Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 14(3), 1228-1239, 2024
Journal of the Institute of Science and Technology, 14(3), 1228-1239, 2024
ISSN: 2146-0574, eISSN: 2536-4618
Makina Mühendisliği / *Mechanical Engineering* **DOI: 10.21597/jist.1481108**
Araştırma Makalesi / *Research Article*
Geliş tarihi / *Received*: 09.05.2024 **Kabul tarihi / *Accepted*: 29.07.2024**

Atıf İçin: Değirmenci, Ü. (2024). Nimonic-60 Süper Alaşımının Sürdürülebilir Koşullar Altında İşlenebilirlik Özelliklerinin Belirlenmesi. *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 14(3), 1228-1239.

To Cite: Değirmenci, Ü. (2024). Determination of Machinability Properties of Nimonic-60 Superalloy Under Sustainable Conditions. *Journal of the Institute of Science and Technology*, 14(3), 1228-1239.

Nimonic-60 Süper Alaşımının Sürdürülebilir Koşullar Altında İşlenebilirlik Özelliklerinin Belirlenmesi

Ünal DEĞİRMENCİ[1*]

Öne Çıkanlar:
- Süper alaşımların işlenebilirliği
- Sürdürülebilir İşleme koşullarının belirlenmesi
- Taguchi istatiksel analiz ile optimizasyon

Anahtar Kelimeler:
- Nimonic-60
- Frezeleme
- İşlenebilirlik
- MQL
- Takım aşınması

ÖZET:

Sürdürülebilir işleme, endüstriyel üretim süreçlerinde çevresel etkileri en aza indirmeyi ve kaynak kullanımını optimize etmeyi amaçlayan bir yaklaşımdır. Bu yaklaşımın temeli, işleme yöntemlerinin kullanımıyla ilişkili çevresel ve ekonomik etkilerin azaltılmasında yatmaktadır. İşleme, metal parçaları şekillendirmek için yaygın olarak kullanılan bir yöntemdir ve bu işlem genellikle enerji yoğun ve israfa neden olur. Sürdürülebilir işleme çeşitli stratejiler içerir. Bunlar arasında yenilenebilir enerji kaynaklarının kullanılması, enerji ve malzeme verimliliğinin arttırılması, geri dönüşüm ve atık yönetiminin iyileştirilmesi, üretim süreçlerinde kesme sıvılarının ve çevresel etkilerin azaltılmasına yönelik malzeme seçimi gibi yöntemler yer almaktadır. Bu çalışmada sanayi alanında önemli bir malzeme olan Nimonic-60 süper alaşımının işlenebilirlik özellikleri incelenmiştir. İşlenebilirlik denemelerinin yapılabilmesi için üç farklı kesme hızı (Vc, 40-50-60 m/dak), diş başına üç farklı ilerleme (fn, 0.050-0.075-0.100 mm/dev) ve üç farklı soğutma/yağlama koşulu (kuru, hava, MQL) kullanıldı. Deneyler bilgisayar kontrollü üç eksenli bir freze makinesi kullanılarak gerçekleştirildi. Ayrıca deney sayısını ve maliyetleri azaltmak amacıyla Taguchi analizi yapılmıştır. Sonuç olarak yüzey pürüzlülüğü, yan aşınma ve kesme sıcaklığı açısından en uygun seçimin Minimum Miktarda Yağlama (MQL) ortamı olduğu sonucuna varılmıştır. Minimum Miktar Yağlama ortamında en düşük yüzey pürüzlülüğü, takım aşınması ve kesme sıcaklığı sırasıyla 0.499µm, 0.201mm ve 66.4 C° olarak ölçülmüştür. Taguchi çalışmasının bulguları, soğutma/yağlamanın yüzey pürüzlülüğü (%56.66), yan aşınma (%87.96) ve kesme sıcaklığı (%78.68) üzerinde en fazla etkiye sahip olduğunu ortaya çıkardı.

