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Modelling and Optimization of Burr Height in Fiber Laser Drilling of Ferritic Stainless Steel

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ABSTRACT

Laser drilling is the nontraditional machining methods that provides the machining of sheet metal parts with high precision and complex geometry. In laser drilling, the main parameters such as the focal point, gas pressure and feed rate directly affecting the cutting process play important role on the quality characteristics of the part. These parameters significantly influence the main machining outputs or responses such as burr formation and hole quality as well as the machining productivity. Thus, it is important to determine the ideal machining parameters during laser drilling, especially in terms of minimum burr formation. In this study, burr formation during laser drilling of ferritic stainless steel was analyzed in detail and mathematical model of burr height (Bh) was developed. Drilling operations were performed at three different focal point, gas pressure and feed rate. According to the experimental results, the smallest Bh value was obtained with focal point of -5, feed rate of 1200 mm/min and gas pressure of 12 bar. Based on analysis of variance, the most important parameter for burr height was found as the feed speed with 38.71%. The cutting parameters, statistically, were evaluated for the burr height. The R^2 value of Bh model obtained by response surface method indicated a robust relationship in high level between the machining parameters and response.

Ferritik Paslanmaz Çeliğin Fiber Lazerle Delinmesinde Çapak Yüksekliğinin Modellenmesi ve Optimizasyonu

MAKALE BİLGİSİ

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Çapak yüksekliği
Matematiksel model

ÖZET

Lazer delme, sac metal parçaların yüksek hassasiyet ve karmaşık geometri ile işlenmesini sağlayan geleneksel olmayan işleme yöntemidir. Lazer delmede, kesme işlemini doğrudan etkileyen odak noktası, gaz basıncı ve ilerleme hızı gibi ana parametreler parçanın kalite özellikleri üzerinde önemli bir rol oynamaktadır. Bu parametreler, çapak oluşumu ve delik kalitesi gibi ana işleme çıktılarını veya tepkilerini ve işleme verimliliğini önemli ölçüde etkiler. Bu nedenle, özellikle minimum çapak oluşumu açısından uygun işleme parametrelerini belirlemek lazerle delme işleminde önemlidir. Bu çalışmada, ferritik paslanmaz çeliğin lazerle delinmesi sırasında çapak oluşumu ayrıntılı olarak analiz edilmiş ve çapak yüksekliğinin (Bh) matematiksel modeli geliştirilmiştir. Delme işlemleri üç farklı odak noktası, gaz basıncı ve ilerleme hızında gerçekleştirilmiştir. Deney sonuçlarına göre, en küçük Bh değeri -5 odak noktası, 1200 mm/dak ilerleme hızı ve 12 bar gaz basıncı ile elde edilmiştir. Varyans analizine göre, çapak yüksekliği için en önemli parametre % 38.71 ile ilerleme hızı bulunmuştur. Kesme parametreleri, çapak yüksekliği için istatistiksel olarak değerlendirilmiştir. Tepki yüzeyi metoduyla elde edilen Bh modelinin R^2 değeri, işleme parametreleri ve çıktı arasında yüksek düzeyde güçlü bir ilişki olduğunu göstermiştir.

1. INTRODUCTION (GİRİŞ)

Laser drilling is known one of the improved machining processes in the manufacturing fields due to their precision, low cost, and high speed of operation. Therefore, it is used in industrial area for produce small hole such as aerospace components [1]. In this method, a laser beam is used as a heat

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source and provides increasing temperature rapidly to the melting. Desired hole quality with highest accuracy can be obtained by controlling the laser machining parameters [2]. At the same time, there are many basic parameters that affect this situation such as laser type and power, cutting speed, assist gas type, gas pressure and workpiece material in laser drilling [3]. In addition to this, ferritic stainless steels are used in numerous industrial areas such as hot water tanks, kitchen utensils, architecture and decorative applications as well as food, automotive and chemical industries due to the good toughness, ductility and outstanding stress-corrosion cracking resistance according to austenitic stainless steels [4-5]. However, because of the low welding capacity of stainless steels, mechanical connections are required for the assembly of some parts made from these materials. In this case, it becomes inevitable to create holes with machining methods such as drill or laser drilling processes. In these processes, it is important to choose the machining parameters that affect the machining outputs such as surface quality, burr formation, dimensional accuracy. Aurich et al. stated that burr formation requires additional processing such as deburring and this increases processing costs [6]. At this point, optimization of the machining parameters is very important for the control of burr formation varying according to the machining method. In this context, some of the studies carried out to understand the effects of machining parameters in laser drilling are summarized below.

