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Multiple Optimization of Cutting Parameters Affecting Kerf Formation and Surface Roughness in Laser Cutting of Al 5052 Alloy

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Abstract: In cutting with laser, appropriate cutting parameters should be selected according to the material being cut. Incorrectly selected parameters affect the dimensional accuracy and surface quality of the cut sheets. In this study, 3 mm thick Al 5052 sheet was cut with laser cutting operation. Kerf formation and surface roughness of the cut sheets were investigated. In order to obtain optimum results with fewer experiments, L_{18} (2^1x3^2) experimental design was made with the Taguchi method. Azote gas was used during cutting. 9 and 12 bar gas pressure, 3000-4000-5000 mm/min cutting speed and 2500-3000-3500 W laser power were selected as cutting parameters. At the end of the experiments, the upper kerf width (KWT), lower kerf width (KWB), kerf taper (KT) and avarage surface roughness (Ra) were measured. Taguchi and multiple analysis were performed to determine the optimum parameters at minimum values. CS was the most effective parameter for KWB and KT. For KWT and Ra, the most effective parameter was P. At the end of the multiple optimizations, the ideal cutting parameters were found as GP 11,6667 bar, CS 4131,3131 mm/min and P 2500 W.

Keywords: Al 5052, laser cutting, kerf formation, surface roughness, Taguchi, multiple optimization

Al 5052 alaşımının Lazer Kesiminde Kerf Oluşumunu ve Yüzey Pürüzlülüğünü Etkileyen Kesme Parametrelerinin Çoklu Optimizasyonu

Öz: Lazer ile yapılan kesmelerde kesilen malzemeye göre uygun kesme parametreleri seçilmelidir. Yanlış seçilen parametreler, kesilen levhalarda ölçü tamlığını ve yüzey kalitesini olumsuz etkilemektedir. Bu çalışmada, 3 mm kalınlığındaki Al 5052 levha, lazer kesme operasyonu ile kesilmiştir. Kesilen levhalardaki kerf oluşumu ve yüzey pürüzlülüğü incelenmiştir. Daha az deney ile optimum sonuçları elde edebilmek için Taguchi metodu ile L_{18} (2^1x3^2) deney tasarımı yapılmıştır. Kesme esnasında azot gazı kullanılmıştır. Kesme parametreleri olarak 9 ve 12 bar gaz basıncı, 3000-4000-5000 mm/min kesme hızı ve 2500-3000-3500 W lazer gücü seçilmiştir. Deneyler sonunda üst kerf genişliği (KWT), alt kerf genişliği (KWB), kerf koniği (KT) ve yüzey pürüzlülüğü (Ra) ölçülmüştür. Minimum değerlerde optimum parametrelerin tespiti için Taguchi ve çoklu analiz yapılmıştır. KWB ve KT için en etkin parametre CS çıkmıştır. KWT ve Ra için ise en etkin parametre P olmuştur. Çoklu optimizasyon sonunda ideal kesme parametreleri GP 11,6667 bar, CS 4131,3131 mm/min and P 2500 W olarak bulunmuştur.

Anahtar Kelimeler: Al 5052, lazer kesim, kerf oluşumu, yüzey pürüzlülüğü, Taguchi, çoklu optimizasyon

1. Introduction

Cutting sheet metals with a laser beam provides many advantages. Laser cutting is fast and cost-effective [1]. In order to obtain the most suitable surface with minimum electrical energy, it is necessary to determine the appropriate cutting parameters [2].

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Laser cutting is one of the unconventional cutting processes used for cutting almost all material classes such as metal, nonmetal, ceramic and composite. Laser cutting is widely used in the production of shapes and different geometries, especially with narrow kerf widths. In other words, laser beam cutting, which is a non-contact process, does not involve any mechanical cutting force and tool wear. Laser beam cutting is a thermal energy-based cutting process carried out by moving a focused laser beam over the surface of the workpiece at an appropriate scanning speed [3,4].

Aluminum alloys are one of the most used materials in the world after steel, due to their superior properties such as high weldability, very good corrosion resistance, high fatigue strength, and cold forming in the form of soft temper [5-8].

Laser cutting is a thermal based process and the number of process parameters used is high. Therefore, the control of the laser cutting process becomes difficult. With this aspect, the study will shed light on the companies working in this sector. In the laser cutting process, the cutting parameters have a great influence on the product. Kerf formation and surface roughness are seriously affected by these parameters. For this reason, the most suitable cutting parameters should be determined according to the material to be cut. In the researches, many studies were found in which the kerf formation and surface roughness in the laser cutting process were examined. Various optimization methods have been used to determine the most suitable cutting parameters [9-11] In recent studies, multiple optimization methods are frequently used. In experiments with more than one output, multiple optimization is used to optimize them all at the same time [12,13].

In the study by Işık et al. [14], the surface roughness and kerf formation obtained after laser cutting of St-37 material were investigated. Cutting frequency, gas pressure and cutting speed consisting of different levels were selected as cutting parameters. They designed their experiments with the Taguchi method and analyzed the results again with Taguchi and ANAVO. Joshi and Sharma [15] investigated the kerf formation and heat affected zones in the laser cutting process of aluminum alloy. They analyzed the cutting parameters with gray relational analysis and fuzzy methods. Parameters such as current, pulse width, pulse frequency and cutting speed were selected as cutting parameters. At the end of the analysis, the pulse frequency was found as the most effective cutting parameter. Sharifi and Akbari [16] subjected the Al 6061-T6 alloy to laser cutting in their work. They choose the cutting speed, power of laser, thickness of plate and distance of nozzle as cutting factors. At the end of the experiments, the cutting edge and cutting zone temperatures were investigated. They found that the most effective parameters were laser power and sheet thickness.

