İmalat Teknolojileri ve Uygulamaları
Cilt: 5, No: 3, 2024 (155-171)
Araştırma Makalesi
e-ISSN: 2717-7475

Manufacturing Technologies and Applications
Vol: 5, Issue: 3, 2024 (155-171)
Research Article
e-ISSN: 2717-7475

Analysis and Optimization of Process Parameters Affecting Form Errors and Surface Roughness in Milling of Aging-Treated AA 6063-T6 Free Form Surfaces

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ARTICLE

Received: *18.08.2024*
Accepted: *23.09.2024*

Keywords:
AA 6063-T6
Aging
Form error
Surface roughness
Optimization

ABSTRACT

This study aimed to examine the microstructure and hardness changes in AA 6063 T6 specimens that underwent an ageing procedure. The second portion involves the machining of free forms surfaces on specimens with varying microstructures and hardness. Four different tool paths, four different cutting speed (Vc), and four different feed rate (f) were employed in the machining of the surfaces. Statistical analysis were conducted to ascertain the optimal cutting parameters and their impact on the output parameters. The experimental design was designed based on the Taguchi L16 index. The form errors and surface roughness values acquired from the tests were analysed statistically using the Signal/Noise (S/N) ratio and analysis of variance (ANOVA) methods. The study found that the sample immersed in 2WQ solution had a minimum hardness value of 71.7 Hv1, whereas the sample aged for 18 hours had a maximum hardness value of 117.7 Hv1. Based on the investigation, it was determined that A4B1C4 yielded the most favourable cutting parameter in terms of form error and surface roughness. This refers to the utilisation of the TP4 tool path, a f of 0.04 mm per tooth, and a Vc of 105 m/min. Based on the data collected, the ANOVA analysis of the 18AQ sample revealed that the cutting parameters with the highest efficacy in minimising form error and surface roughness were a f of 51.18% and 59.07%, respectively. These values represent the optimum values for cutting parameters.

Yaşlandırma İşlemi Uygulanmış AA 6063-T6 Serbest Formlu Yüzeylerin Frezelenmesinde Form Hatalarının ve Yüzey Pürüzlülüğünü Etkileyen Proses Parametrelerinin Analizi ve Optimizasyonu

MAKALE BİLGİSİ

Alınma: *18.08.2024*
Kabul: *23.09.2024*

Anahtar Kelimeler:
AA 6063-T6
Yaşlandırma
Form hatası
Yüzey pürüzlülüğü
Optimizasyon

ÖZET

Bu çalışmanın amacı, yaşlandırma prosedürüne tabi tutulan AA 6063-T6 numunelerindeki mikroyapı ve sertlik değişimlerini incelemektir. İkinci kısım, farklı mikroyapı ve sertliğe sahip numuneler üzerinde serbest formlu yüzeylerin işlenmesini içerir. Yüzeylerin işlenmesinde dört farklı takım yolu, dört farklı kesme hızı (Vc) ve dört farklı ilerleme miktarı (f) kullanılmıştır. Optimum kesme parametrelerini ve bunların çıktı parametreleri üzerindeki etkilerini belirlemek için istatistiksel analiz yapılmıştır. Deneysel tasarım Taguchi L16 dizinine göre tasarlanmıştır. Testlerden elde edilen form hataları ve yüzey pürüzlülük değerleri, Sinyal/Gürültü (S/N) oranı ve varyans analizi (ANOVA) yöntemleri kullanılarak istatistiksel olarak analiz edilmiştir. Çalışmada, 2WQ çözeltisine daldırılan numunenin minimum sertlik değerinin 71.7 Hv1, 18 saat yaşlandırılan numunenin ise maksimum sertlik değerinin 117.7 Hv1 olduğunu bulmuştur. Yapılan inceleme sonucunda A4B1C4'ün form hatası ve yüzey pürüzlülüğü açısından en uygun kesme parametresini verdiği belirlenmiştir. Bu, TP4 takım yolunun, diş başına 0.04 mm'lik bir ilerleme hızının ve 105 m/dak'lık bir kesme hızının kullanılması anlamına gelmektedir. Toplanan veriler ışığında 18AQ numunesinin ANOVA analizi, form hatasını ve yüzey pürüzlülüğünü en aza indirmede en yüksek etkinliğe sahip kesme parametrelerinin sırasıyla %51.18'lik bir ilerleme hızı ve %59.07'lik bir ilerleme hızı olduğunu ortaya koymuştur. Bu değerler kesme parametreleri için optimum değerleri temsil etmektedir.

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To cite this article: Y. Çodur, B. Özlü, H. Demir, Analysis and Optimization of Process Parameters Affecting Form Errors and Surface Roughness in Milling of Aging-Treated AA 6063-T6 Free Form Surfaces, Manufacturing Technologies and Applications, 5(3), 155-171, 2024. https://doi.org/10.52795/mateca.1535125,

1. INTRODUCTION (GİRİŞ)

In recent years, they have been developing the aesthetics of the product by designing products in different forms and surfaces for customer demand and satisfaction in the production sector. In the global market, there are products that incorporate complex geometries, particularly in the manufacturing of injection molds and bending molds, within the aerospace, automotive, medical device, and precision machinery industries [1-3]. The increase in precision in the production of these products also causes the expenditure items to increase and, therefore the cost to increase. In order to reduce the increasing costs, to produce parts with the desired surface quality and geometric tolerances, it is necessary to optimize the tool path and cutting parameters. These parameters are the root cause of surface roughness and form errors. By optimizing them, we can effectively minimize potential errors, thereby reducing costs [3-5]. In the manufacturing sector, the production of products with free-form surfaces is both time-consuming and costly. Especially in the processing of parts with free forms on a CNC vertical machining center, more than 10,000 tool movements are observed. Therefore, the production of free-form surfaces is defined as an “error-prone” process [1]. As a result, it is essential to select and control the cutting parameters, cutting tool and tool path, which have a significant impact on the quality of the manufactured product, to minimize errors in surface roughness and free forms in the machining of these parts.

When the studies conducted in the literature on changes in surface roughness and form error as a result of machining different iron and non-ferrous materials are examined, Yaka et al. [6] the objective was to identify the optimal cutting parameters for achieving the lowest surface roughness on free-form surfaces when milling Al 7075-T6 alloy with various cutting parameters. As a result, the optimum processing parameters were determined as 220 m/min Vc, 1100 mm/min f, 0.5 mm step over and spiral machining. Furthermore, it was shown that augmenting the Vc resulted in a reduction of surface roughness, whilst increasing the f and step over led to a rise in surface roughness. The lowest surface roughness was measured on the spiral tool path. Öztürk et al. [7] an innovative corrective approach has been studied to improve the accuracy of estimating cutting force while milling 3D free-form surfaces by adjusting the calibration coefficient. The cutting force in the machining of 3D free-form surfaces is significantly influenced by the immediate inclination angle. In this study, a novel calibration technique has been created to consider the inclination angle at each cutter positioning point along the tool path. This approach is used for estimating cutting force and simulating 3D free-form surface machining. The values derived from the empirical investigation were juxtaposed with the simulation outcomes, leading to the conclusion that there was concurrence. Wei and Lin [8] a general analytical method systematic for machining free-form surfaces on CNC machines and a post-processor to obtain NC codes have been developed. The developed method includes 5 steps: 1-Finding surface equations, 2-Curvature analysis, 3-Cutting tool selection, 4-Calculation of linear incremental kinematic error and 5-Calculation of tool path distance. As a result, it has been determined that the tool path length decreases when the general analytical method is used in machining free-form surfaces. Yaka et al. [9] they focused on determining the most suitable cutting conditions that provide the lowest form error in milling Al 7075-T6 alloy at different cutting parameters. The study determined that the most effective cutting parameters for minimizing form error include a Vc of 140 m/min, a f of 800 mm/min, a step over of 0.5 mm, and the use of a parallel machining method. Furthermore, this investigation uncovered that the primary elements influencing the form error are step over, Vc, f, and machining techniques, listed in order of significance. Hartomacioğlu [10] the effects of machining strategies and cutting tool geometry on surface roughness and form error in the milling of Al7075 alloy were investigated. As a result, they reported that machining strategies and cutting tool geometry have a significant effect on surface roughness and form error. They stated that there is very little difference between the statistical analysis and experimental results. Çelik et al. [10] the effect of cutting parameters on form error in the machining of AA 5083-H111 alloy was investigated experimentally and statistically. As a result of the measurements, the optimum cutting parameter was determined as 5 mm wall thickness, 0.05 mm/tooth f, and 160 m/min Vc. They reported that laser scanning measurements were higher than three-dimensional coordinate measurement results. As a result of the literature research, it has been seen that there are very few studies investigating the effects of microstructure, hardness, cutting parameters and tool path on surface roughness and form error in the milling of AA 6063-T6 alloy after the aging process, which is used in various industries such as aviation, automotive and marine.

