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Research Article

Optimization of Surface Roughness and Cutting Temperature in Turning of 1.4534 Stainless Steel under Sustainable Conditions

Emine ŞİRİN [a,*]

[a] *Department of Machine and Metal Technologies, Gümüşova Vocational School, Düzce University, Düzce, TURKEY*
** Corresponding author's e-mail address: eminesirin@duzce.edu.tr*
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ABSTRACT

1.4534 stainless steel, which is produced especially for aerospace applications, is frequently preferred in aircraft landing sets under high load and in highly corrosive environments. In addition to its superior properties, its machinability rate is low compared to other stainless steels. Moreover, improving 1.4534 stainless steel's machining performance is crucial since its formability problems. In this study, 1.4534 stainless steel was tested in a series of experiments under sustainable conditions (hBN, CO_2, and hBN+CO_2). Taguchi techniques were used in the experimental design to save cost and time. Three cooling levels (hBN, CO_2, and hBN+CO_2), three cutting speeds (140, 200, and 260 m/min), three feed rates (0.12, 0.16, and 0.20 mm/rev), and a constant cutting speed (0.8 mm) were used in the current study. Analysis of variance (ANOVA) was performed in the current study to determine the extent of the components' effects since cutting temperature and surface roughness were chosen as the performance standard. According to the test results obtained; hBN+CO_2 condition showed the best performance for surface roughness and cutting temperature.

Keywords: *DIN 1.4534, Sustainable Manufacturing, Nanofluid, Cryogenic Cooling, Turning*

1.4534 Paslanmaz Çeliğin Sürdürülebilir Koşullarda Tornalanmasında Yüzey Pürüzlülüğü ve Kesme Sıcaklığının Optimizasyonu

ÖZ

Özellikle havacılık uygulamaları için üretilen 1.4534 paslanmaz çeliği, yüksek yük altındaki uçak iniş takımlarında, yüksek korozif ortamlarda sıklıkla tercih edilmektedir. Üstün özelliklerinin yanında diğer paslanmaz çeliklerle kıyaslandığında işlenebilirlik oranı düşük mertebelerdedir. Dahası şekillendirilebilirliği merak konusu olan 1.4534 paslanmaz çeliğinin işleme verimliliğini artırmak son derece önemlidir. Bu çalışmada 1.4534 paslanmaz çeliği sürdürülebilir koşullar (hBN, CO_2 ve hBN+CO_2) altında bir dizi deneye tabi tutulmuştur. Maliyet ve zaman tasarrufu adına deney tasarımında Taguchi teknikleri kullanılmıştır. Deneyler üç farklı soğutma seviyesinde (hBN, CO_2 ve hBN+CO_2), üç farklı kesme hızı seviyesinde (140, 200 ve 260 m/dak), üç farklı ilerleme oranı seviyesinde (0,12 - 0,16 ve 0,20 mm/dev) ve sabit kesme hızında (0,8 mm) yürütülmüştür. Yüzey pürüzlülüğü ve kesme sıcaklığının performans kriteri olarak tercih edildiği güncel çalışmada, faktörlerin etki düzeyinin anlaşılmasında varyans analizi (ANOVA) kullanılmıştır. Elde edilen sonuçlara göre; yüzey pürüzlülüğü ve kesme sıcaklığı için en iyi performansı hBN+CO_2 koşulu göstermiştir.

Anahtar Kelimeler: *DIN 1.4534, Sürdürlebilir İmalat, Nanoakışkan, Kriyojenik Soğutma, Tornalama*

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I. INTRODUCTION

Stainless steels are alloys containing iron, carbon, molybdenum, chromium, and nickel. Since steels get their stainless properties from chromium, they must have at least 12% chromium in their composition. Due to its strong resistance to corrosion, retention of mechanical capabilities at high temperatures, environmental friendliness, ease of manufacture, and clean qualities, stainless steels are widely preferred materials [1,2]. Depending on their composition, these steels are either austenitic, semi-austenitic, or martensitic [3]. It has excellent mechanical properties, good toughness, and high resistance to surface cracking in harsh environments. Additionally, DIN 1.4534 Mo steel considerably maintains its mechanical qualities in adverse environmental conditions because of its superior corrosion resistance and strength compared to other precipitation-hardening stainless steels [4]. Due to its superior properties, 1.4534 stainless materials are used in the defense industry, aerospace components, food industry, petrochemical industry, and nuclear industry [3]. The extensive machining of these materials is necessary for the use of these stainless steels in a wide range of applications. During the machining process, cooling/lubrication is required for machining efficiency. Since the use of cutting fluid has detrimental impacts on both operator health and the environment, it is important to use environmentally friendly cooling and lubricating approaches [5]. Minimum quantity lubrication (MQL), nanofluid-based MQL, and cryogenic cooling conditions are the base characteristics of sustainable cooling conditions [6]. The MQL method involves using compressed air to atomize a tiny amount of cutting fluid into the cutting zone as an aerosol [7]. The cutting fluid is more efficient in this application since it is applied directly to the cutting zone. In addition, since it evaporates quickly, it does not leave residual oil, and the chips are easy to dispose of. However, the MQL method can be weak under heavy machining conditions [8]. In this situation, nanoparticles are employed to boost the MQL method's effectiveness [9]. Nanofluids are obtained by adding nanosized lubricant solid particles with different ratios and properties into the cutting fluid. MoS_2, hBN, Al_2O_3, SiO_2, CNTs, TiO_2, CuO, GNP, graphite, etc., are generally used as nanoparticles. According to the added nanoparticle properties, nanofluids improve the cutting fluid's physical, tribological, and thermal properties [10]. Studies on MQL and NanoMQL methods were reviewed in the literature. Under dry, MQL, and multi-walled carbon nanotubes (MWCNTs) added nanofluid cutting conditions, Öndin et al. turned PH13-8 Mo stainless steel material. As experimental outcomes, measurements for surface roughness, tool wear, and cutting temperature were examined. The researchers found that the nanofluid cutting condition with the addition of MWCNTs) showed good performance in the experimental outputs [3]. Şirin and Kıvak milling Inconel X-750 under dry, MQL, and nanofluid cutting conditions with the addition of hBN and MoS_2 for the machining performance of the superalloy material. Surface roughness, cutting temperature and force, tool wear and life were all researched by the investigators. At the conclusion of the tests, it was found that the cutting condition with hBN-added nanofluid demonstrated the best machining performance [11].

