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Mathematical Modelling and Multiresponse Optimization to Minimize Surface Roughness in Drilling Custom 450 Stainless Steel

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ABSTRACT

In the present study, drilling tests were carried out on Custom 450 stainless steel workpieces. The influences of control factors (cutting speed-Vc, feed rate-f and drill bit geometry-D) on the drilled holes' surface roughness (Ra) and on the size of adhering workpiece (AW) to the drill bit was examined. The results obtained from tests designed based on the Taguchi's L16 orthogonal array were analysed using ANOVA and grey relational analyses (GRA). Therefore, the control factors and their levels were optimised simultaneously for the quality characteristics (Ra and AW). In addition, mathematical models were also developed using Response Surface Methodology (RSM) in order to estimate the quality characteristics. The used drill bits were examined under digital and scanning electron microscopes and EDX analysis was also carried out on the drill bits. The experimental results showed that the Ra and AW increased with increasing the f. It was also seen that increasing the Vc resulted in decrease in the size of adhering layer and that the drill bit wear became clear at the highest Vc of 60 m/min. According to the ANOVA results, the most effective control factor on Ra was f with 93.11% and Vc with 58.14% on AW. GRA analysis revealed that the most influential control factor was the f and that the optimum levels were 60 m/min Vc, 0.005 m/min f and drill bit 4.

Custom 450 Paslanmaz Çeliğinin Delinmesinde Yüzey Pürüzlülüğünü Minimize Etmek için Matematiksel Modelleme ve Çok Yanıtlı Optimizasyon

MAKALE BİLGİSİ

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ÖZET

Bu çalışmada, Custom 450 paslanmaz çelik iş parçaları üzerinde delme testleri yapılmıştır. Kontrol faktörlerinin (kesme hızı-Vc, ilerleme miktarı-f ve matkap ucu geometrisi-D) delinen deliklerin yüzey pürüzlülüğü (Ra) ve matkap ucuna yapışan iş parçasının boyutu (AW) üzerindeki etkileri incelenmiştir. Taguchi'nin L16 ortogonal dizisine dayalı olarak tasarlanan testlerden elde edilen sonuçlar, ANOVA ve Gri İlişkisel Analizler (GRA) kullanılarak analiz edilmiştir. Kalite karakteristikleri (Ra ve AW) kontrol faktörleri ve seviyelerine bağlı olarak eş zamanlı optimize edilmiştir. Ayrıca, kalite karakteristiklerini tahmin etmek için Tepki Yüzey Metodolojisi (RSM) kullanılarak matematiksel modeller geliştirilmiştir. Kullanılan matkap uçları dijital ve taramalı elektron mikroskoplarında incelenmiş ve EDX analizleri yapılmıştır. Deneysel sonuçlar, Ra ve AW'nin f arttıkça arttığını göstermiştir. Ayrıca Vc'nin artması AW boyutunda azalmaya neden olduğu ve matkap ucu aşınmasının en yüksek Vc olan 60 m/dak'da belirginleştiği görülmüştür. ANOVA sonuçlarına göre Ra üzerinde en etkili kontrol faktörü %93.11 ile f ve AW üzerinde ise %58.14 ile Vc olmuştur. GRA analizi, en etkili kontrol faktörünün f olduğunu ve optimum seviyelerin 60 m/dk kesme hızı, 0.005 m/dk ilerleme ve 4 numaralı matkap ucu olduğunu belirlenmiştir.

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1. INTRODUCTION (GİRİŞ)

Stainless steels, which have high corrosion resistance and mechanical properties, are indispensable materials in all areas of the industry [1-3]. Feature of stainless steels can be altered by heat treatments and/or addition of various alloying elements [4]. Custom 450 is a type of martensitic stainless steel. It is especially suitable for the applications requiring corrosion resistance at high temperatures (650 °C) and used for making components used in submarine applications, nuclear power plants and defense industry [5]. It is stated that Custom 450 is resistant to pitting and corrosion even in salt water atmospheres [5, 6]. The high tensile strengths, low heat transfer coefficient and relatively high ductility of the Custom 450 alloy make it difficult to machine [1-3, 7, 8]. During machining of stainless steel, high cutting forces, strongly adhered chips to the cutting tool and relatively long chips adversely affect the process. Effective machining of these difficult-to-machine materials including Custom 450 is of crucial importance for cost effective manufacturing and sustainability [5].

Drilling with drill bits, which is used with a high rate of approximately 35% among machining methods, is the most important hole drilling method with its economy and simple structure [9-12]. Therefore, many researchers have focused on understanding and solving the potential problems encountered during drilling [13]. The process is influenced by the factors including drilling parameters, workpiece to be drilled and machine tool used. In addition, cutting action in drilling takes place inside the hole and therefore it is not easy to observe the process when compared to other machining processes [14].

Good dimensional accuracy and good surface quality are essential for the mating parts to serve efficiently for a long time. [15-17]. Although it is usually difficult and costly to obtain good surface quality, surface quality of a manufactured product influences its fatigue strength, wear resistance and friction properties significantly [16-18]. During machining, the cutting tools are subjected to high stresses and temperatures. These stress and temperatures cause rapid tool wear. The worn tool adversely affects the surface quality and dimensional accuracy of the workpiece [17, 19]. Poor dimensional accuracy causes the parts to be out of the specified dimensional tolerances.