In this study, experimental design was made with the Taguchi method. Other optimization techniques are available than the Taguchi method. As it is known, optimization techniques have advantages and disadvantages over each other. This study has not been done by comparing optimization techniques with each other. It is possible to obtain optimum values with less experimentation using the Taguchi method. This saves both time and cost. Al 5052 alloy was cut with laser process according to this Taguchi experimental design. Gas pressure (GP), cutting speed (CS) and power (P) were selected as cutting parameters. As output, kerf width of top (KWT), kerf width of bottom (KWB), kerf taper (KT) and average surface roughness (Ra) were measured. The cutting parameters were optimized for the smallest values of the measured outputs.

In the literature review, it was determined that there were not many studies on kerf formation and surface roughness in laser cutting of Al 5052 alloy. For this reason, Al 5052 material was preferred and cutting parameters were optimized in laser cutting. In laser cutting of Al 5052 sheets, optimum levels of process parameters that provide the lowest surface quality and dimensional accuracy were determined.

2. Experimental Methods

2.1. Taguchi Methods

Along with the developing technology, many industrial products have also undergone changes and developments. For the development of products in the manufacturing sector, the cutting parameters must be chosen appropriately during the machining phase. There are many parameters that affect machining. It is necessary to experiment at different levels of each parameter. This significantly increases both the processing time and the cost. For this reason, optimization of cutting parameters is made. Thanks to this method, it is possible to obtain the most accurate result with less experimentation. Taguchi method is also an important optimization method.

Process parameters have been chosen based on the operator experience and advice of the software in the laser machine. It is aimed to determine the optimum levels of the recommended process parameters for Al 5052.

The experiment list was created in the Taguchi method with the determined parameters and levels. In this method using the L_{18} array, the most appropriate experiment was determined. Taguchi calculates the signal/noise (S/N) ratios of the obtained measurements and allows us to analyze according to these values. Since the outputs are desired to be small, the smaller is better S/N calculation method is used [17-19]. The control factors and levels are given in Table 1.

$$\text{Smaller is better: } \frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

Table 1. Cutting parameters and levels.

Laser Cutting Parameters	Unit	Level 1	Level 2	Level 3
Gas Pressure (GP)	bar	9	12	-
Cutting Speed (CS)	mm/min	3000	4000	5000
Power (P)	W	2500	3000	3500

2.2. Materials and Experimental Setup

Al 5052 alloy, which is used in many areas, was used for the experiments. Al 5052 alloys are frequently used in nuclear applications, ship and boat construction, chemical and food industry, architectural applications, pressure and boiling vessels, vehicle bodies, tanker and casing, pipes and rods (in hydraulic construction), office equipment and machine parts.

The chemical content of the Al 5052 alloy used in laser cutting experiments is given in Table 2.

Table 2. Chemical composition of Al 5052 alloy.

Element	Fe	Si	Mn	Cr	Cu	Mg	Zn	Al
% Max.	0,4	0,25	0,1	0,35	0,1	2,8	0,1	Balance

Sheets measuring 200x280x3 mm were used in the experiments. According to Taguchi L_{18} experimental design, 18 cuts were made on the sheet at 80 mm cutting length. Workpiece dimensions, kerf width of top and kerf width of bottom formation are given in figure 1.

The cutting of the Al 5052 plate was cut on the CNC laser cutting machine under azote gas. Experiments were repeated 3 times and averaged. The cuts were made with a 2 mm diameter nozzle. At the end of the cuts, the kerf width of top, kerf width of bottom and surface roughness were measured.