Hence, this study primarily focused on examining the alterations in microstructure and hardness of AA 6063-T6 alloy samples that underwent the ageing process. The second phase of the study involved evaluating the form errors and surface roughness that occurred during the machining of free-form surfaces on samples with varying microstructure and hardness. This evaluation was done by using varied tool paths and cutting parameters. Ultimately, statistical analyses were conducted to ascertain the most suitable tool path and cutting parameters, as well as the impact of these parameters on output parameters.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Experimental Setup (Deney Düzeneği)

This study selected commercially available AA 6063-T6 with dimensions of 40x90x1000 mm as the workpiece. The chemical composition of AA 6063-T6 alloy is given in Table 1.

Table 1. Chemical composition of AA 6063-T6 alloy (AA 6063-T6 alaşımının kimyasal bileşimi)

	Elements								
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Cr**	**Ti**	**Al**
Wt%	0.52	0.35	0.05	0.1	0.6	0.08	0.1	0.15	Bal.

The workpiece was cut to 40x90x140 mm dimensions, and samples were prepared for the ageing process. Table 2 shows the ageing process and coding applied to the samples.

Table 2. Ageing process and coding applied to AA 6063-T6 samples (AA 6063-T6 numunelerine uygulanan yaşlandırma işlemi ve kodlama)

Serial No.	**Aging process**	**Sample Codes**
1	As-Received	AR
2	520°C, 2 h Water Quenched	2WQ
3	155 °C, 5 h Air Quenched	5AQ
4	155 °C, 10 h Air Quenched	10AQ
5	155 °C, 18 h Air Quenched	18AQ
6	155 °C, 22 h Air Quenched	22AQ

For microstructure examinations, the aged samples were first moulded with cold resin and polished with 200, 400, 600, 800, 1200, 1500 and 2500 mesh water sandpaper until the surface scratches were removed. Then, the samples were subjected to a polishing process with 3 µm and 1 µm felt. Samples were cauterized in a Keller solution consisting of 95 ml of pure water, 2.5 ml of nitric acid (HNO3), 1.5 ml of hydrochloric acid (HCl), and 1 ml of hydrofluoric acid (HF) for 5 to 15 seconds. The cauterized samples were cleaned with water and then methanol. The samples microstructural examinations were conducted using a Nikon Epiphot optical microscope. Their hardness measurements were performed with a SHIMADZU brand microhardness tester. Hardness measurements were carried out by applying Hv1 (9.807 N) load for 10 seconds. Each sample was measured ten times. Hardness values were determined by calculating the arithmetic averages of the hardness measurements.

The design of the part to be processed for examination of form errors was made in the Pro Engineer program. The visual and dimensions of the design are given in Figure 1. The literature made the part design. In the same program, tool paths and CNC codes were extracted for machining on the DMG MORI M1 CNC machining centre.

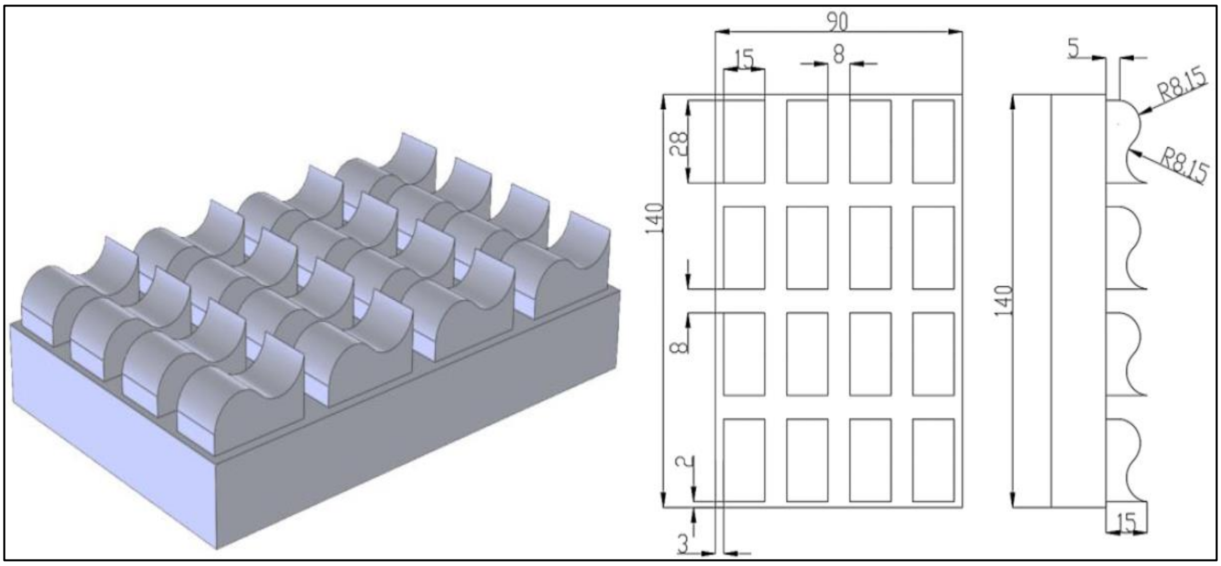


Figure 1. Design and dimensions of the workpiece (İş parçasının tasarımı ve boyutları)

Four different tool paths were selected for machining. These were determined as parallel to the form axis (TP1), 45° to the form axis (TP2), spiral from inside to outside (TP3) and perpendicular to the form axis (TP4). In the study, the tool path names were coded to prevent confusion. The tool path image is given in Figure 2.

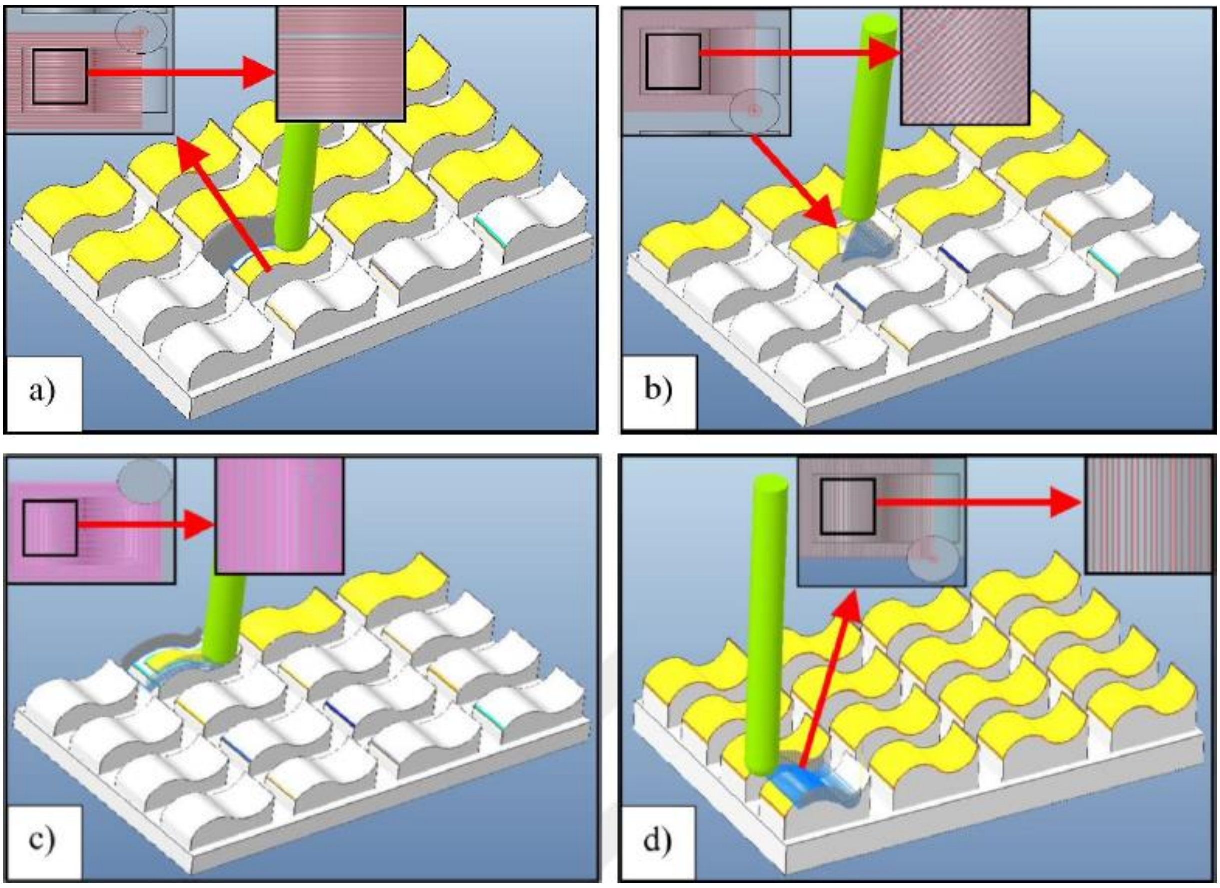
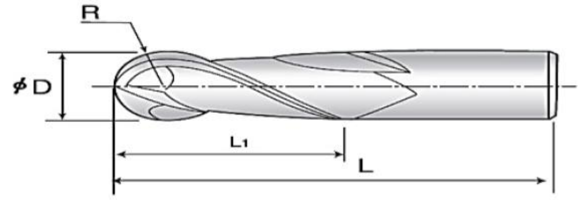


Figure 2. Tool paths used in the experiments. a) Parallel to the form axis, b) 45° to the form axis, c) Spiral from inside to outside, d) Perpendicular to the form axis. (Deneylerde kullanılan takım yolları. a) Form eksenine paralel, b) Form eksenine 45° açıyla, c) İçeriden dışarıya doğru spiral, d) Form eksenine dik.)

