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Effects on Machinability of Minimum Quantity Lubrication Strategy during Milling of ST52 Steel

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Abstract: This study focuses on milling under sustainable cutting conditions of ST52 steel, frequently used in the manufacturing industry. ST52 steel is a good candidate as a workpiece because it is inexpensive and readily available. The cutting zone minimum quantity lubrication technology was used during processing to achieve sustainable conditions. The experiments used three cutting speeds (120-180-240 m min-1), three feed rates (0.12-0.18-0.24 mm rev-1), and a constant depth of cut (0.5 mm). Taguchi L_9 orthogonal array was used to reduce repetitions. The response parameters are surface roughness, flank wear, and cutting temperature. As a result, compared to the dry environment, the minimum quantity lubrication environment improved surface roughness by approximately 62.37%, flank wear by about 9.95%, and cutting temperature by about 13.82%. In addition, the most effective control factors on response parameters were determined by statistical analysis.

ST52 Çeliğinin Frezelenmesi Sırasında Minimum Miktarda Yağlama Stratejisinin İşlenebilirliğe Etkileri

Anahtar Kelimeler
ST52 çelik,
İşlenebilirlik,
Minimum miktarda yağlama,
Taguchi tekniği

Öz: Bu çalışma, imalat sanayisinde sıklıkla kullanılan ST52 çeliğinin sürdürülebilir kesme koşulları altında frezelenmesine odaklanmaktadır. ST52 çeliği, ucuz olması ve kolayca bulunabilmesi nedeniyle iş parçası olarak iyi bir adaydır. Sürdürülebilir koşullara ulaşmak için işleme sırasında kesme bölgesinde minimum miktarda yağlama teknolojisi kullanıldı. Deneylerde üç kesme hızı (120-180-240 m dk^{-1}), üç ilerleme hızı (0.12-0.18-0.24 mm dev^{-1}) ve sabit kesme derinliği (0.5 mm) seçilmiştir. Tekrarları azaltmak için Taguchi L_9 ortogonal dizisi kullanıldı. Yanıt parametreleri; yüzey pürüzlülüğü, kenar aşınması ve kesme sıcaklığıdır. Sonuç olarak minimum miktarda yağlama yapılan ortamda kuru ortama göre yüzey pürüzlülüğünde yaklaşık % 62.37, yanak aşınmasında yaklaşık % 9.95 ve kesme sıcaklığında yaklaşık % 13.82 oranında iyileşme sağlanmıştır. Ayrıca yanıt parametreleri üzerinde en etkili kontrol faktörleri istatistiksel analizlerle belirlenmiştir.

1. INTRODUCTION

With the advancement of technology, the number of organizations in the industrial sector is increasing. Thus, the demand for many materials in the production sector is expanding daily [1]. ST52 steel is one of the most demanded products by companies in the industrial sector all over the world. ST52 structural steels are known as steels containing up to 0.2% carbon [2]. In other words, it can also be called steel with a tensile strength of at least 52 kg mm^{-1}. It can be used in machine parts exposed to constant and variable loads. ST52 steel is frequently preferred, especially in the automotive industry. This material is needed in the industrial sector due to its good applicability. Due to its easy formability, it has a usage area in almost every field.

The process of transforming the raw material into the desired product is called manufacturing. Many different methods can be used in the manufacturing process. These methods can be called machining and chipless manufacturing. In machining methods, machining can be done by removing chips from the workpiece with techniques such as turning, milling, and planing [3, 4]. The chip removal mechanism is a very complex operation. The cutting tool can be exposed to very high internal stress and excessive heat during machining [5].

These stresses and high temperatures cause different wear mechanisms on the cutting tool. Deformations and wear during machining adversely affect the cutting tool and workpiece [6]. Conventional cutting fluids are used in machining to prevent these unfavorable circumstances [7]. These fluids are soluble in water. Although conventional cutting liquids lower the temperatures in the cutting area, they have many negative aspects. These liquids are dangerous to the environment and workers' health. In addition, because they are applied in the form of flood cooling, their costs are high. Many researchers have been drawn to the minimum quantity lubrication (MQL) strategy as an alternative to traditional liquids in recent years [8-11]. The MQL system aims to increase productivity by using high-efficiency cutting fluids sensitively and economically [12]. This technology is highly efficient when compared to flood cooling. Compared to traditional cutting fluids, the MQL strategy is economical and environmentally friendly, especially in machine tools [13]. There are many studies in the literature using the MQL cooling strategy [14-17]. For example, Hadad and Sadeghi [18] investigated the machinability of AISI 4140 steel in an MQL environment. They claimed that when milling AISI 4140 material with MQL, the temperature at the tool-chip interface was around 350 °C lower than in a dry environment. Muhammed and Choudhury [19] used an MQL environment in the milling of AISI 4340. They discovered that using liquids with low viscosity in the MQL environment is more beneficial. They also reported that with the MQL technique, wastes could be reduced, and an environmentally friendly sustainable production could be made. Salur et al. [20] investigated machinability properties by milling AISI 1040 steel in dry and MQL conditions. They reported that the MQL environment outperformed the dry environment, with improvements in all processing parameters.

