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The Experimental Investigation of the Machinability of Armor Steels

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Abstract:- In recent years, the use of materials with ultra-high hardness such as Millux Protection 600T has become widespread in industry. However, the effect of different parameters used in the machining process of such steels, especially factors such as feed rate, cutting speed, depth of cut, and radial depth of cut, on the surface roughness of the final product is still not fully understood. In this context, a study was conducted to evaluate the effects of the mentioned armor steel on surface roughness. Using the Taguchi optimization method, the interaction between processing parameters at specified levels was examined, and attempts were made to determine the optimum values. Within the scope of the study, nine different experiments were conducted using Taguchi's L9 orthogonal array, and the surface roughness data obtained from each experiment were recorded. According to the analysis results, it was determined that the feed rate is the most significant parameter in the milling process, followed by radial depth of cut, depth of cut, and cutting speed, respectively. To achieve optimal results, it is recommended that the feed rate be set to level 1, cutting speed to level 2, depth of cut to level 1, and radial depth of cut to level 3. These findings could provide important guidance in the machining of such steels.

Keywords:- *Processing Parameters; Milling; Taguchi Method; Robust Design; Surface Roughness; Tool Wear; Armor Steel.*

I. INTRODUCTION

Determining the machinability properties of armor steels used in industry holds great importance in the field of materials engineering. Studies conducted in this area aim to enhance the effectiveness of processing methods used in the production of armor steels, optimize material performance, and ultimately develop more reliable and durable armor materials. Machinability determines how successful a material is in machining processes and how easy or difficult these processes are. Therefore, a detailed examination of the machinability properties of armor steels can increase the efficiency of production processes and reduce costs.

The aim of this study is to experimentally investigate the machinability properties of armor steels, contributing to the production of more reliable and effective armor materials in the defense industry. The goal is to develop high-performance, economically sustainable solutions that meet the needs of the defense industry.

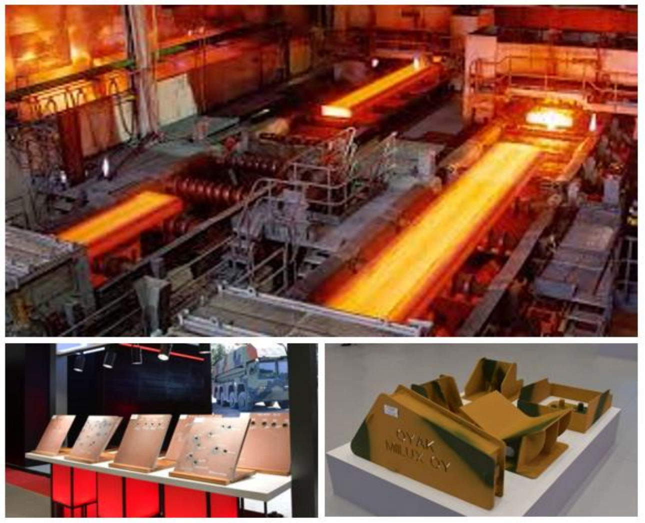

Fig 1 Armor Steels and their Processing [12, 13, 14]

II. LITERATURE REVIEW

In the study conducted by Bağcı and Aykut [1], the determination of cutting parameters for surface milling of a cobalt-based alloy named Stellite 6 and the achievement of low surface roughness values were aimed. Milling parameters such as cutting depth, feed rate, and cutting speed were investigated, and various experiments were conducted using the L27 orthogonal array. Optimum values were determined using the Taguchi experimental design method, and it was shown that feed rate, cutting depth, and cutting speed significantly influenced surface roughness.

In the study conducted by Zahoor et al. [2], the effect of forced vibration induced by the spindle on vertical milling operation was investigated. The influence of feed rate, axial depth of cut, and spindle-level vibrations on surface roughness, dimensional accuracy, and tool wear was evaluated. AISI P20 material and a solid carbide cutting tool were used. Significant parameters were determined using the Taguchi L9 standard orthogonal array, and ANOVA analysis was performed. The effect of vibration amplitude and axial depth of cut on surface roughness was determined, with vibration amplitude being identified as the most influential factor. It was observed that high vibration amplitude and feed rate led to excessive tool wear.

Özbek et al. [3] used the Taguchi L9 experimental design to determine the optimal cutting parameters with CVD-coated tungsten carbide inserts for turning hardened AISI 420 stainless steel. In the study aimed at achieving the lowest flank wear values, the parameters of 0.08 mm/rev feed rate, 0.6 mm depth of cut, and 170 m/min cutting speed were identified as the most suitable. ANOVA analysis showed that the feed rate had the greatest impact (47.04%) on flank wear. Cutting speed (36.28%) and depth of cut (4.10%) were other significant factors.