Determination of Machinability Properties of Nimonic-60 Superalloy Under Sustainable Conditions

Highlights:
- Machinability of Super alloys
- Determination of Sustainable Processing conditions
- Optimization with Taguchi statistical analysis

Keywords:
- Nimonic-60
- The milling
- Machinability
- MQL
- Tool wear

ABSTRACT:

Sustainable machining is an approach that aims to minimize environmental impacts and optimize resource use in industrial production processes. The basis of this approach lies in reducing the environmental and economic impacts associated with the use of machining methods. Machining is a widely used method for shaping metal parts, and this process is often energy-intensive and wasteful. Sustainable machining involves various strategies. These include methods such as the use of renewable energy resources, increasing energy and material efficiency, improving recycling and waste management, and selecting materials to reduce cutting fluids and environmental impacts in production processes. In this study, the machinability properties of Nimonic-60 superalloy, which is an important material in the field of industry, were examined. In order to conduct machinability trials, three different cutting speeds (Vc, 40-50-60 m/min), three different feed rates per tooth (fn, 0.050-0.075-0.100 mm/rev), and three different cooling/lubrication conditions (dry-air-MQL) were used. The trials were conducted using a computer-controlled three-axis milling machine. Additionally, Taguchi analysis was performed to reduce the number of experiments and costs. Consequently, it was concluded that the most optimal choice for surface roughness, flank wear, and cutting temperature was the Minimum Quantity Lubrication (MQL) environment. Minimum surface roughness, tool wear and cutting temperature in the MQL environment were measured as 0.499µm, 0.201mm and 66.4 C° respectively. The Taguchi study findings revealed that cooling/lubrication had the most impact on surface roughness (56.66%), flank wear (87.96%), and cutting temperature (78.68%).

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[1] Ünal DEĞİRMENCİ (**Orcid ID:** 0000-0003-1480-2488), Department of Machinery and Metal Technologies, Bingöl University, Bingöl, Türkiye

***Corresponding Author:** Ünal DEĞİRMENCİ, e-mail: udegirmenci@bingol.edu.tr

INTRODUCTION

Machining is a prevalent manufacturing technique used in several industrial production processes. This method involves operations such as cutting, drilling, and milling to obtain the required shape and size from a piece of material (Akgün et al., 2023; Cantero et al., 2018; Şap, 2023b). Machining has a wide range of applications in various sectors, such as automotive, aviation and machinery manufacturing (Değirmenci et al., 2023; Elbah et al., 2013; Özlü et al., 2023; Usca et al., 2024). While machining has traditionally been used primarily for metal materials, it has increasingly become significant in the processing of other materials such as plastics, composite materials, and ceramics (Gupta & Laubscher, 2016). This method has become an indispensable part of industrial production processes as it provides high precision, surface quality and production efficiency (Gupta et al., 2017). The basic principle of machining is to create chips of the desired shape and size on the material with the help of a cutting tool. This process is characterized by cutting forces and thermal effects applied to the material (Hsiao et al., 2020; Şap, 2023a). Choosing the right cutting parameters and using the appropriate tool material is of great importance for the efficiency and quality of the process (Hussain et al., 2020). Cutting fluids used in machining operations provide crucial tasks, including enhancing the surface quality of the workpiece and prolonging the lifespan of the tools (Islam et al., 2017; S. Şap et al., 2022). However, traditional cutting fluids raise sustainability concerns due to their environmental impact and health risks. In this context, sustainable cutting fluids are defined as formulations that consist of environmentally friendly ingredients and keep the waste generated during the process to a minimum (Kulkarni & Dabhade, 2019). Alternatives such as biodegradable oils, water-based cutting fluids and oils used in minimum quantities have begun to replace traditional cutting fluids (Makhesana et al., 2022; Usca, 2023; Usca et al., 2023). The use of sustainable cutting fluids represents an important step towards the sustainability of machining processes by contributing to reducing environmental impacts and improving occupational health and safety standards (Marques et al., 2015). One of these modern lubrication strategies is the minimum quantity lubrication (MQL) system. In this system, a better cooling process is achieved by sending pressurized oil to the cutting area (Mia et al., 2018; Usca et al., 2022). At the same time, it can be more economical since less amount of coolant is used.

In the manufacturing industry, improving product quality, reducing costs and increasing process efficiency are constantly sought goals. To achieve these goals, various quality control and improvement methods have been developed. One of these methods is the Taguchi technique (Bagci, 2016). Taguchi Technique is a statistical method used in quality improvement and process optimization and provides significant advantages in manufacturing processes (Bilga et al., 2016). Taguchi technique offers a systematic approach to identify the effects of process variables and factors that need to be optimized (Canyılmaz & Kutay, 2003). Using experimental design matrices, the effects of process variables are statistically analyzed and critical factors are identified. In this way, uncertainties in the process are reduced and undesirable variations are controlled (Cetin et al., 2011).