In this study, different machining parameters and different cooling/lubrication strategies were used during the milling of ST52, which is widely used in the manufacturing industry. There are limited studies in the literature on the processing of ST52 steel with environmentally friendly cooling/lubrication strategies. However, the limited number of studies supports the original side of the article. Three different cutting speeds (120-180-240 m min^{-1}), three different feed rates (0.12-0.18-0.24 mm rev^{-1}), and three different cooling/lubrication environments were used in the experiments (dry-air-MQL). To reduce the number of experiments and costs, the Taguchi L_9 orthogonal array was used. Obtained results were analyzed comparatively.

2. MATERIAL AND METHOD

In this study, ST52 material, which is a commercially available low-carbon steel, was used as the workpiece. This material has usage areas in almost every field of the industrial sector. Sample dimensions are in the form of a 50x50x5 mm plate. Table 1 shows the chemical compositionof the workpiece.

Table 1. Chemical composition of ST52 [21]

Material	Carbon (wt.%)	Silicon (wt.%)	Manganese (wt.%)	Phosphorus (wt.%)	Sulfur (wt.%)	Chromium (wt.%)	Molybdenum (wt.%)
ST52	max 0.20	max 0.21	1.2	0.01	max 0.035	0.008	max 0.005

The experiments were carried out on a computer numerically controlled milling machine (DAHLIH MCV-860). As cutting tools, AlTiN-coated carbide inserts were used. Cutting speed (120-180-240 m min^{-1}), feed rate (0.12-0.18-0.24 mm rev^{-1}), and cutting environment were all variables (dry-air-MQL). The cutting depth was calculated to be 0.50 mm. The machinability parameters were determined by considering the characteristics of the workpiece and the recommendations of the cutting tool manufacturer. Three different parameters were selected to cool/lubricate the chip tool interface. Air cooling and MQL system compared to a dry environment. Air cooling is done with the help of a compressor connected to the machine tool. The MQL environment was implemented through a Werte Micro Stn-15 model system. The cutting fluid in the MQL system is delivered to the cutting environment in the form of pressure and mist at regular intervals. The cutting tool and workpiece are therefore effectively cooled with a small amount of coolant. The nozzle was placed at a distance of 40 mm from the cutting zone, taking into account the manufacturer's recommendations (7 bar compressor pressure, liquid flow rate 45 mL h^{-1}, spray angle 40°). Pressurized oil was transferred to the cutting zone in a pulverized manner from a 5 mm diameter nozzle. After the experiment, the wear amount and images of the cutting tool were determined with the help of the Insize ISM-PM200SA Digital Microscope. Temperatures in the cutting zone during tests were measured by means of a thermal imager (Testo 871). To get an idea about the surface integrity of the processed material, a TIME3200 model surface roughness measuring device was preferred. The arithmetic mean was taken by measuring five times in each sample.

