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An Experimental Investigation into The Optimal Processing Conditions for The Diamond Paste Polishing of SKD 61 Mold Steel

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ABSTRACT

In this study, the effect of diamond paste polishing parameters such as polishing time, axial loading and spindle speed on the surface roughness and specular reflectance of SKD 61 mold steel were experimentally investigated. The experiments were conducted based on the Taguchi orthogonal array. The statistical significance of the each factor and their interactions on the measured responses and optimal parameter level settings were determined using analysis of variance (ANOVA) and main effect plots. In order to predict the each output characteristic, a linear regression equation was developed. Polished surfaces were studied using atomic force microscope (AFM). The developed models predicted the responses with an R^2 of 0.74 and 0.85 for surface roughness and specular reflectance, respectively.

SKD 61 Kalıp Çeliğinin Elmas Pastayla Parlatma İşleminde Optimal İşleme Koşulları Üzerine Deneysel Bir İnceleme

MAKALE BİLGİSİ

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Anahtar Kelimeler:
Ayna yüzey
Ultra yüksek hassas işleme
Elmas pastayla parlatma
Optimizasyon

ÖZET

Bu çalışmada, parlatma süresi, eksenel yükleme ve fener mili hızı gibi elmas macunuyla parlatma parametrelerinin SKD 61 kalıp çeliğinin yüzey pürüzlülüğü ve speküler yansıması üzerindeki etkisi deneysel olarak araştırılmıştır. Deneyler Taguchi ortogonal deneysel tasarım dizisine göre yapılmış olup her bir faktörün istatistiksel önemi ve ölçülen yanıtlar ile optimal parametre seviyeleri üzerindeki etkileşimleri varyans analizi (ANOVA) ve esas etki grafikleri kullanılarak belirlenmiştir. Her bir çıktı karakteristiğini tahmin etmek için doğrusal bir regresyon denklemi geliştirilmiştir. Parlatılan yüzeyler atomik kuvvet mikroskobu (AFM) kullanılarak incelenmiştir. Geliştirilen modeller, yüzey pürüzlülüğü ve speküler yansıma için sırasıyla 0.74 ve 0.85'lik bir R^2 ile yanıtları tahmin etmiştir.

1. INTRODUCTION (GİRİŞ)

The quality of an engineering surface has to satisfy the increasing demands for machine parts. Fabricating a high precise surface in machining mass standards has recently been the focus of attention. According to the Taniguchi classification of the machining techniques, the surfaces about an accuracy of 0.1 µm is accepted as precision machining while 0.01 µm was regarded as high precision machining [1]. Super-finished and mirror surfaces (Ra <0.1µm) find an increasing application especially in electronic components, casing for consumer electronics, optics, tribology, micro mechanics and micro fluids [2]. In the field of optical surfaces, the reflectivity has to be as possible as high and the allowable average roughness (Ra) value should be lower than 10 nm [3]. Since the presence of oxygen in the atmosphere, the colored materials such as aluminum and copper give matt surfaces which reduce the life of molds significantly. Therefore, researchers have attempted to produce the steel molds mirror surfaces [4]. Polishing is a micro chip material removal process by the rubbing of peaks to produce a smooth and shiny surface with a significant specular reflection [5].

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The process of polishing with an abrasive wheel leads to many undesirable surface defects. During the polishing process, the micro sized abrasive grains which are continuously in contact with the workpiece are generally blunted due to the friction; therefore, the forces and thickness of the metamorphic layer are increased to produce burning effects on the machined surface. Moreover, the removed micro chips from the surface during polishing process are accumulated between the abrasive grains reduce the efficacy of the abrasive wheels [6]. The generated surface textures are consisting of many marks and scratches by the scooping and ploughing actions of the abrasive particles. On the other hand, chemical polishing processes have also several limitations including delaminating at weak interfaces, corrosive attacks from slurry and chemicals stress cracking [7]. Apart from the abrasive wheel, chemical mechanical [8-10], magnetic compound fluid slurry [11,12], phosphate laser glass polishing [13], dynamic friction polishing processes [14], diamond pastes are the most frequently used abrasives to obtain the desired mirror-like glossy and smooth surfaces [15-17]. Steel mirror surfaces can be achieved by different methods such as diamond tool turning, grinding and polishing. On the other hand some kind of dental nanocomposites can be polished by diamond paste polishing [18]. The aim of this study was to determine the influence of diamond paste finishing parameters on surface roughness and mirror reflectivity of polished mold steel of SKD 61. For this purpose, the rotation speed of workpiece, the polishing time and axial loads were changed between a certain interval to explore their effects on polishing qualities