This work included the milling of Nimonic-60 superalloy utilizing various cutting settings and different cooling/lubrication processes. To achieve this objective, we conducted analyses on surface roughness (R_a), flank wear (V_b), and cutting temperature (T_c). In addition, the Taguchi analysis was used to minimize the number of tests and associated expenses.

MATERIALS AND METHODS

Nimonic-60 superalloy was used as the test sample. Materials were purchased from Birçelik company. Test samples were prepared by cutting them to have a diameter of 50 mm and a thickness of 20 mm. Table 1 displays the precise chemical makeup of the Nimonic-60 superalloy.

Table 1. Chemical composition of Nimonic-60 superalloy

Ni	Cr	Mo	C	Si	Mn	S	P	N	Fe
9	18	0.75	0.1	4.5	9	0.03	0.06	0.08	Balance

The experiments were carried out on a Dahlih MCV-860 model three-axis computer-controlled milling machine. In milling experiments, MAS 403 BT 40 ER 32x70 coded holder was used as the tool holder, and Al-TiN coated HM90 APKT 1003PDR IC908 coded cutting tool tip was used as the cutting tool tip. The cutting inserts were mounted on the face milling tool coded APKTHM10 12-1-120. The milling process was carried out with the down milling strategy using the CAM program with the "Zig" tool path. The processing width is 12mm and the processing length is 45mm. Three V_c (40-50-60 m/min), three f_n (0.050-0.075-0.100 mm/rev), a single cutting depth (0.2 mm) and three cooling/lubrication environments (dry-air-MQL) were selected in the experiments. R_a, V_b and T_c analyses were performed as output parameters. The use of Taguchi analysis aimed to minimize the number of tests conducted and associated expenditures. Table 2 shows the experimental design (Taguchi L_9).

Table 2. Taguchi experimental design (L_9)

Exp. No	V_c (m/min)	fn (mm/rev)	Cooling/lubrication
1	40	0.05	Dry
2	50	0.075	Dry
3	60	0.1	Dry
4	40	0.075	Air
5	50	0.1	Air
6	60	0.05	Air
7	40	0.1	MQL
8	50	0.05	MQL
9	60	0.075	MQL

Three distinct cooling/lubrication methods (dry-air-MQL) were used to decrease the temperatures in the cutting zone during processing. The cooling of the cutting area is achieved by means of the air system that is linked to the machine tool. Within the MQL environment, a nozzle is used to disperse cutting fluid into the cutting region. The liquid outlet diameter of the MQL nozzle is 3 mm. The MQL nozzle is fixed at a distance of approximately 300 mm from the cutting area and at a 45° angle. MQL was applied to the cutting area using a Werte STN 15 model spray device. For the MQL system, air pressure was set to 8 bar and cutting fluid flow rate was set to 35 mL/h. KT2000, which has a hydrodynamic lubrication feature, was used as cutting fluid. The density of this cutting fluid at 20˚C is 0.85g/m3 and its viscosity is 12cst at 40˚C.

The quality of the sample surfaces was assessed using a TIME3200 model R_a instrument. R_a measurements were taken five times from each sample and average R_a values were obtained. The temperatures occurring in the cutting zone during processing were recorded with a BOSCH GTC 400C model thermal camera. The thermal camera was positioned at a distance of roughly 350 mm from the workpiece. Following the studies, the wear processes taking place on the cutting tool were identified using an Insize ISM PM200SB type optical microscope. Figure 1 displays the processing center and the equipment used in the studies.