Pak and Moradi investigated the parameters of laser percussion drilling process of nickel-base superalloy Inconel 718 with thickness of 1 mm in the study. Laser power, laser pulse frequency and assist gas pressure has been selected as the laser drilling process parameters. They found that laser pulse frequency has a direct influence on the diameter of the entrance hole. Also, it has been understood that entrance, exit hole diameter and hole taper increases with increasing laser power [1]. Jarosz et al. studied effect of the cutting speed on heat-affected zone (HAZ) and surface roughness in laser cutting of AISI 316L stainless steel. It has been determined that cutting speed has a significant effect on surface roughness, width of the heat-affected zone and presence of macro irregularities, such as presence of dross, molten and burnt material [3]. Ozaki et al. examined cutting properties of SUS304 stainless steel by using AGF laser cutting 2. Laser power and cutting speed were varied in order to study the effect of these parameters on cutting properties. They found that when laser power was 2.0 kW, cutting speed could be increased up to 100 mm/s, and kerf width at specimen surface was 0.28 mm [7]. Kotadiya and Pandya optimized the laser power, cutting speed and gas pressure using response surface method (RSM) and analysis of variance (ANOVA) in laser cutting of stainless steel in terms of the surface roughness. They found that the most important parameter was laser power [8]. Wandera and Kujanpaa researched optimization of the fiber laser cutting parameters taking into account cutting speed, focal point and focal length. They indicated that dross-free cut edges with lower surface roughness and lower deviation could be obtained by decreasing cutting speed, using longer focal length, and with focal position located on the bottom workpiece surface. It has been determined that this dross-free cut edge, lower surface roughness and lower deviation were found at the 254 mm focal length, cutting speed of 1.0 m/min, and focal position located on the bottom workpiece surface [9]. Chatterjee et al., statistically examined the effects of parameters on hole surface quality in laser drilling. According to ANOVA, they have been found that important machining parameters are pressure and laser frequency [10]. Petru et al. studied influence of cutting parameters on heated-affected zone after laser cutting process. It has been stated that in case of using continuous CO_2 laser, the degree of thermal influence on the workpiece does not related to only feed rate, but also other parameters. They also indicated that suitable chosen parameters are provides good results in terms of the quality of cutting surface and the size of heat-affected zone [11]. Moradi and Golchin examined effects of process parameters on Inconel 718 workpiece using finite elements method (FEM) and statistical modelling optimization in fiber laser drilling operation. At the statistical analysis conducted, it has been found that the entrance and exit hole diameters, the hole taper angel, and the weight of mass removed from the hole increase, by an increase in each of the input variables (laser pulse frequency, laser power, laser focal plane position and duty cycle). They determined that good agreement between simulation and optimization results [12]. Satpute et al. investigated the effects of machining parameters on hole inlet-exit circularity and HAZ in laser drilling of 1.2 mm thick soft steel. They stated that both the inlet and exit circularities were significantly affected by laser power and gas pressure. Also, it has been determined that HAZ is influenced by laser power and scanning speed [13]. Yüce researched effects of the laser power, cutting speed and focal length on surface roughness and kerf width in fiber laser cutting of AISI 304 stainless steel. He optimized the process parameters using RSM. It has been determined that focal length has an important effect on surface roughness and kerf width [14].

It is determined from the literature studies that there is no research on the laser drilling of ferritic stainless steels. On the other hand, in the manufacturing industry, the removal of burrs that emerge from after machined part can be caused negative consequences in terms of both cost and time. Also, it can be caused deformation for precision parts. Therefore, it is necessary to analyze the effect of drilling parameters on the burr formation. In this study, the effects of laser machining parameters in fiber laser drilling of the AISI 430 ferritic stainless steel was investigated as experimentally and statistically. Three different gas pressure, focal point and feed speed were used in the experiments. Effects of the machining parameters on burr height were evaluated by analysis of variance (ANOVA) in laser drilling of the stainless steel. Also, a mathematical model was developed for the burr height by means of experimental data.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

AISI 430 ferritic stainless steel has been used as workpiece material with thickness of 5 mm. Nitrogen gas has been selected in order to avoid carbon dioxide and vaporization in the beam path during fiber laser drilling. The chemical composition of the AISI 430 stainless steel material are shown in Table 1 [15].