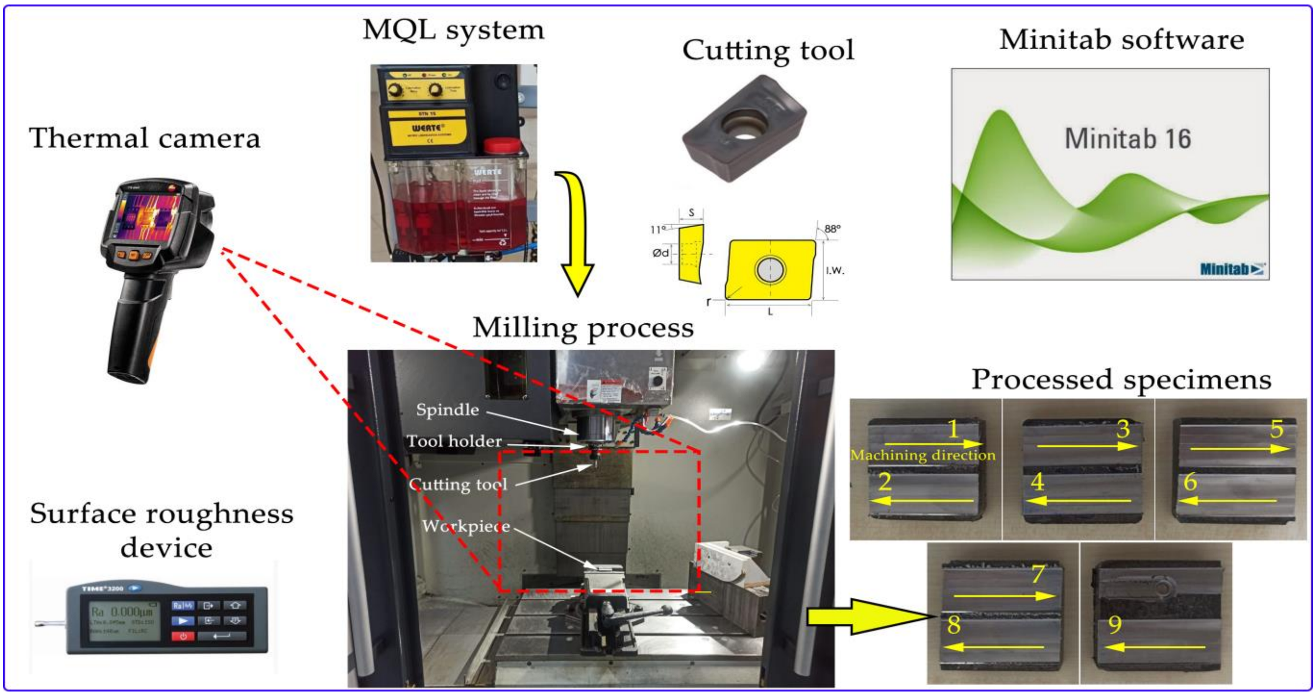

Figure 1. Experimental setup

Taguchi L_9 orthogonal array is designed to obtain more results with a minimum number of experiments. To cut expenses and discover the most effective parameters, many researchers choose the Taguchi approach. In Table 2, the Taguchi L_9 design is given. The process conditions and stages are shown in Table 3. An equation is applied to establish a relationship between the experimental results obtained in the Taguchi technique and the desired values. This equation is converted into a signal-to-noise (S/N) ratio via Minitab software. Since the smallest values are better in the results of the machinability experiments, the "smaller is better" equation was used. S/N ratios were found with the help of the Equation 1.

$$S/N = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} (y^2) \right] \quad (1)$$

Here y; response parameters n; the repeating number for the test conditions, i; It represents n repetition times.

Table 2. Taguchi L_9 (3^3) design

Exp. number	**Cutting speed (m min^{-1})**	**Feed rate (mm rev^{-1})**	**Cooling/ Lubrication**
1	120	0.12	Dry
2	120	0.18	Air
3	120	0.24	MQL
4	180	0.12	Air
5	180	0.18	MQL
6	180	0.24	Dry
7	240	0.12	MQL
8	240	0.18	Dry
9	240	0.24	Air

Table 3. Variables and steps of process

Milling parameters	**Unit**	**Levels**		
		1	**2**	**3**
Cooling conditions	-	Dry	Air	MQL
Cutting speed, (V_c)	m min^{-1}	120	180	240
Feed rate, (f_n)	mm rev^{-1}	0.12	0.18	0.24

3. RESULTS AND DISCUSSION

Milling studies on ST57 were carried out in a variety of cutting conditions and with different processing settings. The findings of surface roughness, tool wear, cutting temperature, and statistical analysis were carefully analyzed.

3.1. Surface Roughness Analysis

Surface integrity is very important in machinability studies. Therefore, it is necessary to fully understand the surface roughness values in the surface integrity of the test sample. Figure 2 depicts 3D surface graphs illustrating the relationship between various cutting conditions, cutting environments, and surface quality. The lowest surface roughness values were measured as 1.996 µm in a dry environment, 1.256 µm in the air environment, and 0.751 µm in the MQL environment. It seems that the best cutting environment is MQL. It was determined that the MQL environment provides an improvement of approximately 62.37% compared to the dry environment and approximately 40.20% compared to the air environment. With MQL environment, cooling and lubrication processes are carried out in the cutting zone [22]. In this way, surface roughness can also be reduced. In dry machining conditions, cutting temperatures can reach maximum levels. Therefore, some wear occurs on the cutting tool. Due to these adverse conditions, the surface roughness may deteriorate. Cutting variables and cutting environments can have a significant impact on surface roughness. When the 3D visuals are inspected, it is clear that the surface roughness rises as the cutting speed increases and reduces when the feed rate increases. As a result, the obtained results can be said to be in line with previous research.