Parts with good surface quality and close tolerances are often aimed to be produced at reasonable cost [12, 18]. For this reason, various optimization techniques have recently been utilized to determine the optimum machining conditions [20, 25]. Öktem et al. used the Genetic Algorithm (GA) to determine the optimum cutting conditions for minimum surface roughness in milling die steel surfaces, and the RSM to obtain the analytical model. Their methodology was capable of reducing the surface roughness (Ra) by about 10% [26]. Suresh et al. used the RSM to estimate the roughness value of the surface machined by turning steel materials with carbide cutting tools. In addition, the optimum values of the cutting variables were determined by GA. [27]. Günay and Meral developed the analytical model with the RSM depending on the Vc (cutting speed) and f (feed rate) on the Fc (cutting force), AW and Ra in the drilling process, and optimized the variables with the GRA. In their study on ferritic stainless steel, they stated that the Fc and Ra value decreased with the increase in Vc, and the Aw and Vc are directly proportional [20]. Zhang et al. used the Taguchi method to optimize the surface quality in the drilling process. Spindle speed, f, pecking amount and drill bit type were determined as control factors. They explained that the optimization was valid with the verification experiments they performed with the optimum control factor and levels they obtained [28]. Abbas et al. estimated the machining time, Ra and machining cost in CNC machines depending on the Vc, cutting depth and f. They made their predictions using AN. They stated that the predictive values they obtained were consistent and the model could be used with confidence [29]. Toulfatzis et al. realized turning tests on three lead-free brass alloys based on Taguchi's L16 series. ANOVA was utilized to state the effects of Vc, depth of cut, f, and workpiece material on Fc and Ra [30]. Çaydaş et al. examined the performances of different drill bit materials (HSS, carbide and coated HSS) in drilling of AISI 304 steel. The drilling experiments were achieved based on Taguchi's L9 series. The influence of spindle speed, f, drill point angle and number of holes on the Ra, drill bit wear, burr height and hole diameter were evaluated. Their experimental results showed that coated HSS drill bits performed best state of affairs of tool life, hole quality and Ra [31]. Çiçek et al. performed drilling tests on AISI 304 workpieces for the purpose of investigating the effects of the drill bit cryogenic process and drilling parameters on Ra and hole quality. The tests were done based on Taguchi's L27 full factorial design with a series (mixed type). They used ANOVA to determine the most significant experiment variable. In addition, they developed a model by RSM to obtain the best Ra and ovality [32]. Mavi investigated the effects of drilling parameters on deviation from geometric and dimensional tolerances when drilling a stainless steel. The experimental design was based on L18 orthogonal array. The results were analyzed using grey relational analyses (GRA) [33]. Orak et al. optimized the cutting parameters in the turning process in terms of surface roughness, noise and tool wear using a hybrid decision making algorithm using Artificial Neural Networks (ANN) – TOPSIS. They emphasized that the method they developed will be used successfully in reducing vibrations [34]. Benefit et al. they subjected the AA7075 alloy tempered under different conditions to a series of drilling tests at different drilling parameters. They used the Response Surface Method (RSM) to evaluate the experimental results [35].

Work to date shows that considerable studies were carried on drilling of various grades of stainless steel. Custom 450 is an important martensitic stainless-steel grade and work on drilling this material is limited. The purpose of this study is to investigate the influence of f, Vc and drill bits geometry on Ra and adhering workpiece size (AW) when drilling Custom 450 stainless steel. Optimum drilling conditions and their levels were aimed to be determined using GRA. In addition, analytical models of Ra and AW were also aimed to be developed using RSM.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Material, Equipment and Experimental Conditions (Malzeme, Ekipman ve Deney Koşulları)

Ingredient and various properties of Custom 450 martensitic stainless steel are given in Table 1. Workpieces were cut off from Ø60 cylindrical Custom 450 billet for drilling test. These workpieces were machined to 14 mm height so that the drilling depth was at least three times the drill bit diameter of 4.5 mm. Four different solid carbide twist drill bits were used. Drill geometry and coating details are given in Table 2. 3 factors (Vc, f and drill bit geometry) and four levels were determined for Taguchi's L16 in experimental design (Table 3). Taguchi experimental design is an experimental design method developed to determine the most appropriate combination of the levels of control factors that cause variability in the product or process, and to minimize the variability in the product and process. Considering the most effective machining parameters and levels that will affect the relevant experiments, the experiments should be carried out in accordance with the L16 orthogonal experiment design. In the Taguchi experimental design, which was used to obtain accurate results in a short time and at low cost, the experiments were not repeated.

The catalog numbers given in Table 2 give the international codes of the manufacturer, and the grade gives the applied coating class. KCPK15 refers to multilayered TiN+MT+TiCN+Al_2O_3 CVD coating, KC7315 and KC7325 refers to TiAlN-PVD coating, and MG10 refers to nACo coating. The drilling parameters were selected based on the manufacturer's suggestions and previous studies. In addition, before starting the experiments, a preliminary experiment was carried out at the highest cutting speed and feed rate determined with each drill bit.

Table 1. Ingredient and various properties of Custom 450 (Custom 450'nin içeriği ve çeşitli özellikleri) [36]

Density - 20 ºC *(g/cm³)*	7.75
Brinell (Ball) Hardness *(HB)*	278
Yield Strength *(N/mm²)*	814
Ultimate Strength *(N/mm²)*	979
Elasticity Modulus *(GPa)*	200
Poisson's Ratio	0.29
Thermal Conductivity - 20 ºC *(W/(mK))*	15
Composition	Fe:75%, Cu:1.25%-1.75%, Ni:5%-7%, Cr:14%-16%, Mo:0.5%-1%

Table 2. Manufacturer codes of drill bits and its coating details (Matkap uçlarının üretici kodları ve kaplama detayları)

Drill bits	1	2	3	4
Manufacturer	Kennametal	Kennametal	Kennametal	Toolex
ISO Catalogue Number and Grade	B221A04500HP-KCPK15	B966A04500-KC7315	B042A04500CPG-KC7325	BE0450X2C24AS6N058-MG10

Table 3. Drilling parameters and levels (Delme parametreleri ve seviyeleri)

Experimental factors	Vc *(m/min)*	f *(mm/rev)*	D
Code	A	B	C
Levels	15 – 30 – 45 – 60	0.005 – 0.020 – 0.035 – 0.050	1 – 2 – 3 – 4

The drilling tests were conducted dry on an Arion IMM-600 CNC machine. The cylindrical workpieces were clamped rigidly using a four-jaw precision chuck. Solid carbide drill bits were clamped to the spindle of the machining center using a suitable collet. The tool overhang was kept constant for all drilling tests, because changing the tool overhang will affect the test results. Through holes were drilled on the workpieces.

