stainless steel are given in Table 1.

Table 1. Chemical structure and mechanical properties of AISI 304 stainless steel.

	C	Mn	Si	P	S	Cr	Ni	N	Fe
Wt%	0.055	1.38	0.56	0.024	0.02	18.4	8.2	0.04	Balance

2.2. Surface roughness measurements

Mahr brand (Mahr Marsurf PS 10), a surface roughness device widely used in the industry, was used to measure the surface quality of the cut surfaces. In surface roughness measurements, three different measurements were taken from the cut surfaces, and the average value was used as the surface roughness in experimental and statistical results.

2.3. Machinability experiments and optical images

Laser cutting experiments were carried out on a Gweike LF-4020GA fiber laser cutting machine, and kerf widths were measured with a polarized digital microscope model AM 4113ZT from Dino-Lite.

2.4. Experiment parameters

The machining parameters used in the experimental study were selected based on literature research and machine catalogues. Table 2 shows the selected editing parameters and their levels.

Table 2. Cutting process parameters and levels.

Laser cutting parameters	**Symbol**	**Levels**		
		Level 1	**Level 2**	**Level3**
Gas pressure (Bar)	A	5.1	6.4	8
Cutting speed (mm/min)	B	2048	2560	3200
Focus (mm)	C		-4	
Frequency (Hz)	D		5000	
Nozzle height (mm)	E		0.4	
Gas	F		Nitrogen	

3. Results and Discussion

3.1. Surface roughness and kerf width measurements

The results obtained through the preferred experimental setup were shown in Table 3. How the parameters affect the results is evaluated by comparing the results with each other.

Table 3. Results obtained from the experimental study

Experiment no	Focus (mm)	Nozzle height (mm)	Gas	Frequency (Hz)	Pressure (Bar)	Cutting speed (mm/min)	Ra (µm)	Kerf width (mm)	
								Top	Bottom
1	-4.0	0.4	Nitrogen	5000	5.1	2048	3.118	0.567	0.357
2					5.1	2560	2.639	0.564	0.352
3					5.1	3200	2.450	0.549	0.347
4					6.4	2048	3.126	0.580	0.373
5					6.4	2560	2.847	0.573	0.358
6					6.4	3200	2.748	0.559	0.355
7					8.0	2048	3.827	0.584	0.379
8					8.0	2560	3.675	0.578	0.366
9					8.0	3200	3.655	0.576	0.363

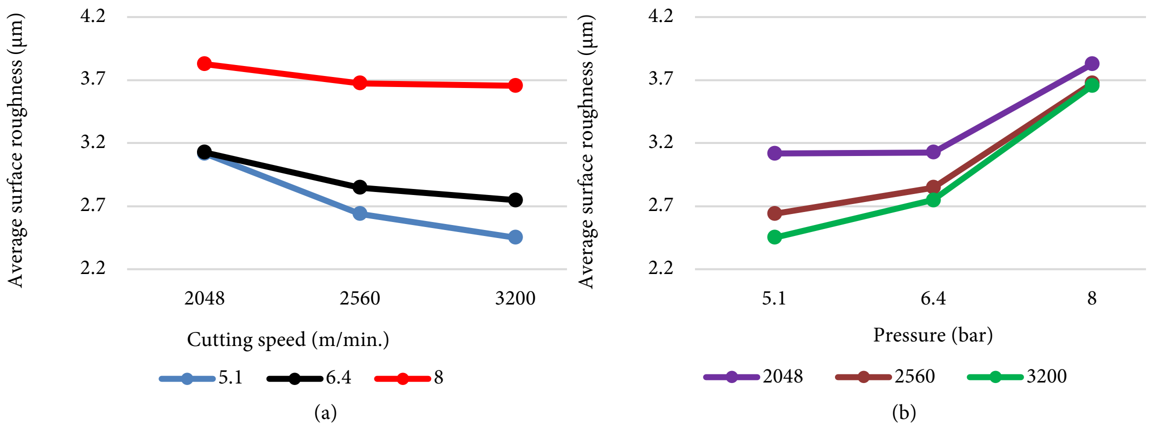


Figure 2. Graph of surface roughness depending on (a) cutting speed and (b) pressure.