Hastelloy X superalloy material was exposed to machining tests by Şirin et al. in dry, MQL, SDS, and GA surfactant added graphene (GNP), and hBN nanofluid conditions. In terms of hole quality, cutting force, surface roughness, tool wear, tool life, and burr height, the researchers discovered that the hBN+GNP nanofluid condition with SDS surfactant performed better than other conditions [12]. In order to evaluate the tool life, surface roughness, cutting temperature, and tool wear characteristics, Yıldırm et al. turned Inconel 625 superalloy material under dry, MQL, and hBN added nanofluid cutting conditions. According to the study's outcomes, the hBN-added nanofluid cutting condition demonstrated good machining performance [8].

Cryogenic cooling is another form of sustainable cooling lubrication. Cryogens such nitrogen, carbon dioxide, helium, neon, and argon are injected into the cutting zone during the cryogenic cooling process to assure cooling [13]. Cryogenic cooling is preferred, especially in materials with high temperatures during machining. However, the cryogenic cooling method reduces the temperature value, which helps the plastic deformation of metals too much, making chip removal difficult and negatively affecting the surface quality [14,15]. In order to avoid all these disadvantages, hybrid cooling/lubrication conditions are among the ecological methods used recently. Hybrid methods increase machining efficiency by cooling and lubrication at the same time. Some of the studies conducted by researchers are given below.

Gupta et al. examined the tool wear criterion in detail by turning AA2024-T351 alloy material under MQL and cryogenic cutting conditions. They found that cryogenic conditions resulted in significant improvements in tool wear [16]. Ross et al. Ross machined Monel 400 material on a lathe under dry MQL, CO_2 and CO_2+MQL (CMQL) cutting conditions and investigated the surface roughness, cutting temperature, tool wear, chip morphology and microhardness criteria. They found that CMQL cooling condition showed positive performance in cutting temperature, tool wear and surface roughness outputs [17]. Çelik et al. turned AISI 2507 duplex stainless steel using MQL, cryogenic, and hybrid (MQL+cryogenic) cutting conditions in order to study the surface quality of the material. According to the experimental findings, hybrid cutting conditions were the best for cutting in terms of surface quality [15]. Şirin, turned Haynes 25 super alloy materials under dry, MQL, GNP, MWCNT, MWCNT and hybrid GNP/MWCNT added nanofluid and N_2 cryogenic and GNP/MWCNT+N_2 cutting conditions. As a result of the experimental study, it was determined that while the N_2 condition showed superior performance in terms of cutting temperature, the hybrid GNP/MWCNT+N_2 cutting condition showed superior performance in terms of surface roughness and tool wear [18]. Pereira et al. turned an AISI 304 stainless steel sample under dry, MQL, cryogenic, and MQL+cryogenic cutting conditions to examine cutting force, surface integrity, and tool wear. The researchers discovered that the hybrid cutting condition produced superior machining efficiency outcomes [19]. Şirin studied the surface roughness and topography, cutting temperature, vibration, tool wear, tool life, and hBN added nanofluid and cryogenic cutting conditions when turning AISI 904L stainless steel alloy. As a result of the research, the author found that hBN+Cryogenic cutting condition showed good performance [20].

An in-depth review of the literature reveals that cryogenic treatment and MQL conditions improve machinability efficiency. However, it is understood that studies on 1.4534 stainless steel material are insufficient. In particular, there are no studies on cryogenic and hybrid cooling / lubrication of 1.4534 stainless steel material. Thanks to this study, it is aimed to bring the study in which 1.4534 stainless steel material is turned under sustainable cooling / lubrication conditions to the literature. Cutting settings included three different cooling/lubrication conditions (hBN, CO_2, and hBN+CO_2), three distinct cutting speeds (140, 200, and 260 m/min), three distinct feed rates (0.12, 0.16, and 0.20 mm/rev), and a constant depth of cut of 0.8 mm. Cutting temperature and Ra values of the machined surfaces were evaluated in turning experiments. In the current study using Taguchi L9 experimental design, the impact of cutting settings on surface roughness and cutting temperature was studied using the ANOVA approach.

II. MATERIALS and METHODS

The Accuway JT150 CNC lathe, which has a highest speed of 4500 rpm, was used for the turning tests. For the tests, a piece of stainless steel with a DIN 1.4534 specification and dimensions of 250 mm in length and 50 mm in diameter was employed. Material denominations, chemical properties, and physical and mechanical properties of 1.4534 Mo steel are given in Table 1.