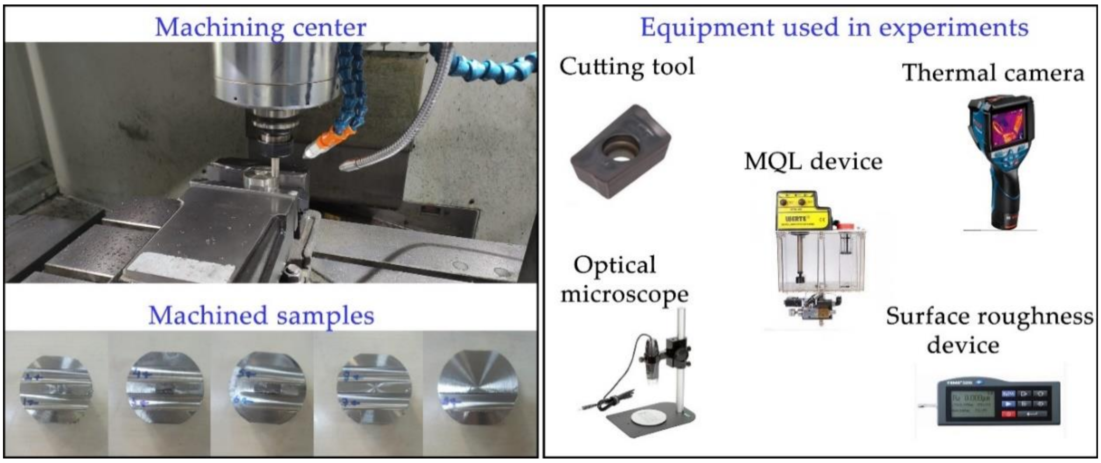

Figure 1. Experimental scheme

RESULTS AND DISCUSSION

Surface roughness

The surface quality of components in the manufacturing business has a substantial influence on the functional performance, longevity, and aesthetic look of the product (Musfirah et al., 2017; ÖZlÜ, 2022). Thus, it is crucial to guarantee and enhance the surface quality in industrial manufacturing operations. Surface quality directly affects the performance of the product. Especially in the production of precision parts, R_a and smoothness are critical for the functionality and compatibility of the part (Nimel Sworna Ross & Manimaran, 2019; Özlü et al., 2021). Surface irregularities or defects can affect the functionality of the part, complicate assembly processes and reduce the durability of the product (Öndin et al., 2020; Özlü, 2021). The durability of the product is significantly influenced by the surface quality. A smooth and homogeneous surface increases the part's resistance to wear and tear. Additionally, surface defects or cracks can adversely affect the mechanical properties of the part and cause loss of strength over time (Patel et al., 2021).

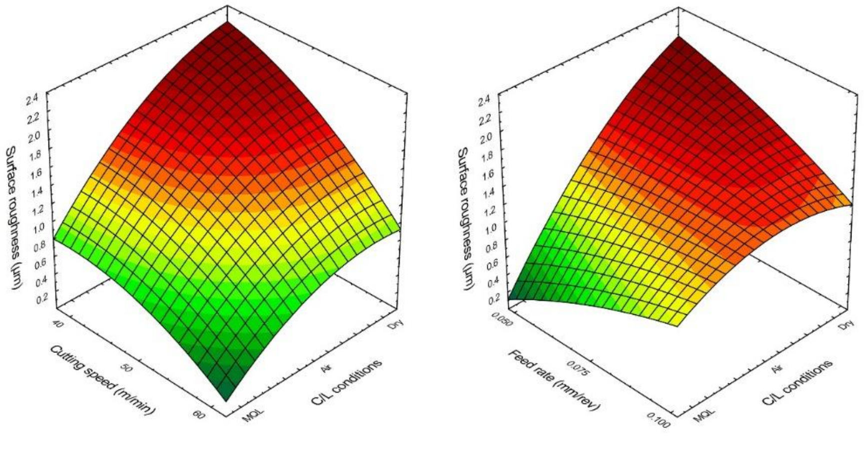

Figure 2. The impact of various cutting settings and environmental conditions on the roughness of a surface

Surface quality is important from an aesthetic point of view. Customers often care about the appearance and texture of products. A smooth, homogeneous and attractive surface makes the product more attractive in the market and increases customer satisfaction. Particularly in the automotive, electronics and consumer products industries, high-quality surface treatment can strengthen the product's brand image and provide a competitive advantage. Figure 2 illustrates the impact of various cutting settings on R_a, as measured by the Ra value. From the graphs, the highest surface roughness was obtained as 2.137 µm in a dry environment, at a cutting speed of 40 m/min and a feed rate of 0.05 mm/rev. It can be seen that the surface quality increases when we move from a dry environment to a compressed air condition. The minimum surface roughness obtained was 0.499 µm at a cutting speed of 60 m/min, a feed rate of 0.075 mm/rev and in the MQL environment. The study found that surface roughness decreased when the cutting speed increased, but the increase in feed rate led to an increase in surface roughness.