Table 1. Chemical composition of the workpiece material (wt.%) (İş parçası malzemesinin kimyasal bileşimi)

C	Mn	P	S	Si	Cr	Ni
0.12	1.0	0.045	0.03	1.0	16.0-18.0	0.75

All laser drilling experiments were carried out in Nukon laser machine with 2.4 kW power. Machining parameters were chosen feed rate, gas pressure and focal point. Experiments were carried out with three different levels of machining parameters selected according to the recommendations of the laser machine manufacturer and the data obtained from the literature (Table 2). According to Taguchi L_{27} orthogonal array, 27 holes have been obtained in fiber laser drilling operations. Design of experiments and statistical analysis have been performed by using MINITAB software. The experiments were repeated twice and evaluations were made by taking the arithmetic average of the burr height. The burr heights formed at the hole exit were measured with a micro camera as named CLEMEX. A mathematical model was developed for predicting the burr height via response surface method (RSM). Investigation procedure is shown in Figure 1 with sample burr height and drilled part.

Table 2. Parameters and levels (Parametreler ve seviyeleri)

Parameter	Level 1	Level 2	Level 3
Focal point (*Fp*, mm)	-5	-4	-3
Feed rate (*f*, mm/min)	1200	1600	2000
Gas pressure (*P*, bar)	12	15	18

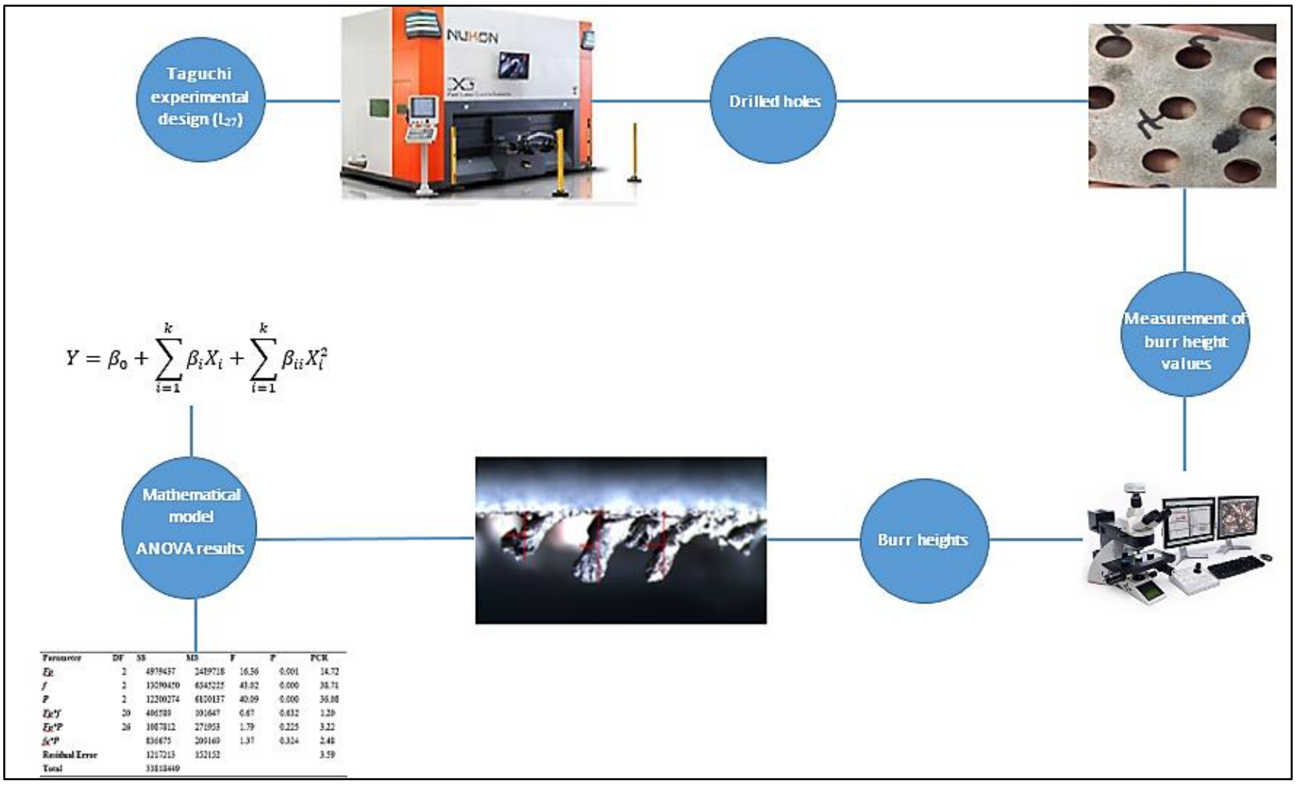

Figure 1. Investigation procedure (Araştırma prosedürü)