Table 1. *1.4534 Stainless steel denominations, chemical properties, and physical and mechanical properties*

Material denominations	AMS 5629, AMS 2300, AMS 2315, DIN 1.4534, X3CrNiMoAl13-8-2, S13800
Chemical composition	Al: 1.06, C: 0.044, Cr: 12.51, Ni: 8.09, Si: 0.07, Mo: 2.1, Mn: 0.04, P: 0.005
Physical and Mechanical specifications	Tensile strength : 1413 MPa Yield strength : 1310 MPa Elongation : 10% Hardness : 43 HRc

Sandvik ISO SNMG 120404-MF 2220 coded insert cutting tools were used in turning experiments. Ti+Al_2O_3+TiN coating of the insert cutting tools was performed by the CVD method and specially produced for stainless steels. A Sandvik holder with the code PSBNR 2525 M 12 was used to mount the cutting tools on the CNC lathe. 1.4534 stainless steel test material was rigidly clamped between the chuck and tailstock. SKF Vario device was used in MQL experiments, and pressure (air: 8 bar), flowrate (60 mL/h), nozzle specification (specially produced from stainless steel material, nozzle diameter 2 mm), nozzle distance (20 mm) were kept constant in all experiments. Falcon K 151 high-performance oil was used as pure oil in MQL experiments. Table 2 lists the details of the MQL base oil that was utilized.

Table 2. *MQL basefluid specifications*

Appearance	Light yellow
Viscosity at 40 °C (*)	8.5 cSt
Viscosity at 100 °C (*)	2.5 cSt
Density at 20 °C (*)	0.860 g/cm³
Flashpoint (DIN EN ISO 2592)	200 °C
Note: (*) ASTM D 7042	

Pure oil was mixed with 0.6% by volume of hBN nanoparticles (Nanografi Turkey) to generate nanofluid combinations. hBN nanoparticles are 99.95% pure and have an average size of 70 nm. The two-step process was chosen to generate the nanofluids because it is simple to use and less expensive. In the two-step method, nanoparticles are directly mixed in solid form with a base liquid. In the mixing process, it is seen that different approaches are applied in the literature. The most widely used mixing process was preferred and used in the current study. Firstly, solid dry nanoparticles were added directly to pure oil and mixed with a Daihan mechanical mixer HS 100D at 800 rpm for 1 hr. Secondly, a Termal magnetic stirrer N11151 M was used for 1 hr and 1550 rpm. Thirdly, it was mixed with a Bandelin ultrasonic mixer SonoPuls Hd3200 at 20 kHz for 0.5 hr. After mixing, the experiments were started without keeping the fresh nanofluids. No surfactant was preferred in the mixing process due to its disadvantages (foaming, decreasing thermal conductivity, increasing viscosity, etc.).

Snowy CO_2 was preferred for cryogenic cooling. CO_2 was stored in a storage cylinder (Özoto) at 50 bar pressure. During the experiments, 20 mL/h flow rate, 8 bar pressure, and nozzle values (30 degrees angle, stainless steel material, 2 mm diameter, 20 mm distance) were taken constant.

During the turning experiments, an Optris infrared (IR) camera PI 450 was used to capture the hotpoint temperature value in the cutting zone online. The calibration was completed online, and the IR camera was placed 300 mm away from the cutting zone. The manufacturer's catalog value was used to determine the emissivity value, which came to be 0.6. In the industrial sector, the degree of surface roughness on machined surfaces is crucial. Since professionals in academia and in the industrial sector regularly employ a typical surface roughness (Ra) value, Ra roughness characteristic values were taken into account in this study. According to ISO 4287:1997, measurements of surface roughness were taken. Ra measurements were performed using a mobile Mahr Marsurf PS10 equipment, which was calibrated initially. The information was gathered by averaging three separate values obtained from the machined surface's beginning, middle, and end. The sampling width and evaluation distance for evaluating surface roughness were measured 0.8 mm, 4.8 mm, respectively. Figure 1 illustrates the experimental configuration.