In the study conducted by Kara [4], the optimization of cutting parameters in the fine chip milling process of Hardox 400 steel was investigated. Using the Taguchi L16 experimental design, cutting speed and cooling method were identified as control factors, and optimal surface roughness values were determined. Variance analysis revealed the effects of the control parameters on surface roughness. It was determined that the most favorable results were obtained with a cutting speed of 120 m/min and wet cooling method.

In the study by Kara [5], the Taguchi method was used to determine the optimal cutting parameters for finish milling of AISI P20+S plastic mold steel. Experiments were conducted on four parameters including cutting speed, feed rate, depth of cut, and cooling method. The analysis revealed that the best results were achieved with a cutting speed of 150 m/min, a feed rate of 0.1 mm/tooth, a depth of cut of 0.16 mm, and wet cooling method.

Kara and Öztürk [6] study determined the optimal cutting conditions for turning operations. Through Taguchi experiments and regression analysis, it was identified that TiAlN-coated tools exhibited the best performance, while PVD-coated carbide tools provided the most favorable outcomes.

In the study by Tlhabadira and colleagues [7], the Taguchi method was employed to reduce surface roughness during the milling process of AISI P20. Autodesk Fusion 360 was utilized to model the stress, displacement, and thermal behavior of the cutting tool and workpiece under various cutting conditions. Experiments were planned using a three-factor, three-level L9 orthogonal array. Statistical analysis determined the optimal machining parameters that produced the least surface roughness: depth of cut (2-3 mm), cutting speed (275 m/min), spindle speed (5471 rpm), and feed rate (2188 mm/min).

In the study by Moayyedian and colleagues [8], the effects of surface roughness on Hardox 600 wear plate were examined using the Taguchi method. Nine separate experiments were conducted on parameters such as spindle speed, feed rate, radial depth of cut, and cutting depth. The optimal level for each parameter was determined through signal-to-noise ratio and variance analysis. The most suitable parameters for minimum surface roughness were identified as radial depth of cut 33%, cutting depth 0.2 mm, spindle speed 250 rpm, and feed rate 25 mm/min.

In the study by Amol Vikas Joshi and team [9], the Taguchi method was employed to reduce the surface roughness of a casting part such as a Jacquard body. Spindle speed, feed rate, and cutting depth were controlled using a three-factor, three-level L9 orthogonal array. The results obtained from the experiments showed that the minimum surface roughness was achieved at a feed rate of 0.7 mm/rev, a spindle speed of 225 rpm, and a cutting depth of 1.5 mm. It was observed that an average feed rate and low cutting depth provided better surface quality at higher spindle speeds.

III. METHODOLOGY

➢ *Material Selection and Properties*

The steel armors used for ballistic protection today are generally divided into three main categories: rolled homogeneous armor (RHA), high hardness armor (HHA), and ultra-high hardness armor (UHA). These various types of armor are commonly used in a wide range of applications, from ballistic panels to vehicle armor [9].

In the experimental study, the commonly used Millux Protection 600T (UHHA) armor steel was preferred. This particular type of steel is available in thicknesses ranging from 4.00 to 20.00 mm and has hardness values of 570-650 HBW (55-61 HRC). Protection 600T provides high resistance against ballistic penetration with yield strength of 1400 N/mm^2 and tensile strength ranging from 1950-2150 N/mm^2 in the ultra-high hardness range.

Table 1 Properties of Arm or Steels [10]

Properties	**MIL-A-12560**	**MIL-A-46100**	**MIL-A-46173**
Hardness (HB)	277-388	477-534	477-601
Yield Strength (MPa)	1150	≥1100	≥1100
Tensile Strength (MPa)	1250	≥1600	≥1700
Elongation %	≥10	≥9	≥8
Toughness	20-30	30-40	30

Table 2 Protection 600T Chemical Composition Compound [11]

Steel Type	**Thick.** (mm)	**C** (%)	**Si** (%)	**Mn** (%)	**P** (%)	**S** (%)
Ultra-High Hardness Armor Steel (UHHA)	4.00-20.00	0.45	0.70	0.80	0.015	0.004
		Cr (%)	**Ni** (%)	**Mo** (%)	**B** (%)	
		0.50	3.00	0.60	0.003	

- *Test Samples and Cutting Tools*

The shapes and dimensions of the test specimens, as well as the advancement and rotation direction of the scanning head, are detailed in Figure 2 with red arrows. Considering material and processing costs, the specimens were prepared in three different types according to the lateral step amounts, which are the experimental factors.