Machining experiments were carried out on a DMG MORI M1 CNC machining centre with a Siemens control unit with a power of 13 kW and a maximum speed of 12000 rpm. The study selected a solid 4BN1000DD022A standard uncoated carbide ball nose end mill as the cutting tool. Visual and technical information about the end mill is shown in Table 3.

Table 3. Visual and technical information of the end mill (Uç frezenin görsel ve teknik bilgileri)

Cutting diameter, D *(mm)*	10
Overall length, L *(mm)*	100
Depth of cut maximum L_1 *(mm)*	26
Profile radius, R *(mm)*	5



Mitutoyo Surface SJ-210 model surface roughness device was used to measure the roughness values of the processed surfaces. The roughness value of the surface was determined by measuring from 4 different points of the processed form surfaces and calculating the arithmetic average of these results. DEA GLOBAL 12.22.10 brand coordinate measuring device was used to measure form errors. During the measurement of form errors, the workpieces were fixed to the plate of the CMM device with various apparatus. After the workpiece is fixed to the plate, the next step is to start the measurement process. Here, the solid model of the workpiece was loaded into the PC-DMIS CAD software used for controlling the CMM device in IGES format. Subsequently, probes used during the measurement process were selected and calibrated. Following this, reference points necessary for measuring the samples were established. In the next stage, points were determined by touching the surfaces on the samples that created the elements to be measured. During the measurement, 6 points were measured from each surface. The measurement results were reported in the PC-DMIS software. Form errors were determined by matching the CMM results with the design measurements.

The target of the parts produced by machining is to produce low-cost and high-quality products in a short time. For this purpose, optimum values of input parameters used during processing must be found. One of the optimization methods developed to achieve this target is the Taguchi method. The Taguchi method uses orthogonal arrays to significantly reduce the number of experiments and minimize the effects of uncontrollable factors. In this study, quality features for AA 6063-T6 samples were determined as form errors and surface roughness. The cutting parameters to be considered in the study were determined as tool path, Vc and f. The cutting parameters and levels to be used in the processing of each sample are given in Table 4. Since the aim of this study is to minimize form errors and surface roughness, the "Smallest Best" approach given in Equation 1 was used.

$$S/N = -10 \log 1/n \left(\sum y^2\right) \quad (1)$$

In Equation 1, n represents the number of experiments performed, and y represents the measured value. The Taguchi L16 orthogonal array was chosen to identify the optimal values of cutting parameters and evaluate their impact. Furthermore, the studies involved a depth of cut of 0.5 mm and step over of 0.3 mm.

Table 4. Control factors and levels used in the experiments (Deneylerde kullanılan kontrol faktörleri ve seviyeleri)

Symbols	**Cutting parameters**	**Units**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
A	Tool Path	-	TP1	TP2	TP3	TP4
B	Feed rate (f)	*(mm/tooth)*	0.04	0.08	0.12	0.16
C	Cutting speed (Vc)	*(m/min)*	60	75	90	105

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

3.1. Evaluation of Microstructure and Hardness Results (Mikroyapı ve Sertlik Sonuçlarının Değerlendirilmesi)

This part of the study examines the microstructure and hardness changes of AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples prepared after the ageing process. Figure 3 shows the samples' microstructure images, and Figure 4 shows the differences in hardness values.

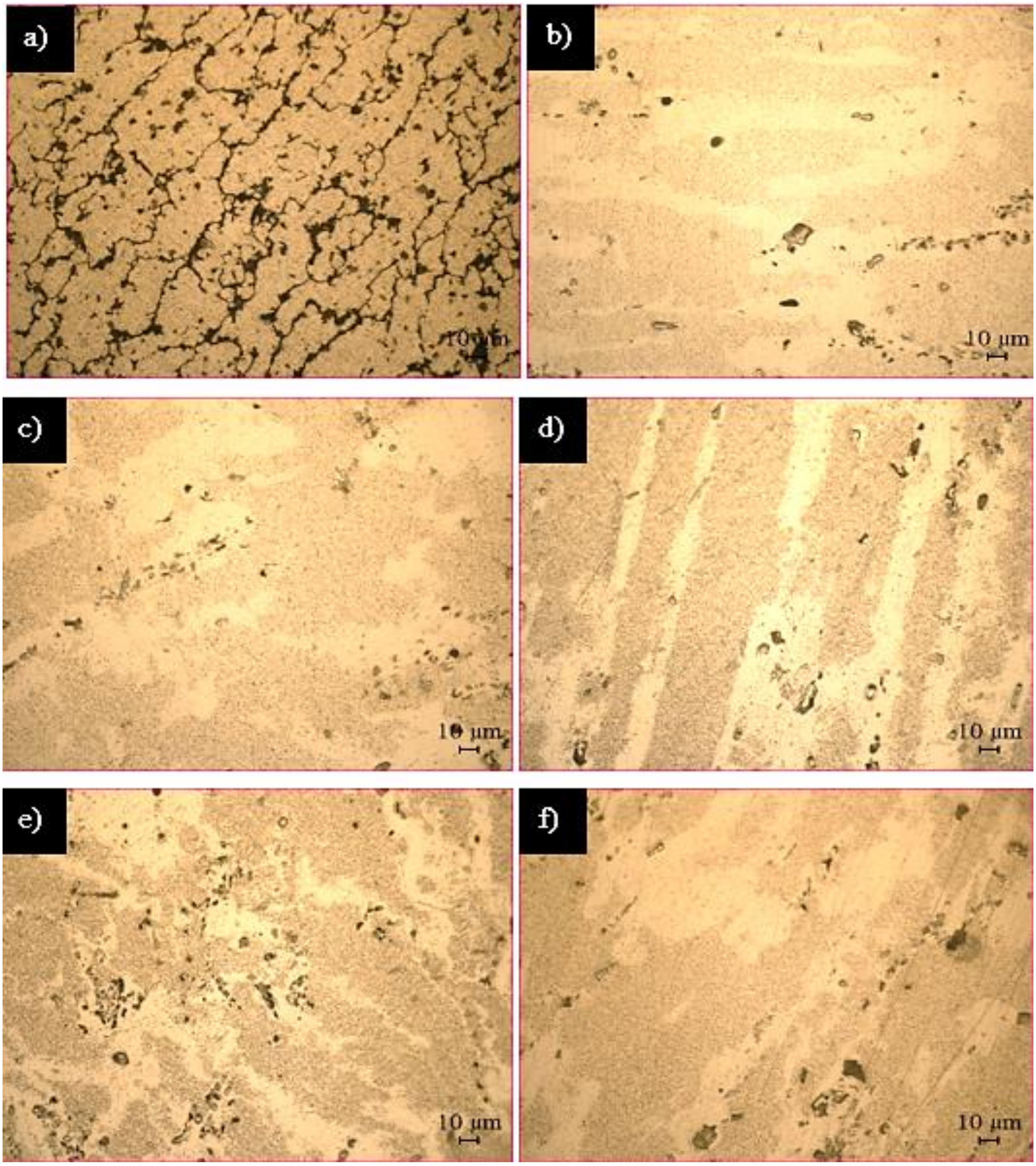


Figure 3. Microstructure images of samples of AA 6063 T6 aluminium alloy; a) AR, b) 2WQ, c) 5AQ, d) 10AQ, e) 18AQ and f) 22AQ

When the microstructure of the AR sample belonging to AA 6063-T6 is examined in Figure 3-a, it is seen that the grains are distributed homogeneously within the structure. When the microstructure of the 2WQ sample is examined in Figure 3-b, it is seen that the precipitates in the microstructure of the AR are dissolved, and saturated structures are formed. In addition, it is seen that the microstructure of the 2WQ sample is more coarse-grained than the microstructure of the AR. In the 2WQ sample, the dissolution of solutions and the formation of coarse grains facilitate dislocation movement, decreasing the strength of the material [11]. When the microstructures of the 5AQ, 10AQ and 18AQ samples are examined in Figure 3-c-d-e, the amount of precipitate increases, especially in the 18AQ sample, due to the increase in the aging time. It is also observed that a more homogeneous structure is formed with the increase of the ageing period. The homogeneous distribution of small and medium-sized precipitates seen in the microstructure of the 18AQ sample has been reported to play an important role in increasing the strength of the sample [12,13]. When the microstructure of the 22AQ sample is examined in Figure 3-f, it is seen that the grain size increases again with the increase in ageing time and the grain boundaries become more distinct. This parallels the literature research that shows that an increase in grain size causes a decrease in hardness [14].