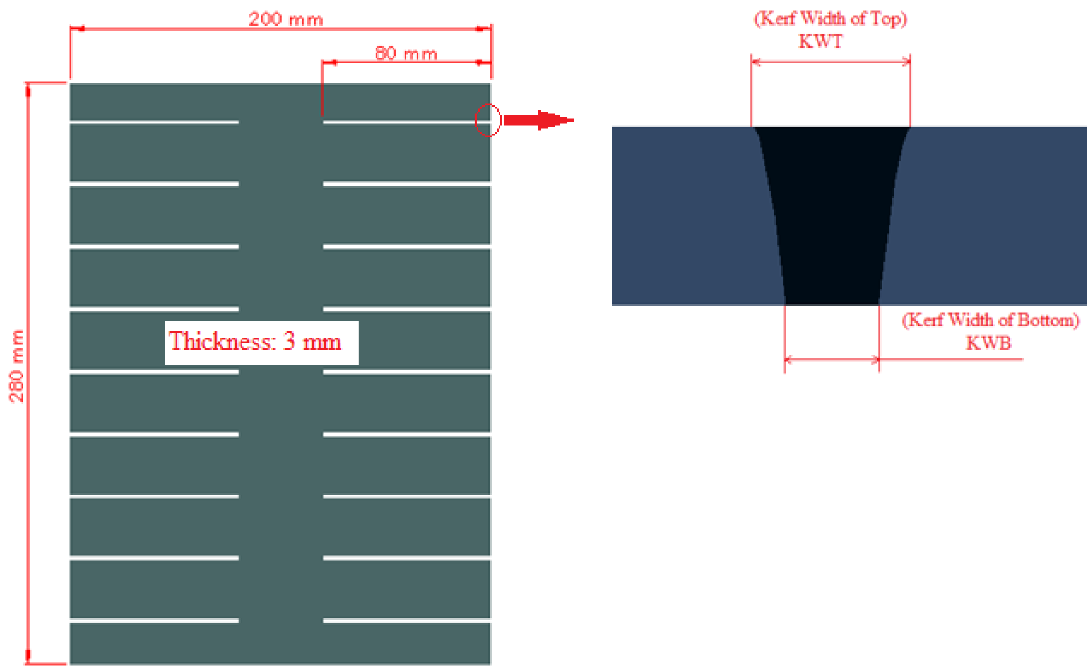

Figure 1. Workpiece dimensions, kerf width of top and kerf width of bottom

Kerf width measurements were made by taking images with the Dino-Lite Digital Microscope. The images taken from the microscope were transferred to the AutoCAD program and dimensioned on the image. For the kerf width of top and kerf width of bottom, measurements were taken from three different points at 80 mm cutting length and average values were written. After determining the kerf width of top and kerf width of bottom, the kerf taper was calculated according to equation 2. Surface roughness values were measured with Mitutoyo SJ-210 device. Roughness values were also measured from three different regions and perpendicular to the cutting direction. Averages of surface roughness values were written.

$$KT= [(KWT-KWB)180] / (2\pi t) \tag{2}$$

3. Results and Discussion

In Table 3, the list of Taguchi L_{18} design is given. KWT, KWB, KT and Ra values are also given in Table 3. KWT and KWB were measured in mm, surface roughness was measured in microns. The unit of KT was taken as degree. In the kerf measurements, it is seen that the kerf width increases towards the end. It is due to the heat increase in the material. Kerf widths were averaged [20].

In Figure 2, the KWT, KWB, KT and Ra values obtained as a result of the experiments are presented with combined graph. Looking carefully at Table 2, the smallest kerf taper appears to be in Experiment 7, with the smallest Ra value in Experiment 18.

3.1. Taguchi Results

In this section, the KWT, KWB, KT and Ra values were obtained. Experiments results were analyzed by Taguchi and multiply analysis. Before starting the analysis, the distribution of the test results was examined in the normal distribution. The normality test value must be P≥0,05 [21]. In

Figure 3, the distributions of test result and P values obtained according to the normality test are seen as graphs.

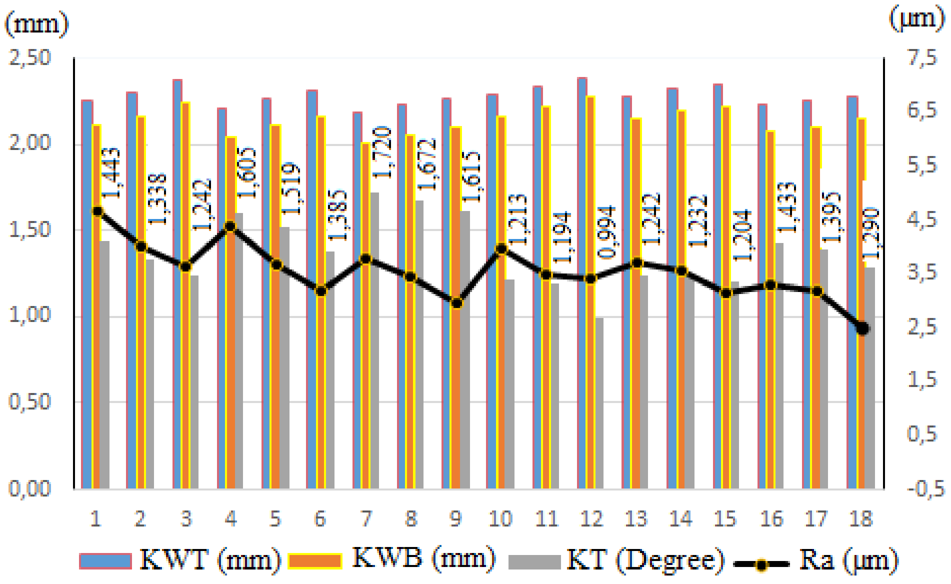

Figure 2. Combined graph of KWT, KWB, KT and Ra

Table 3. The list of Taguchi L_{18} design and. KWT, KWB, KT and Ra values.

Experiment Number	GP (bar)	CS (mm/min)	P (W)	KWT (mm)	KWB (mm)	KT (degree)	Ra (µm)
1	9	3000	2500	2,26	2,11	1,443	4,681
2	9	3000	3000	2,30	2,16	1,338	4,013
3	9	3000	3500	2,37	2,24	1,242	3,642
4	9	4000	2500	2,21	2,04	1,605	4,384
5	9	4000	3000	2,27	2,11	1,519	3,671
6	9	4000	3500	2,31	2,17	1,385	3,191
7	9	5000	2500	2,19	2,01	1,720	3,8
8	9	5000	3000	2,23	2,06	1,672	3,447
9	9	5000	3500	2,27	2,10	1,615	2,944
10	12	3000	2500	2,29	2,16	1,213	3,972
11	12	3000	3000	2,34	2,21	1,194	3,494
12	12	3000	3500	2,38	2,28	0,994	3,405
13	12	4000	2500	2,28	2,15	1,242	3,718
14	12	4000	3000	2,33	2,20	1,232	3,567
15	12	4000	3500	2,35	2,22	1,204	3,153
16	12	5000	2500	2,23	2,08	1,433	3,29
17	12	5000	3000	2,25	2,10	1,395	3,186
18	12	5000	3500	2,28	2,15	1,290	2,515

All outputs were greater than 0,05. After performing the normality test, Taguchi and multiply analysis were carried out.

KWT, KWB, KT and Ra values should be small in terms of surface quality and dimensional accuracy while laser cutting operation. For this reason, the smaller is better option was selected when performing the Taguchi analysis.