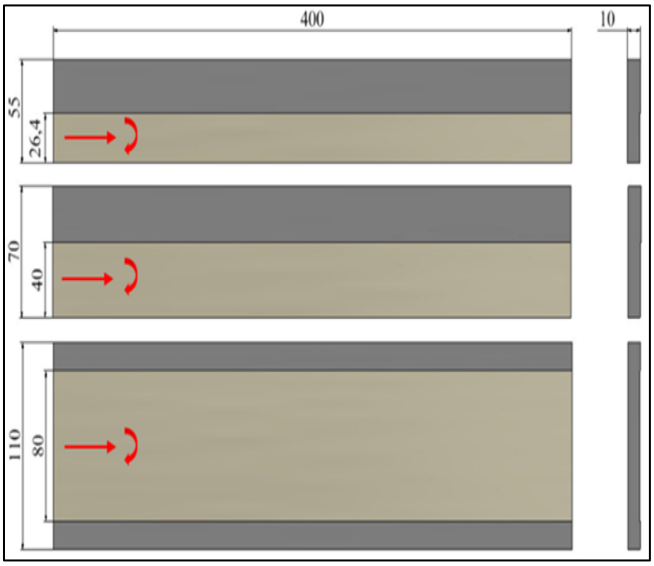

Fig 2 Shape and Dimensions of Test Samples

In the study, a PVD-coated AlTiN 3PKT 150508R-M TT2510 hard carbide cutting tool was preferred. The selection of the cutting tool material was made considering the necessity for the tool to be harder than the material being machined. The dimensional measurements of the used cutting tool are provided in Figure 3, while the dimensional measurements of the scanning head used are given in Figure 4.

IC	RE	BS	S	APMX	ap (min)	ap (max)	fz (max)	fz (min)
10.70	0.80	1.60	5.00	11.00	3.00	9.00	0.170	0.070

Fig 3 Dimensional Dimensions of the Cutting Tool

DC	CICT	DCONMS	DHUB	OAL	APMX	ℹ	Arbor ℹ	Mtg. Ref	MIID
80.00	7	27.00	58.00	50.00	11.00	O	A	SH M12X1.75X35	3PKT 150508R-M

Fig 4 Dimensional Dimensions of the Milling Head

➢ *Selection and Execution of Experimental Parameters*

In machining processes, there are many factors that determine surface roughness. The material properties of the workpiece, the type of cutting tool, cutting speed, feed rate, depth of cut, generated heat, use of coolant, and the structural characteristics of the machine tool are just a few of these factors. Any change in these factors can lead to changes in surface roughness. During processing, the fundamental factors determining surface roughness are clearly shown in Figure 5 as a graph called the Ishikawa diagram.

Table 3 Display of Level Values and Experimental Order According to the L9 Orthogonal Array

Trial	Order of experiment	A	B	C	D
1	6	350	190	0.20	33
2	3	350	250	0.35	50
3	1	350	315	0.50	100
4	5	500	190	0.35	100
5	2	500	250	0.50	33
6	8	500	315	0.20	50
7	4	650	190	0.50	50
8	7	650	250	0.20	100
9	9	650	315	0.35	33

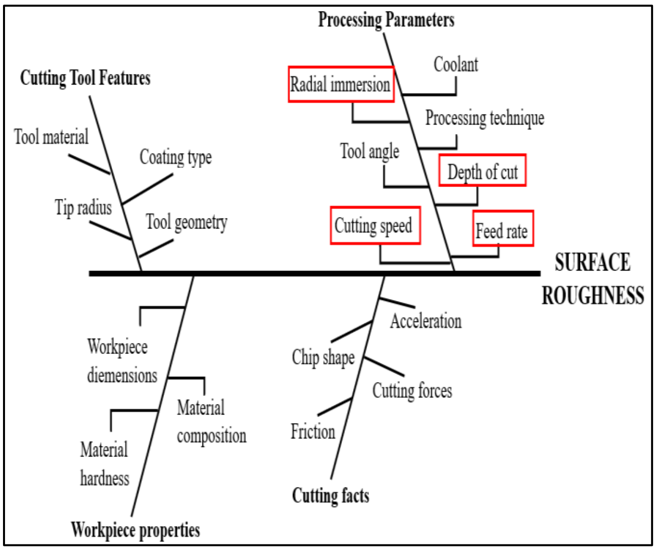

Fig 5 Cause and Effect Diagram for Quality Characteristics

The variable parameters selected for the Taguchi experimental design method and their level values are shown in Table 4.

Table 4 Factor Levels to be used in the Experiment

Parameters	Level 1	Level 2	Level 3
Feed rate (mm/min), A	350	500	650
Spindle speed (m/min), B	190	250	315
Depth of cut (mm), C	0.2	0.35	0.5
Radial immersion (%), D	33	50	100

The Ishikawa diagram assisted in identifying four 3-level factors for parameter design. The diversity of levels and total degrees of freedom for factor selection were considered for orthogonal array selection. Following the determination of degrees of freedom, an L9 orthogonal array was selected, and factors were assigned to this array. Table 5 presents the Taguchi L9 orthogonal array for the selected four parameters.