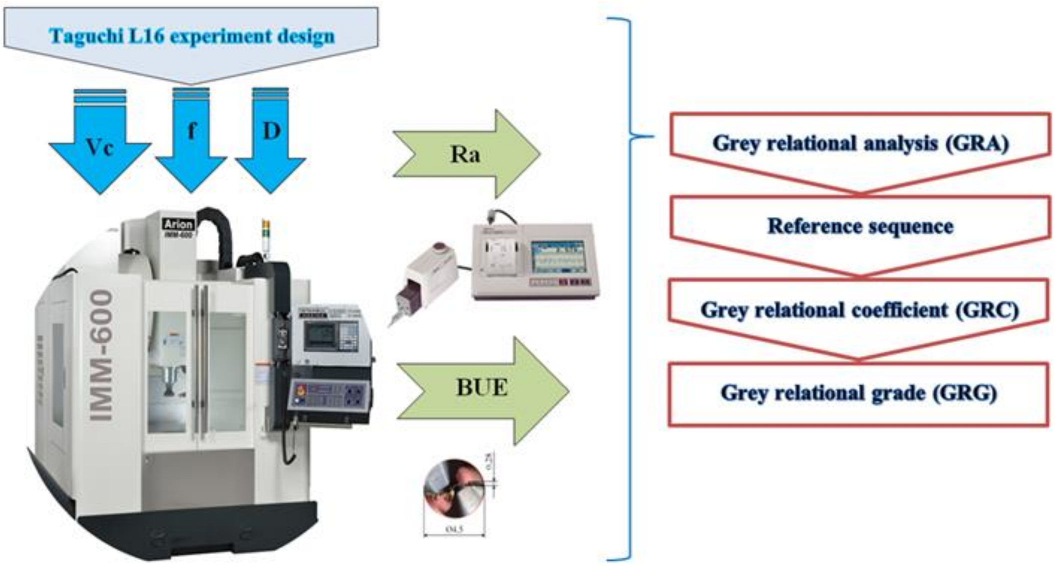

Figure 1. The experimental setup and statistical sequence (Deneysel kurulum ve istatistiksel sıra)

Surface roughness is a sensitive quality criterion that is effective on properties such as the actual contact area, fatigue and corrosion resistance of the manufactured parts. When the surface is examined from a micro point of view, it is seen that it consists of many crack, crater, waviness, intrusion and hill recesses and protrusions. There are several measuring points that define the surface roughness. Except for special applications and ultra-sensitive surfaces, it is very difficult, time consuming and far from economical to examine the entire surface in terms of these measuring points. Measurements are made with a stylus-tipped profilometer on the sample lines that will best show the roughness value of the whole surface. Movement of the stylus tip along the sample line creates a curve that represents the roughness depending on the radius of the stylus tip. A straight line is formed from the middle of the sum height of this curve (mean line). The curve creates a field and another line is obtained that cuts this area in the middle. The difference between the mean line and this line gives the mean surface roughness (Ra). Ra is the surface roughness definition that gives the most general information about the whole surface.

Ra values were obtained with a Mitutoyo SJ-410 profilometer with a cut-off wavelength (cut length) of 0.8 mm and a gauge length of 5.6 mm (ISO 4288:2000). Ra values at different angles (120°) for each hole were measured three times and averaged. The images of AW to drill bit's were obtained using a Dinolite AM7115MZT digital microscope. The digital microscope used is LED-illuminated, 5 megapixels with 2592×1944 resolution, with brightness reduction feature and digital

220 magnification features. The AW was defined using AutoCAD software. In addition, At the end of the experiment, the drill bits were detailed with Carl Zeiss scanning electron microscope (SEM). EDX analyses were also performed. Figure 1 shows the experimental setup and statistical sequence.

2.2. Statistical Methods (İstatistiksel Yöntemler)

Grey system theory can be useful to make decision and to carry out analyses in the case of poor, incomplete and uncertain information [37-39]. Various methods under grey relational analysis such as grey modelling, grey prediction and grey decision making have been applied to various fields. Scientists have often used these methods to make decision [40, 41]. In grey relational analysis, best fit values of the controlling factors and their levels for multiple quality characteristics are determined simultaneously [42].

Table 4. Steps and equations in GRA optimization (GRA optimizasyonundaki adımlar ve eşitliklikler) [20, 40]

Steps	Definition	Equation No	Equation
1	Definition of reference series	1	$Y_0 = (Y_{0,1}, Y_{0,2}, \ldots, Y_{0,n})$
2	Data normalisation	2	$Y_{i,k} = \frac{Y_{i,k}^0 - \min(Y_{i,k}^0)}{\max(Y_{i,k}^0) - \min(Y_{i,k}^0)}$
		The larger - the better	
		3	$Y_{i,k} = \frac{\max(Y_{i,k}^0) - (Y_{i,k}^0)}{\max(Y_{i,k}^0) - \min(Y_{i,k}^0)}$
		The smaller-the better	
		4	$Y_{i,k} = 1 - \frac{\lvert Y_{i,k}^0 - Y^0 \rvert}{\max(Y_{i,k}^0 - Y^0)}$
		The nominal-the better	
		$y_{i,k}^0$: Original series, $Y_{i,k}$:Series after pre-processing, $\max(Y_{i,k}^0)$:The maximum value of $Y_{i,k}^0$, $\min(Y_{i,k}^0)$:The minimum value of $Y_{i,k}^0$, Y^0:Intended value.	
3	Comparison of series	5	$Y_i = (Y_{i,1}, Y_{i,2}, \ldots, Y_{i,n})\, i = 1, 2, \ldots, m$
		i = 1…m and k = 1…n: The measurement data and their responses, respectively.	
4	GRC	6	$\xi_{i,k} = \frac{\Delta_{min} + \xi\, \Delta_{max}}{\Delta_{0,i,k} + \xi\, \Delta_{max}}$
		$\Delta_{0,i,k}$: Deviation series $\Delta_{0,i,k} = \lvert x_{0,k}^* - x_{i,k}^* \rvert$ Δ_{min} and Δ_{max}: Minimum and maximum values of all series. ξ: Identification or distinguishing coefficient ($\xi = 0.5$ is used in experimental studies).	
5	GRG	7	$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_{i,k}$
		n: The number of response properties	
6	Determination of optimum control factors: The strongest relation is related to the level having the largest GRG value.		