Increasing the cutting speed decreased the average surface roughness (Figure 2a) while increasing the gas pressure increased the surface roughness (Figure 2b). The lowest surface roughness was measured as 2.450 µm at 3200 m/min cutting speed and 5.1 bar pressure, and the highest surface roughness was measured as 3.827 µm at 2048 m/min cutting speed and 8 bar pressure. The decrease in Ra with increasing cutting speed may be because the low cutting speed during the laser cutting process increases the heat generated in the cutting zone. This causes an increase in the amount of melt in the cut area. Moreover, removing residual melt using gas can increase the amount, thickness, and irregularity of the pattern formed on the surface. This, in turn, leads to heightened surface roughness [12].

Measurements were taken from the cut test material's top and bottom surfaces around the cut's entrance, middle and end using an optical microscope. The average value of these measurements was determined as the material's top and bottom kerf width. The optical image of the top of the cut test materials was shown in Figure 3.

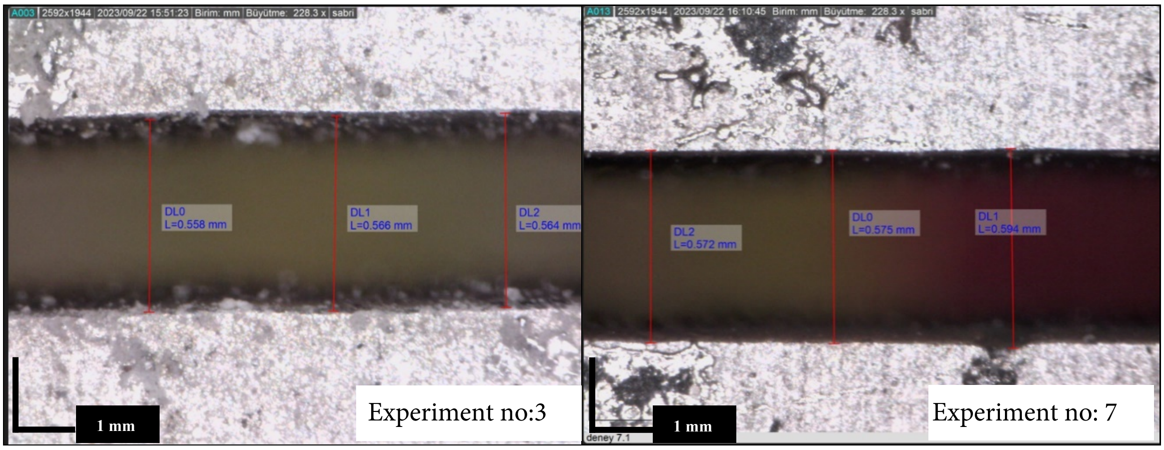
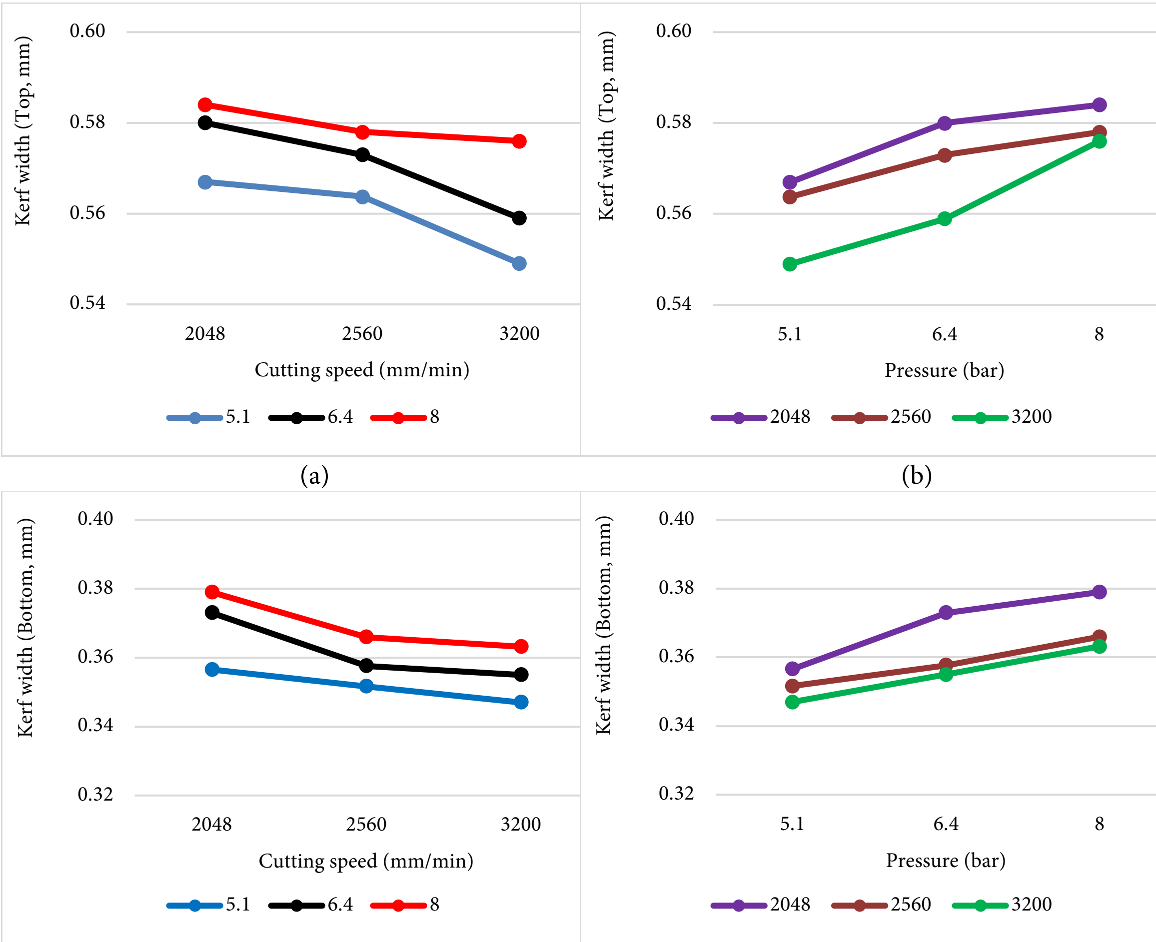