Table 5 L9 orthogonal array of the Taguchi method for four selected parameters

Trials	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Due to the high cost of the cutting tool inserts and armor steel material used in the experiments, the number of repetitions was set to 1. The order of experiments was randomly selected to minimize the influence of unknown noise factors, determined by drawing lots for this purpose. Since it was neither difficult nor expensive to change the levels during this process, the experiment sequence was completely defined as random. As a result, the experiment sequence was determined as 3, 5, 2, 7, 4, 1, 8, 6, 9. Table 5 shows the level values and experiment sequence according to the L9 orthogonal array.

Figure 6(a) illustrates the surface milling process of the test specimen, while (b) shows the connection of the test specimens to the milling table according to the lateral step values.

Fig 6 (a) Test Sample Surface Milling Process, (b) Connecting the Test Samples to the Milling Table According to the Radial Immersion

The surface roughness values occurring in the test specimens subjected to surface milling with the specified levels and control factors were determined by performing three repeated measurements at 50, 200, and 350mm positions from where the scanning head started the milling process using the "SURFTEST SJ-201P portable surface roughness testing device", and their averages were taken. Figure 7 illustrates the measurement of surface roughness of the test specimen with the surface roughness measurement device.

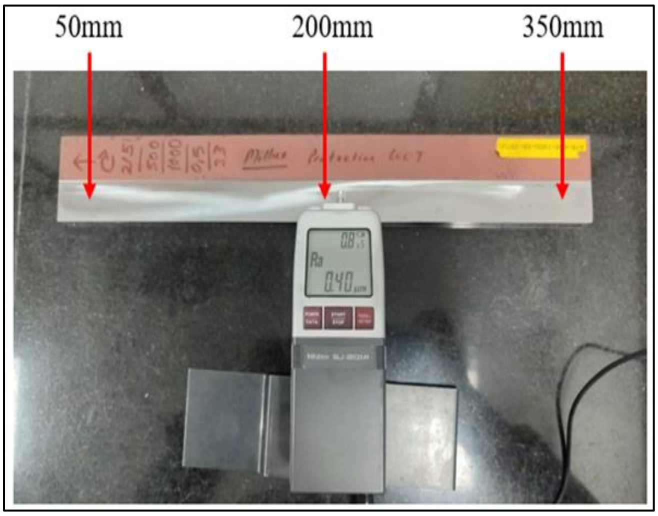

Fig 7 Measuring Surface Roughness

During the milling process, the processing time of each experiment was measured with the help of a stopwatch. The obtained measurement results were compared with theoretical calculations of time. In the comparison, milling times of 82 seconds at a feed rate of 350 mm/min, 57 seconds at a feed rate of 500 mm/min, and 44 seconds at a feed rate of 650 mm/min were determined. Depending on the feed rates, milling times at positions of 50, 200, and 350 mm were calculated for nine experiments, with one measurement taken for every three experiments. The obtained comparisons of feed rates, positions, and times are presented in Table 6. The position-dependent values of feed rates and surface roughness measurements, along with their average values, are depicted in Ra-Time graphs in Figure 8 for a feed rate of 350 mm/min, Figure 9 for a feed rate of 500 mm/min, Figure10 for a feed rate of 650 mm/min, and Figure 11 for the average value graph.