3. EXPERIMENTAL AND STATISTICAL RESULTS (DENEYSEL VE İSTATİSTİKSEL SONUÇLAR)

3.1. Evaluation of Burr Height (Çapak Yüksekliğinin Değerlendirilmesi)

Another important machining output that should be focused in the drilling process is the formation of burr. The burr height is influenced by many conditions such as on the machining parameters, material type and laser type. Understanding of burr formation is quite difficult in the laser drilling. Because the molten material formed in the laser drilling process cannot be totally eliminated, after resolidification at the entry, side wall and/or exit of the hole, it creates splash, recast-layer and burr, respectively. However, burr formation depending on machining parameters can be controlled and minimized. Also, it is very important to obtain the needed product quality by using controllable machining parameters within the framework of sustainability. For this reason, burr height values of hole exit were measured after laser drilling experiments and the effect of machining parameters on burr formations were investigated. In Figure 2, the burr height values obtained within the scope of the study are given depending on the focal point (-5, -4 and -3 mm) and other machining parameters (pressure and feed rate).

First of all, nonuniform burr formation is observed around the hole exit for all machining conditions, for example as seen in Figure 1. This result can be attributed to the dynamic characteristics of the molten material quantity, which changes depending on the machining parameters. In the light of the obtained data, it is observed that the burr height grows with increasing feed rate at constant gas pressure. Also, it was determined that the burr height decreases with the increase of pressure at a constant feed rate. However, it was found that as the gas pressure continued to increase, the values of the burr height increases at constant feed rate. For this reason, it can be said that 15 bar gas pressure is the critical level for the burr height in laser drilling of the stainless steel (Figure 2). On the other hand, a mechanical force on the workpiece may occur due to high gas pressure in laser drilling. Thus, the molten material easily can remove. The decrease of the burr height can be attributed this situation. But, if the pressure go on to increase, the rising cooling speed can hinder the eject of the molten material. For this reason, values of the burr height may increase depend on the this situation [16]. In the present study, a result similar to the situation mentioned above was obtained, and it is seen that the burr height increases as the gas pressure increases from 15 bar to 18 bar (Figure 2).

As a result of the performed laser drilling operations, the lowest burr height was found as 504 µm at a feed speed of 1200 mm/min, focal point of -5 and gas pressure of 15 bar. The highest burr height was determined 4039 µm at a feed speed of 2000 mm/min, focal point of -3 and gas pressure of 18 bar. At constant focal point of -3 and gas pressure of 12 bar, it was calculated that with rise of the feed speed from 1200 to 1600 and from 1600 to 2000 mm/min, the burr height was increased 20.54% and 26.22%, respectively. When looking at the same conditions in terms of -4 focal point, the burr height increased by 11.57% and 12.94%, respectively; for the -5 focal point, increases of 20.84% and 12.85% were found, respectively. At constant focal point of -3 and gas pressure of 15 bar, it was calculated that with increase of the feed speed from 1200 to 1600 and from 1600 to 2000 mm/min, the burr height was increased 32.5% and 55.26%, respectively. When looking at the same conditions in terms of -4 focal point, the burr height increased by 88.90% and 134.72%, respectively; for the -5 focal point, increases of 35.12% and 145.52% were achieved, respectively. At constant focal point of -3 and gas pressure of 18 bar, it was calculated that with increase of the feed speed from 1200 to 1600 and from 1600 to 2000 mm/min, the burr height was increased 127.73% and 77.54%, respectively. When considering the same conditions for -4 focal point, the burr height increased by 68.12% and 60.60%; for the -5 focal point, increase of 538.68% and 129.98% were found, respectively. Consequently, the lowest burr height was obtained as 504 found as 504 µm at a feed speed of 1200 mm/min, focal point of -5 and gas pressure of 15 bar.