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Experimental Setup (Deney Düzeneği)

Prior to the polishing experiments, the specimens were cut and machined with a ceramic tool under high rpm turning conditions to eliminate the surface tracks. Thereafter, sample surfaces were ground with 80 to 1200 mesh sandpaper until the tool marks of the abrasive grains are completely removed from the surface. To avoid the surfaces overheating and absorption of paste particles, a diamond paste was used with granulometry finer than 3 microns. The SKD 61 mold steel with a hardness of 20 HRC was used as the test material. The experiments were conducted using a CNC milling machine with a maximum speed of 3500 rpm. The experimental setup is given in Figure 1.

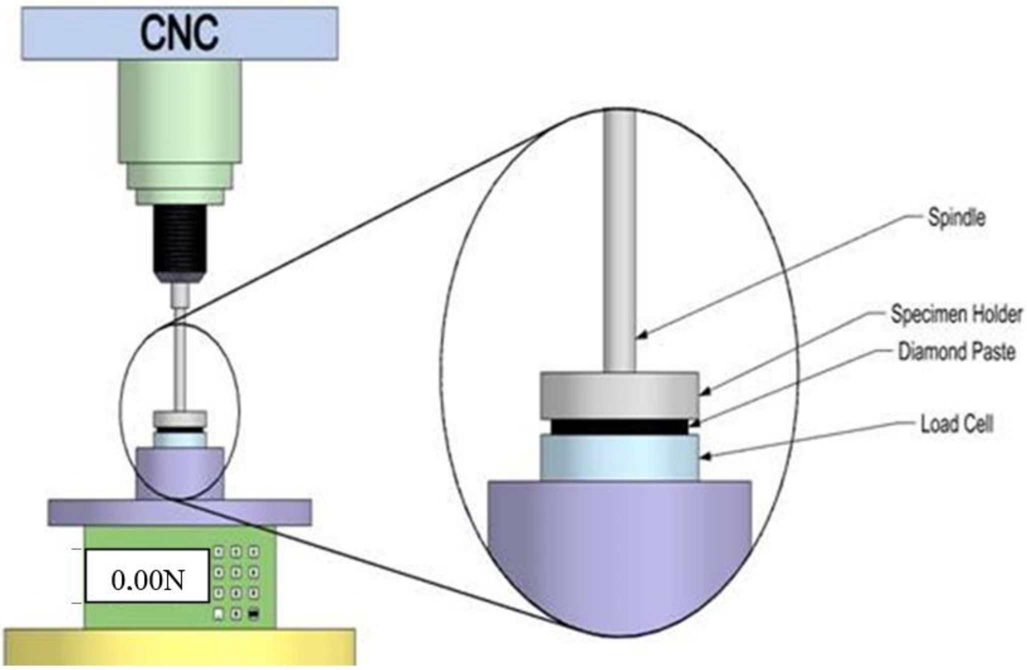

Figure 1. Experimental setup (Deney düzeneği)

As shown in Fig. 1, the specimens were connected to the spindle. The spindle is controlled down in the z axis and pressure is applied to the load cell located on the base of the machine. The spindle is controlled by moving the desired axial load is provided and the experiments were started. Between each polishing step, the black residue remaining on the samples were removed by gently rubbing them off in an alcohol bath with the same type of polishing silk cloth just used. The polishing quality was quantified in terms of the average surface roughness (Ra) and surface reflectivity. The average surface roughnesses of the samples were measured by using a Mitutoyo Surftest SJ–201 portable device. The specular reflection of the mirror surfaces was determined by measuring the angle between incoming laser light with respect to the surface normal. In experimental studies, the most efficient parameters which detected by previous researches, spindle speed (rpm), axial load (N) and polishing time (min.) were chosen as variable parameters. With these polishing parameters and their levels, a Taguchi L27 orthogonal array was chosen for the experimental design. The experimental parameters and their levels are provided in Table 1 and the sequence of the experiments is provided in Table 2. The surface properties of polished samples were investigated by atomic force microscope (AFM), in contact mode. 1 Hz scan rate and 256 x256 resolutions were used to obtain topography on a 40x40 μm^2 scanning area. A Shimadzu UV–2600 spectrophotometer was used to measure the specular reflectance of samples.