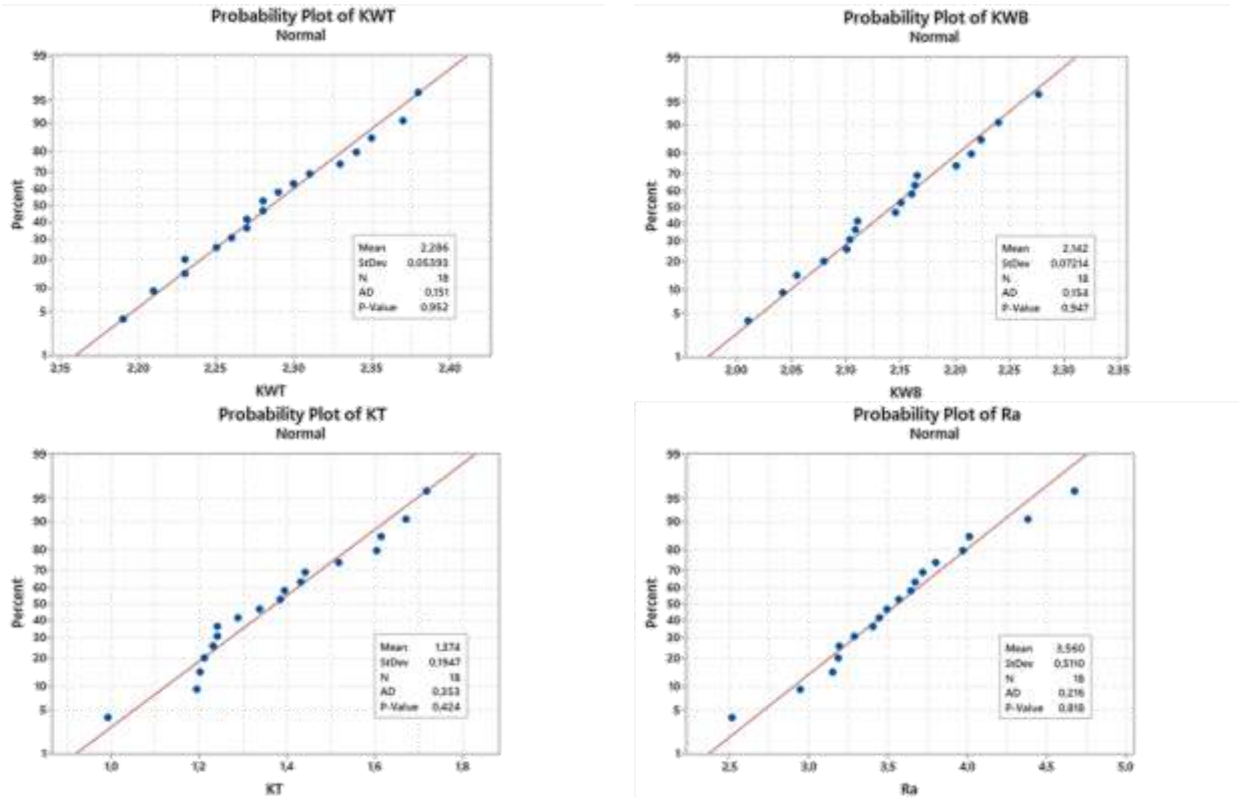

Figure 3. Normality tests for the analysis of KWT, KWB, KT and Ra

In this method, S/N ratios were created. These ratios were used for the analysis of the experimental results. The S/N ratios of KWT, KWB, KT and Ra are seen in Table 4. The highest ratios for S/N ratios were obtained as -6,80888 for KWT, -6,06392 for KWB, 0,05550 for KT and -8,0108 for Ra.

Table 4. S/N ratios for KWT, KWB, KT and Ra.

Experiment Number	S/N (dB)			
	KWT	KWB	KT	Ra
1	-7,08217	-6,48153	-3,18337	-13,4068
2	-7,23456	-6,68908	-2,52639	-12,0694
3	-7,49497	-7,00496	-1,88270	-11,2268
4	-6,88785	-6,20111	-4,11002	-12,8374
5	-7,12052	-6,48976	-3,63177	-11,2957
6	-7,27224	-6,70916	-2,83119	-10,0785
7	-6,80888	-6,06392	-4,70928	-11,5957
8	-6,96610	-6,25624	-4,46459	-10,7488
9	-7,12052	-6,44852	-4,16157	-9,3788
10	-7,19671	-6,70113	-1,67991	-11,9802
11	-7,38432	-6,90747	-1,54203	-10,8665
12	-7,53154	-7,14345	0,05550	-10,6423
13	-7,15870	-6,64877	-1,88270	-11,4062
14	-7,34712	-6,85240	-1,81563	-11,0461
15	-7,42136	-6,94270	-1,61124	-9,9745
16	-6,96610	-6,36127	-3,12566	-10,3439
17	-7,04365	-6,46091	-2,89089	-10,0649
18	-7,15870	-6,62855	-2,21051	-8,0108