Figure 3. Optical image of the top of the cut experimental materials.

The results have been graphed and shown in Figure 4 for the convenience of the readers.



(c) (d)

Figure 4. Kerf widths: (a) and (b) top kerf widths, (c) and (d) bottom kerf widths depending on cutting speed and pressure, respectively.

The analysis showed that as the cutting speed increased and the gas pressure decreased, both the top and bottom kerf widths decreased. Conversely, decreased cutting speed and increased gas pressure resulted in an increase in both the top and bottom kerf widths (Figure 4). The minimum upper kerf width measured was 0.549 mm, observed at a cutting speed of 3200 mm/min and a pressure of 5.1 bar. Conversely, the maximum upper kerf width recorded was 0.584 mm at a cutting speed of 2048 mm/min and a pressure of 8 bar. Additionally, the narrowest total kerf width measured was 0.347 mm at a pressure of 5.1 bar and 3200 mm/min cutting speed. Notably, the bottom kerf width remained consistently smaller than the top kerf width throughout the study. This phenomenon can be attributed to the adequate interaction time between the laser beam and the material surface. During this interaction, the metal that melted and passed through the material thickness at the cutting zone was effectively removed without solidifying at the bottom due to the high gas pressure assistance [12, 13].

The burr formation on the bottom kerf of the test specimens at the lowest and highest surface roughness were examined, and their photographs were shown in Figure 4.