Table 1. Polishing parameters and their factor levels (Parlatma parametreleri ve faktör seviyeleri)

Parameter	**Level 1**	**Level 2**	**Level 3**
Spindle speed (rpm)	1000	1500	2000
Axial load (N)	5	10	15
Polishing time (min)	2	4	6

Table 2. Experimental layout using an L27 orthogonal array and measurement results (L27 ortogonal deney dizisi ve ölçüm sonuçları)

Exp. No	**Spindle Speed (rpm)**	**Axial Load (N)**	**Polishing Time (min)**	**Surface Roughness**	**Specular Reflectance (%)**
1	*1500*	15	6	0.0320	12.322
2	1500	15	4	0.0310	12.228
3	1000	10	6	0.0486	9.859
4	2000	15	2	0.0226	15.502
5	2000	15	4	0.0222	16.121
6	1000	5	2	0.1000	9.386
7	1000	15	2	0.0450	10.153
8	1500	10	6	0.0340	11.979
9	1500	10	4	0.0350	11.956
11	1500	5	2	0.0400	11.166
12	100	5	6	0.0610	9.608
13	2000	15	6	0.0210	17.625
14	1000	15	6	0.0403	11.067
15	2000	5	2	0.0300	12.506
16	1500	5	6	0.0363	11.313
17	2000	10	2	0.0260	12.799
18	1000	10	2	0.0593	9.704
19	1500	15	2	0.0340	12.179
20	1000	10	4	0.0500	9.741
21	1500	5	4	0.0376	11.222

22	2000	10	4	0.0260	12.799
23	2000	10	6	0.0256	12.901
24	1500	10	2	0.0360	11.686
25	2000	5	4	0.0280	12.594
26	1000	15	4	0.0410	11.041
27	1000	5	4	0.0860	9.566

3. EXPERIMENT AND OPTIMIZATION RESULTS (DENEY VE OPTİMİZASYON SONUÇLARI)

3.1. Reflection properties of polished specimens (Parlatılmış numunelerin yansıma özellikleri)

The reflectance of a surface can be measured by the means of internal or external reflectances. The radiation beam passes through a crystal in the structure of the material for internal reflectance measurements; however the specimen surface directly reflects the beam in external reflectance measurements [4,19,20]. External reflectance can be categorized into two groups: diffuse and specular reflectances (SR). Mirror –like surfaces reflects the concentrated lights around the specular angle due to very low surface roughness values. As the surface roughness increases, reflections become increasingly diffuse, and the surface appears matt/dull. SR is a more useful and nondestructive way to study the mirror- like reflection characteristics of the machined/polished metal surfaces applied in industry. In this measurement, the angle of incidence is equal to the reflection angle of radiation quantity of light deflection is significantly depends on the surface roughness of the samples [21]. As previously reported [22], the light scattering by the surface roughness of the mirror materials is directly related to the wavelength and incidence angle. The measured specular reflectance spectra for the all polished specimens are shown in Fig. 2. A sharpen reflectance peak losses in the wavelength range around 200 nm can be seen for all samples. The reflectance distribution is gradually decreasing at a longer wavelength for all polished surfaces. This result is coherent with the light cattering theory of mirror surfaces which shows an inversely proportional relation between wavelength and scattering distribution width [23].