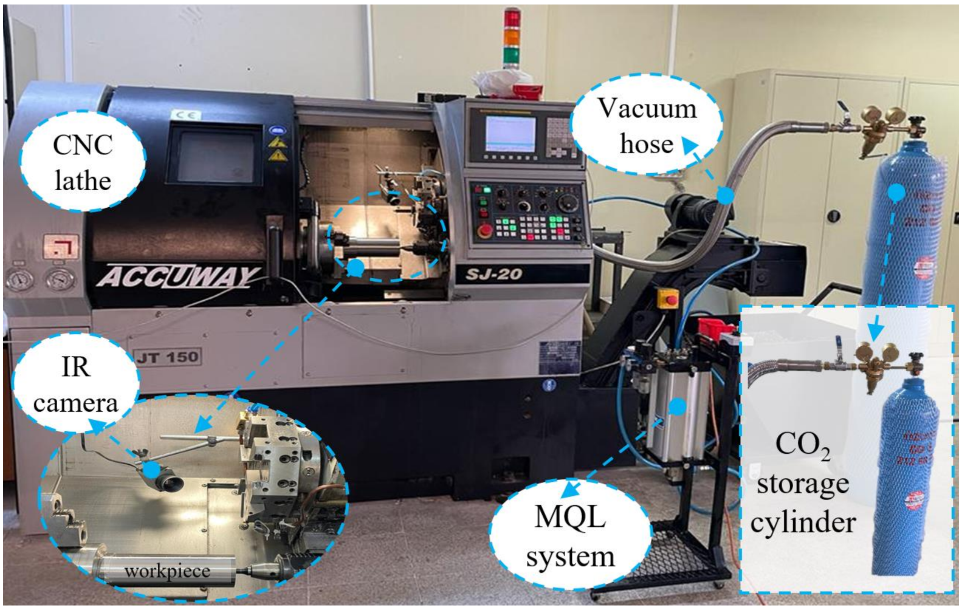

Figure 1. *Details and main components of the experimental setup*

III. TAGUCHI OPTIMIZATION

The experimental designs were prepared by considering Taguchi methods. Taguchi's experimental design method is an effective optimization method used to reduce processing costs by performing the minimum number of experiments. Taguchi method successfully analyzes optimization problems by predicting the results in advance. This optimization method saves time and cost by avoiding unnecessary experiments [21].

The metal forming industry frequently prefers the Taguchi optimization method to use time efficiently and reduce costs. In this study, Taguchi L9 experimental design was selected. In the optimization technique, cutting speed, cooling/lubrication conditions, feed rate were expressed by the abbreviation Vc, CL, and f respectively and were determined as factors. One of the crucial factors in operating components is surface quality. One of the other factors affecting surface quality is cutting temperature. For this reason, surface quality and cutting temperature were determined as output parameters. Table 3 lists the control variables and levels.

Table 3. *Levels of the controls in the Taguchi experimental design*

Factors	**Symbol**	**Unit**	**Levels**		
			1	**2**	**3**
Cooling/Lubrication	A	(CL)	hBN	CO_2	hBN+CO_2
Cutting speed (Vc)	B	(m/min)	140	200	260
Feed rate (f)	C	(mm/rev)	0.12	0.16	0.20

The Taguchi optimization approach produces functions that are translated into signal-to-noise (S/N), and the deviations between the required data and the experimental data are analyzed. Depending on the kind of function, the nominal best, biggest best, and smallest best approaches are employed to calculate S/N ratios. In this study, since the Ra and cutting temperature values are required to be low, the smallest best function equation (Equation 1) is used.

$$\eta = \frac{S}{N_S} = -10log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

The number of experiments and observed data are expressed as η and y in the equation, respectively. Following each test, the arithmetic average of three measurements taken from the machined surface was utilized to determine Ra values. Table 4 lists the values of Ra, cutting temperature, and S/N ratios that were determined.

Table 4. *Ra, T values, and S/N ratios obtained from the experiments*

No	**A** *CL*	**B** *(V_C, m/min)*	**C** *(f, mm/rev)*	**Ra** *(μm)*	**Ra - S/N** *(db)*	**T** *(°C)*	**T - S/N** *(db)*
1	hBN	140	0.12	1.054	-0.45681	170	-44.6090
2	hBN	200	0.16	1.187	-1.48901	186	-45.3903
3	hBN	260	0.20	1.812	-5.16157	191	-45.6207
4	CO_2	140	0.16	1.031	-0.26236	133	-42.4770
5	CO_2	200	0.20	1.987	-5.96541	145	-43.2274
6	CO_2	260	0.12	0.794	2.00359	152	-43.6369
7	hBN+CO_2	140	0.20	1.790	-5.05706	143	-43.1067
8	hBN+CO_2	200	0.12	0.516	5.75262	152	-43.6369
9	hBN+CO_2	260	0.16	0.965	0.31245	166	-44.4022

If the Table 4 is checked, Ra, T, Ra -S/N, and T-S/N are determined as 1.237 µm, 159.78 °C, -1.14706 dB, and -44.0119 dB, respectively. As a result of the analysis, the S/N response chart of the Ra quality characteristic is given in Table 5.

Table 5. *Table of S/N responses for Ra values*

Levels	**Control factors**		
	Cooling/lubrication *(CL)*	**Cutting speed** *(V_C, m/min)*	**Feed rate** *(f, mm/dev)*
	A	**B**	**C**
1	-2.3691	-1.9254	**-2.4331**
2	-1.4081	**-0.5673**	-0.4796
3	**0.3360**	-0.9485	-5.3947
Delta	2.7051	1.3581	7.8278

The values bolded in Table 5 give the highest orders of S/N values and the optimum conditions for the control factors. Ra surface roughness values, control factors, and optimum conditions for the factors are given in Figure 2.

When Figure 2 and Table 5 are evaluated together, it can be concluded that the optimum value of Ra surface roughness (0.516 µm) is obtained in A3, B2 and C1 conditions. To put it another way, the ideal circumstances for average roughness Ra in the machining of stainless steel material 1.4534 were identified as hBN+CO_2 hybrid cooling/lubrication condition, 200 m/min cutting speed, and 0.12 mm/rev feed rate.