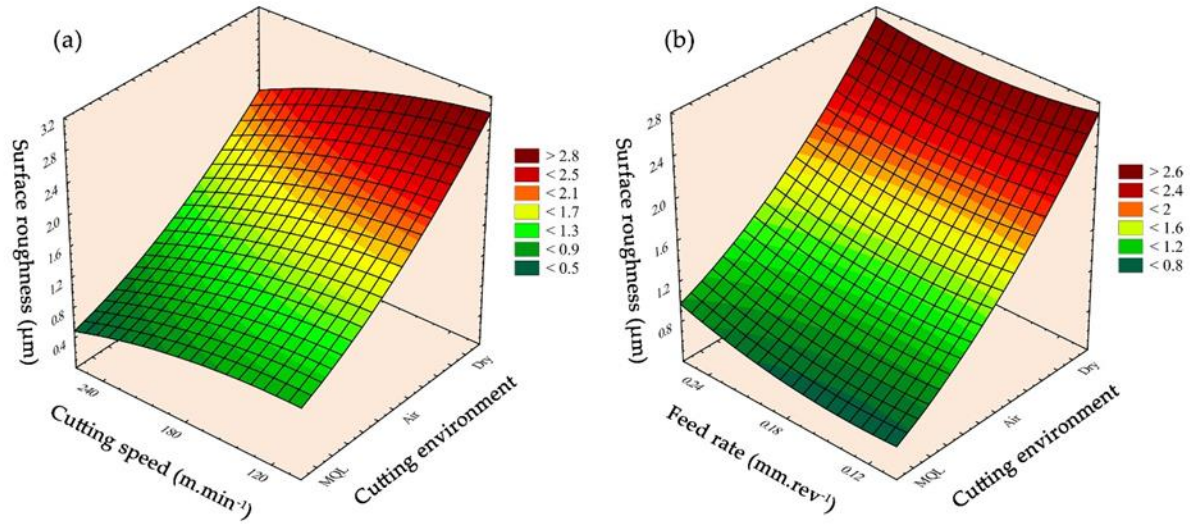

Figure 2. 3D surface plots showing the relationship of surface roughness with various conditions; a) Cutting speed-Cutting environment, b) Feed rate-Cutting environment

3.2. Flank Wear Analysis

Tool wear is a phenomenon that severely affects all parameters in machining. It is a parameter that must be monitored to maintain tool life and surface integrity [23]. Figure 3 depicts 3D surface plots that demonstrate the effects of various cutting conditions (cutting speed, feed rate) and cutting environments (dry, air, MQL) on flank wear. The lowest flank wear values; were 462 µm in the dry environment, 437 µm in air, and 416 µm in the MQL environment. MQL environment has an improvement of approximately 9.95% compared to the dry environment and about 4.80% compared to the air environment. When evaluated in terms of flank wear, it is seen that the best cutting environment is MQL. High temperatures in the cutting zone in a dry environment can cause plastic deformation and cause severe damage to the cutting tool [24]. Therefore, the amount of flank wear increases more in dry conditions. When cutting parameters were evaluated, an increase in flank wear values was seen as cutting speed was increased (Figure 3a). The opposite is true for feed rate. The flank wear, on the other hand, diminishes when the feed rate increases.