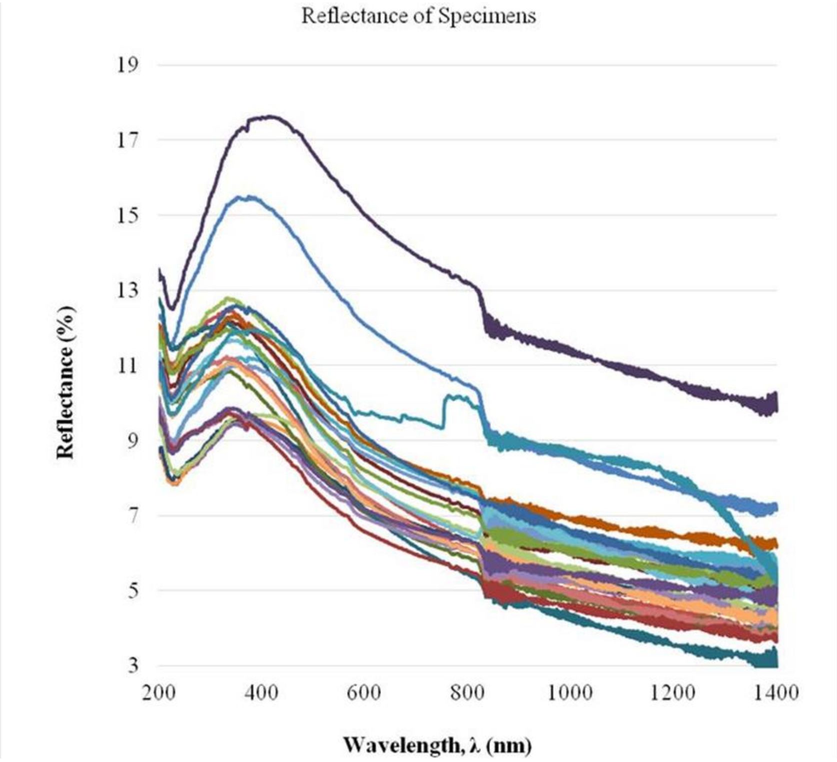

Figure 1. Plotting of the specular reflectance versus wavelengths for polished specimens (Parlatılmış numunlere ait dalga boyuna göre speküler yansıma diyagramı)

When reflectance values are evaluated with the surface roughness results given in Table 2, the 13th experiment with lowest surface roughness (Ra=0.021) gives the highest reflectance (17.625%) and a linear relation between surface roughness and reflectance was recorded. The 6th experiment gave the worst results by means of surface roughness and reflectance (Ra=0.1; Reflectance=9.386%).

2D and 3D AFM images of 13th and 6th samples are given in Fig. 3a and Fig. 3b respectively. As clearly seen from Fig. 3, the 2D surface of polished 6th specimen consists of some furrowed and micro ploughed topography which causes the reduction of reflectance. 13th sample showed relatively smoother surface with a low height of peak to valley and swiped lines and grooves. On the other hand, Fig. 4 shows the picture of these specimen surfaces which is reflecting the word "FUTF" representing "Firat University Technology Faculty". A good and clear reflection of "FUTF" can be observed for the 13th sample's center zone and the surface of this sample can be considered as mirror-like. However, the outer annual surface of 6th sample seems to blurred and do not give a clear reflection of "FUTF".