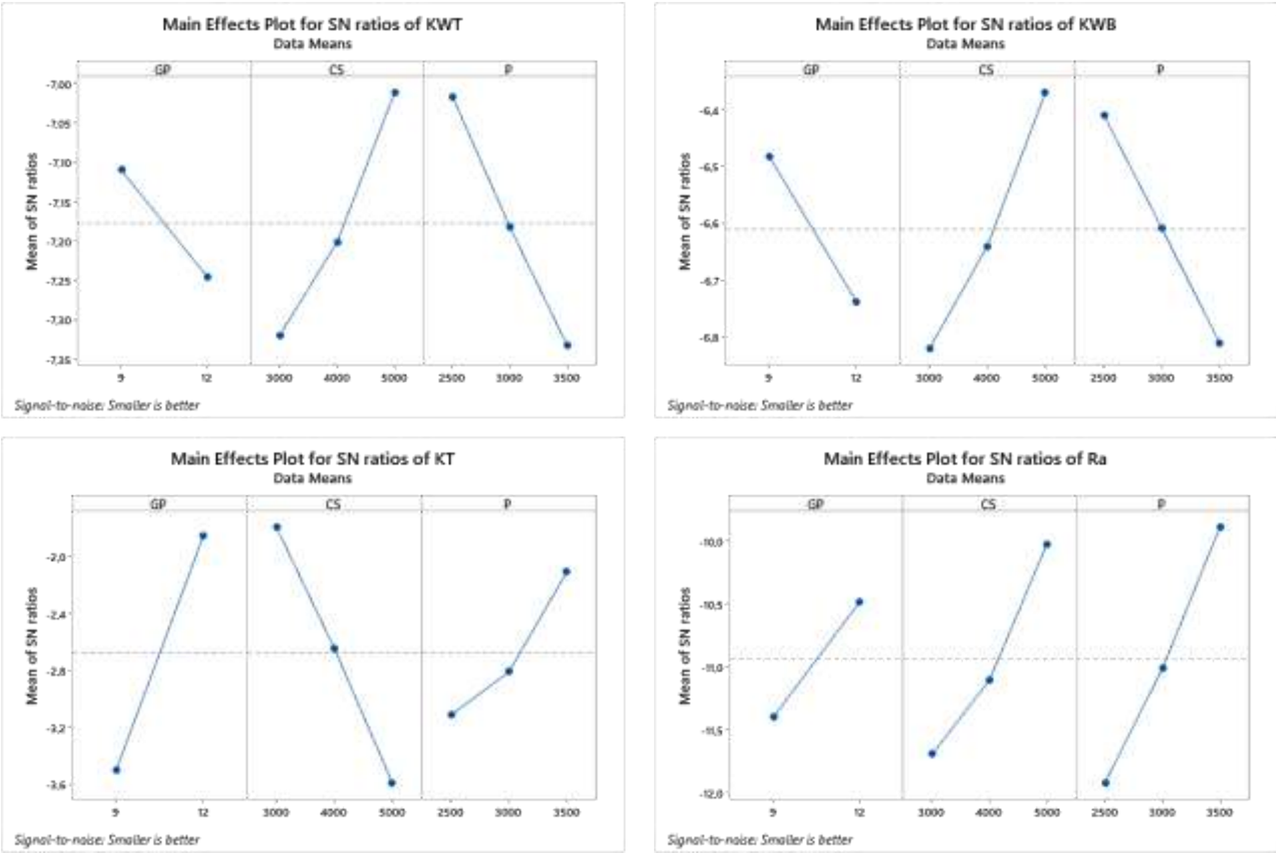

Figure 4. Response graphs for KWT, KWB, KT and Ra

Table 5. Response values for S/N ratios of KWT, KWB, KT and Ra.

KWT				KWB			
Level	GP	CS	P	Level	GP	CS	P
1	-7,110	-7,321	-7,017	1	-6,483	-6,821	-6,410
2	-7,245	-7,201	-7,183	2	-6,739	-6,641	-6,609
3		-7,011	-7,333	3		-6,370	-6,813
Delta	0,136	0,310	0,316	Delta	0,256	0,451	0,403
Rank	3	2	1	Rank	3	1	2
KT				Ra			
Level	GP	CS	P	Level	GP	CS	P
1	-3,500	-1,793	-3,115	1	-11,404	-11,699	-11,928
2	-1,856	-2,647	-2,812	2	-10,482	-11,106	-11,015
3		-3,594	-2,107	3		-10,024	-9,885
Delta	1,644	1,801	1,008	Delta	0,923	1,675	2,043
Rank	2	1	3	Rank	3	2	1

Response graphics for KWT, KWB, KT and Ra are given in Figure 4. The graphs in figure 4 should be analyzed to reach optimum levels of cutting parameters. In the analyzes, optimum levels for KWT were found as GP 9 bar, CS 5000 mm/min, P 2500 W. Optimum levels for KWB were found as GP 9 bar, CS 5000 mm/min and P 2500 W. Optimum levels for KT were found as GP 12 bar, CS 3000 mm/min, P 3500 W. For Ra, the optimum levels were found as GP 12 bar, CS 5000 mm/min and P 3500 W.

In Table 5, response values for S/N ratios of KWT, KWB, KT and Ra are given. Rank values give the order of effectiveness of the parameters. The most effective parameter for KWB and KT was CS. The CS was followed by P and GP for KWB and CS was also fallowed by GP and P, respectively. The most effective parameter for KWT and Ra was P. The P was followed by CS and GP, respectively.

3.2. ANOVA Results

ANOVA results are given in Table 6. The numbers in the cell where the regression row and the contribution column overlap indicate the total % effect of the cutting factors. If P <0,05, we can say that the model is meaningful [22]. In Table 6, total P values for KWT, KWB, KT and Ra appear to be less than 0,05.

Tablo 6. ANOVA results for KWT, KWB, KT an Ra.