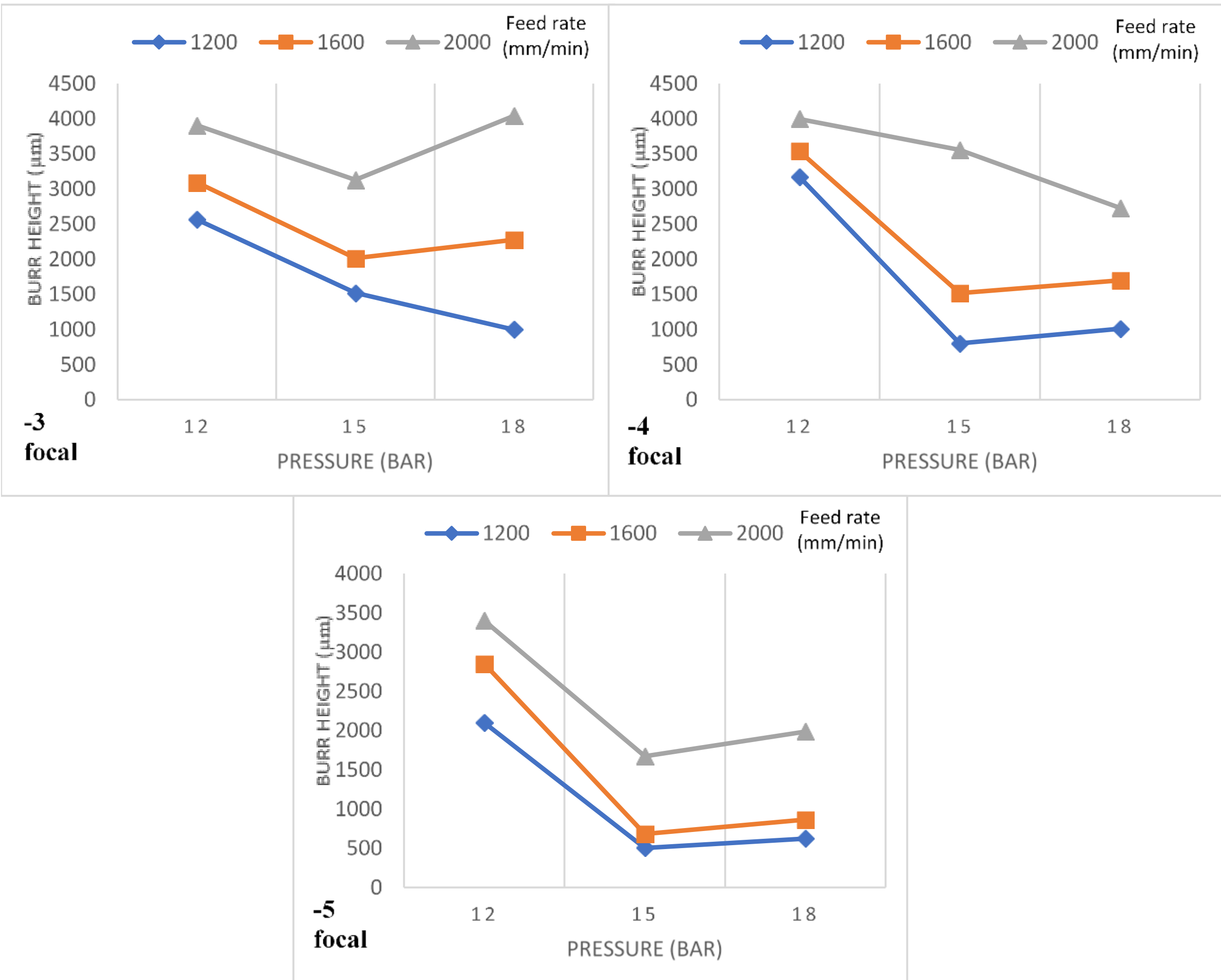

Figure 2. Change of burr height depending on machining parameters (İşleme parametrelerine bağlı çapak yükseklik değişimi)

The effects of machining parameters on the burr height was detected by analysis of variance (ANOVA). The ANOVA was carried out at 95% confidence level. If P value less than 0.05, the parameters are significance on the response. The results are shown in Table 3. When evaluate the ANOVA results, it was determined that the feed speed has the highest effect with a 38.71 % of PCR in laser drilling. In addition, the gas pressure, has another important effect with a 36.08% of PCR. Lastly, it has been seen that the focal point has effect on burr height with a 14.72% of PCR.