In this study, the Ra and AW to the drill bit were defined as the quality characteristic. These characteristics were optimised simultaneously based on Vc, f and D in drilling Custom 450 stainless steel using GRA. Table shows the steps in the optimisation and the equations used.

3. EXPERIMENTAL RESULTS AND DISCUSSION (DENEYSEL SONUÇLAR VE TARTIŞMA)

The experimentally measured Ra and AW to the drill bit's cutting edges (D) are given in Table 5. As can be seen from Table 5, the lowest and highest values for Ra are 0.246 µm and 2.064 µm, respectively, while the lowest and highest values for AW are 0.13 mm and 0.56 mm, respectively. It is seen that the differences between these values are quite high, which indicates that the experimental parameters (quality characteristic) and the results (control factors) are highly correlated with each other.

Table 5. The experimentally obtained Ra and AW values (Deneysel olarak elde edilen Ra ve AW değerleri)

Test	**Vc** *(m/min)*	**f** *(mm/rev)*	**D**	**Ra** *(μm)*	**AW** *(mm)*
1	15	0.005	1	0.246*	0.38
2	15	0.020	2	1.087	0.44
3	15	0.035	3	1.252	0.48
4	15	0.050	4	1.724	0.56**
5	30	0.005	2	0.506	0.20
6	30	0.020	1	1.114	0.28
7	30	0.035	4	1.284	0.41
8	30	0.050	3	2.006	0.36
9	45	0.005	3	0.536	0.19
10	45	0.020	4	1.147	0.21
11	45	0.035	1	1.310	0.28
12	45	0.050	2	2.027	0.39
13	60	0.005	4	0.775	0.13*
14	60	0.020	3	1.148	0.23
15	60	0.035	2	1.644	0.25
16	60	0.050	1	2.064**	0.34
		Average		1.242	0.32

* The lowest value, ** The highest value

3.1. Surface Roughness – Ra (Yüzey Pürüzlülüğü – Ra)

The lowest Ra value of 0.246 µm is obtained at Vc: 15 m/min and f: 0.005 mm/rev with drill bit 1, while the highest Ra of 2.064 µm is obtained at Vc: 60 m/min and f: 0.050 mm/rev with drill bit 1 control factors and levels. ANOVA was applied to find the effect (percent contribution) of Vc, F and D on Ra and the results are presented in Table 6. In terms of F ratios and P values, Vc and f seem to be effective and statistically significant on quality characteristics (F ratio > Fα: 0.05: 5.99 and P value < 0.05). The percentage contributions (PCR) of the quality characteristics (Vc, f and D) are 4.80%, 93.11% and 1.30%, respectively.

Based on variance analysis (ANOVA), the highest percentage contribution rates belong to f and Vc. Figure 2 gives the influence of variations in f and Vc on Ra. It can be seen from Figure 2 that increasing f significantly increases Ra. Increasing f values increases the cross-sectional zone of undeformed material and therefore the amount of plastic deformation also increases [39]. High amount of plastic deformation, in turn, increases the required forces and vibration in drilling. In addition, the high ductility of workpiece material causes some of the deformed material to adhere to the drill bit. This adhered material is also considered to increase the Ra [4, 43-46].

Table 6. Variance analysis results of Ra (Ra'nın varyans analizi sonuçları)

Source	**DF**	**Seq SS**	**Adj MS**	**F ratios**	**P values**	**PCR**
Vc	3	0.22017	0.07339	7.36	0.020	4.80
f	3	4.26916	1.42305	142.72	0.000	93.11*
D	3	0.03598	0.01199	1.20	0.386	0.78
Error	6	0.05982	0.00997			1.30
Total	15	4.58514				100.00
R^2	98.70%					

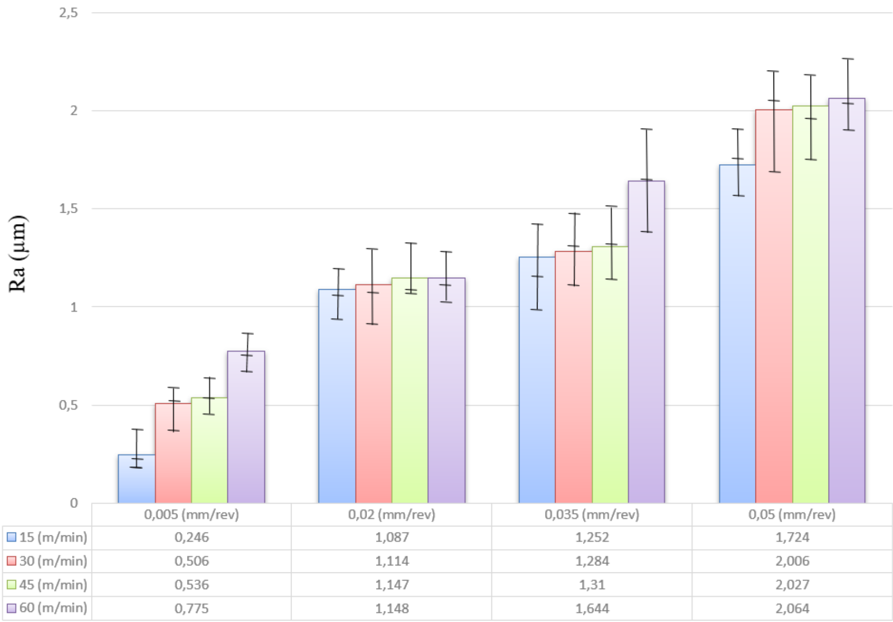

Figure 2. Vc - f interactions of Ra values (Ra değerlerinin Vc – f etkileşimi)