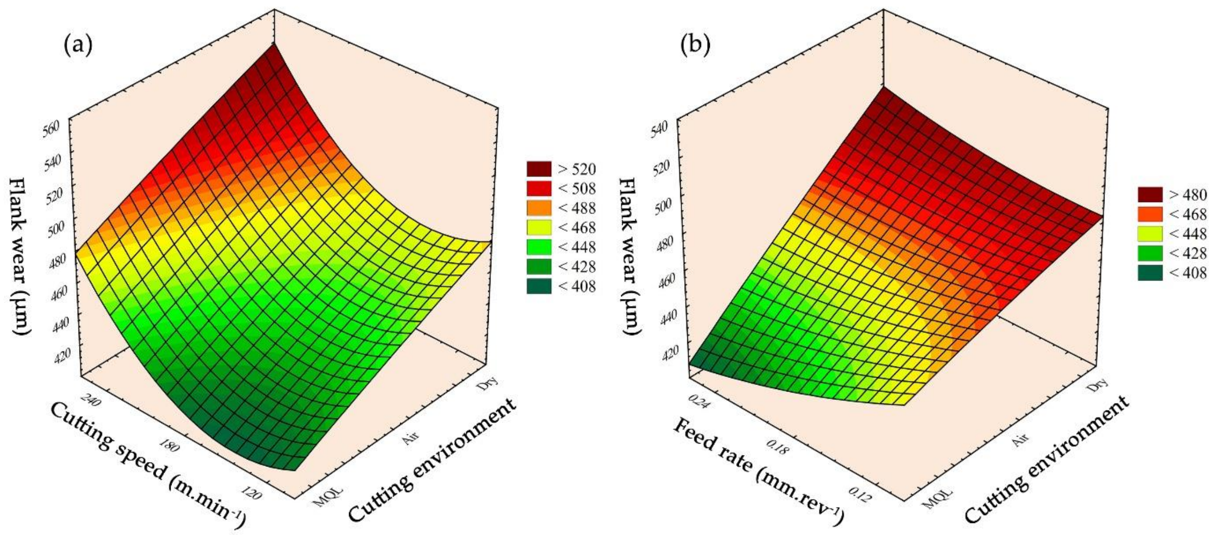

Figure 3. 3D surface plots showing the relationship of flank wear with various conditions; a) Cutting speed-Cutting environment, b) Feed rate-Cutting environment

Figure 4 depicts the wear dimensions of cutting tools following milling experiments at various cutting conditions, feed rates, and cutting speeds of 120 m min^{-1}. According to the photographs obtained from the optical images, it is seen that the amount of flank wear decreases as you go from the dry environment to the MQL environment. Furthermore, it was revealed that when the feed rate increased, the flank wear values reduced.

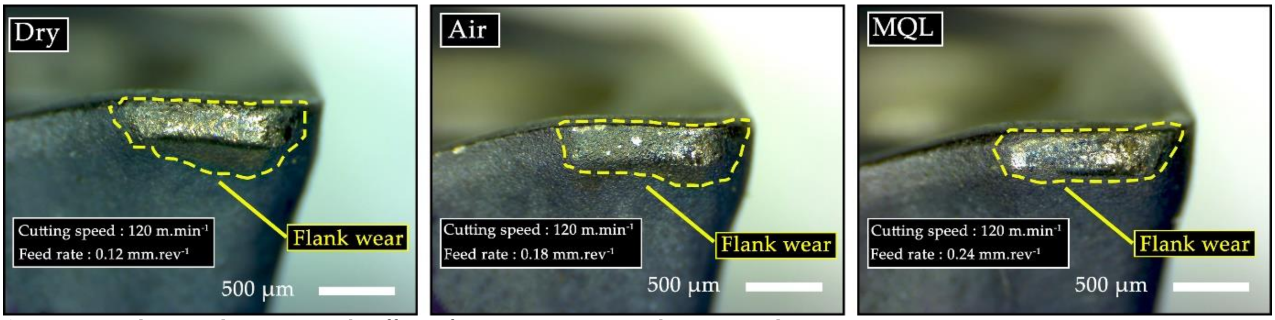

Figure 4. Optical images demonstrating the effects of various parameters on the cutting tool

3.3. Cutting Temperature Analysis

In machining, cutting temperature is one of the most critical parameters determining cutting tool wear and surface roughness. Heat is generated on the workpiece and cutting tool during machining owing to friction. However, this temperature can reach very high levels in the tool-chip interface. The temperatures measured in this study are those in the cutting zone between the cutting tool and the workpiece. Temperatures occurring at the tool-chip interface cannot be reduced by conventional coolants. Because high cutting and feed rates might make fluid penetration into the cutting zone harder [25]. Figure 5 shows 3D surface graphs that show the influence of different processing settings on cutting temperature. As can be seen from the 3D graphics, it is seen that the cutting temperature decreases as you go from the dry environment to the MQL environment. The cutting fluid may be effectively transferred to the chip tool interface in a pressured and pulverized state thanks to the MQL system. Thus, high temperatures caused by the friction of hard particles breaking off from both the cutting tool and the workpiece in the cutting zone are reduced. The lowest cutting temperature; was determined as 104.9 °C in a dry environment, 95.6 °C in an air environment, and 90.4 °C in an MQL environment. It was revealed that in the MQL environment, the cutting temperature reduced by approximately 13.82% when compared to the dry environment and by roughly 5.43% when compared to the air environment. The cutting temperature, on the other hand, rises as the cutting speed and feed rate rise. Because more friction occurs as the cutting speed and feed rate increase, plastic deformation increases and the temperature rises to higher levels.