The hardness of the AR sample used in the experiments has been measured as 113 Hv1 (Figure 4). The hardness of the 2WQ sample taken into solution decreased by 33% to 75.7 Hv1. It has been reported that this decrease in the hardness of the 2WQ sample taken into solution compared to the AR sample will decrease the hardness due to the dissolution of AR in the solution process [15]. Then, an increase in hardness values has been observed in parallel with the increase in ageing time in 5AQ, 10AQ and 18AQ samples. The highest hardness has been measured in the 18AQ-aged sample with a hardness value of 133 Hv1. The increase in hardness can be attributed to the diffusion-assisted mechanism and the hindrance of dislocation movement by impurity atoms, namely foreign particles of the second phase. This is due to the high void concentration that occurs in the material after undergoing solution treatment at 520 °C. It has been shown that when the ageing time and temperature increase, the density in the Guinier-Preston (GP) region and the degree of irregularity in the lattices lead to an increase in the mechanical characteristics of the aluminium alloy [16].

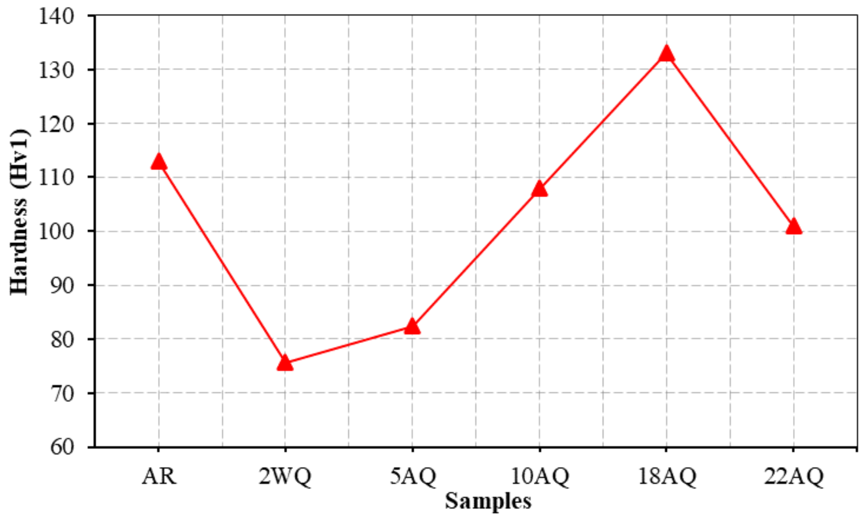


Figure 4. Hardness results of samples of Al 6063 T6 alloy (Al 6063 T6 alaşımı numunelerinin sertlik sonuçları)

The hardness of the 22AQ sample with the highest ageing time is 101 Hv1. It has been reported that as the ageing time increases, the precipitates in the microstructure interact with each other, decreasing the number of precipitates and increasing their size [17,18]. Accordingly, it has been stated that dislocation movements due to increased precipitate size cannot be prevented and will decrease hardness [15].

3.2. Evaluation and Statistical Analysis of Form Error (Form Hatasının Değerlendirilmesi ve İstatiksel Analizi)

The form error changes obtained from milling the aging-treated AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples with different tool paths and cutting parameters have been evaluated. Furthermore, the signal-to-noise ratio (S/N ratio) has been computed to assess the impact of different tool paths and cutting parameters on the form error. The application of Analysis of

Variance (ANOVA) has been used to ascertain the interaction between different tool paths and cutting parameters.

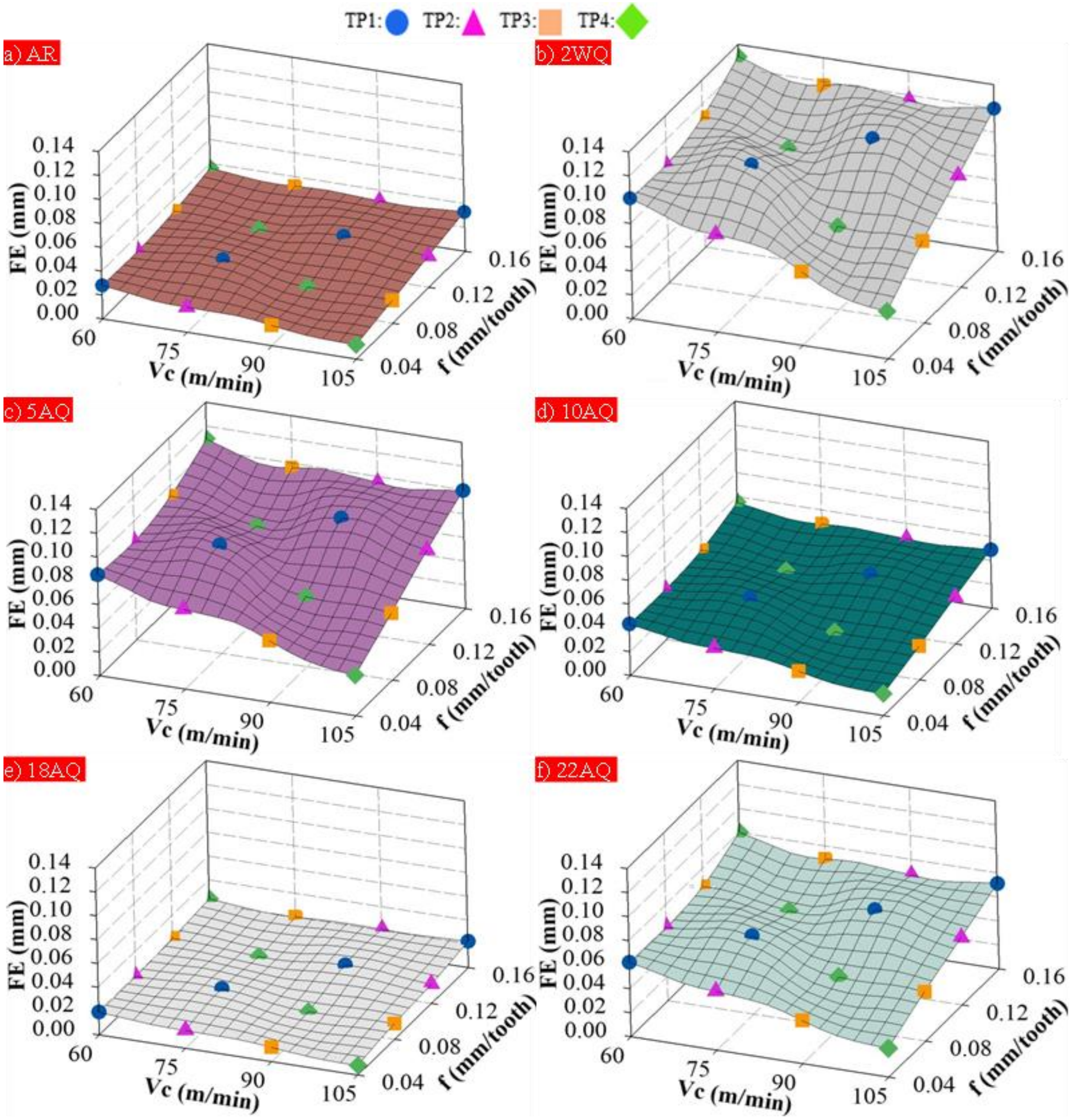


Figure 5. Differences in form errors depending on tool paths and cutting parameters (Takım yollarına ve kesme parametrelerine bağlı olarak form hatalarındaki farklılıklar)

The differences in form errors obtained from milling the AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples with different tool paths and cutting parameters are shown in Figure 5. The AR sample was machined using the TP4 tool path, with a f of 0.04 mm/tooth and a Vc of 105 m/min. The minimal form error measured was 0.012 mm. By augmenting the f by 0.16 mm/tooth while maintaining the same tool path and reducing the Vc to 60 m/min, the form error experienced a 200% rise, reaching 0.036 mm. The minimum error recorded was 0.04 mm when the 2WQ sample, which had a 27% decrease in hardness compared to the AR sample, was machined using the TP4 tool path, a f of 0.04 mm/tooth, and a Vc of 105 m/min. The maximum form error value was reached among the experiments conducted with a form error of 0.13 mm by increasing the f by 0.16 mm/tooth in the same tool path and decreasing the Vc to 60 m/min. It has been observed that the 5AQ and 10AQ samples, which exhibited increased hardness with an increase in ageing time, also showed a tendency for reduced form error. In the conducted study, the most significant finding was that the 18AQ sample, which had a hardness of 133 Hv1 after 18 hours of ageing, exhibited the lowest form error of 0.008 mm when machined using the TP4 tool path at a f of 0.04 mm/tooth and a Vc of 105 m/min. This value is the lowest form error obtained in all samples and experiments. It has been determined that with the increase in ageing time, the hardness of the 22AQ sample decreased to 133 Hv1, leading to a subsequent increase in form error. The study found that when the Vc and f increased, the occurrence of form error decreased. When the effects of the tool path on the form error were examined, the minimum form error was obtained in the tool path with the machining strategy perpendicular to the form axis. In contrast, the maximum form error was observed in the tool path with the machining strategy parallel to the form axis. Another point that attracted attention during the form error measurements was that the maximum form errors occurred where the tool climbed the ramps on the form.