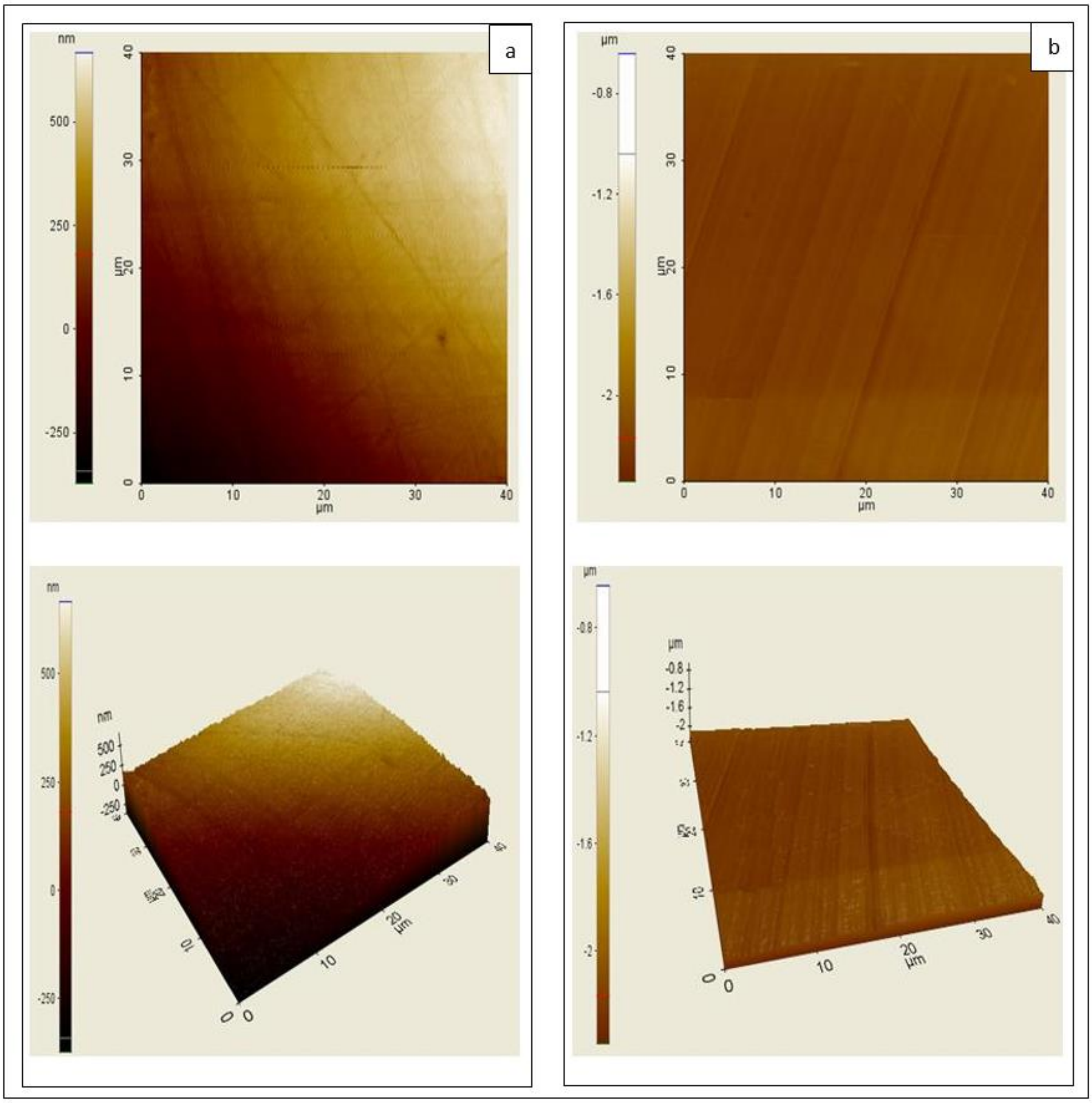

Figure 3. (a) 2D and 3D AFM image of 13th sample (b) 2D and 3D AFM image of 6th sample ((a) 13.numunenin 2 ve 3 boyutlu AKM görüntüsü, (b) 6. numunenin 2 ve 3 boyutlu AKM görüntüsü)