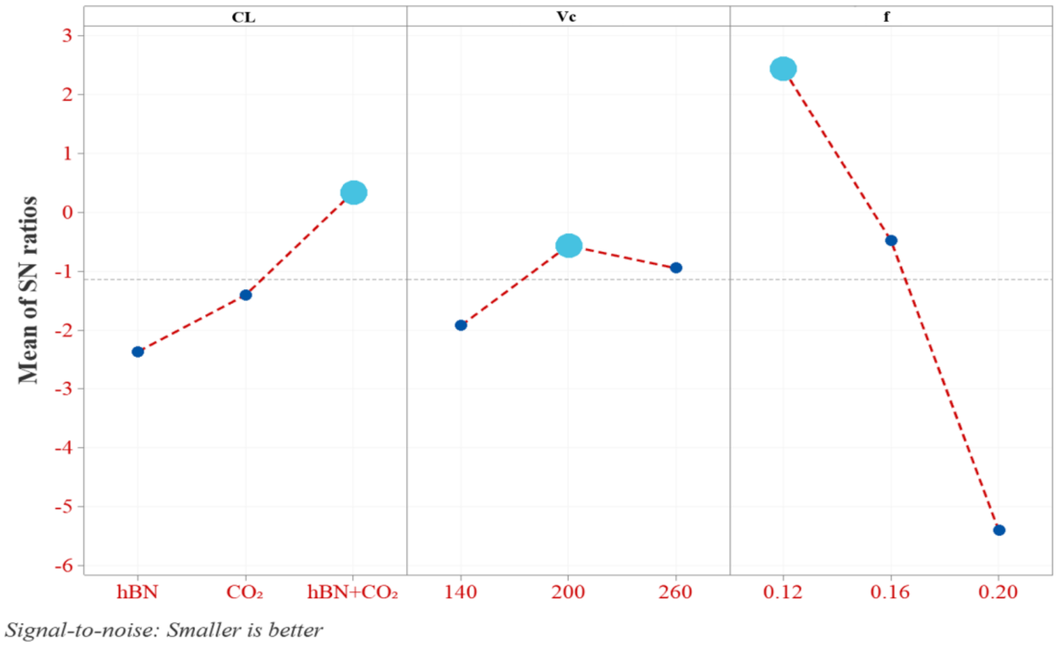

Figure 2. *S/N ratio effect graph of Ra values*

As a result of the optimization, the S/N response chart of the T quality outputs are given in Table 6. The values bolded in Table 5 give the highest orders of S/N values and the optimum conditions for the control factors.

Table 6. *S/N response table for T values*

Levels	Control factors		
	Cooling/lubrication *(CL)*	**Cutting speed** *(V_C, m/min)*	**Feed rate** *(f, mm/dev)*
	A	**B**	**C**
1	-45.21	**-43.40**	**-43.96**
2	**-43.11**	-44.08	-44.09
3	-43.72	-44.55	-43.98
Delta	2.09	1.16	0.13

T cutting temperature values, control factors, and optimum conditions for the factors are given in Figure 3.

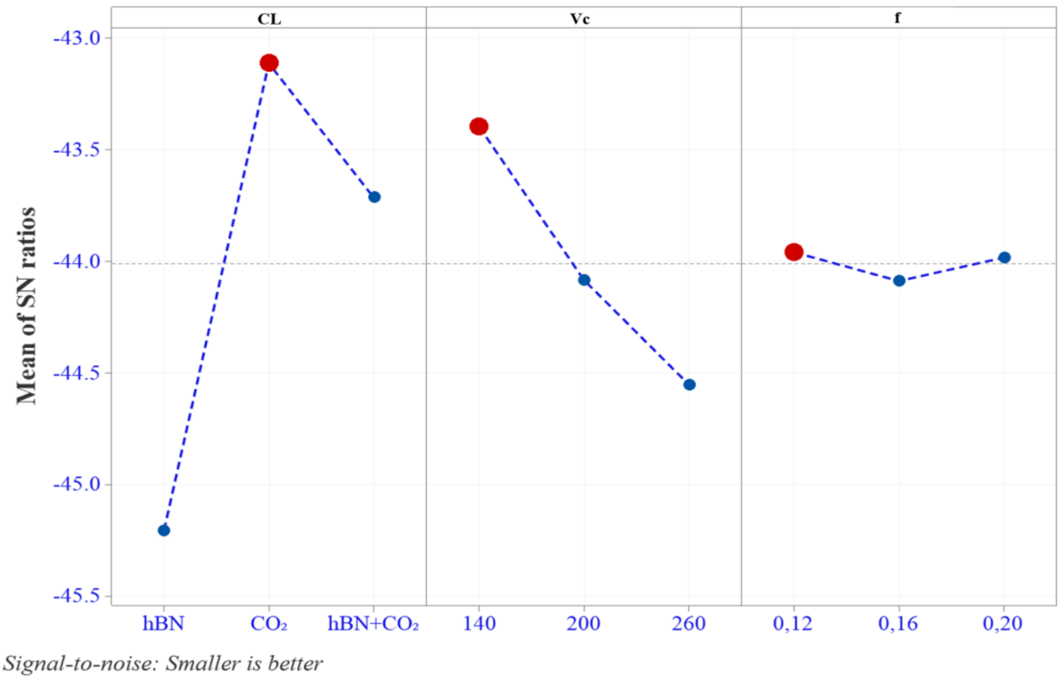

Figure 3. *S/N ratio effect graph of T values*

When Figure 3 and Table 6 are evaluated together, it can be concluded that the optimum value of T cutting temperature is obtained in A2, B1, and C1 conditions. The optimum conditions for cutting temperature in the machining of 1.4534 stainless steel material were determined as CO_2 hybrid cooling/lubrication condition, Vc 140 m/min cutting speed, and f 0.12 mm/rev feed rate.