Flank wear

In the manufacturing industry, cutting tool wear is a common problem that has a significant impact on the efficiency, quality and costs of production processes. Wear of cutting tools can reduce the material processing efficiency in the cutting process, negatively affect the surface quality of processed parts and increase production costs (Pusavec et al., 2014). For this reason, various researches have been conducted on cutting tool wear and solution strategies have been developed. Various strategies have been developed to reduce or control cutting tool wear. These include optimizing cutting parameters, selection of appropriate cutting tool materials, use of advanced coating technologies and design of effective cooling and lubrication systems (Salur, 2022). Additionally, high-tech machine tools and automation solutions such as cutting tool monitoring systems can be used to monitor and continuously optimize wear levels (E. Şap et al., 2022). Research on cutting tool wear and developed solution strategies play an important role in increasing productivity, improving quality and reducing costs in the manufacturing industry (Sarıkaya & Güllü, 2015). These studies make a valuable contribution to minimizing cutting tool wear in industrial processes and ensuring the sustainability of production processes. Figure 3 shows the effect of various cutting parameters on flank wear. When the graphs were analyzed, the highest flank wear was obtained in a dry environment (0.411 mm) at a cutting speed of 60 m/min and a feed rate of 0.100 mm/rev. It has been observed that tool wear improves in the compressed air environment. The best flank wear was detected in the MQL environment compared to other environments. The smallest wear on the side of the tool (0.201 mm) was obtained in the cutting process at 40 m/min cutting speed, 0.100 mm/rev feed rate and MQL environment. It was observed that the increase in cutting speed caused a partial increase in flank wear, while the increase in feed led to a decrease in flank wear.

Wear on cutting tools is generally a complex process and occurs through the interaction of various mechanisms (Sharma et al., 2015). These mechanisms are affected by factors such as various forces, temperature, material properties and processing conditions to which the tool is exposed during the cutting process. Adhesive wear occurs when the cutting surface and the tool come into contact at elevated temperatures and pressures. In this scenario, the surface of the material being worked on sticks to the cutting tool and results in changes to the tool's surface. High temperature and friction increase this adhesion process and lead to tool wear (Singh et al., 2018). Hard or abrasive particles on the workpiece can create friction and wear on the surface of the cutting tool. These particles hit the cutting tool during the material processing process, creating scratches and grooves on its surface (Thakur et al., 2015). Under some machining conditions, chemical interactions may occur between the workpiece material and the cutting tool. These interactions can create chemical wear or erosion on the surface of the cutting tool. Figure 4 shows optical images showing the wear mechanisms occurring on the cutting tool.

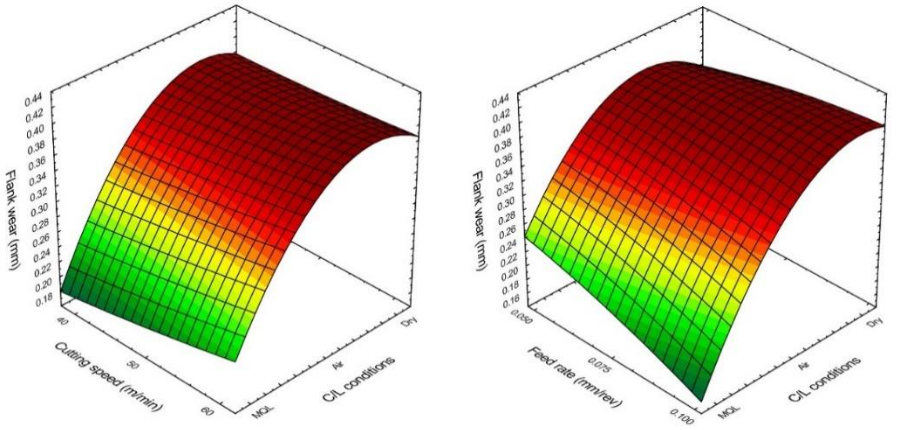

Figure 3. The impact of various cutting settings and environmental conditions on the development of V_b.