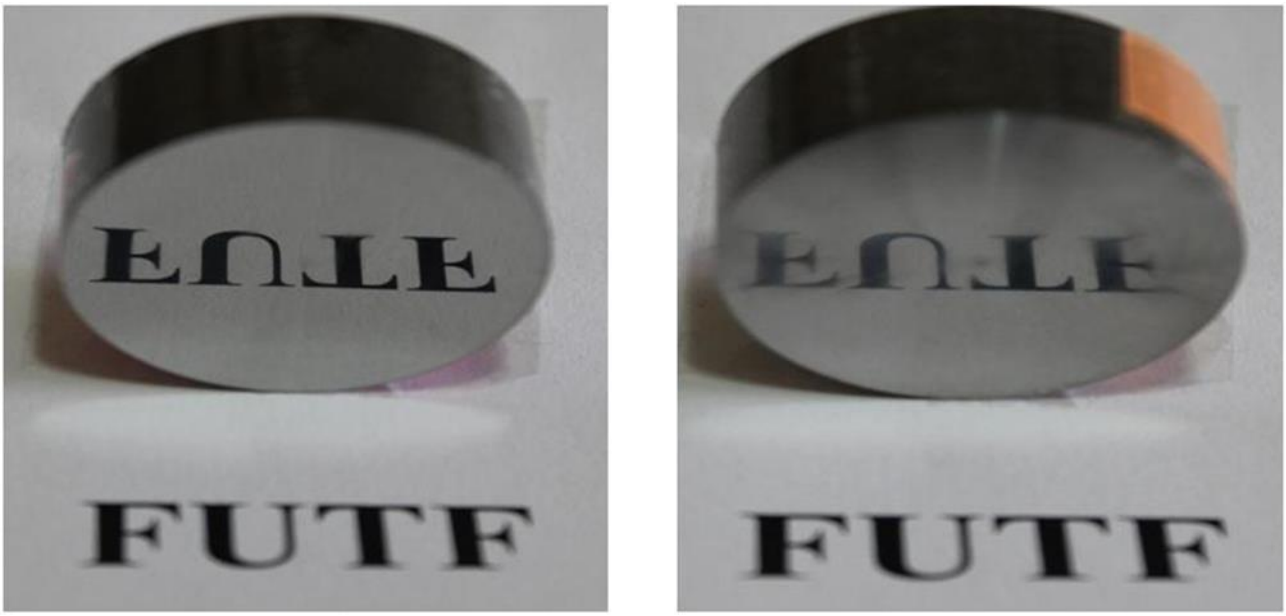

Figure 4. Reflection of 6th and 13th specimens after diamond paste polishing process (6 ve 13. numunelerin elmas pastayla parlatma işleminden sonraki yansıma görüntüleri).

A uniform surface roughness profile was recorded for 13th sample along the measurement length as shown in Fig. 5-a, while the profile of 6th sample was not regular (Fig.5-b). This sample was polished at low axial loading and polishing time conditions (see Table 3). The diamond paste micro particles between the polishing silk and workpiece surface are easily ablated from the center of the wheel to the outward due to the weak loading force. Therefore, the polishing effects of these particles on the specimens were less than the center region owing to the dreg of these particles on the side of polishing wheel.

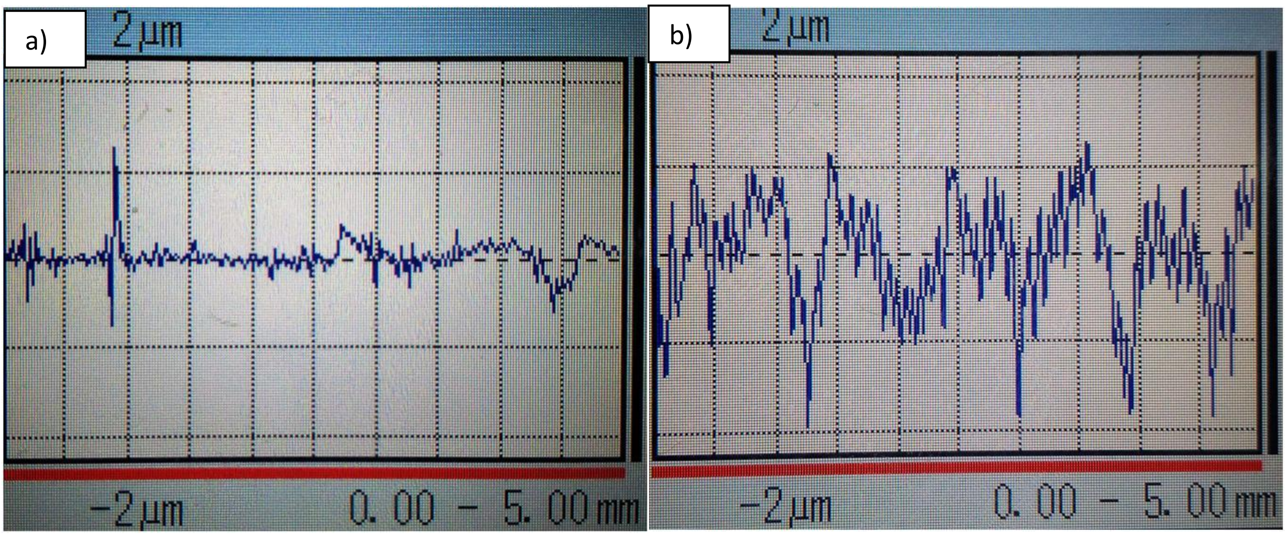

Figure 5. a)Surface roughness profile of 13th sample, b) Surface roughness profile of 6th sample (a) 13. numunenin yüzey pürüzlülük profili, b) 6. numunenin yüzey pürüzlülük profili)

3.2. Analysis of Results (Sonuçların Analizi)

The experimentally gathered data through Taguchi L27 orthogonal array was carried out MINITAB R15 package program for analyzing the results. In order to determine the statistical effects of each polishing parameter on the surface roughness and specular reflectance, the analysis of means (AOM) and analysis of variance (ANOVA) was performed to the study. The analysis was carried out at 95% confidence level (or P – values are less than 0.05). Main effects plots were used to see the effect of the polishing parameters on both surface roughness and specular reflection. The main effects of polishing parameters on the surface roughness are shown in Fig. 6. From this graph, the surface was decreased from 0.059 to 0.035µm when the revolution speed increases 1000 to 1500 rpm and it gets better with 2000rpm. Similar trends in the change of surface roughness with the axial load and polishing time were observed with a more slightly decrease.