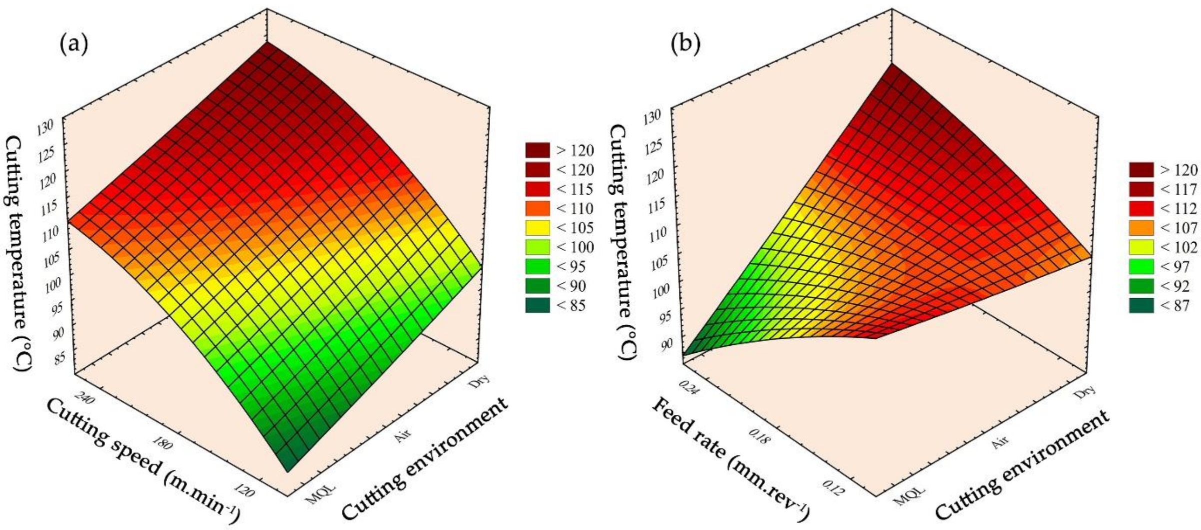

Figure 5. 3D surface plots showing the relationship of cutting temperature with various conditions; a) Cutting speed-Cutting environment, b) Feed rate-Cutting environment

3.4. Statistical Analysis

For researchers, experiments can often be difficult and costly. The higher the number of experiments, the higher the cost and burden. In this method, which was invented by a researcher named Taguchi, the number of experiments can be reduced by using the loss function resulting from the mean target deviations. In the Taguchi method, response parameters are defined in the first place, and then a standard way is followed by choosing the S/N ratios [26]. Response parameters; surface roughness (R_a), Flank wear (V_b) and Cutting temperature (T_c). Table 4 displays the experimental results as well as the S/N ratios. The Taguchi method focuses on the S/N ratio since noise has an effect on the response parameters. Maximum S/N ratios are required for positive results of response parameters. Therefore, the S/N ratios are; It is based on 1.5454 dB for R_a, -52.3819 dB for V_b and -39.1234 dB for T_c.

Table 4. S/N percentages and tests data

Experiment number	R_a (µm)	V_b (µm)	T_c (°C)	S/N for R_a (dB)	S/N for V_b (dB)	S/N for T_c (dB)
1	2.565	471	104.9	-8.1817	-53.4604	-40.4155
2	1.859	437	95.6	-5.3855	-52.8096	-39.6092
3	1.047	418	90.4	-0.3989	-52.4235	**-39.1234**
4	1.402	459	112.2	-2.9349	-53.2363	-40.9999
5	0.837	416	103.9	**1.5454**	**-52.3819**	-40.3323
6	2.705	462	110.4	-8.6433	-53.2928	-40.8594
7	0.751	464	110.1	2.4872	-53.3304	-40.8357
8	1.996	517	123.7	-6.0032	-54.2698	-41.8474
9	1.256	481	113.4	-1.9797	-53.6429	-41.0923

Figure 6 depicts main effect graphs created with Minitab software that show the effects of response parameters on control factors. The larger the impact of the control factor on the response parameter, the steeper the lines in the graphs. It is observed that the cutting environment line is more vertical in the surface roughness and flank wear graphics. According to this, the most effective control factor in surface roughness and flank wear is the cutting environment. In terms of cutting temperature, however, the cutting speed control factor was found to be more upright. As can be observed, cutting speed is the most efficient temperature control component. On all response characteristics, the feed rate was shown to be the least effective control factor.