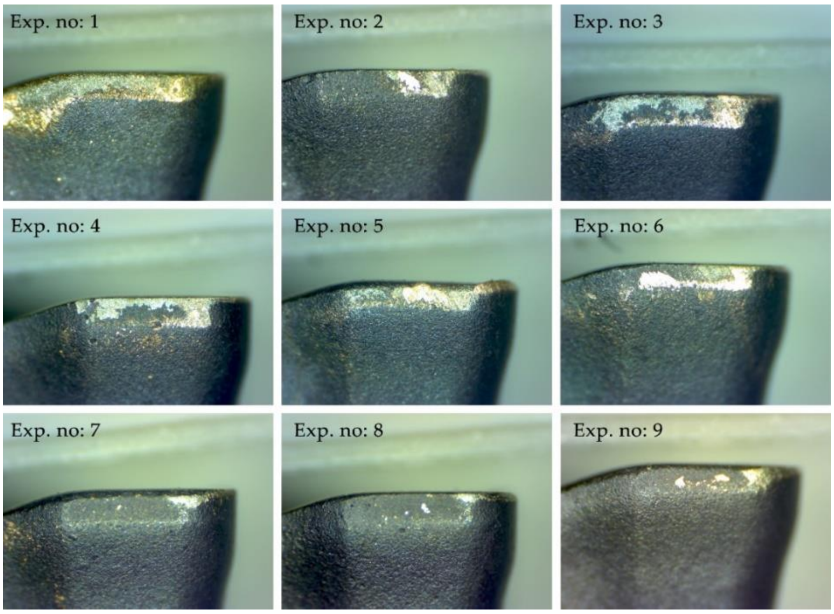

Figure 4. Photographs depicting the physical damage on the cutting tool

Cutting temperature

High temperatures are generated in the contact zone between the cutting tool and the workpiece during the cutting process. The elevated temperatures arise as a result of the cutting process's inherent characteristics and are influenced by elements such as the workpiece's material qualities, cutting circumstances, and the cutting tool's shape (Tu et al., 2023). Elevated temperatures in the cutting zone may induce alterations in the material structure of the workpiece and impact the physical and chemical characteristics of the interaction between the workpiece and the cutting tool. The primary factors contributing to elevated temperatures in the cutting zone are cutting forces, friction, and deformation. Cutting forces are the forces applied by the cutting tool in the process of cutting the workpiece, and these forces can cause plastic deformation and high temperatures in the material structure of the workpiece. Friction is a phenomenon that generates energy at the interface between the cutting surface and the tool, which may then be transformed into elevated temperatures. Deformation encompasses the plastic deformation that takes place in the material structure of the workpiece as it is being cut, leading to the generation of high temperatures (Wang et al., 2015). The effects of elevated temperatures in the cutting zone are varied. Primarily, elevated temperatures may induce thermal distortions in the material composition of the workpiece, thereby impacting the surface integrity of the workpiece. In addition, high temperatures may alter the thermal characteristics of the material being worked on and impact the ultimate qualities of the workpiece. Furthermore, elevated temperatures may have a substantial influence on the deterioration of tools and the efficiency of cutting operations. Figure 5 illustrates the impact of various cutting settings on the T_c.

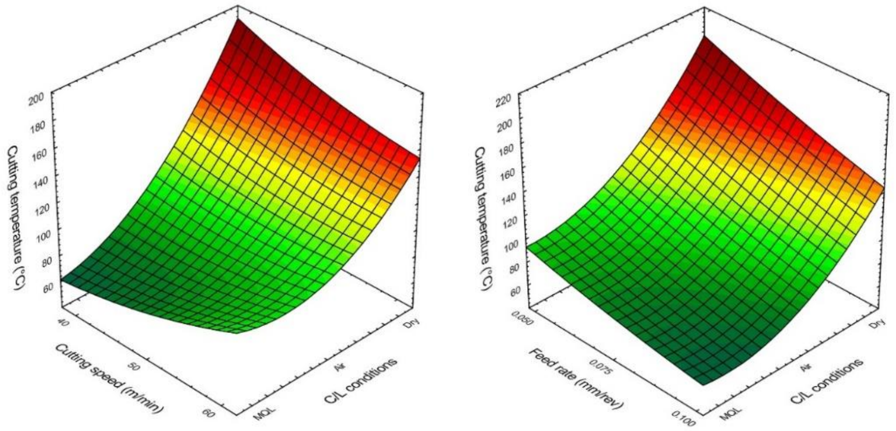

Figure 5. The impact of various cutting settings and environmental conditions on T_c.