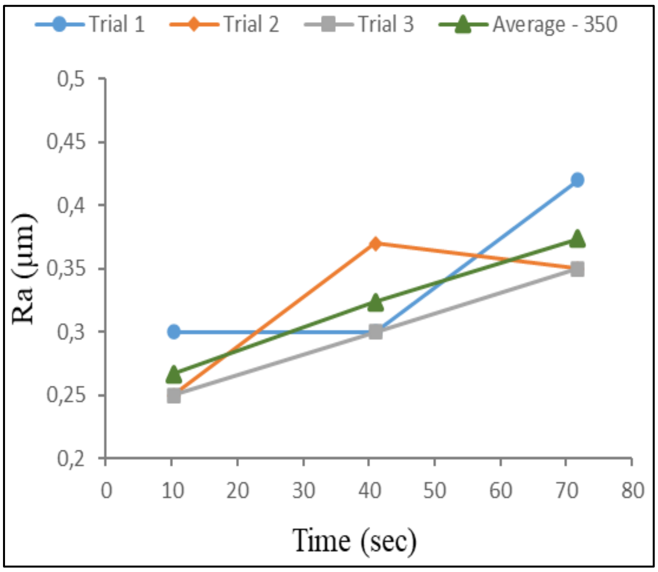

Fig 8 Ra-Time Graphs of Surface Roughness Values for Feed Rate of 350 mm/min

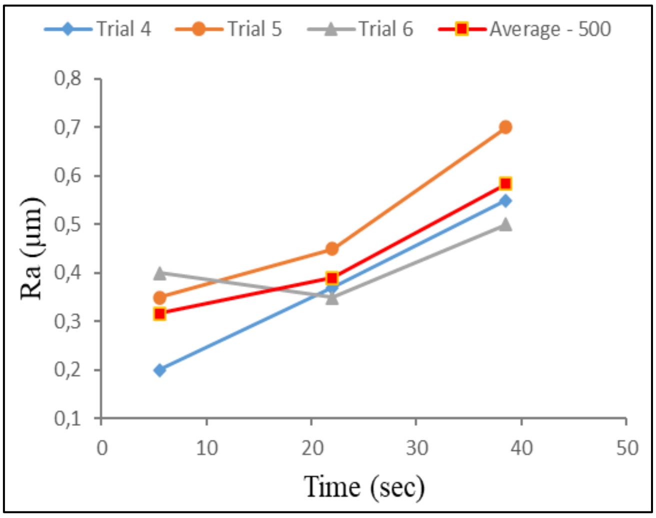

Fig 9 Ra-Time graphs of surface roughness values for feed rate of 500 mm/min

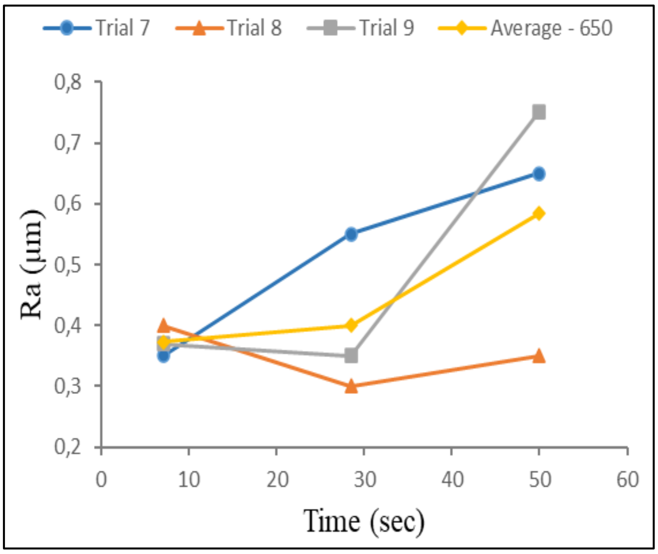

Fig 10 Ra-Time Graphs of Surface Roughness Values for Feed Rate of 650 mm/min

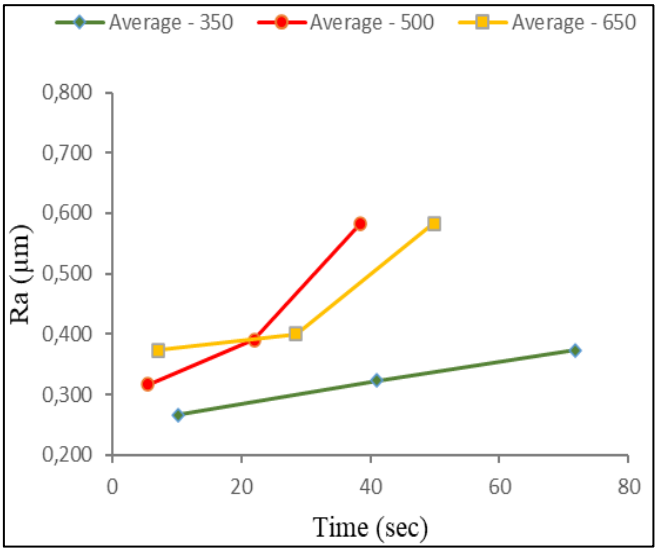

Fig 11 Ra-Time Graphs of Surface Roughness Values for the Average Value Graph

Table 6 Giving Times Depending on Location and Progress Speed

Feed Rate (mm/min)	Position (mm)	Time (sec)
350	50	10,25
	200	41
	350	71,75
500	50	7,12
	200	28,5
	350	49,87
650	50	5,5
	200	22
	350	38,5

The amount of wear on the cutting tool inserts during the surface milling process of the test specimens was observed using the "TONPOP USB digital microscope". A total of sixty-three images were taken, seven for each experiment. The images of the cutting tool inserts were scored based on the amount of wear, and average cutting tool wear rates were determined for each experiment. Lines were drawn at equal intervals on the visual taken from the unused cutting tool insert, and numbers from zero to ten were assigned. Figure 12 illustrates the scoring based on the amount of cutting tool wear. According to the random sequence, the wear of cutting tool inserts numbered 1, 3, 5, and 7, connected to the scanning head for the first conducted experiment, are shown in Figure 13 sequentially as (a), (b), (c), and (d). Table 7 shows the scores given according to the amount of wear on the cutting tool inserts.