KWT							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0,046531	94,11%	0,046531	0,015510	74,52	0,00000001
GP	1	0,005689	11,51%	0,005689	0,005689	27,33	0,00012786
CS	1	0,020008	40,47%	0,020008	0,020008	96,13	0,00000012
P	1	0,020833	42,13%	0,020833	0,020833	100,10	0,00000009
Error	14	0,002914	5,89%	0,002914	0,000208		
Total	17	0,049444	100,00%				
KWB							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0,084621	95,65%	0,084621	0,028207	102,55	0,00000000
GP	1	0,017735	20,05%	0,017735	0,017735	64,48	0,00000131
CS	1	0,037185	42,03%	0,037185	0,037185	135,19	0,00000001
P	1	0,029701	33,57%	0,029701	0,029701	107,98	0,00000006
Error	14	0,003851	4,35%	0,003851	0,000275		
Total	17	0,088472	100,00%				
KT							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0,61698	95,73%	0,61698	0,205662	104,67	0,00000000
GP	1	0,30440	47,23%	0,30440	0,304399	154,92	0,00000001
CS	1	0,24101	37,40%	0,24101	0,241014	122,66	0,00000003
P	1	0,07157	11,11%	0,07157	0,071572	36,43	0,00003063
Error	14	0,02751	4,27%	0,02751	0,001965		
Total	17	0,64449	100,00%				
Ra							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	4,0993	92,34%	4,0993	1,36644	56,24	0,00000005
GP	1	0,6701	15,09%	0,6701	0,67010	27,58	0,00012243
CS	1	1,3501	30,41%	1,3501	1,35005	55,57	0,00000308
P	1	2,0792	46,83%	2,0792	2,07917	85,58	0,00000024
Error	14	0,3401	7,66%	0,3401	0,02429		
Total	17	4,4394	100,00%				

In addition, the % contribution rate and P values of the factors are given in Table 6. The P factor was the most effective parameter with a contribution rate of 42,13% to KWB and 46,83% to Ra.

The parameter that contributed the most to the KWB results was CS with 42,03%. These results confirm the Taguchi analysis. However, in the analysis of variance, the parameter that contributed the most to KT was GP with 47,23%. However, CS was found to be the most effective parameter for KT in the Taguchi analysis. Since the KT result is obtained from the KWT and KWB values, it is difficult to get reliable results. In addition, the exact measurement may not be taken because chips are formed at the bottom of the plate. Özlü [23] found the CS as the most effective parameter for laser cutting of Al 5083 sheet. This result confirms the Taguchi analysis.

Regression analyzes were performed using the linear regression method. The R^2 values found by the equation obtained at the end of the analyzes are given in Table 7. According to Table 7, R^2 values were found to be 94,11% for KWT, 95,65% for KWB, 95,73% for KT and 92,34% for Ra. Since the results are high, we can say that the experiments are reliable [24].

Table 7. Regression equations for KWT, KWB, KT and Ra.

	Equation	**R^2 (%)**
KWT	2,0744 + 0,01185 GP- 0,000041 CS + 0,000083 P	94,11
KWB	1,8462 + 0,02093 GP- 0,000056 CS + 0,000100 P	95,65
KT	2,181- 0,08669 GP + 0,000142 CS- 0,000154 P	95,73
Ra	8,749- 0,1286 GP- 0,000335 CS- 0,000832 P	92,34