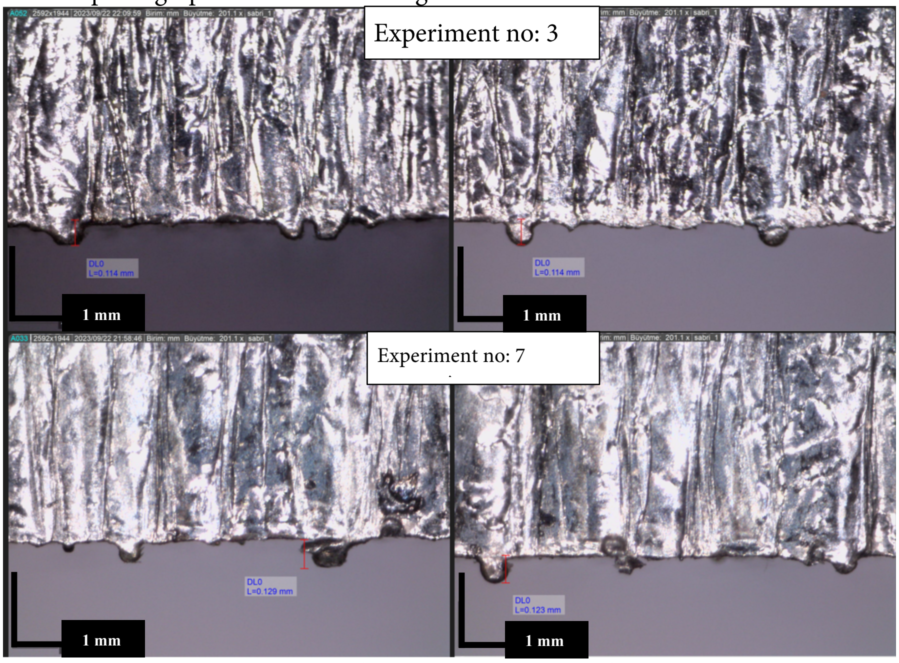


Figure 5. Burr formations in the bottom kerf width

The burr width at the bottom of the material with the lowest surface roughness was 0.114 mm in the mean, while the burr width at the highest surface roughness was approximately 0.125 mm in the mean (Figure 5). These results show that the preferred cutting parameters contribute to the burr formation.
The lower parts of the cut materials were examined, and the surface heat formations at the bottom of the part were shown in Figure 6. When the heat distribution on the material was examined, it was 0.227 mm in mean at 5.1 bar and 3200 mm/min cutting speed, while 0.258 mm was measured in the experiment performed at 8 bar pressure and 3200 mm/min cutting speed. The heat distribution width also increased when the pressure and cutting speed increased.

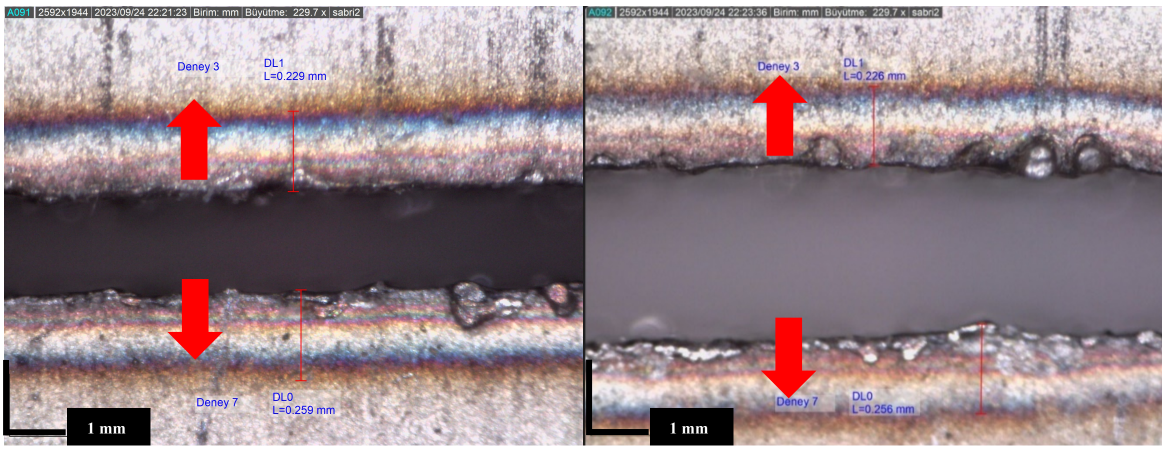


Figure 6. Heat distribution patterns at the bottom of the cut materials (HAZ: Heat Affected Zone) [14]