Table 3. ANOVA results for Bh (Çapak yüksekliği için ANOVA sonuçları)

Parameter	DF	SS	MS	F	P	PCR
Fp	2	4979437	2489718	16.36	0.001	14.72
f	2	13090450	6545225	43.02	0.000	38.71
P	2	12200274	6100137	40.09	0.000	36.08
*Fp*f*	20	406589	101647	0.67	0.632	1.20
*Fp*P*	26	1087812	271953	1.79	0.225	3.22
*f*P*		836675	209169	1.37	0.324	2.48
Error		1217213	152152			3.59
Total		33818449				

3.2. Response Surface Methodology Based Mathematical Modeling (Yanıt Yüzey Metodolojisi Tabanlı Matematiksel Modelleme)

Mathematical modeling can be constituted using different techniques for obtained an output parameter (response) in any field depending on numerous input parameters. By the way, response surface methodology (RSM) is a technique commonly used to develop mathematical model for predicting the response and understand the interactions between machining parameters and responses. Also, statistical analysis of output parameters with RSM is possible depending on the experimental results [17]. In this regard, the mathematical model of burr height was created by using RSM with the data gained during drilling of AISI 430 ferritic stainless steel. The mathematical model for the response was developed with the full quadratic regression model:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 \quad (1)$$

In Eq. (1), Y is the dependent variable, β_0 is constant regression coefficient, β_i and β_{ii} are regression coefficient, X_i is uncoded (real) values of independent variable and k is parameter number. Developed models based on the focal point (F_p), feed speed (f) and gas pressure (P) for burr height (B_h) is shown in Eq. (2).

$$Bh = 19482 - 3901Fp - 4.04f - 2837P - 323Fp^2 + 0.001613f^2 + 86.8P^2 + 0.448Fpf + 73FpP + 0.1845fP \quad (2)$$

The coefficients of determination (R^2) value was found to determine the quality of the mathematical model created using response surface methodology. In other words, it can be said that R^2 is define the relationship between the machining parameters and the responses. Comparison of the experimental and predicted results is shown in Figure 3 for burr height (Bh).

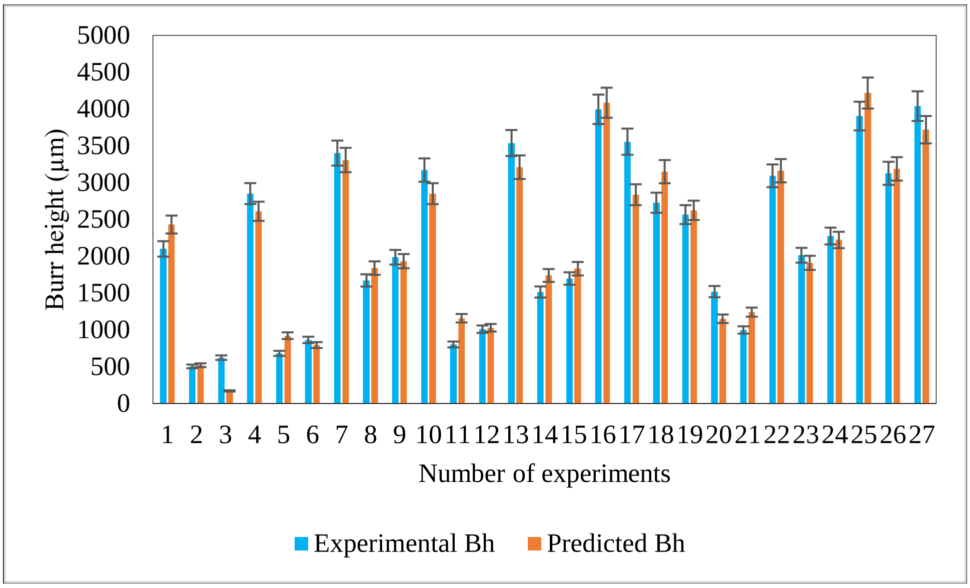

Figure 3. Comparison of the experimental and predicted results for Bh (Bh için deneysel ve tahmini sonuçların karşılaştırılması)

The coefficient of determination for predicting the burr height was found as 94.09%. The R^2 value and the error bars shown in Figure 3 indicated that the developed model is reliable and strong of the relationship between the machining parameters and response.

4. CONCLUSIONS (SONUÇLAR)

In this study, the effects of machining parameters in fiber laser drilling of the ferritic stainless steel was investigated and also a mathematical model was developed by response surface methodology for the burr height. The obtained results are listed below.