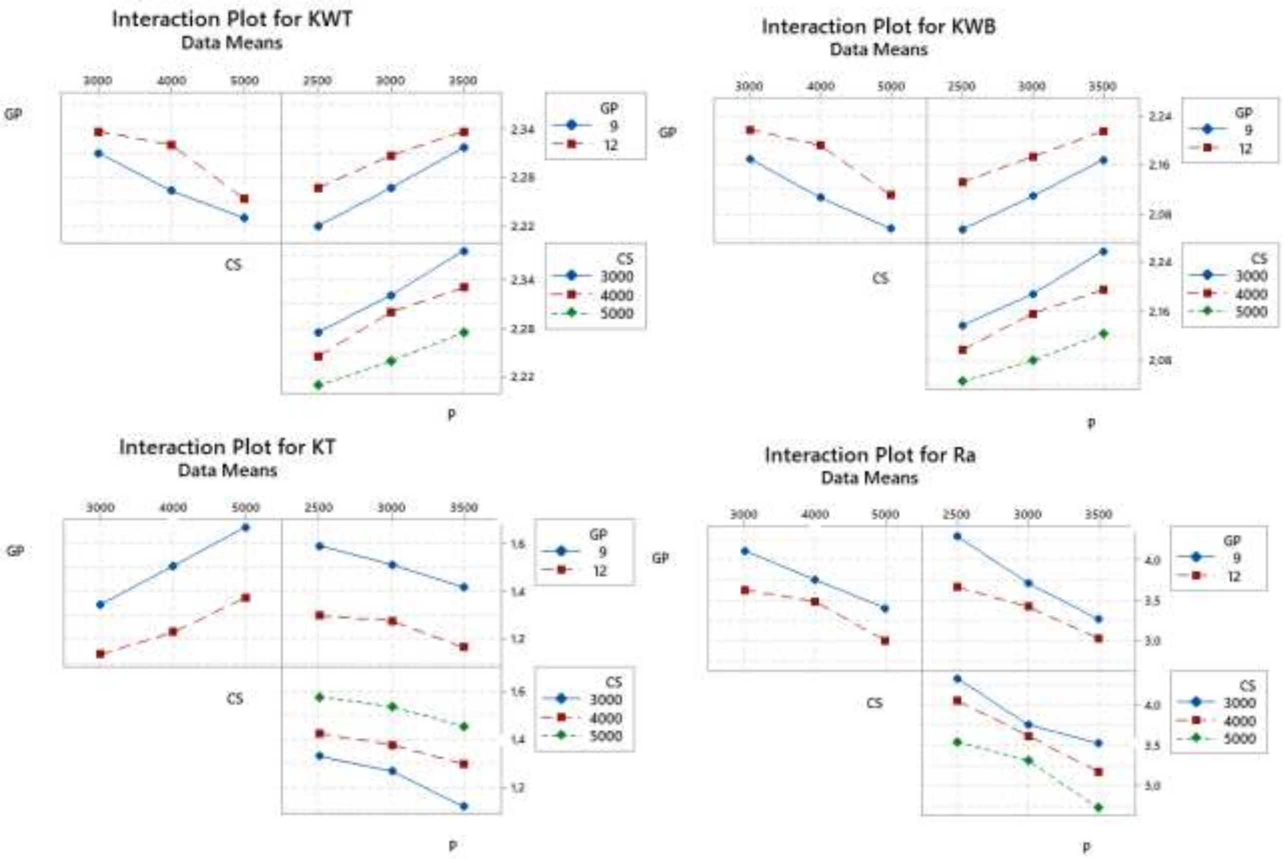

Figure 5. Interaction plots of parameters

The interaction plot helps to analyze the effect of interaction between two variables on outputs by fixing other variables at their optimized levels. Any individual factor interacts with any or all of the other factors, creating the possibility of multiple interactions [25]. Figure 5 shows the interactions of the input parameters for the KWT, KWB, KT and Ra results. In the graph, parallel lines indicate no interaction, and non-parallel lines indicate interaction. The more parallel the lines, the less interaction. There is no complete parallelism between the factors in the graph. KWT, KWB, KT and Ra results show a moderate interaction between parameters.

3.3. Multiple Optimization Results

Multiple optimization method is used in cases where there is more than one answer [26]. Multiple optimizations were made for KWT, KWB, KT and Ra responses by using the response optimizer function in the Minitab program. Since KWT, KWB, KT and Ra values were desired to be minimum while entering the optimization to the system, the objective function was chosen as minimum. As a result of multiple optimizations, GP 11,6667 bar, CS 4131,3131 mm/min and P 2500 W were found as desired levels. Desirabilty value was found to be 0,6584. The result of multiple optimization is given in Figure 6.

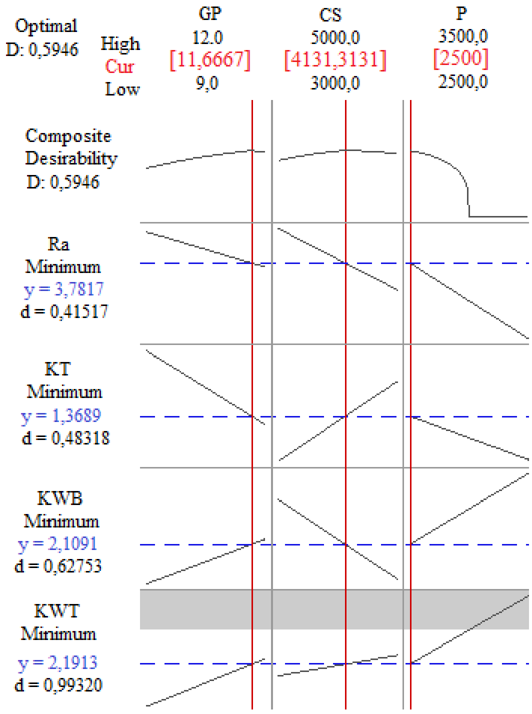

Figure 6. Multiple optimization result graph

4. Conclusion and Recommendations

There are not many or no articles evaluating the effects of machining parameters on process outputs in laser cutting of Al 5052 alloy. For this purpose, it was concluded that such a study is necessary and this study was carried out.

In this study, 3 mm thick Al 5052 alloy was cut with a CNC laser cutting machine under azote gas. At the end of the experiments, the kerf width of top, kerf width of bottom, kerf taper and surface roughness were measured. Three different levels of CS and P and two different levels of GP were selected as cutting parameters. In order to obtain optimum results with minimum experimentation, experimental design and analysis of results were made by Taguchi method. The prominent results are given below:

- As the cutting length increased, the heat on the workpiece also increased and the kerf widths became larger towards the end.

- It was observed that Ra values decreased in the experiments performed at the highest values of GP, CS and laser P.
- Optimum cutting parameters for lowest TKW and BTW: GP= 9 bar, CS= 5000 mm/min, P= 2500 W in Taguchi analysis.
- Optimum cutting parameters for the lowest value of KT: GP= 12 bar, CS=3000 mm/min, P=3500 W in Taguchi analysis.
- Optimum cutting parameters for the lowest Ra value: GP= 12 bar, CS= 5000 mm/min, P=3500 W in Taguchi analysis.
- In Taguchi analysis, CS was the most effective parameter for KWB and KT. For KWT and Ra, the most effective parameter was also P.
- In ANOVA, the most effective parameter was P for KWT and Ra, CS was the most effective parameter for KWB. Contrary to Taguchi results, the most effective parameter for KT was GP instead of CS.
- Correlation coefficients (R^2) were found to be 94,11% for KWT, 95,65% for KWB, 95,73% for KT and 92,34% for Ra.
- In interaction analysis of parameters, KWT, KWB, KT and Ra results show a moderate interaction between parameters.
- Desirabilty value was found to be 0,5946 in multiply optimization. GP 11,6667 bar, CS 4131,3131 mm/min and P 2500 W were found as ideal levels acording to the multiply optimization.

Yazarların Katkıları

HY makaledeki analiz ve çalışmalarını yürüttü, makale yazımını yaptı. Makalenin son halini okudu ve onayladı.

Çıkar Çatışması

Yazar, çıkar çatışması olmadığını beyan eder.

Refereneces

[1]. Yilbas, B.S., Shaukat, M.M., Ashraf, F., Laser cutting of various materials: Kerf width size analysis and life cycle assessment of cutting process, Optics & Laser Technology, 2017, 93, 67-73.