Table 3. ANOVA results for surface roughness (Yüzey pürüzlülükleri için ANOVA sonuçları)

Polishing parameter	Degree of freedom	Sum of squares	Mean square	F ratio	% Cont.	P value
Spindle speed	2	0.005393	0.002696	17.93	59.91	0.000
Axial Load	2	0.001443	0.000721	2.29	16.02	0.123
Polishing Time	2	0.000244	0.000122	0.33	2.71	0.720
Error	2	0.00236	0.00118	-	21.36	-
Total	8	0.00944	-	-	100	-

Table 3 shows the result of ANOVA analysis for surface roughness. The percentage contribution of each polishing factor on the surface roughness, indicating their degree of statistical influence on the results is listed in this table. The spindle speed was found the most efficient factor with the maximum contribution (59.91%). Axial loading was the second ranking factor on the surface roughness with a contribution value of 16.02%. The statistical effects of axial loading and polishing time on the surface roughness were not significant because P values of them were greater than 0.05. The combination of highest levels of factors was found good on surface roughness. The main effect plots and ANOVA analysis results for specular reflectance are given in Figure 7 and Table 4, respectively. As seen from Fig.7, the specular reflectance was increased from 10.01% to 13.93% when spindle speed was increased from 1000 to 2000 rpm. This indicates approximately 28.14% increase in reflectance. Spindle speed was found again the most important factor on specular reflectance with the highest contribution of 66.56%. Axial loading and polishing time factors were followed by 20.07% and 0.93%.

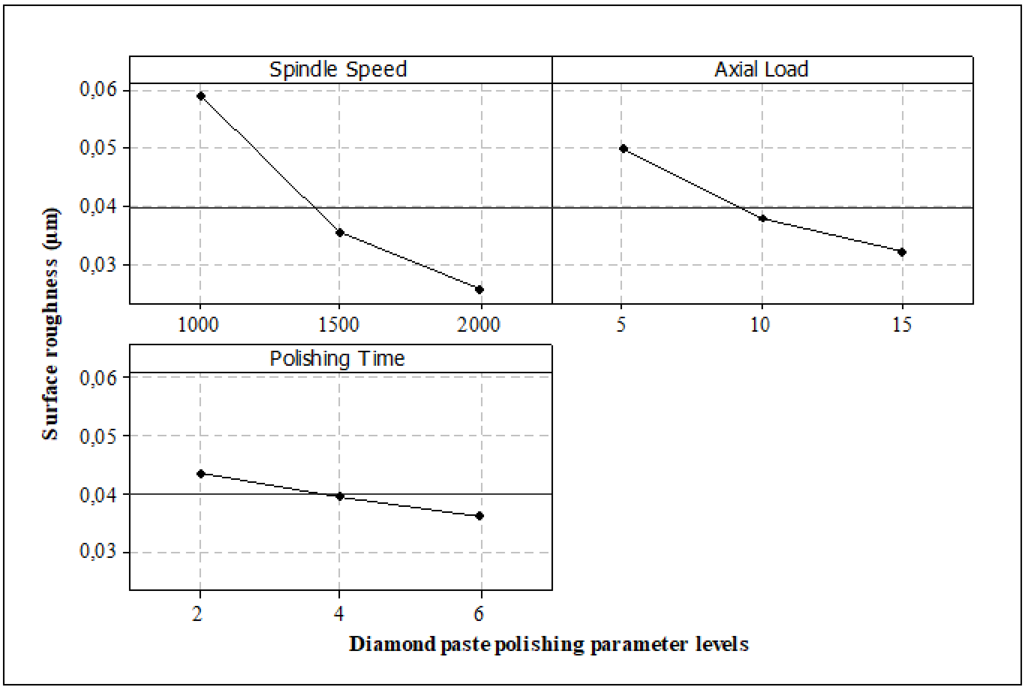

Figure 6. Main effects plot for surface roughness (Yüzey pürüzlülüğü esas etki grafiği) .