If we evaluate the conditions affecting the form error results in general, it is known that machinability improves with increasing the hardness of aluminium. The high ductility of aluminium with low hardness increases the tendency to stick to the cutting tool during processing. It is thought that this will increase form errors [16]. According to the literature, cutting forces decrease as Vc increases and feed amount decreases [19]. Moreover, the anticipated drop in cutting forces is predicted to diminish tool deflection, hence leading to a reduction in form error.

As a result of the experiments, the form errors and S/N ratios of AR, 2WQ, 5AQ, 10AQ, 18AQ, and 22AQ samples are given in Table 4. As a result of milling experiments, the average form errors of AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples 0.026 mm, 0.096 mm, 0.079 mm, 0.040 mm, 0.018 mm and 0.057 mm, respectively, and the average S/N ratios were calculated as 31.947 dB, 20.745 dB, 22.357 dB, 28.348 dB, 35.456 dB and 25.232 dB, respectively.

Table 4. Experimental results and S/N ratios. (Deneysel sonuçlar ve S/N oranları.)

Test Id	AR (mm)	AR S/N Ratio (dB)	2WQ (mm)	2WQ S/N Ratio (dB)	5AQ (mm)	5AQ S/N Ratio (dB)	10AQ (mm)	10AQ S/N Ratio (dB)	18AQ (mm)	18AQ S/N Ratio (dB)	22AQ (mm)	22AQ S/N Ratio (dB)
1	0.028	31.057	0.101	19.914	0.085	21.412	0.043	27.331	0.019	34.425	0.062	24.152
2	0.031	30.173	0.111	19.094	0.091	20.819	0.046	26.745	0.020	33.979	0.065	23.742
3	0.032	29.897	0.114	18.862	0.095	20.446	0.047	26.558	0.021	33.556	0.068	23.350
4	0.033	29.630	0.120	18.416	0.099	20.087	0.049	26.196	0.022	33.152	0.071	22.975
5	0.021	33.556	0.082	21.724	0.067	23.479	0.034	29.370	0.015	36.478	0.049	26.196
6	0.027	31.373	0.099	20.087	0.083	21.618	0.042	27.535	0.019	34.425	0.061	24.293
7	0.026	31.701	0.094	20.537	0.079	22.047	0.039	28.179	0.016	35.918	0.056	25.036
8	0.031	30.173	0.116	18.711	0.095	20.446	0.047	26.558	0.021	33.556	0.067	23.479
9	0.017	35.391	0.062	24.152	0.052	25.680	0.026	31.701	0.012	38.416	0.036	28.874
10	0.019	34.425	0.069	23.223	0.056	25.036	0.028	31.057	0.013	37.721	0.041	27.744
11	0.030	30.458	0.109	19.251	0.091	20.819	0.045	26.936	0.021	33.556	0.065	23.742
12	0.032	29.897	0.117	18.636	0.096	20.355	0.048	26.375	0.020	33.979	0.069	23.223
13	0.012	38.416	0.040	27.959	0.034	29.370	0.018	34.895	0.008	41.938	0.024	32.396
14	0.019	34.425	0.070	23.098	0.059	24.583	0.029	30.752	0.012	38.416	0.042	27.535
15	0.026	31.701	0.094	20.537	0.077	22.270	0.039	28.179	0.017	35.391	0.056	25.036
16	0.036	28.874	0.130	17.721	0.109	19.251	0.055	25.193	0.024	32.396	0.080	21.938

The S/N response table was used to analyze the effect of each cutting parameter on the form error. The S/N response table for the form error is given in Table 5. Table 5 shows the optimum levels of the cutting parameters for optimum form errors for each sample. The levels of the cutting parameters for the form error values of the samples are given in Table 5, and the graphs of these values are shown in Figure 6. When Table 5 and Figure 6 are examined, the optimum form error value was measured as 0.008 mm as a result of machining the AQ18 sample in the TP4 tool path, at a f of 0.04 mm/tooth and a Vc of 105 m/min.

Table 5. S/N response table for form error. (Form hatası için S/N yanıt tablosu.)

	Control Factors					
	A	B	C	A	B	C
	AR Sample			2WQ Sample		
Level 1	30.19	34.60	30.44	19.07	23.44	19.24
Level 2	31.70	32.60	31.33	20.26	21.38	20.00
Level 3	32.54	30.94	32.47	21.32	19.80	21.21
Level 4	33.35	29.64	33.54	22.33	18.37	22.53
Delta	3.16	4.96	3.10	3.26	5.07	3.29
	A	B	C	A	B	C
	5AQ Sample			10 AQ Sample		
Level 1	20.69	24.99	20.78	26.71	30.82	26.75
Level 2	21.90	23.01	21.73	27.91	29.02	27.67
Level 3	22.97	21.40	22.79	29.02	27.46	28.89
Level 4	23.87	20.03	24.14	29.75	26.08	30.08
Delta	3.18	4.95	3.36	3.05	4.74	3.33
	A	B	C	A	B	C
	18 AQ Sample			22 AQ Sample		
Level 1	33.78	**37.81**	33.70	23.55	27.90	23.53
Level 2	35.09	36.14	34.96	24.75	25.83	24.55
Level 3	35.92	34.60	35.99	25.90	24.29	25.81
Level 4	**37.04**	33.27	**37.18**	26.73	22.90	27.04
Delta	3.26	4.54	3.48	3.17	5.00	3.51