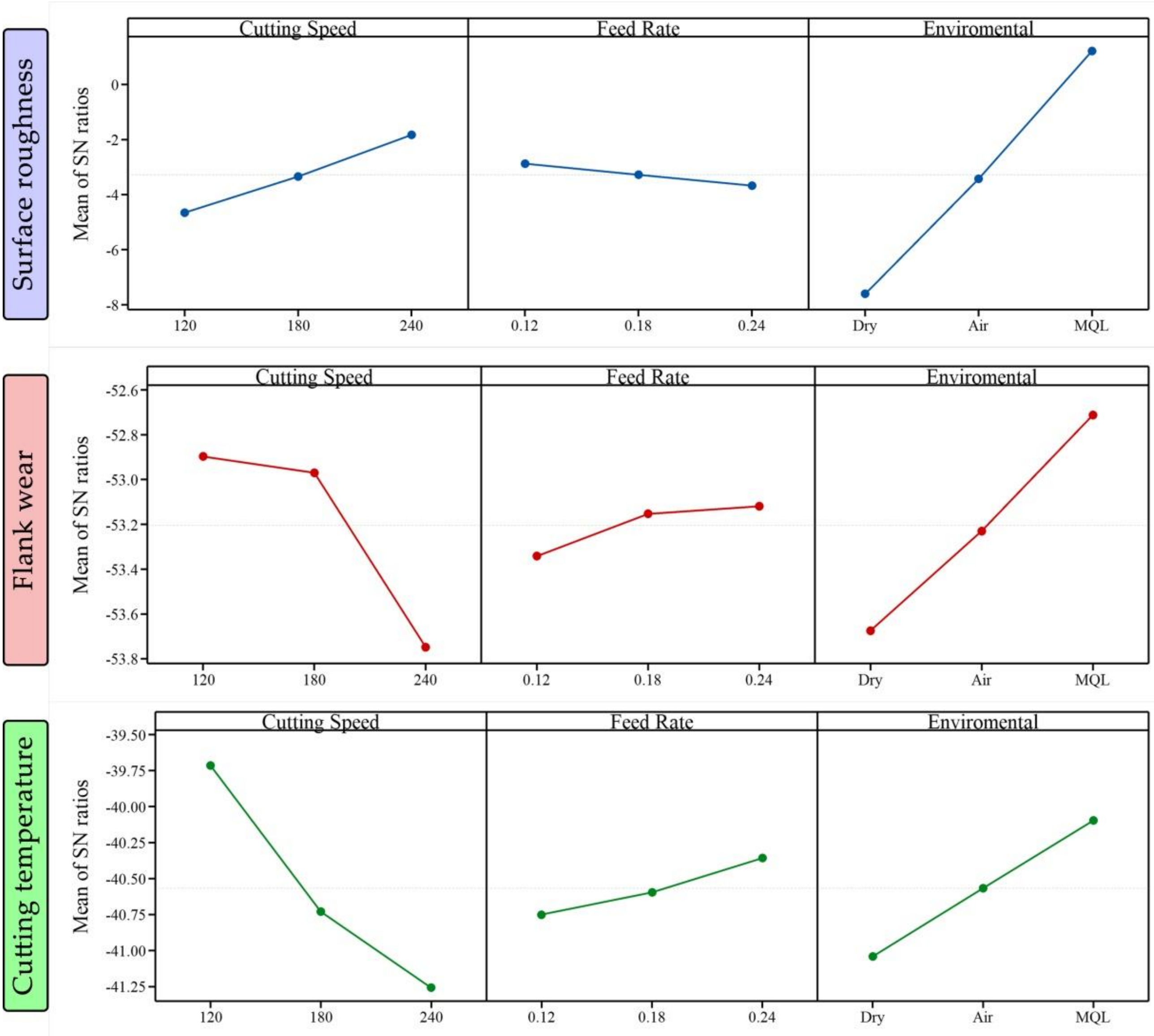

Figure 6. Plots of main effects of control factors on response parameters

Table 5 shows the analysis of variance (ANOVA) table for all response parameters and contribution rates. ANOVA provides information on the importance of control factors based on the averages of response parameters in different combinations. The analysis was based on the level of significance. For example, a P value of 0.05 in the table is deemed significant. Adj SS corrected the sum of squares, Adj MS corrected the mean squares, and F and P values in the table demonstrate the significance of control variables. The contribution rates of the most influential factors specified in the main impact graphs are given as numerical values in this table. According to the table, the cutting environment was the most effective factor for surface roughness (88.971%), the cutting environment was the most effective factor for flank wear (48.678), and the cutting speed was the most effective factor for cutting temperature (69.048). According to the table, the significance levels of the most effective control factors are; It was determined as 0.013 for surface roughness, 0.034 for flank wear, and 0.022 for cutting temperature. Since all control factors were <0.05, the analysis can be said to be significant.