[2]. Nagai, H., Hishii, M., Shibayama, K., Nagai, A., Akiba, T. O., High-pressure sealed CW CO 2 laser with high efficiency, IEEE Journal of Quantum Electronics, 1982, 18(3), 416-422.

[3]. Steen, W.M., Laser material processing, Springer, (3rd end.), 1991, New York.

[4]. Sharma, V., Kumar, V., Multi-objective optimization of laser curve cutting of aluminium metal matrix composites using desirability function approach, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2016, 38(4), 1221-1238.

[5]. Stournaras, A., Stavropoulos, P., Salonitis, K., Chryssolouris, G., An investigation of quality in CO2 laser cutting of aluminum, CIRP J Manuf Sci Technol, 2009, 2 (1), 61-69.

[6]. Yi, G., Sun, B., Poplawsky, J.D., Zhu, Y., Free, M.L., Investigation of pre-existing particles in Al 5083 alloys, J Alloys Compd, 2018, 740, 461-469.

[7]. Chen, Y., Ding, H., Li, J., Cai, Z., Zhao, J., Yang, W., Influence of multi-pass friction stir processing on the microstructure and mechanical properties of Al-5083 alloy, Mater Sci Eng A, 2016, 650, 281-289.

[8]. Yana, J., Hodge, A.M., Study of β precipitation and layer structure formation in Al 5083: The role of dispersoids and grain boundaries, J Alloys Compd, 2017, 703, 242-250.

[9]. Wang, J., An experimental analysis and optimisation of the CO2 laser cutting process for metallic coated sheet steels, The International Journal of Advanced Manufacturing Technology, 2000, 16(5), 334-340.

[10]. Chaki, S., Bathe, R. N., Ghosal, S., Padmanabham, G., Multi-objective optimisation of pulsed Nd: YAG laser cutting process using integrated ANN–NSGAII model, Journal of Intelligent Manufacturing, 2018, 29(1), 175-190.

[11]. Chakraborty, S., Bhattacharyya, B., Diyaley, S., Applications of optimization techniques for parametric analysis of non-traditional machining processes: a review, Management Science Letters, 2019, 9(3), 467-494.

[12]. Rao, R., Yadava, V., Multi-objective optimization of Nd: YAG laser cutting of thin superalloy sheet using grey relational analysis with entropy measurement, Optics & Laser Technology, 2009, 41(8), 922-930.

[13]. Akkuş, H., Experimental and Statistical Investigation of Surface Roughness in Turning of AISI 4140 Steel, Sakarya University Journal of Science, 2019, 23(5), 775-781.

[14]. Işık, R., Özlü, B., Demir, H., St-37 Malzemesinin Lazer ile Kesme İşleminde Seçilen Parametrelerin Etkisinin Deneysel ve İstatiksel Olarak İncelenmesi, Firat University Journal of Engineering, 2021, 33(1).

[15]. Joshi, P., Sharma, A., Simultaneous optimization of kerf taper and heat affected zone in Nd-YAG laser cutting of Al 6061-T6 sheet using hybrid approach of grey relational analysis and fuzzy logic, Int J Precis Eng, 2018, 54, 302-313.

[16]. Sharifi, M., Akbari, M., Experimental investigation of the effect of process parameters on cutting region temperature and cutting edge quality in laser cutting of AL6061T6 alloy, Optik 2019, 184, 457-463.

[17]. Özlü, B., Akgün, M., Demir, H., AA 6061 Alaşımının tornalanmasında kesme parametrelerinin yüzey pürüzlülüğü üzerine etkisinin analizi ve optimizasyonu, Gazi Mühendislik Bilimleri Dergisi (GMBD), 2019, 5(2), 151-158.

[18]. Asiltürk, I., Akkuş, H., Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method, Measurement, 2011, 44(9), 1697-1704.

[19]. Erkan, Ö., Sur, G., Nas, E., Investigation Of Surface Morphology Of Drilled Cfrp Plates And Optimization Of Cutting Parameters, Surface Review and Letters, 2020, 27(09), 1950209.

[20]. Rajaram, N., Ahmad, J.S., Cheraghi, SH., CO2 laser cut quality of 4130 steel, Int J Mach Tools Manuf., 2003, 43(4), 351-358.

[21]. Dubey, A.K., Yadava, V., Multi-objective optimisation of laser beam cutting process, Opt Laser Technol, 2008, 40(3), 562-570.

[22]. Özlü, B., Sleipner soğuk iş takım çeliğinin tornalanmasında kesme parametrelerinin kesme kuvveti, yüzey pürüzlülüğü ve talaş şekli üzerine etkisinin incelenmesi. Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi, 2021, 36(3), 1241-1252.

[23]. Özlü, B., Experımental and Statistical Investigation of the Effects of Cutting Parameters on Kerf Quality and Surface Roughness in Laser Cutting of Al 5083 Alloy, Surface Review and Letters, 2021, 2150093.

[24]. Leone, C., Genna, S., Caggiano, A., Tagliaferri, V., & Molitierno, R., Influence of process parameters on kerf geometry and surface roughness in Nd: YAG laser cutting of Al 6061T6 alloy sheet, The International Journal of Advanced Manufacturing Technology, 2016, 87(9), 2745-2762.

[25]. Abdulaziz, K., Aslan, M., Yılmaz, N. F., Halil, K., Al-Mg-SiC Kompozitlerin Görünür Yoğunluklarının Taguchi Analizi, El-Cezeri Journal of Science and Engineering, 2020, 7(2), 773-780.

[26]. Akkuş, H., Yaka, H., Optimization of Turning Process By Using Taguchi Method, Sakarya Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 2018, 22(5), 1444-1448.