3.2. Taguchi method

The Taguchi method, widely used today, was used to determine the ideal optimum conditions by statistically analyzing the data obtained from the experiments. This method was very effective in determining the optimum cutting parameters without performing experiments on the same type of material at different machining parameters by analyzing the existing data [15-17]. Analyses using signal/noise ratios were also considered in determining the optimal cutting parameters. To obtain the lowest surface roughness, the "Smallest is Best" approach given in Equation 1 was chosen. The signal/noise analysis of the obtained results was shown in 4.

$$S/_N = -10log\frac{1}{n}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (1)$$

Table 4. Signal/noise values of samples cut by laser cutting method.

Level	Pressure (Bar)	Cutting speed (mm/min)
1	-8.697	-10.478
2	-9.256	-9.607
3	-11.407	-9.274
Delta	2.710	1.204
Rank	1	2

The value closest to zero in the signal/noise tables indicates the ideal value for that factor [18]. The optimum value for pressure was realized at Level 1, and the optimum value for cutting speed was realized at Level 3 (Figure 6 and Table). It was also observed that the optimum parameters were 5.1 bar for pressure and 3200 mm/min for cutting speed. These results show that the ideal cutting process is realized at these parameters. The similarity of the statistical and experimental results obtained increases the accuracy of our argument.

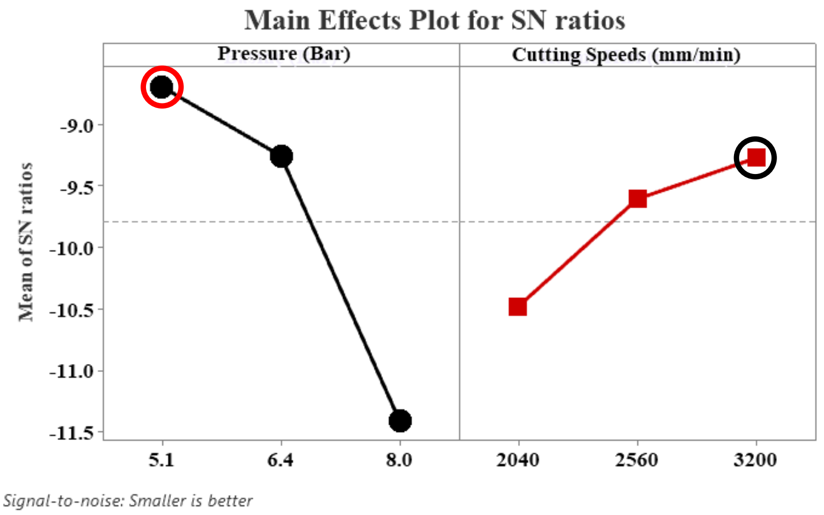


Figure 7. Signal/noise ratios for pressure and cutting speed.

3.3. ANOVA

ANOVA statistical method is used to determine the percentage of impact of the parameters on the results [19]. The variance analysis in the present study was performed at a 95% confidence level. The % effect values in Table indicate the degree of effect of the parameters on the results. The less than 5% P-value indicates that the parameter is significant [20]. The most effective parameter influencing the surface roughness among the pressure and cutting speed factors was the cutting speed at 70.74% (Table 5).

Table 5. ANOVA results

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Pressure (Bar)	2	0.008278	12.35%	0.008278	0.004139	1.46	0.334
Cutting speed (mm/dak)	2	0.047429	70.74%	0.047429	0.023714	8.36	0.037
Error	4	0.011341	16.91%	0.011341	0.002835		
Total	8	0.067048	100.00%				
R-sq				83.09%			

3.4. Regression analysis

The above-mentioned experimental procedures must be repeated for each set of parameters to predict the different results that may occur at different processing parameters of the material used in the experimental study [21]. This may result in high labour, time, energy, and material costs. Regression analysis provides an ideal mathematical model using enough available data. The ideal mathematical model obtained for this study was shown in Equation 2. In the present study, the R2 value, which expresses the mathematical model consistency, was calculated as 88.01%. Since the R2 value is above 85%, the results of different machining parameters can be predicted without performing new experiments.

$$Surface\ Roughness\ (\mu m) = 1.766 + 0.3455\ Pressure - 0.000343\ Cutting\ speed \quad (2)$$

4. Conclusion

The cutting process of AISI 304 stainless steel material was carried out at different parameters with a laser cutting machine widely used in industry, and the significant outcomes in the present study were summarized below.