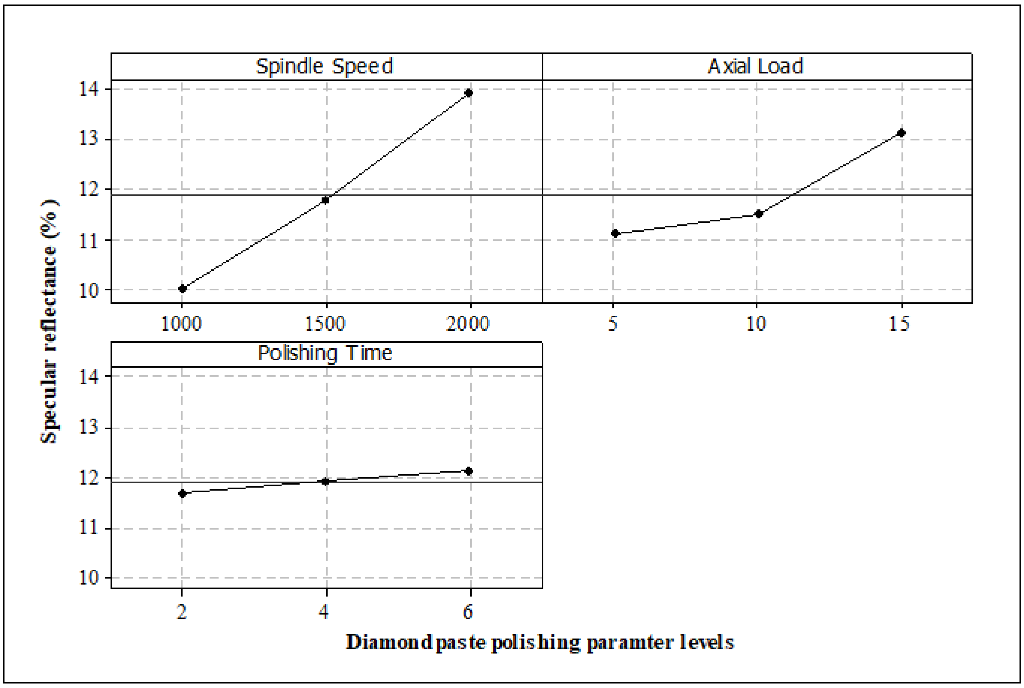

Figure 7. Main effects plot for specular reflectance (Speküler yansıma için esas etki grafiği)

Table 4. ANOVA results for specular reflectance (Speküler yansıma için ANOVA sonuçları)

Polishing parameter	Degree of freedom	Sum of squares	Mean square	F ratio	% Cont.	P value
Spindle speed	2	69.51	34.76	23.89	66.56	0.000
Axial Load	2	20.95	10.48	3.01	20.07	0.068
Polishing Time	2	0.97	0.49	0.11	0.93	0.894
Error	2	15.238	7.61	-	12.44	-
Total	8	106.668	-	-	100	-

On the other hand, regression analysis is performed to the study in order to determine the mathematical relationship between the polishing process parameters and surface roughness and specular reflectance. A linear model was constructed between the factors and responses. The regression equations for surface roughness and specular reflectance are as follow:

Surface roughness = 0.115 – 0.000034 Spindle Speed – 0.00176 Axial Load - 0.00184 Polishing Time
Specular reflectance = 3.53 + 0,00392 Spindle Speed + 0.203 Axial Load+ 0.116 Polishing Time

The R^2 values indicate that the predictors explain 74 and 85% of the variance in surface roughness and specular reflectance, respectively.

4. CONCLUSIONS (SONUÇLAR)

In this study, an experimental investigation was performed to consider surface roughness and specular reflectance in diamond paste polishing of SKD61 mold steel used in industry. The experiments were performed using an L27 Taguchi orthogonal array. Three important polishing parameters such as spindle speed, axial loading and polishing time were considered for the present research. The relative effects of each factor and combination of factors on responses were obtained by analysis of variance (ANOVA). Linear regression models were developed. The polished surfaces were also studied by using atomic force microscope (AFM). The following conclusion can be drawn:

1. The surface roughness was decreased with an increase in the factor level of polishing parameters, while the specular reflectance was tendency of increase at the same conditions.

2. According to the ANOVA results, the most important factor on both surface roughness and specular reflectance was found as spindle speed with 59.91% and 66.56%, respectively. Axial loading and polishing time were not statistically significant parameters on responses with lower P values.

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