3.2. Adhering Workpiece to The Drill Bit's Cutting Edges – AW (İş Parçasının Matkap Ucu Kesici Kenarlarına Yapışması – AW)

The measured AW to the D used in drilling Custom 450 workpiece are given in Table 5. The lowest AW of (0.13 mm) is obtained at 60 m/min Vc and 0.005 mm/rev f with drill bit 4, while the highest size of 0.56 mm is obtained at 15 m/min Vc and 0.050 mm/rev f with drill bit 4. Based on the ANOVA results given in Table 7, it can be said that Vc and f are statistically significant on the AW (P value < 0.05, F ratio > Fα: 0.05: 5.99).

Table 7. ANOVA for the AW (AW için ANOVA)

Source	DF	Seq SS	Adj MS	F ratios	P values	PCR
Vc	3	0.122006	0.040669	22.58	0.001	58.14*
f	3	0.076855	0.025618	14.22	0.004	36.63
D	3	0.000163	0.000054	0.03	0.992	0.08
Error	6	0.010808	0.001801			5.15
Total	15	0.209833				100.00
R^2	94.85%					

These results and higher coefficient of determination values (94.85%) indicate a strong correlation between the variation of control factors and results. The PCR of the control factors on the AW are also given in Table 7. Accordingly, the contributions of Vc, f and D are 58.14%, 36.63% and 0.08%, respectively. In the surface graph in Figure 3, it is seen that the changes in Vc and f values have a significant effect on AW (especially affected by Vc changes).

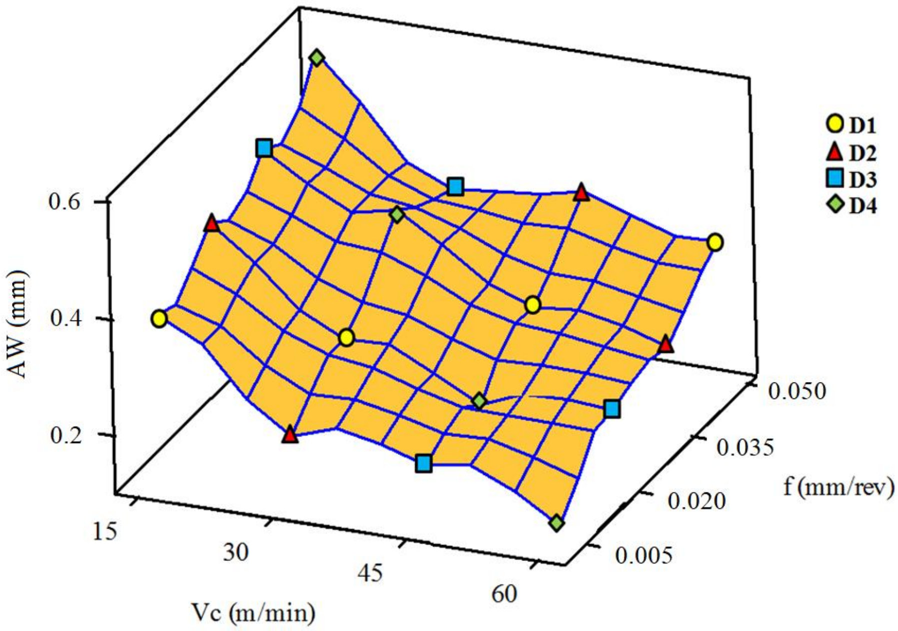

Figure 3. Influence of Vc, f and D on the AW values (AW değerlerinin Vc, f ve D üzerindeki etkisi)

Workpiece material tends to adhere strongly to the drill bit's cutting edges due to the high temperature and high stresses during drilling. This is the case especially in machining of austenitic stainless steel [43, 47] and is not desirable. This adhered workpiece usually causes rapid tool wear and poor surface quality.