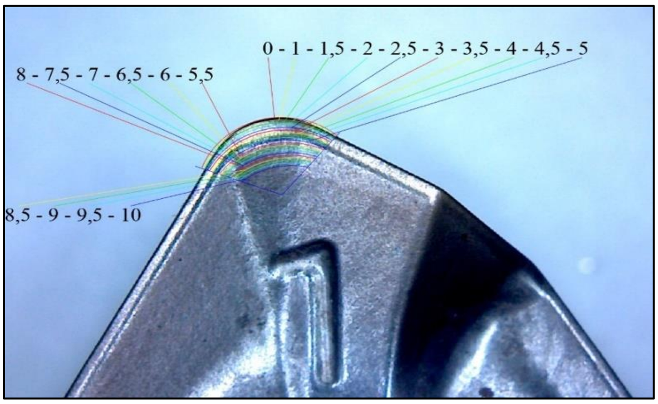

Fig 12 Scoring of the Amount of Tool Tip Wear

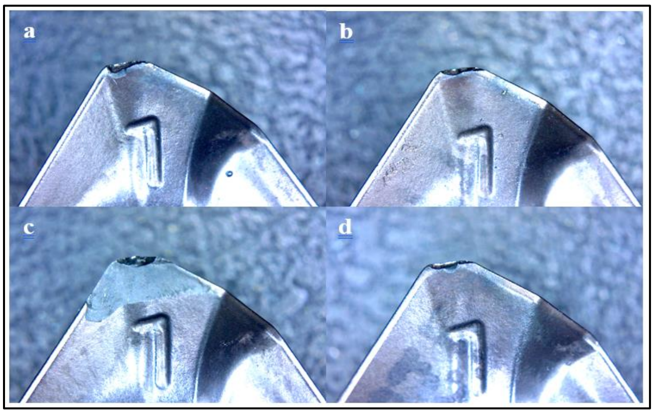

Fig 13 Example Representation of Tool Tip Wear

The surface roughness and cutting tool wear rates resulting from the measurements, observations, and scoring are provided in Table 7.

Table 7 Average Surface Roughness and Tool Tip Wear Values

Trial	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Ra	0,34	0,32	0,30	0,37	0,50	0,42	0,52	0,35	0,49
Vb	1,79	4,14	4,86	5,21	1,86	4,43	1,07	6,14	2,64

IV. RESULTS AND DISCUSSIONS

Analytical calculations of the experimental study results were conducted, and using Minitab 18 statistical software, analysis of Signal-to-Noise (S/N) ratio, ANOVA variance analysis, and parameter interaction plots were generated. While analysis and interaction plots of the measured surface roughness results were obtained, the cutting tool wear rates were qualitatively scored based on wear ratios, as the cutting tool wear rates could not be measured quantitatively, analysis work was not conducted for them.

A. Analysis of Signal-to-Noise Ratio

Table 8 displays the Signal-to-Noise (S/N) ratios obtained with the Taguchi L9 experimental design for Ultra-High Hardness Armor Steel Protection 600T, along with the experimental results of Ra, surface roughness values.

The most effective among the control factors, including feed rate, cutting speed, depth of cut, and lateral step amount, was determined using the Taguchi-based response table to identify the optimal levels of Ra performance characteristics. Table 9 provides the S/N response table, while Table 10 presents the importance and result table for Ra. It was found that the feed rate was the most influential parameter on Ra. The graphs in Figure 11 illustrate the effects of control factors on S/N values for Ra in Protection 600T ultra-high hardness armor steel. The graphs in Figure 12, on the other hand, demonstrate the effects of control factors on surface roughness values of Protection 600T armor steel.

The optimal cutting parameters for surface roughness (Ra) (Figure 11) were determined to be the 1st level of feed rate (A1 - 350 mm/min), the 2nd level of cutting speed (B2 - 250 m/min), the 1st level of depth of cut (C3 - 0.2 mm), and the 3rd level of radial immersion (D3 - 100%).

Table 8 S/N Ratios Obtained According to the L9 Orthogonal Array

Trial	**Control Factors**				**Surface Rouhgness Ra** (µm)	**S/N Ratio Ra** (db)
	A (Vf)	**B** (Vc)	**C** (ap)	**D** (ae)		
1	350	190	0,2	33	0,34	9,370
2	350	250	0,35	50	0,32	9,816
3	350	315	0,5	100	0,30	10,457
4	500	190	0,35	100	0,37	8,566
5	500	250	0,5	33	0,50	6,021
6	500	315	0,2	50	0,42	7,597
7	650	190	0,5	50	0,52	5,730
8	650	250	0,2	100	0,35	9,118
9	650	315	0,35	33	0,49	6,196

Table 9 S/N Severity and Consequence Chart

S/N (µm)				
Level	**A**	**B**	**C**	**D**
1	0,321	**0,410**	0,369	**0,443**
2	0,430	0,391	0,395	0,419
3	**0,452**	0,402	**0,439**	0,341
Delta	0,131	0,019	0,070	0,102
Rank	1	4	3	2