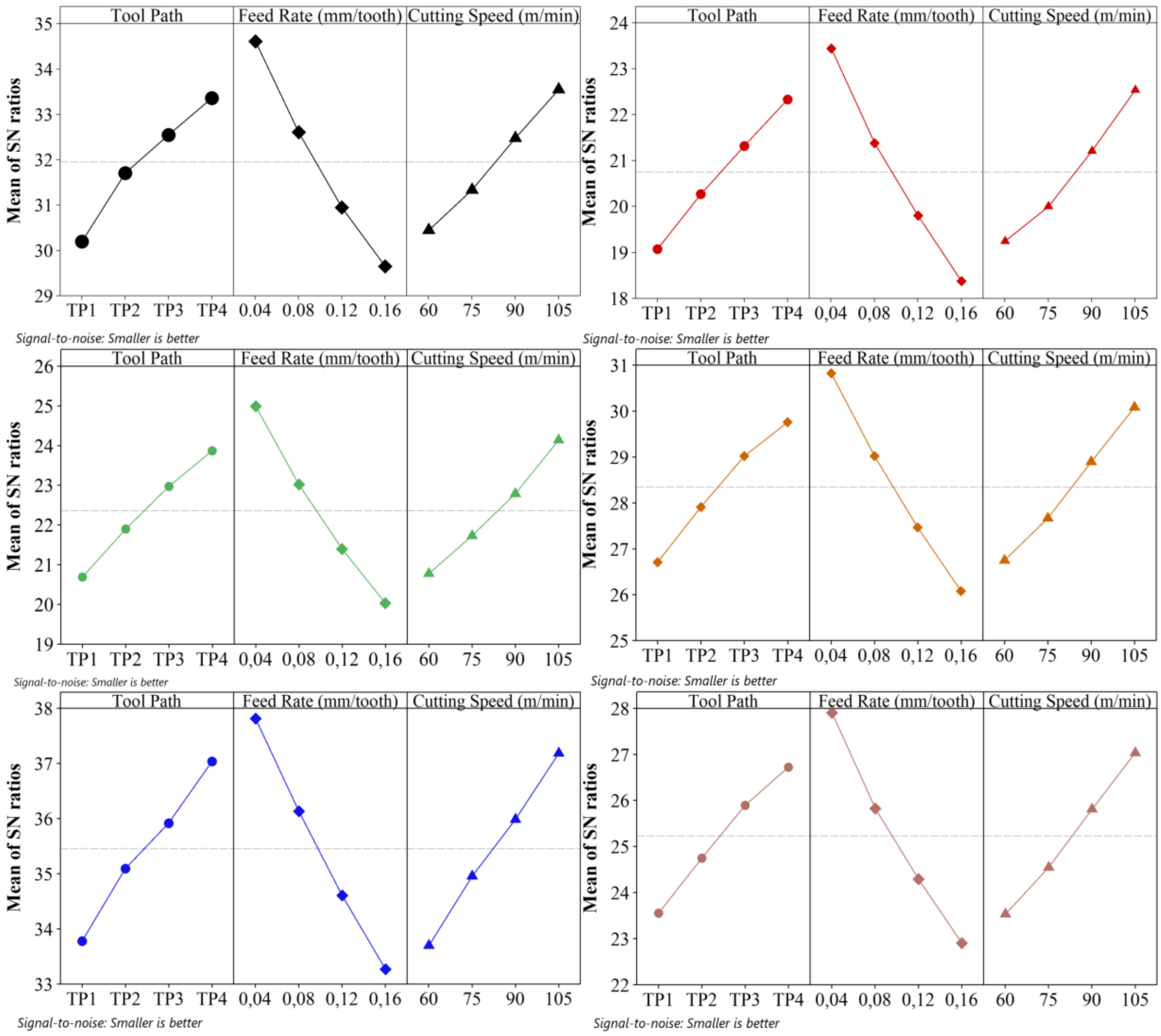


Figure 6. Main effect plot of S/N ratios for form error. (Form hatası için S/N oranlarının ana etki grafiği.)

Analysis of ANOVA is commonly employed to assess the interaction between cutting parameters. To analyses the effects of tool path, Vc and f on form error in the machining of AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples, Variance Analysis has been applied. Table 6 shows the ANOVA results obtained for form error. ANOVA analysis were conducted with a confidence level of 95% [20-23]. Statistical significance is attributed to the influence of cutting parameters on form error when the P value in Table 6 is less than 0.05. For AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples, the most effective cutting parameter on the measured form error was found to be the f with 58.61%, 58.39%, 57.30%, 55.15%, 51.18% and 55.31%, respectively. The average form error due to the analysis was found to be 0.606%. The average error percentage for form error in the analysis results is relatively low. This result confirms the results obtained in the experimental studies.

Table 6. Results of analysis of variance (ANOVA) for form error (Tablo 6. Form hatasına ilişkin varyans analizi (ANOVA) sonuçları)

Factors	Degree of freedom	Sum of squares	Mean of squares	F value	P value	Contribution rate (%)
AR Sample						
TP	3	0.000139	0.000046	23.08	0.001	20.04
f (mm/tooth)	3	0.000405	0.000135	67.50	0.000	58.61
Vc (m/min)	3	0.000135	0.000045	22.58	0.001	19.61
Error	6	0.000012	0.000002			1.74
Total	15	0.000691				100
2WQ Sample						
TP	3	0.001777	0.000592	22.63	0.001	19.26
f (mm/tooth)	3	0.005385	0.001795	68.60	0.000	58.39
Vc (m/min)	3	0.001904	0.000634	24.25	0.001	20.64
Error	6	0.000157	0.000026			1.70
Total	15	0.009222				100
5AQ Sample						
TP	3	0.001197	0.000399	20.37	0.002	19.08
f (mm/tooth)	3	0.003594	0.001198	61.17	0.000	57.30
Vc (m/min)	3	0.001363	0.000454	23.21	0.001	21.74
Error	6	0.000117	0.000020			1.87
Total	15	0.006271				100
10AQ Sample						
TP	3	0.000288	0.000096	19.96	0.002	18.92
f (mm/tooth)	3	0.000840	0.000280	58.19	0.000	55.15
Vc (m/min)	3	0.000366	0.000122	25.36	0.001	24.04
Error	6	0.000029	0.000005			1.90
Total	15	0.001523				100
18AQ Sample						
TP	3	0.000061	0.000020	18.62	0.002	20.44
f (mm/tooth)	3	0.000152	0.000051	46.62	0.000	51.18
Vc (m/min)	3	0.000077	0.000026	23.85	0.001	26.18
Error	6	0.000006	0.000001			2.20
Total	15	0.000296				100
22AQ Sample						
TP	3	0.000608	0.000203	16.90	0.002	18.24
f (mm/tooth)	3	0.001845	0.000615	51.25	0.000	55.31
Vc (m/min)	3	0.000810	0.000270	22.51	0.001	24.30
Error	6	0.000072	0.000012			2.16
Total	15	0.003336				100

3.3. Evaluation and Statistical Analysis of Surface Roughness (Yüzey Pürüzlülüğünün Değerlendirilmesi ve İstatiksel Analizi)

The surface roughness alterations resulting from milling AR, 2WQ, 5AQ, 10AQ, 18AQ, and 22AQ samples during the ageing process were assessed using different tool paths and cutting parameters. Furthermore, the signal-to-noise ratio was computed to assess the impact of different tool paths and cutting parameters on surface roughness. An analysis of variance (ANOVA) was conducted to assess the interaction between different tool paths and cutting parameters.

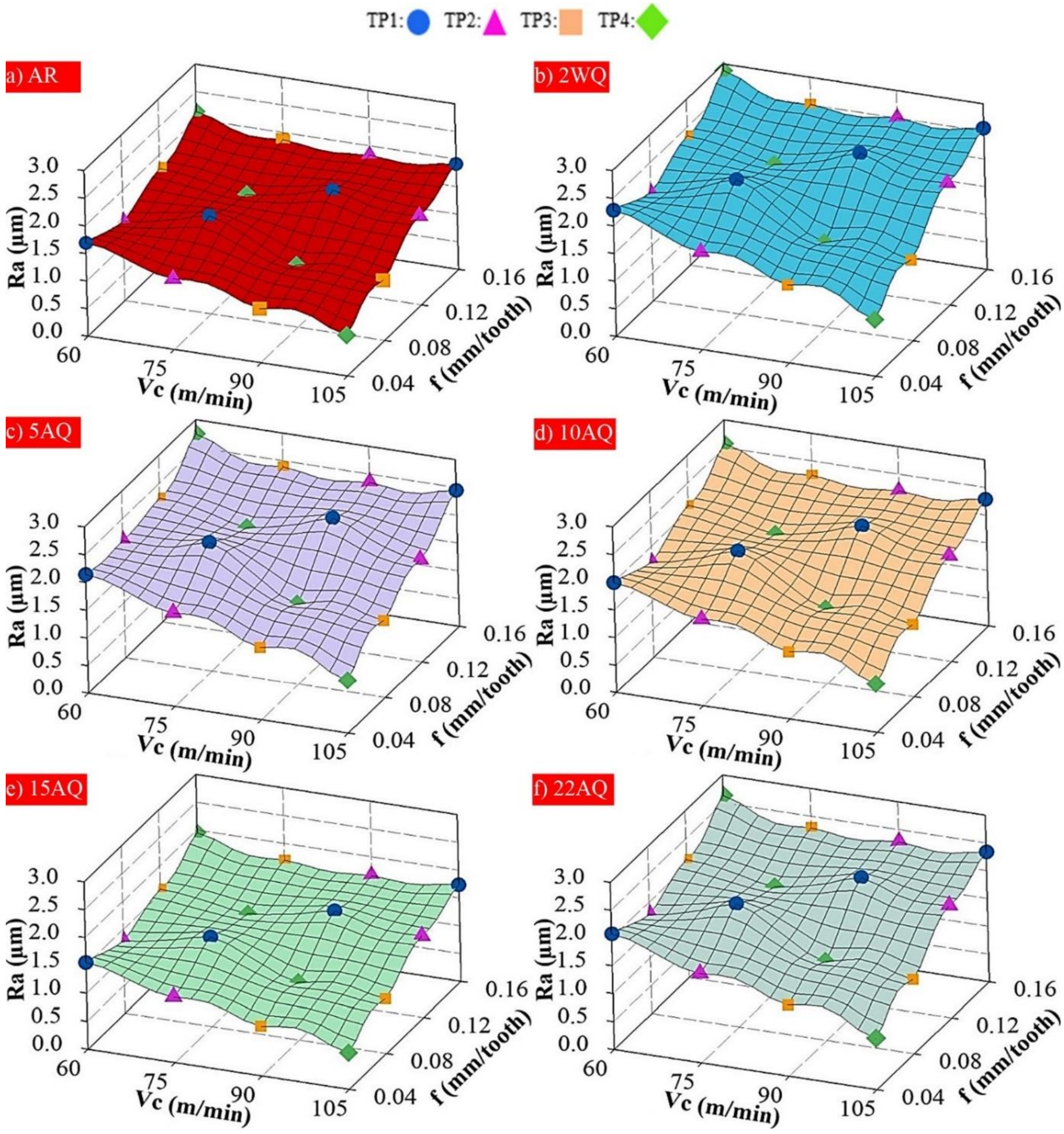


Figure 7. Differences in surface roughness depending on tool paths and cutting parameters (Takım yollarına ve kesme parametrelerine bağlı olarak yüzey pürüzlülüğünde farklılıklar)