- The lowest surface roughness was 2.450 µm at 3200 m/min cutting speed, and 5.1 bar pressure, and the highest surface roughness was 3.827 µm at 2048 m/min cutting speed and 8 bar pressure.
- The lowest top kerf width was 0.549 mm at 3200 mm/min cutting speed and 5.1 bar pressure, and the highest top kerf width was 0.584 mm at 2048 mm/min cutting speed and 8 bar pressure.
- The lowest kerf width was realized in the lower kerf width with 0.347 mm at 5.1 pressure and 3200 mm/min cutting speed.
- When the heat diffusion on the material was examined, a mean of 0.227 mm was measured at 5.1 bar and 3200 mm/min cutting speed, while a mean of 0.258 mm was measured in the experiment performed at 8 bar pressure and 3200 mm/min cutting speed.
- When the pressure and cutting speed increased, the heat release width increased.
- When the signal/noise ratios were analyzed, it was calculated that the optimum parameter was Level 1 (5.1 bar) for pressure and Level 3 (3200 mm/min) for cutting speed.
- When the variance results were analyzed, it was determined that the most significant parameter affecting the surface roughness among the pressure and cutting speed factors was the cutting speed with 70.74%.

Conflict of Interest Statement

No conflict of interest was declared by the authors.

References

[1] R. Işık,B. Özlü, and H. Demir, "Experimental and statistical investigation of the effect of the parameters selected in cutting process with laser St-37 material," *Firat University Journal of Engineering*, vol. 33, no. 1, pp. 161-171, October 2021, doi: 10.35234/fumbd.769716

[2] F. Mert, M. Tunç, and G. Sur, "*AISI 304 Çeliğinin lazer ile kesilmesinde kesme parametrelerinin yüzey pürüzlülüğüne etkisinin incelenmesi*," in 5th International Symposium on Innovative Technologies in Engineering and Science 29-30 September 2017 (ISITES2017 Baku-Azerbaijan), 2017, pp. 190-198. https://isites.info/PastConferences/ISITES2017/

[3] A. Arif and B. S. Yilbas, "Thermal stress developed during the laser cutting process: consideration of different materials," *The International Journal of Advanced Manufacturing Technology*, vol. 37, pp. 698-704, June 2008, doi: 10.1007/s00170-007-1020-1

[4] K. Nyon, C. Nyeoh, M. Mokhtar, and R. Abdul-Rahman, "Finite element analysis of laser inert gas cutting on Inconel 718," *The International Journal of Advanced Manufacturing Technology*, vol. 60, pp. 995-1007, June 2012, doi: 10.1007/s00170-011-3655-1

[5] C. Wandera, "Laser cutting of austenitic stainless steel with a high quality laser beam," Ms Thesis, Lappeenranta University Of Technology, Finland 2006.

[6] İ. Cebeci, Ö. Barış, and H. Demir, "Investigation the effect of cutting parameters on surface roughness, kerf width and dross height in laser processing of AISI 304 stainless sheet material," *Niğde Ömer Halisdemir University Journal of Engineering Sciences*, vol. 11, no. 2, pp. 410-415, April 2022, doi: 10.28948/ngmuh.764983

[7] M. Madic and M. Radovanovic, "Investigation into the effect of the cutting parameters on the burr height in CO2 laser nitrogen cutting of AISI 304 stainless steel," *Metalurgia International*, vol. 17, no. 7, p. 74, 2012.

[8] R. Yılmaz, "Optimum design of laser head carrier bridge system used in laser cutting machinery," Ms Thesis, Necmettin Erbakan University, Türkiye 2019.