Table 10 Ra Severity and Consequence Chart

Ra (µm)				
Level	**A**	**B**	**C**	**D**
1	**9,881**	7,889	**8,695**	7,196
2	7,395	**8,318**	8,193	7,714
3	7,015	8,084	7,403	**9,381**
Delta	2,866	0,430	1,293	2,185
Rank	1	4	3	2

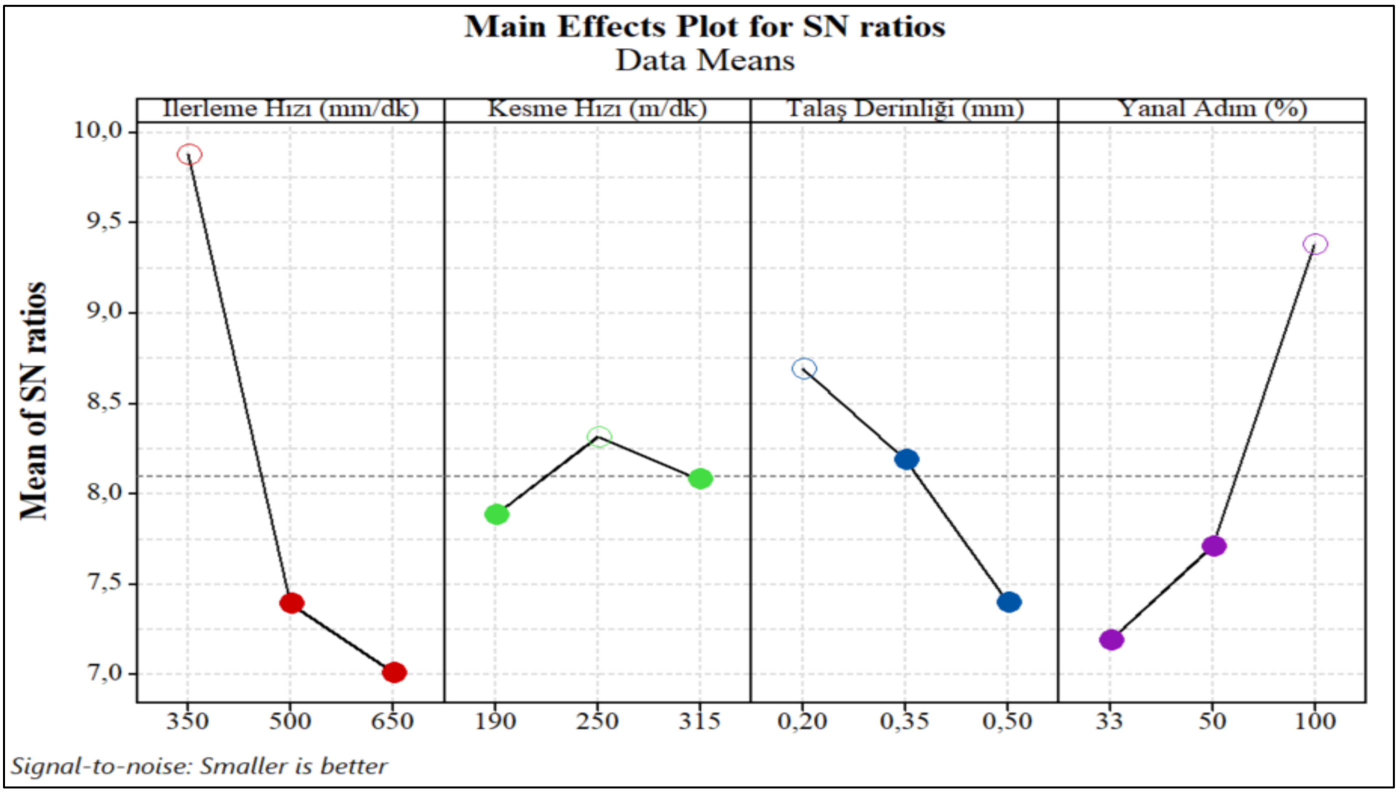

Fig 14 Effects of Process Parameters on S/N Ratio

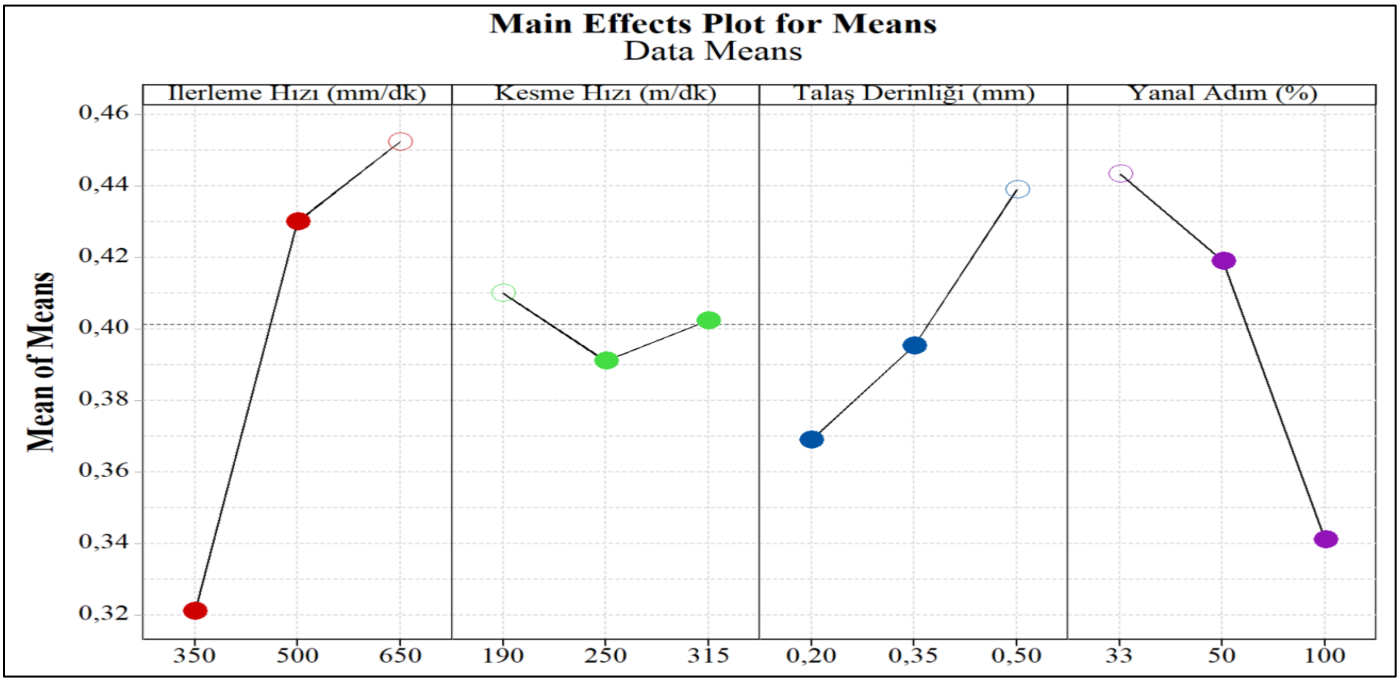

Fig 15 The Effects of Active Process Parameters on Surface Roughness

B. *ANOVA Analysis*

In an experimental design, variance analysis (ANOVA) is conducted to determine the individual interactions and effects of all control factors, while regression analysis is employed to measure the relationship between two or more quantitative variables. Table 11 provides the ANOVA results, indicating the effects of feed rate, cutting speed, depth of cut, and lateral step at a 95% confidence interval and 5% significance level on Ra, surface roughness. In this study, the ANOVA results revealed that the most influential parameter on Ra was factor A (feed rate) with an effect rate of 57.73%. Factors D (lateral step) and C (depth of cut) followed with effect rates of 31.04% and 10.11%, respectively. It was observed that the effect of factor B (cutting speed) was inadequate compared to the other parameters.

Table 11 ANOVA Results Table for Ra

Variance Source	**Degree of Freedom** (Dof)	**Sum of squares** (SS)	**Cont. Rate**	**Mean Square** (MS)	**F Ratio**
A (Vf)	2	14,544	57,74%	7,272	*
B (Vc)	2	0,278	1,10%	0,139	*
C (ap)	2	2,548	10,11%	1,274	*
D (ae)	2	7,82	31,04%	3,910	*
Error	0	*	*	*	
Total	8	25,189	100,00%		

V. CONCLUSION