III. RESULTS AND DISCUSSION

A. ASSESSMENT OF EXPERIMENTAL RESULTS

A. 1. Assessment of Surface Roughness Ra

The Ra variation due to cutting speed and feed rate in turning of DIN 1.4534 stainless steel is given in Figure 4. When the graph is analyzed, Ra diminished as cutting speed arose before increasing once again. The most effective value on Ra in terms of cutting speed was obtained at a cutting speed of 200 m/min, which is the medium cutting speed. When Figure 4 is examined further, it is seen that the lowest Ra value is obtained at a feed rate of 0.12 mm/rev, and the highest feed rate value is obtained at a feed rate of 0.20 mm/rev. When the feed rate is increased, Ra levels are shown to rise, indicating a decline in surface quality. Larger machining gaps occur on the workpiece surfaces as a result of an increase in the cutting tool's path during a given period of time [22]. Accordingly, feed rate is more efficient than cutting speed in terms of surface roughness [23]. The feed rate is the most efficient parameter for Ra, according to studies in the literature [24,25]. Given that a higher feed rate will result in a smaller tool radius for the nose to create more surface area on the workpiece [26], it can be inferred that it will result in an increase in the surface roughness value.

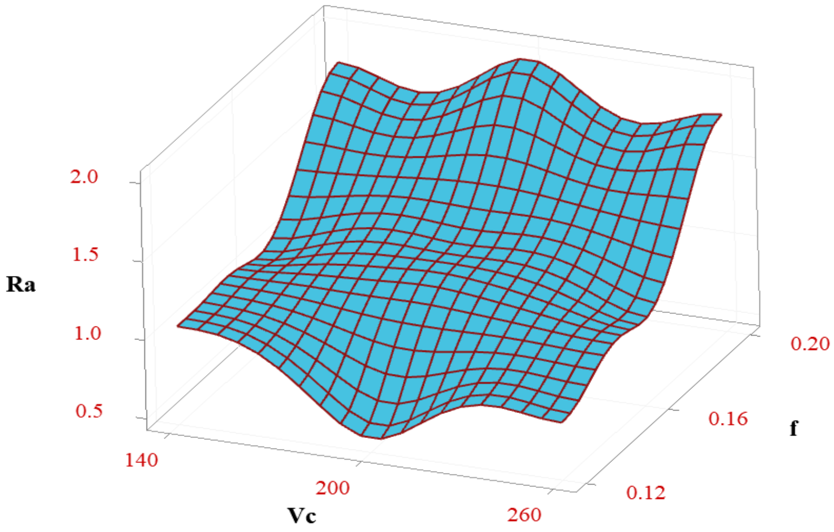

Figure 4. *Ra surface roughness, cutting speed, and feed rate variations.*

A. 2. Assessment of Ra Results under Different Conditions

In this phase of the investigation, the Ra values of the cooling/lubrication conditions were compared to the dry cutting condition. Several tests were run for this purpose at a constant cutting speed of 260 m/min and a feed rate of 0.20 mm/rev. Figure 5 displays the Ra values that the experiments achieved.

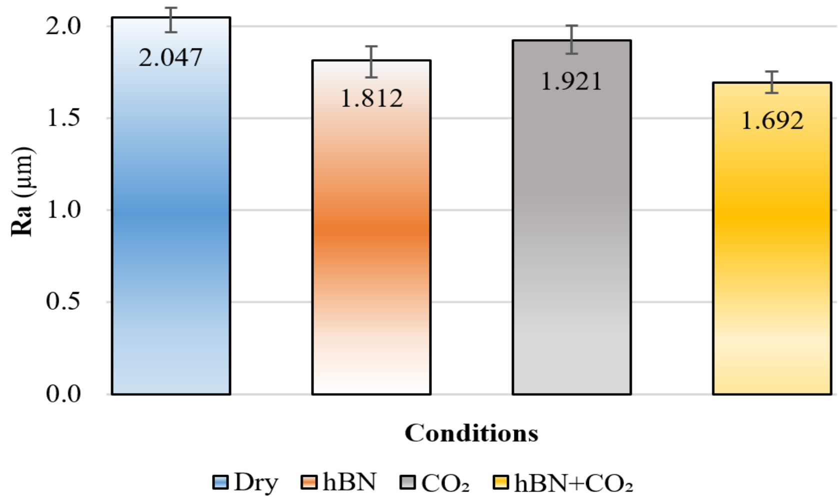

Figure 5. *Ra surface roughness varies depending on the cooling and lubrication conditions.*

Figure 5 indicates that the greatest (2.047 µm) and lowest (1.692 µm) surface roughness outputs were derived in dry and hBN+CO_2 hybrid conditions, respectively. In other words, compared to the dry cutting condition, the Ra surface roughness value tended to drop by 17.34% in the hBN+CO_2 hybrid cutting condition. Contrasted with the dry cutting situation, the hBN and CO_2 cutting conditions were reduced by 11.48% (1.812 µm) and 6.15% (1.921 µm), respectively.

Because the nanofluid with spherical hBN nanoparticles added offers excellent lubrication on the surface of the workpiece by having both polishing and mending effects on the surface, the hBN condition may be improved than dry cutting condition [11,12].

The low temperature values measured in the cryogenic cutting condition made the plastic deformation that helps chip formation difficult. Therefore, since the chip is difficult to separate from the cutting zone, it negatively affects the surface quality [27]. According to research published in the literature, cryogenic situations create problematic chip separation from the workpiece by lowering the cutting temperature below the plastic deformation limit [27,28]. In hybrid conditions, it is seen that a good surface quality is obtained due to effective lubrication by the nanofluid condition and cooling by the cryogenic condition. Similar situation was emphasized in the literature studies [20,29].