Analyzed were the temperatures captured from the cutting zone during processing using a thermal camera. The highest temperatures were measured as 173.4 °C at 40 m/min cutting speed, 0.05 mm/rev feed rate and dry environment. Based on this investigation, it has been shown that the cutting temperature decreases in the transition from a dry environment to a compressed air environment. Minimum temperatures were reached in the MQL cutting environment. The cutting temperature was minimized to 66.4 °C using a cutting speed of 40 m/min, feed rate of 0.100 mm/rev, and MQL environment. It was found that the cutting temperature increased with the increase in cutting speed and decreased with the increase in feed rate.

Statistical analysis

Taguchi technique is a widely used optimization method to increase quality and minimize process variations in manufacturing processes (Özlü & Akgün, 2024). This method includes steps such as determining process parameters and factors, creating experimental plans, and collecting and analyzing data. The importance of the Taguchi technique is closely related to the quality improvement and cost savings achieved in manufacturing processes. An important aspect of using the Taguchi technique in manufacturing processes is that it allows the effects of process parameters to be determined and these parameters to be optimized. Taguchi's experimental plans provide maximum information with a minimum number of experiments and make it possible to evaluate the effects of process parameters quickly and effectively. In this way, by adjusting the process parameters correctly, quality is improved, defective product rates are reduced and productivity is increased. The data obtained from the experiments were evaluated with signal-to-noise (S/N) according to the smallest better result for each parameter. Experimental results and S/N ratios are given in Table 3.

Table 3. Experimental results and signal-to-noise (S/N) ratios

Exp. No	Ra (µm)	Vb (mm)	Tc (°C)	S/N (dB) for Ra	S/N (dB) for Vb	S/N (dB) for Tc
1	2.137	0.384	173.4	-6.596	8.3134	-44.781
2	1.765	0.375	154.8	-4.935	8.5194	-43.795
3	1.104	0.411	131.7	-0.859	7.7232	-42.392
4	1.707	0.388	90.9	-4.645	8.2234	-39.171
5	1.612	0.357	76.9	-4.147	8.9466	-37.719
6	0.881	0.376	123.6	1.100	8.4962	-41.840
7	1.065	0.201	66.4	-0.547	13.9361	-36.443
8	0.732	0.271	88.8	2.710	11.3406	-38.968
9	0.499	0.256	78.2	6.03799	11.8352	-37.8641

Taguchi methodology is a widely used technique for optimizing manufacturing processes and improving quality. Main effect plots are an important tool for analyzing the results of Taguchi experiments and determining the effects of process parameters. These graphs are used to visually represent the impact of the amounts of factors (often process parameters) employed in experiments on output variables. Figure 6 illustrates the impact of control variables on the outcome variables.

ANOVA, or Analysis of Variance, is a statistical technique used to ascertain whether there are significant differences in means across groups. ANOVA assesses variations among groups by analyzing variance. This method is often used to compare the mean values of groups and to determine how groups vary according to an independent variable. The basic hypothesis of ANOVA assumes that there is no difference between groups, and this hypothesis is tested by comparing the between-group variance with the within-group variance. If the difference between groups is above the within-group variance, then it is considered a statistically significant difference between groups. Table 4 displays the ANOVA findings and the percentage of influence that the control variables have on the response parameters. If the P value shown in the table is below 0.05, it may be concluded that the analysis is statistically significant. The findings indicated that cooling/lubrication had the most impact on R_a (56.66%), V_b (87.96%), and T_c (78.68%). The second highest effect on surface roughness belongs to the cutting speed (41.83%), and on the cutting temperature, the feed rate (19.58%). On flank wear, cutting speed and feed rate have almost the same effect.