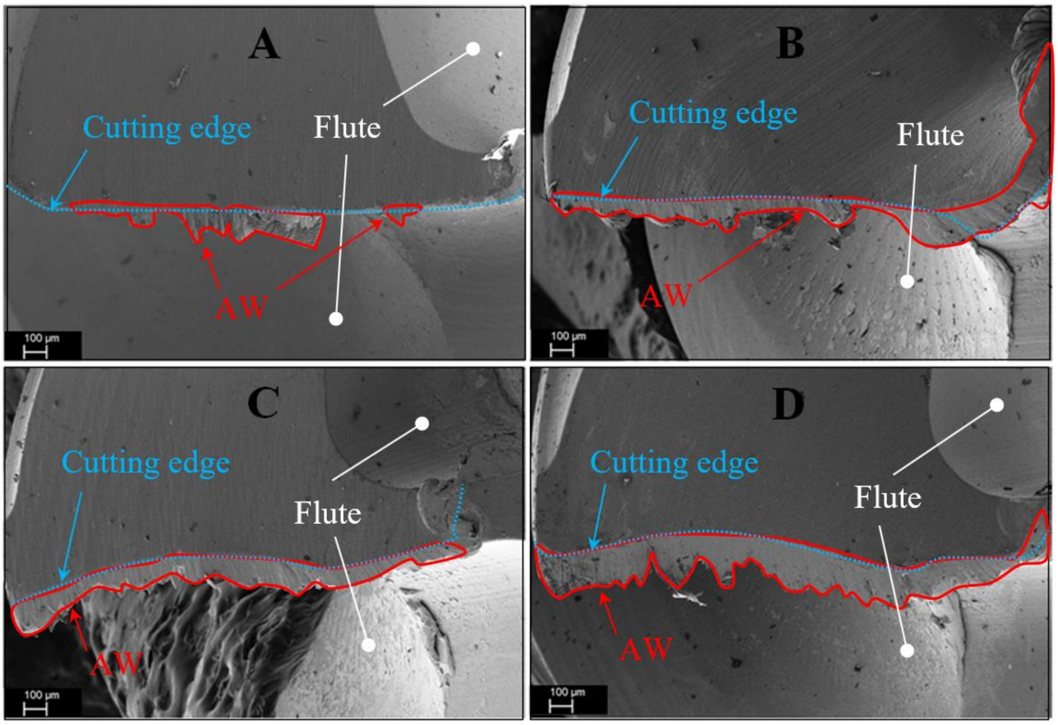

Figure 4. SEM images of the drill bits used at 15 m/min Vc at various f: A: 0.005 mm/rev, B: 0.0020 mm/rev, C: 0.0035 mm/rev and D: 0.050 mm/rev (Vc=15 m/dk'de matkap uçlarının SEM görüntüleri, A: 0,005 mm/dev, B: 0,0020 mm/dev, C: 0,0035 mm/dev ve D: 0,050 mm/dev)

Figure 4 shows the SEM images of the D used at 15 m/min Vc and various f, while Figure 5 shows the SEM images of the D used at 0.050 m/min f and various Vc. In Figure 4, it is seen that increasing the f increases the size of adhered workpiece. This increase can be attributed to increased forces and temperatures during drilling due the increasing cross-sectional area of uncut chip thickness with increasing f. However, increasing the Vc decreases the size of adhered workpiece, Figure 5. Moreover, no adhered workpiece is seen at the highest Vc of 60 m/min, Figure 5D.

However, Figure 5D also shows the worn and locally fractured cutting edges of the D. Further increase in the temperature with the increasing Vc decreases the bonding force between the drill bit's cutting edges and adhered workpiece and this, in turn, leads to detachment of the adhered workpiece [43].

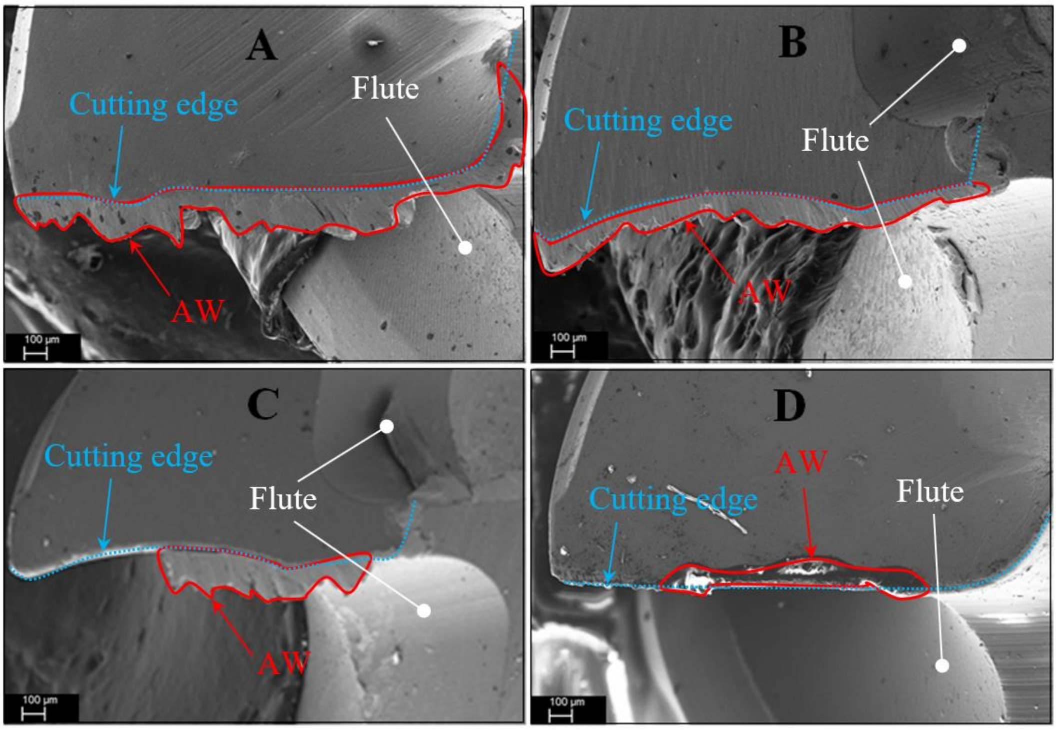

Figure 5. SEM images of the drill bits used at f: 0.050 mm/rev and at various Vc: A: 15 m/min, B: 30 m/min, C: 45 m/min and D: 60 m/min (f=0,050 mm/dev'de matkap uçlarının SEM görüntüleri, A: 15 m/dk, B: 30 m/ dk, C: 45 m/ dk ve D: 60 m/ dk)