A. 3. Assessment of Cutting Temperature T Results

The variance of the highest temperatures recorded in the cutting zone while turning of 1.4534 stainless steel material depending on the cooling/lubrication condition and cutting speed is given in Figure 6. When analyzing the graph, it is seen that the cutting temperature tends to increase as the cutting speed increases. The lowest value in terms of cutting temperature was observed at the lowest cutting speed of 140 m/min, while the highest value was observed at the cutting speed of 260 m/min. It can be interpreted that the increase in cutting temperature increases in direct proportion to the increase in cutting speed.
Since it has been shown via literature research that as cutting speed increases, it also increases the cutting temperature [25,30]. The evaluation of the cooling and lubricating situations reveals that the CO_2 condition yields the lowest cutting temperature. Then came the hBN+CO_2 condition and the hBN condition, respectively. A cooling environment of around -80 °C may be created using only liquid CO_2 [31]. As a result, the CO_2 cryogenic cooling condition performed best in the cutting zone. This circumstance is supported by studies in the literature, which claim that CO_2 cryogenic cooling settings exhibit high performance [32].

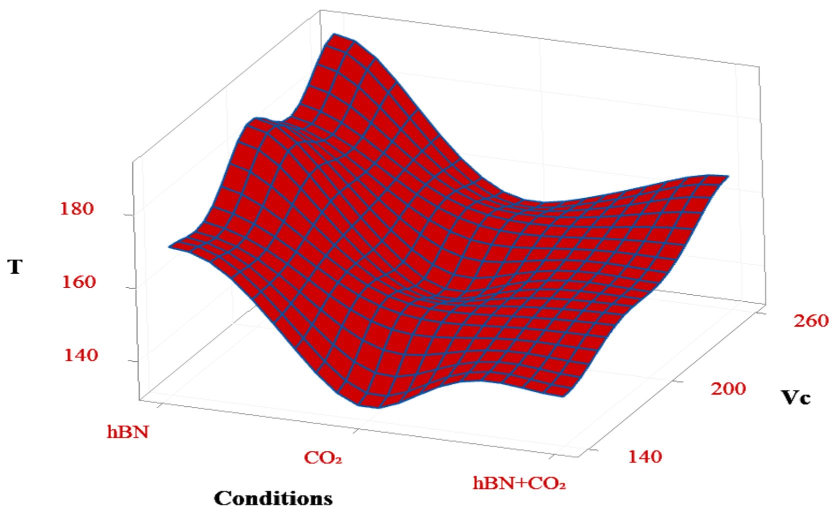

Figure 6. *Cutting temperature variation depends on cooling conditions and cutting speed.*

A. 4. Assessment of Cutting Temperature T Results under Different Conditions

Heat is created during machining as a result of the friction between the cutting tool and the workpiece [33]. These temperatures affect chip formation and surface quality. These temperature values, which help plastic deformation during chip formation, are evaluated. The values showing the maximum cutting temperature measured with an infrared camera in the cutting zone are given in Figure 7.

Figure 7 presented that, as predicted, cryogenic (CO_2) cutting condition had the lowest cutting temperature value (158 °C), whereas the dry condition without either cooling or lubrication had the highest temperature value (243 °C). Cutting temperature values were found to be lower when the hBN nanoparticle-containing nanofluid was employed, contrasted with the dry cutting situation. Depending on the circumstance of the dry cutting, a decrease of 21.39% and 30.49% was observed compared to hBN and CO_2+hBN hybrid cutting conditions, respectively. hBN nanoparticles' high thermal conductivity coefficient allows them to be useful in lowering the temperature in the cutting zone [34]. After the CO_2 (158 °C) cutting situation, the lowest recorded temperature (169 °C) was measured in the hybrid (hBN+CO_2) cutting condition with an increase of 6.96%. In cryogenic cutting conditions, the cutting zone is effectively cooled. A similar situation was emphasized in the studies conducted in the literature [28].

In hybrid conditions, cutting temperatures showed a small rise, due to the effect of the lubrication provided by the nanofluids and the decrease in the effect of cryogenic cooling. Similar results were observed in previous studies [29].

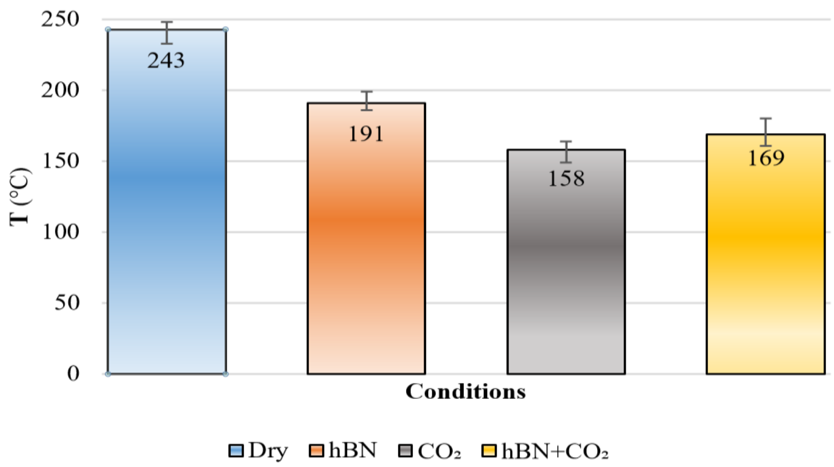

Figure 7. *Variation in cutting temperature according to cooling/lubrication conditions.*

B. ANOVA RESULTS

B. 1. Surface Roughness Ra ANOVA Results

The interactions between the control factors utilized in the experimental design were ascertained using the ANOVA approach. The surface roughness ANOVA findings are displayed in Table 7. P-values, DF (degrees of freedom), SS (sum of squares), MS (mean squares), F-values, and % effect ratios The amount of significance of each variable on the findings is shown by PCR [35].