Table 5. ANOVA table for factors affecting response parameters and contribution rates

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution rate (%)
Surface roughness							
Cutting speed (m min^{-1})	2	11.978	11.978	5.9892	7.73	0.115	9.123
Feed rate (mm rev^{-1})	2	0.954	0.954	0.4771	0.62	0.619	0.727
Environmental	2	116.817	116.817	58.4083	75.42	**0.013**	**88.971**
Residual Error	2	1.549	1.549	0.7744	-	-	1.180
Total	8	131.298	-	-	-	-	100.000
Flank wear							
Cutting speed (m min^{-1})	2	1.33177	1.33177	0.66589	26.81	0.036	46.569
Feed rate (mm rev^{-1})	2	0.08626	0.08626	0.04313	1.74	0.365	3.016
Environmental	2	1.39209	1.39209	0.69605	28.03	**0.034**	**48.678**
Residual Error	2	0.04967	0.04967	0.02483	-	-	1.737
Total	8	2.85979	-	-	-	-	100.000
Cutting temperature							
Cutting speed (m min^{-1})	2	3.68712	3.68712	1.84356	44.36	**0.022**	**69.048**
Feed rate (mm rev^{-1})	2	0.23405	0.23405	0.11703	2.82	0.262	4.383
Environmental	2	1.33563	1.33563	0.66782	16.07	0.059	25.012
Residual Error	2	0.08312	0.08312	0.04156	-	-	1.557
Total	8	5.33993	-	-	-	-	100.000

Figure 7 represents graphs comparing experimental results of response parameters with results estimated by ANOVA. As seen from the graphs, surface roughness shows 98.82% accuracy, flank wear 98.26%, and cutting temperature 98.44% accuracy. Statistical analysis accepts it when the success rate is 85% and above. It is understood that high success rates were achieved in this study.

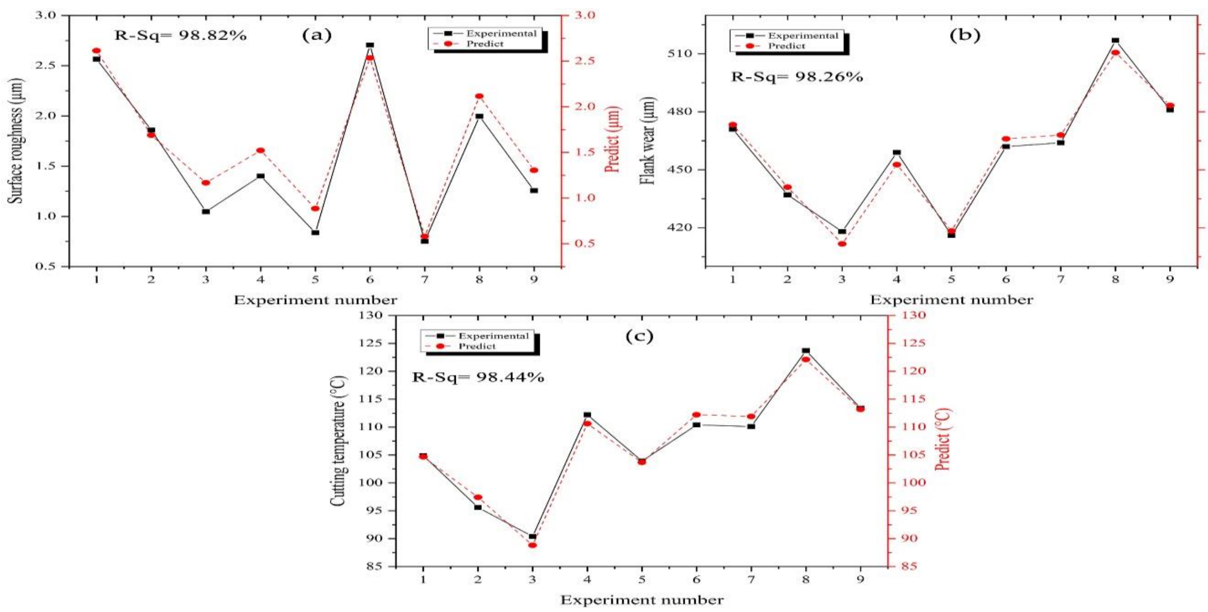

Figure 7. Comparison of experimental and projected findings for the response parameters

4. CONCLUSION

This study investigated the milling of ST52 steel under different cooling/lubrication conditions. For this purpose, surface roughness, flank wear, and cutting temperature were analyzed. In addition, Taguchi analysis was performed to reduce the number of experiments and costs. The results are as follows.

- In the surface roughness test, the MQL environment produced the lowest value (0.751 m). The MQL environment improved by roughly 62.37% as compared to the dry environment.
- The lowest flank wear value was obtained as a result of machining in the MQL environment and recorded as 416 µm. Flank wear is reduced by approximately 9.95% compared to a dry environment.
- The MQL environment had the lowest temperature (90.4 °C) in the cutting temperature experiments. When compared to the dry environment, the MQL environment reduced the cutting temperature by approximately 13.82%.
- The most effective control factors on the response parameters were determined by statistical analysis; it was determined the cutting environment for surface roughness (88.971%) and flank wear (48.678), and cutting speed (69.048) for cutting temperature.

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