- It was obviously determined that the burr height values for each focal point are increased with the rise of feed speed at constant gas pressure.

- It has been determined that the height of the burr was decreased with the increase of the gas pressure from 12 bar to 15 bar at constant feed speed. But, in the second stage, it has been observed that the burr height was increased with the increase of the gas pressure 15 bar to 18 bar.

- The optimum machining parameters were found as feed speed of 1200 mm/min, focal point of -5 and gas pressure of 15 bar for minimize the burr height.

- Based on ANOVA results, it was determined that the most influence parameter for burr height was found feed speed with 38.71 of % PCR in laser drilling.

- The R^2 value of Bh model obtained by response surface method indicated a robust relationship in high level between the machining parameters and response.

REFERENCES (KAYNAKLAR)

1. A.M. Pak, M. Moradi, Hole geometry features analysis in fiber laser percussion drilling process, International Journal of Advances in Mechanical and Automobile Engineering, 2(1): 18-21, 2015.
2. B.S. Yilbas, Laser Drilling Practical Applications, Springer, Berlin, 2013.
3. K. Jarosz, P. Löschner, P. Nieslony, Effect of cutting speed surface quality and heat-affected zone in laser cutting of 316L stainless steel, International Conference on Manufacturing Engineering and Materials, 6-10 June 2016, NovýSmokovec.
4. M. Taskin, U. Caligulu, The effect on the joining of welding power on the laser welding of couple steels AISI 430/1010, Firat University Journal of Engineering Science, 21(1): 11-22, 2009.
5. N. Fujita, K. Ohmura, A. Yamamoto, Changes of microstructures and high temperature properties during high temperature service of Niobium added ferritic stainless steels. Material Science and Engineering A, 351(1-2): 272-281, 2003.

6. J.C. Aurich, D. Dornfeld, P.J. Arrazola, V. Franke, L. Leitz, S. Min., Burrs-Analysis, control and removal, CIRP Annals, 58(2): 519-542, 2009.
7. H. Ozaki, Y. Koike, H. Kawakami, J. Suzuki, Cutting properties of austenitic stainless steel by using laser cutting process without assist gas, Hindawi Publishing Corporation Advances in Optical Technologies, 1-8, 2012.
8. D.J. Kotodiya, D.H. Pandya, Parametric analysis of laser machining with response surface method on SS-304, Procedia Technology, 23:376-382, 2016.
9. C. Wandera, V. Kujanpaa Optimization of parameters for fibre laser cutting of a 10 mm stainless steel plate, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225:641-649, 2011.
10. S. Chatterjee, K. Abhishek, S.S. Mahapatra, Study on surface quality of laser drilled holes: parametric optimization using harmony search algorithm, International Journal of Materials, Mechanics and Manufacturing, 5(4): 251-254 2017.
11. J. Petru, T. Zlamal, R. Cep, K. Monkova, P. Monka, Influence of cutting parameters on heat-affected zone after laser cutting, Tehnicki Vjesnik, 20(2): 225-230, 2013.
12. M. Moradi, E. Golchin, Investigation on the effects of process parameters on laser percussion drilling using finite element methodology; statistical modelling and optimization, Latin American Journal of Solids and Structures, 14: 464-484, 2017.
13. Y.R. Satpute, K.H. Inamdar, An investigation of CO_2 laser drilling, Journal of Emerging Technologies and Innovative Research, 6(3): 124-128, 2016.
14. C. Yüce, Paslanmaz çelik malzemelerin fiber lazer kesiminde proses parametrelerinin optimizasyonu, Uludağ Üniversitesi Mühendislik Fakültesi Dergisi, 24(2): 685-696, 2019.
15. H. Uzun, Paslanmaz çeliğin fiber lazerle kesilmesinde işleme parametrelerinin optimizasyonu, Yüksek Lisans Tezi, Karabük Üniversitesi Fen Bilimleri Enstitüsü, Karabük, Türkiye, 2019.
16. W. Duan, K. Wang, X. Dong, X. Mei, W. Wang, Z. Fan, Experimental characterizations of burr deposition in Nd: YAG laser drilling: a parametric study, International Journal of Advanced Manufacturing Technology, 76:1529-1542, 2014.
17. R.H. Myers, D.C. Montgomery, C.M. Anderson-Cook, Response Surface Methodology: Process and Product Optimization Using Designed Experiments, 4th ed. John Wiley & Sons, Inc., New York, 2016.