[9] M. Ürgüplü and S. Köksal, "*The Effect of laser cutting process parameters on the quality of metalic componenets*," in 3rd International Symposium on Innovative Technologies in Engineering and Science, 2015, pp. 865-874. https://conferencealerts.com/show-event?id=144184

[10] İ. Cebeci, Ö. Barış, and H. Demir, "Investigation of the Effect of Cutting Parameters on Cutting Quality in Laser Cutting of AISI 310 Quality Austenitic Stainless Steel Sheet Material " *Journal of the Institute of Science Technology*, vol. 10, no. 4, pp. 2791-2799, December 2020, doi: 10.21597/jist.764067

[11] N. A. Özbek, A. Çiçek, M. Gülesin, and O. Özbek, "Evaluation of machinability of AISI 304 and AISI 316 austenitic stainless steels," *Journal of Polytechnic*, vol. 20, no. 1, pp. 43-49, May 2017, doi: 10.2339/2017.20.1 43-49

[12] A. Mustafa and F. Yücelişli, "Investigation of the effect on cutting quality of process parameters in fiber laser cuttingof Ti-6Al-4V Alloy " *Science and Eng. J of Fırat Univ.* , vol. 30, no. 2, pp. 215-223, September 2018.

[13] J. Powell, S. Al-Mashikhi, A. Kaplan, and K. Voisey, "Fibre laser cutting of thin section mild steel: An explanation of the ‘striation free’ effect," *Optics Lasers in Engineering*, vol. 49, no. 8, pp. 1069-1075,August 2011, doi: 10.1016/j.optlaseng.2011.03.011

[14] O. Özbek, "Effects of deep cryogenic treatment with different holding times on the mechanical properties of Al 7050-T7451 alloy friction stir welding," *Materials Testing*, vol. 65, no. 3, pp. 364-377, March 2023, doi: 10.1515/mt-2022-0277

[15] İ. Çiftçi and H. Gökçe, " Optimisation of cutting tool and cutting parameters in machining of molybdenum alloys through the Taguchi Method," *Journal of the Faculty of Engineering and Architecture of Gazi University*, vol. 34, no. 1, pp. 201-214, March 2019, doi: 10.17341/gazimmfd.416482

[16] H. Gökçe and M. Biberci, "Investigation of thrust force, drill bit temperature and burr height in the drilling of aluminum alloy used in ammunition wing drive systems," *Experimental Techniques*, vol. 46, no. 4, pp. 691-705, August 2022, doi: 10.1007/s40799-021-00501-0

[17] B. Özlü, "Investigation of the effect of cutting parameters on cutting force, surface roughness and chip shape in turning of Sleipner cold work tool steel," *Journal of the Faculty of Engineering Architecture of Gazi University*, vol. 36, no. 3, pp. 1241-1251, January 2021, doi: 10.17341/gazimmfd.668169

[18] N. A. Özbek, M. İ. Karadag, and O. Özbek, "Optimization of flank wear and surface roughness during turning of AISI 304 stainless steel using the Taguchi method," *Materials Testing*, vol. 62, no. 9, pp. 957-961, February 2020, doi: 10.3139/120.111571

[19] O. Tuncel and H. Aydın, "Optimization of Nd: YAG laser welding factors of cold rolled strenx 700 CR steel by taguchi method," *Cukurova University Journal of the Faculty of Engineering*, vol. 38, no. 1, pp. 85-92, March 2023, doi: 10.21605/cukurovaumfd.1273719

[20] Y. Harun and R. Atılkan, "Optimization of machining parameters in drillıing of nickel based superalloys wıth gray relational analysis and taguchi," *Kahramanmaras Sutcu Imam University Journal of Engineering Sciences*, vol. 26, no. 2, pp. 363-378, May 2023, doi: 10.17780/ksujes.1167745

[21] B. Özlü, "Experimental and statistical investigation of the effects of cutting parameters on kerf quality and surface roughness in laser cutting of Al 5083 alloy," *Surface Review Letters*, vol. 28, no. 10, p. 2150093, September 2021, doi: 10.1142/S0218625X21500931