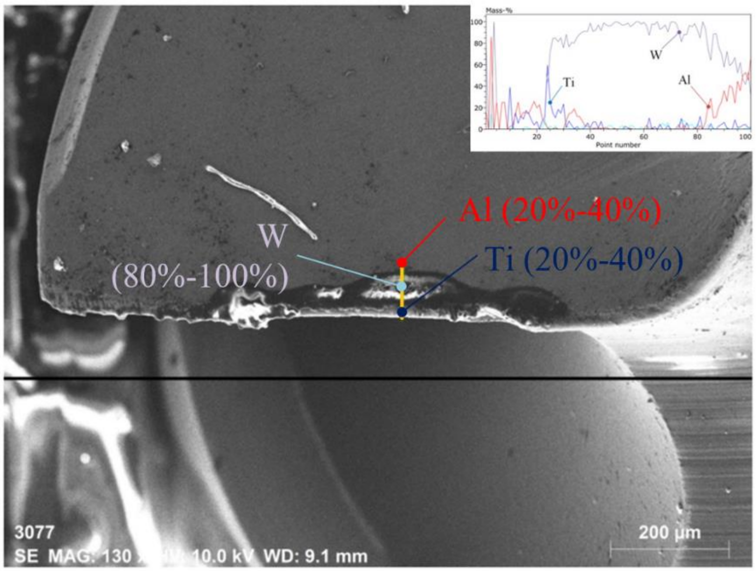

Figure 6. EDX analysis result of the used drill bit (Kullanılan matkap ucunun EDX analiz sonucu)

From Figure 5D, it is also considered that adhesive wear is the dominant wear mechanism in the drill bit wear. When there is an adhered workpiece material on the cutting tool, it is likely that the particles of the cutting tool wear away through workpiece seizure and pull-out process during machining [45-49]. EDX analysis result given in Figure 6 reveals that AlTiN coating on the drill bit was detached and the main element (W) of the drill bit's substrate came out.

3.3. Optimization with GRA (GRA optimizasyonu)

The obtained Ra and AW values in the drilling of Custom 450 stainless steel and ANOVA results show the presence of different control factors and levels for optimum drilling conditions. For drilling efficiency, simultaneous optimization for the both quality characteristics of Ra and AW is of crucial importance. For this purpose, the first step in GRA is normalization of the experimental results. For the quality characteristics, lower values of the experimental results are desired. Equation 3 is applied to the experimental results and normalized values are calculated. The second step is to find the GRC values using the normalized values and Equation 6. Finally, GRC values and GRG values (using Equation 7) are calculated. The calculated GRA values are given in Table 8.

Table 8. Experimentally obtained results and calculated GRA values (Deneysel olarak elde edilen sonuçlar ve hesaplanan GRA değerleri)

Test	Experimental results		Normalized values		GRC		GRG	Order
	Ra (*μm*)	AW (*mm*)	Ra	AW	Ra	AW		
1	0.246	0.38	1.0000	0.4186	1.0000	0.4624	0.7312	4
2	1.087	0.44	0.5374	0.2791	0.5194	0.4095	0.4645	10
3	1.252	0.48	0.4466	0.1860	0.4747	0.3805	0.4276	12
4	1.724	0.56	0.1870	0.0000	0.3808	0.3333	0.3571	16
5	0.506	0.20	0.8570	0.8372	0.7776	0.7544	0.7660	3
6	1.114	0.28	0.5226	0.6512	0.5115	0.5890	0.5503	7
7	1.284	0.41	0.4290	0.3488	0.4669	0.4343	0.4506	11
8	2.006	0.36	0.0319	0.4651	0.3406	0.4831	0.4119	14
9	0.536	0.19	0.8405	0.8605	0.7581	0.7818	0.7700	2
10	1.147	0.21	0.5044	0.8140	0.5022	0.7288	0.6155	5
11	1.310	0.28	0.4147	0.6512	0.4607	0.5890	0.5249	8
12	2.027	0.39	0.0204	0.3953	0.3379	0.4526	0.3953	15
13	0.775	0.13	0.7090	1.0000	0.6321	1.0000	0.8161	1
14	1.148	0.23	0.5039	0.7674	0.5019	0.6825	0.5922	6
15	1.644	0.25	0.2310	0.7209	0.3940	0.6418	0.5179	9
16	2.064	0.34	0.0000	0.5116	0.3333	0.5059	0.4196	13

Table 9. Response table for GRG (GRG için yanıt tablosu)

Control factors	Levels				Delta (max-min)
	1	2	3	4	
Vc	0.4951	0.5447	0.5764	0.5865**	0.0914
f	0.7708**	0.5556	0.4802	0.3960	0.3748*
Drill bit	0.5565	0.5359	0.5504	0.5598**	0.0239

Mean GRG: 0.5507
* The most important control factor, ** Optimum level

In GRG response table (Table 9) built using averages of GRG values belonging to the same levels of each control factor, the highest values among the levels determine the optimum level, while the highest difference among the levels indicates the most important control factor. By taking into these definitions, level 4 is for the cutting speed (60 m/min), level 1 is for the feed rate and level 4 is for the drill bit (D:4) are determined as the optimum levels (Run: 13). In addition, the most important control factor is seen to be f with a value of 0.3748.

3.4. Mathematical Modelling with RSM (RSM ile Matematiksel Modelleme)

Response surface methodology (RSM) is used to develop analytical models of the quality characteristics by carrying out full quadratic regression model (Equation 8) of control factors. In Equation 8, η is the predicted response (Ra and AW), β_0 is the constant in regression equation, β_i and β_{ii} are the regression coefficients, X_i are the values of independent variables and k is the number of parameters. The developed models for the Ra and AW are given in Equations 9 and 10. The predicted values through Equations 9 and 10 and the experimental results are given in Figures 7 and 8 comparatively. In addition, determination coefficients (R-Sq) are also given in Figures 7 and

8 for the analytical models. Accordingly, R-Sq values of the mathematical models for the Ra and AW are 96.9% and 94.7%, respectively. These results indicate the reliability and can be used effectively.