95% confidence and 5% significance limits were used for this study. F values are used to compare the effects of control variables in an ANOVA. The factor that affects the result the most is the factor with the largest F value [36].

The ANOVA findings show that the feed rate (C), at a rate of 90.60%, is the parameter that has the greatest impact on surface roughness. The findings of the ANOVA showed that the control parameters influencing surface roughness are C (feed rate-f) 90.60%, A (cooling method-CL) 5.18%, and B (cutting speed-Vc) 0.76%, respectively. The error in the calculation of the analysis was 3.47%.

Table 7. Results of surface roughness from analysis of variance.

Factors	Degree of Freedom *[DF]*	Sum of Squares *[SS]*	Mean of Squares *[MS]*	F Ratio	P Value	Impact Ratio *[PCR] (%)*
A	2	0.10704	0.053520	1.49	0.401	5.18
B	2	0.01567	0.007836	0.22	0.821	0.76
C	2	**1.87389**	**0.936946**	**26.12**	**0.037**	**90.60**
Error	2	0.07174	0.035872			3.47
Total	8					100.00

B. 2. Cutting Temperature ANOVA Results

As in the case of surface roughness, ANOVA method was used for the interactions between the control factors in the experimental design. Table 8 displays the ANOVA findings for cutting temperature. The significant level of each variable on the outcomes is shown by the P-values, degrees of freedom (DF), sum of squares (SS), mean squares (MS), F-values, and percent effect ratios (PCR) [35]. 95% confidence and 5% significance limitations were used for this study.

The impact of the control variables in the ANOVA is assessed by examining the F values. The variable with the highest F value is the component that has the most impact on the outcome. According to the ANOVA results, cooling method (A) is the most effective parameter, with 77.92% at cutting temperature. According to the ANOVA results, the control factors that are effective in cutting temperature are A (cooling method-CL) 77.92%, B (cutting speed-Vc) 21.26%, and C (feed rate-f) 0.64%, respectively. The error detected in the calculation of the analysis is 0.18%.

Table 8. Analysis of variance results of cutting temperature.

Control Factors	Degree of Freedom *[DF]*	Sum of Squares *[SS]*	Mean of Squares *[MS]*	F Ratio	P Value	Impact Ratio *[PCR] (%)*
A	2	**2449.56**	**1224.78**	**440.92**	**0.002**	**77.92**
B	2	668.22	334.11	120.28	0.008	21.26
C	2	20.22	10.11	3.64	0.216	0.64
Error	2	5.56	2.78			0.18
Total	8					100.00

IV. CONCLUSION

In the present study, 1.4534 Mo stainless steel turned under dry, hBN doped nanofluid, CO_2 and hBN+CO_2 hybrid cryogenic cooling/lubrication conditions. Performance criterias were preferred: surface roughness and cutting temperature during the turning process. The turning process was carried out at three different cutting speeds (140, 200, and 260 m/min), feed rates (0.12, 0.16, and 0.20 mm/rev), and constant depth of cut (0.8 mm). The optimum machining conditions were determined using Taguchi optimization method. The effect ratios of the experimental elements were ascertained using the ANOVA approach. The general findings obtained at the end of the sustainable turning process are given below.

- As a result of the evaluation of Ra values, the best surface quality was obtained under hBN+CO_2 hybrid cutting condition, 200 m/min cutting speed, and 0.12 mm/rev feed rate conditions. Compared to dry conditions, hBN, CO_2, and hBN+CO_2 cutting conditions reduced Ra values by 11.48%, 6.15%, and 17.34%, respectively.

- A2, B1, and C1 were the best configuration for the cutting temperature results. In other words, the optimum condition of cutting temperature for turning DIN 1.4534 stainless steel was CO_2 condition, 140 m/min cutting speed, and 0.12 mm/rev feed rate. Compared to the dry condition, hBN, CO_2, and hBN+CO_2 conditions reduced the cutting temperature values by 21.39%, 35%, and 30.49%, respectively.

- According to the results of ANOVA analysis Ra, the most effective parameter was feed rate with 90.6%, followed by cooling/lubrication conditions with 5.18% and cutting speed with 0.76%.

- When the ANOVA results of the temperature in the cutting zone were analyzed, the most effective parameter was the cooling/lubrication condition with 77.92%. Cooling/lubrication conditions were followed by cutting speed with 21.26% and feed rate with 0.64%. In ANOVA analysis, the error rates for Ra and T were 3.47% and 0.18%, respectively.

Overall evaluation of the study: The 1.4534 Mo stainless steel workpiece sustained turning experiments were successful. Moreover, it can be said that cryogenic CO_2 cooling was very successful in reducing the temperature in the cutting zone. For surface finish Ra, it was discovered that the hybrid hBN+CO_2 condition outperformed all other conditions.

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