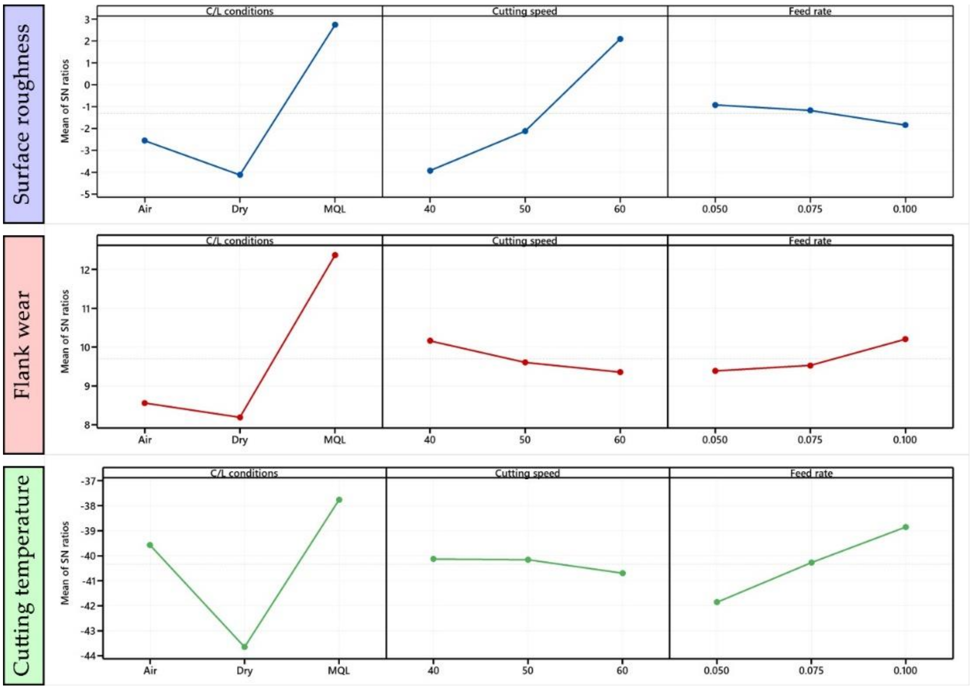

Figure 6. Main impact charts

Table 4. ANOVA results and contribution rates

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution rate (%)
R_a							
Cooling/lubrication	2	77.627	77.627	38.8133	111.3	0.009	**56.662**
Cutting speed	2	57.311	57.311	28.6554	82.18	0.012	41.833
Feed rate	2	1.365	1.3645	0.6823	1.96	0.338	0.996
Residual error	2	0.697	0.6974	0.3487			0.509
Total	8	136.999					100.000
V_b							
Cooling/lubrication	2	32.21	32.21	16.1049	14.39	0.065	**87.967**
Cutting speed	2	1.021	1.021	0.5105	0.46	0.687	2.788

Table 4. ANOVA results and contribution rates (Continued)

Feed rate	2	1.147	1.147	0.5736	0.51	0.661	3.133
Residual error	2	2.238	2.238	1.1191			6.112
Total	8	36.616					100.000
T_c							
Cooling/lubrication	2	54.7264	54.726	27.3632	91.77	0.011	**78.680**
Cutting speed	2	0.6116	0.6116	0.3058	1.03	0.494	0.879
Feed rate	2	13.6211	13.621	6.8106	22.84	0.042	19.583
Residual error	2	0.5963	0.5963	0.2982			0.857
Total	8	69.5555					100.000

CONCLUSION

This research aimed to examine the machinability characteristics of the Nimonic-60 superalloy under various cutting settings and cutting conditions. Furthermore, the use of Taguchi analysis resulted in a reduction in both the number of trials conducted and the associated expenditures. The outcomes are as stated.

- The highest surface roughness was obtained in experiments in dry environments. Although the use of air medium reduces the roughness, the lowest Ra values were obtained in the MQL environment. The minimum R_a achieved was 0.499 µm, which occurred when the V_c was set at 60 m/min, the f_n was 0.075 mm/rev, and the machining was performed in a MQL environment.
- Research has shown the most significant wear in trials conducted in dry conditions. It has been observed that tool wear decreases in the air environment. However, the lowest tool wear occurred in the MQL environment. The minimum V_b of 0.201 mm was achieved by using a V_c of 40 m/min, a f_n of 0.100 mm/rev, and a MQL environment.
- Research has shown that T_c drop while transitioning from a dry environment to a MQL environment. The maximum temperatures were achieved in a cutting environment with low humidity, followed by a cutting environment with compressed air. The T_c reached its minimum value of 66.4 °C when the V_c was set at 40 m/min, the f_n was 0.100 mm/rev, and the cutting process was carried out in a MQL environment.
- Based on the findings of the Taguchi study, it was concluded that cooling/lubrication had the most impact on R_a (56.66%), V_b (87.96%), and T_c (78.68%)

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