Figure 7 shows the surface roughness changes obtained by milling AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples with different tool paths and cutting parameters. As a result of the experiments, it was observed that the surface roughness values , depending on the tool path and cutting parameters, varied between 0.66 µm and 2.88 µm. When Figure 7 is examined, the surface roughness of the AR sample was measured as 0.74 µm with the TP4 tool path, 0.04 mm/tooth f and 105 m/min Vc. With the same tool path, the f was increased by 0.16 mm/tooth, and the Vc was reduced by 60 m/min, resulting in an 189.2% increase in the surface roughness value of 2.14 µm. After the solution treatment, the hardness of the 2WQ sample, which decreased to 75.7 Hv1, was processed with the TP4 tool path, 0.04 mm/tooth f and 105 m/min Vc, resulting in a 37.8% increase in surface roughness compared to the AR sample, measured as 1.02 µm. With the same tool path, the surface roughness value reached the maximum value in all experiments, reaching 2.88 µm, with the advancement amount being increased by 0.16 mm/tooth and the Vc is reduced to 60 m/min. With the ageing period increasing to 18 hours, 18AQ sample, whose hardness reached the highest value with 133 Hv1, was processed with the TP4 tool path, 0.04 mm/tooth advancement amount and 105 m/min Vc, and the lowest surface roughness value of 0.66 µm was reached among all values. After this point, it was observed that the surface roughness values tended to increase again in the processing of the 22AQ sample, whose hardness decreased as a result of the ageing process. As a result, in the study, while the minimum surface roughness was measured in the processing of the 18AQ sample, which reached maximum hardness after the ageing process, the maximum surface roughness was measured in the processing of the 2WQ sample with the lowest hardness. This showed us that the increase in hardness due to the ageing period of the AA 6063-T6 alloy positively affected the surface roughness. Upon evaluating the surface roughness with respect to cutting parameters, it was found that increasing the Vc and decreasing the f had a favourable impact on the surface roughness [24]. Regarding tool path, the tool path processed in the same direction as the surface roughness measurement direction yielded the best surface roughness. However, it was noticed that the tool path processed in the direction perpendicular to the surface roughness measurement direction resulted in the highest surface roughness.

The surface roughness values and S/N ratios measured as a result of processing the samples of AA 6063-T6 alloy to which the ageing process was applied in different tool paths and processing parameters are shown in Table 7. As a result of the milling experiments, the averages of the surface roughness values obtained for AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples were calculated as 1.54 µm, 2.09 µm, 1.98 µm, 1.85 µm, 1.40 µm and 1.90 µm, respectively, and the average values of the S/N ratios were calculated as -3.421 dB, -6.114 dB, -5.618 dB, -5.021 dB, -2.574 dB and -5.279 dB, respectively.

Table 7. Experimental results and S/N ratios for surface roughness.

Test Id	AR (µm)	AR S/N Ratio (dB)	2WQ (µm)	2WQ S/N Ratio (dB)	5AQ (µm)	5AQ S/N Ratio (dB)	10AQ (µm)	10AQ S/N Ratio (dB)	18AQ (µm)	18AQ S/N Ratio (dB)	22AQ (µm)	22AQ S/N Ratio (dB)
1	1.69	-4.558	2.28	-7.159	2.14	-6.608	1.99	-5.977	1.55	-3.807	2.07	-6.319
2	1.78	-5.008	2.44	-7.748	2.32	-7.310	2.16	-6.689	1.61	-4.137	2.21	-6.888
3	1.84	-5.296	2.51	-7.993	2.35	-7.421	2.21	-6.888	1.67	-4.454	2.28	-7.159
4	1.91	-6.608	2.56	-9.188	2.44	-8.755	2.29	-8.199	1.74	-4.811	2.33	-7.347
5	1.28	-2.144	1.77	-4.959	1.69	-4.558	1.57	-3.918	1.17	-1.364	1.60	-4.082
6	1.44	-3.167	1.96	-5.845	2.11	-6.486	1.72	-4.711	1.30	-2.279	1.78	-5.008
7	1.61	-4.137	2.21	-6.888	1.84	-5.296	1.91	-5.621	1.46	-3.287	2.01	-6.064
8	1.83	-5.249	2.51	-7.993	2.35	-7.421	2.2	-6.848	1.66	-4.402	2.28	-7.159
9	0.98	0.175	1.41	-2.984	1.31	-2.345	1.22	-1.727	0.89	1.012	1.28	-2.144
10	1.09	-0.749	1.46	-3.287	1.39	-2.860	1.31	-2.345	0.98	0.175	1.33	-2.477
11	1.75	-4.861	2.34	-7.384	2.23	-6.966	2.10	-6.444	1.58	-3.973	2.12	-6.527
12	1.87	-5.437	2.51	-7.993	2.39	-7.568	2.24	-7.005	1.70	-4.609	2.29	-7.197
13	0.74	2.615	1.02	-0.172	0.95	0.446	0.88	1.110	0.66	3.609	0.92	0.724
14	1.13	-1.062	1.54	-3.750	1.45	-3.227	1.36	-2.671	1.03	-0.257	1.41	-2.984
15	1.52	-3.637	2.07	-6.319	1.94	-5.756	1.82	-5.201	1.38	-2.798	1.87	-5.437
16	2.14	-5.621	2.88	-8.165	2.74	-7.748	2.57	-7.197	1.95	-5.801	2.63	-8.399

The S/N response table was utilised to examine the impact of each cutting parameter on the form error. The containing the signal-to-noise response for surface roughness can be found in Table 8. The Table 8 displays the optimal cutting parameters required to get the best surface roughness for each sample. The levels of cutting parameters for surface roughness values of the samples are given in Table 8, and the graphs of these values are shown in Figure 8. When Table 8 and Figure 8 are examined, the optimum surface roughness value was measured as 0.66 µm as a result of machining the AQ18 sample in the TP4 tool path at a f of 0.04 mm/tooth and a Vc of 105 m/min.

Table 8. S/N response table for surface roughness (Yüzey pürüzlülüğü için S/N tepki tablosu)

	Control Factors					
	A	B	C	A	B	C
	AR Sample			2WQ Sample		
Level 1	-5.368	-0.978	-4.552	-8.022	-3.819	-7.138
Level 2	-3.674	-2.496	-4.057	-6.421	-5.158	-6.755
Level 3	-2.718	-4.483	-2.858	-5.412	-7.146	-5.680
Level 4	-1.926	-5.729	-2.220	-4.602	-8.335	-4.884
Delta	3.442	4.751	2.332	3.420	4.516	2.255
	5AQ Sample			10 AQ Sample		
Level 1	-7.524	-3.266	-6.952	-6.938	-2.628	-6.082
Level 2	-5.940	-4.971	-6.298	-5.274	-4.104	-5.703
Level 3	-4.935	-6.360	-5.104	-4.380	-6.039	-4.534
Level 4	-4.071	-7.873	-4.117	-3.490	-7.312	-3.764
Delta	3.452	4.607	2.835	3.449	4.684	2.319
	18 AQ Sample			22 AQ Sample		
Level 1	-4.3021	-0.1373	-3.9648	-6.928	-2.955	-6.563
Level 2	-2.8330	-1.6242	-3.2267	-5.578	-4.339	-5.901
Level 3	-1.8486	-3.6280	-2.0253	-4.586	-6.297	-4.861
Level 4	-1.3115	-4.9057	-1.0784	-4.024	-7.525	-3.791
Delta	2.9906	4.7684	2.8865	2.904	4.570	2.772