In milling operations, the selection of different machining parameters is crucial for surface roughness quality and tool life. In this experimental study, the effect of different machining parameters on the surface roughness of Millux Protection 600T armor plate in milling operations was analyzed. Nine different experimental studies were conducted based on the Taguchi optimization method for the selected parameters. Signal-to-Noise (S/N) ratio and Analysis of Variance (ANOVA) were applied to determine the optimum level and contribution percentage.

The optimum levels of individual parameters for surface roughness were determined as follows: feed rate (A) level 1, cutting speed (B) level 2, depth of cut (C) level 1, and lateral step (D) level 3. The contribution percentages of the selected parameters are as follows: 57.73% for feed rate, 31.04% for lateral step, and 10.11% for depth of cut. The percentage contribution of cutting speed to surface roughness value is negligibly small.

The variance analysis of the conducted experiment revealed that the feed rate was the most important parameter with the highest contribution percentage, followed by the lateral step. However, the importance levels of the depth of cut and cutting speed vary. The number of selected parameters to evaluate the surface roughness of the chosen material constitutes the main limitations of this study. It is observed that the results obtained with both analytical and analysis methods through the designed experimental method are approximately consistent, indicating the validity of the experiment with a 90% accuracy rate. Considering different process parameters during the processing of armor steel with high wear resistance and hardness is recommended for future research endeavors.

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