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 \quad (8)$$

$$Ra = 0.115086 - 0.00415593\,Vc + 42.662\,f + 0.0916951\,D + 2.91667 \times 10 - 6\,Vc2 - 0.0339646\,Vc \times f + 0.00380417\,Vc \times D - 27.6389\,f2 - 2.39811\,f \times D - 0.0337188\,D2 \quad (9)$$

$$BUE = 0.543205 - 0.0154486\,Vc + 2.88547\,f + 0.0135245\,D + 0.000133186\,Vc2 + 0.0490007\,Vc \times f - 0.000310768\,Vc \times D - 14.2436\,f2 - 0.0365091\,f \times D + 0.0019548\,D2 \quad (10)$$

The values obtained as a result of drilling experiments and calculations are quite close. These results prove that the variables used in the experiments (control factors) are highly effective variables on surface roughness and adhesion to the cutting tool, which are determined as quality characteristics [20, 41, 50]. However, it is seen that there is a difference of 3.1% in the surface roughness and 5.3% in the amount of adhesion to the cutting tool. Although these values are small, they show that the results are also affected by factors other (such as machine tool, environment, ambient temperature, measuring device) than the determined quality characteristics [45, 51].

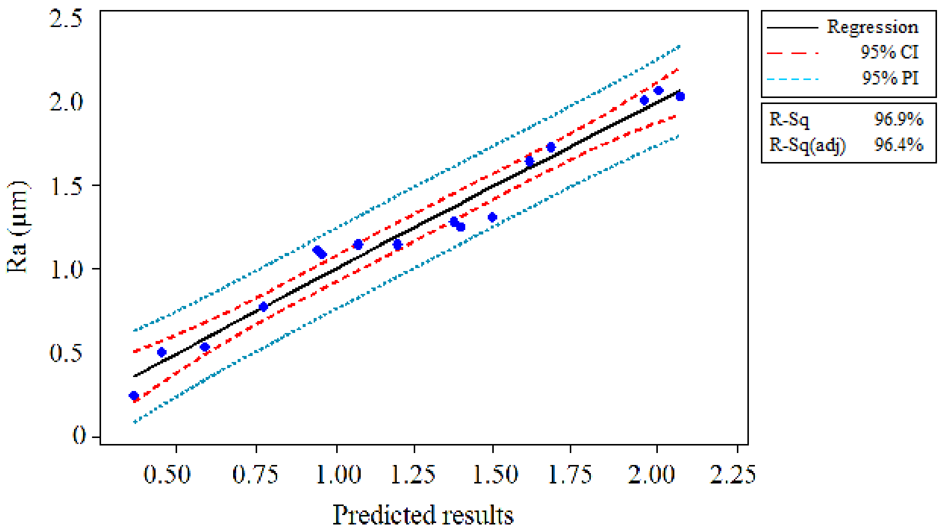

Figure 7. Comparison of experimentally obtained and calculated results for Ra (Ra için deneysel olarak elde edilen ve hesaplanan sonuçların karşılaştırılması)

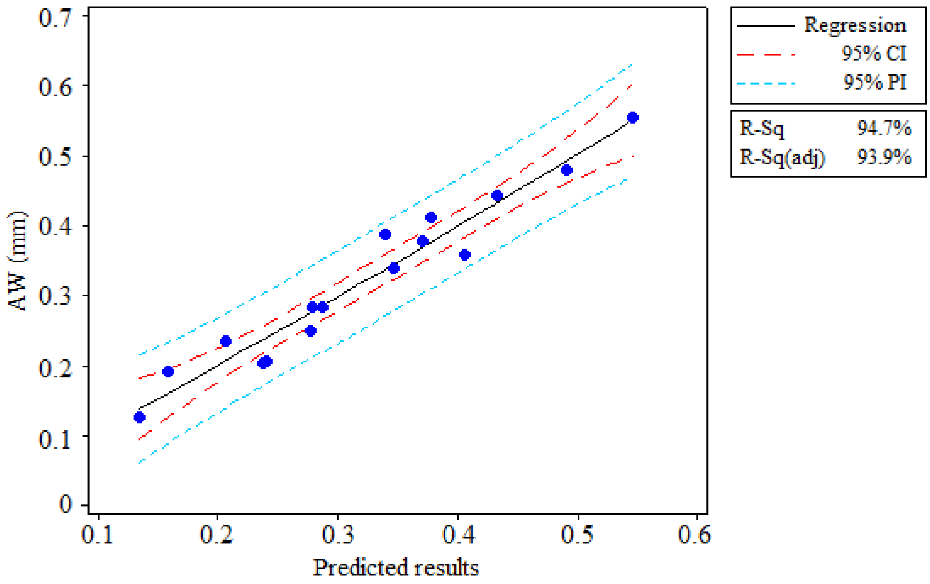

Figure 8. Comparison of experimentally obtained and calculated results for AW (AW için deneysel olarak elde edilen ve hesaplanan sonuçların karşılaştırılması)

4. CONCLUSIONS (SONUÇLAR)

In this study, drilling tests were carried out on a Custom 450 austenitic stainless steel workpiece. The surface roughness (Ra) and size of adhering workpiece (AW) to the drill bit's cutting edges were determined. Based on the control factors, simultaneous optimisation was performed through grey relational analysis (GRA) method. In addition, mathematical models for the Ra and AW were obtained through response surface methodology (RSM). The following conclusions can be drawn from the present work:

- Increasing the feed rate values increased the Ra and AW to the drill bits' cutting edges.
- AW decreased significantly with increasing the cutting speed. This decrease was considered to be result of increased temperature.
- From ANOVA, the feed rate and cutting speed were found to be the most influential control factors on the Ra and AW. The influence of feed rate on the Ra was 93.11%, while the influence of the cutting speed on the AW was 58.14%.
- At the highest cutting speed, adhesive wear mechanism was seen to be dominant on the drill bit wear.
- The simultaneous optimisation through grey relational grade (GRG) revealed that the feed rate was the most important control factor with a value of 0.378.
- High R^2 values of the developed mathematical models indicated that these models can be used effectively (Ra: 96.9% and AW: 94.7%).

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