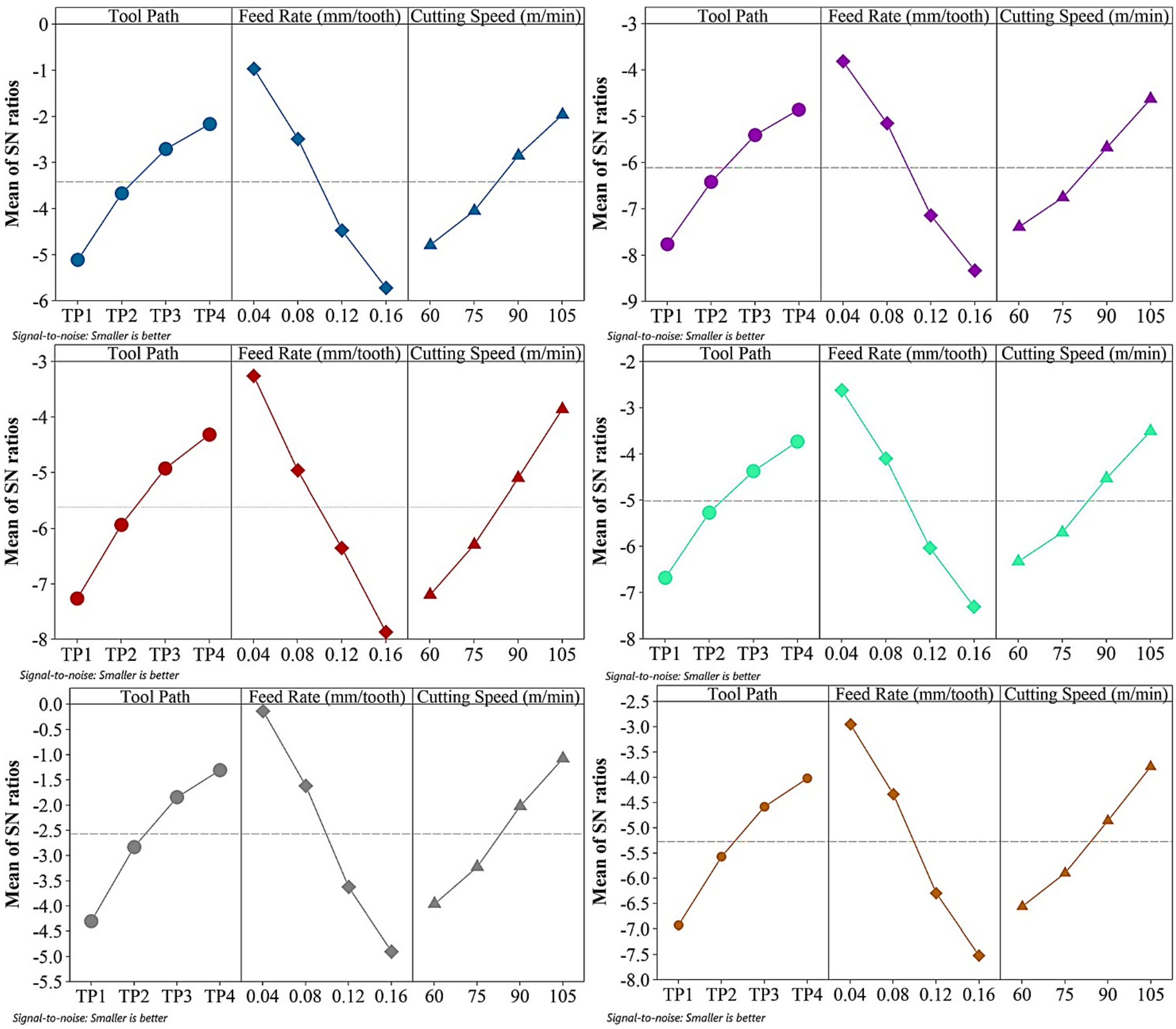


Figure 8. Main effect plot of S/N ratios for surface roughness (Yüzey pürüzlülüğü için S/N oranlarının ana etki grafiği)

The ANOVA analysis results for the surface roughness achieved as a result of machining the samples of Al 6063-T6 alloy to which the ageing process was applied are presented in Table 9. ANOVA analyses were performed at a 90% confidence level [25,26]. In Table 9, it was observed that when the P value was less than 0.05 for all samples, the tool path, Vc, and f had a certain effect on the surface roughness. When Table 9 was examined, it was determined that the most effective cutting parameter on the measured surface roughness for AR, 2WQ, 5AQ, 10AQ, 18AQ and 22AQ samples was the f with 59.72%, 58.59%, 53.88%, 59.51%, 59.07% and 59.07%, respectively. In the analysis results, the average error percentage for surface roughness was quite low. The average form error for surface roughness was found to be 2.38%. This result confirms the results obtained in the experimental studies.

Table 9. Analysis of variance (ANOVA) results for surface roughness (Yüzey pürüzlülüğü için varyans analizi (ANOVA) sonuçları)

Factors	Degree of freedom	Sum of squares	Mean of squares	F value	P value	Contribution rate (%)
AR sample						
TP	3	0.65605	0.218683	37.98	0.000	28.39
f (*mm/tooth*)	3	1.38015	0.460050	79.89	0.000	59.72
Vc (m/min)	3	0.24035	0.080117	13.91	0.004	10.40
Error	6	0.03455	0.005758			1.49
Total	15	2.31110				100
2WQ Sample						
TP	3	1.21222	0.40407	36.27	0.000	30.03
f (*mm/tooth*)	3	2.36467	0.78822	70.76	0.000	58.59
Vc (m/min)	3	0.39232	0.13077	11.74	0.006	9.72
Error	6	0.06684	0.01114			1.66
Total	15	4.03604				100
5AQ Sample						
TP	3	1.08025	0.360083	78.85	0.000	29.23
f (*mm/tooth*)	3	1.99115	0.663717	145.34	0.000	53.88
Vc (m/min)	3	0.59690	0.198967	43.57	0.000	16.15
Error	6	0.02740	0.004567			0.74
Total	15	3.69570				100
10AQ Sample						
TP	3	0.93092	0.310306	34.01	0.000	28.52
f (*mm/tooth*)	3	1.94227	0.647423	70.97	0.000	59.51
Vc (m/min)	3	0.33562	0.111873	12.26	0.006	10.28
Error	6	0.05474	0.009123			1.68
Total	15	3.26354				100
18AQ Sample						
TP	3	0.36967	0.12322	9.40	0.011	19.10
f (*mm/tooth*)	3	1.14317	0.38106	29.07	0.001	59.07
Vc (m/min)	3	0.34372	0.11457	8.74	0.013	17.76
Error	6	0.07864	0.01311			4.06
Total	15	1.93519				100
22AQ Sample						
TP	3	0.6496	0.21652	8.35	0.015	19.34
f (*mm/tooth*)	3	1.9843	0.66142	25.51	0.001	59.07
Vc (m/min)	3	0.5699	0.18996	7.33	0.020	16.96
Error	6	0.1556	0.02593			4.63
Total	15	3.3593				100

4. CONCLUSIONS (SONUÇLAR)

This study evaluates the microstructure and hardness variations of samples of AA 6063-T6 alloy that underwent the ageing process. The second component of the study involved evaluating the form errors and surface roughness that occurred during the machining of free-form surfaces. This evaluation was conducted on samples with varying microstructure and hardness, using varied tool paths and cutting parameters. Ultimately, statistical analyses were conducted to ascertain the impact of tool paths and cutting settings on output parameters. The findings derived from the current investigation are as follows:

- ✓ When the microstructure of the AR sample is examined, it is seen that the equiaxed grains in the rolling direction have recrystallized, and as a result of the solution heat treatment and artificial ageing process, small secondary phase particles are seen in the microstructure. It is observed that the precipitates dissolved and saturated structures were formed in the microstructure of the 2WQ sample. In addition, the microstructure consists of coarser grains.
- ✓ It is observed that the amount of precipitate increases in the microstructure of the 18AQ sample obtained by increasing the ageing period to 18 hours and forming a more homogeneous structure. In the microstructure examination of the 22AQ sample obtained by increasing the ageing period to 22 hours, it is observed that the grain size increases with the increase in the ageing period and the grain boundaries become more distinct.
- ✓ While the hardness of the sample taken into 2WQ solution was measured as the lowest value with 71.7 Hv1, the 18AQ sample obtained in 18 hours of the ageing period had the highest hardness value with 117.7 Hv1.
- ✓ The minimum error recorded was 0.008 mm in the 18AQ sample using the TP4 tool path, a f of 0.04 mm/tooth, and a Vc of 105 m/min. The maximum error recorded was 0.13 mm in the 2WQ sample using the TP4 tool path, a f of 0.16 mm/tooth, and a Vc of 60 m/min.
- ✓ The 18AQ sample with TP4 tool path, 0.04 mm/tooth f, and 105 m/min Vc had the lowest surface roughness, measuring at 0.66 µm. The maximum surface roughness recorded was 2.88 µm in the 2WQ sample using the TP4 tool path, a f of 0.16 mm/tooth, and a Vc of 60 m/min.
- ✓ The statistical study yielded the optimal cutting parameters for form error and surface roughness, which are A4B1C4, TP4 tool path, 0.04 mm/tooth f, and 105 m/min Vc.
- ✓ In light of the results obtained, the ANOVA analysis of the 18AQ sample, where the optimum values were obtained, showed that the most effective cutting parameters on form error and surface roughness were 51.18% and 59.07% f, respectively.

ACKNOWLEDGMENT (TEŞEKKÜR)

This study was supported by Karabük University Scientific Research Projects Unit. Project Number: KBÜ-BAP FYL-2020-2139.

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