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Multi-Criteria Performance Analysis of Dry, Vortex Air and Compressed Air Environments in Turning Hastelloy X Superalloy

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ABSTRACT

Hastelloy X superalloy, which exhibits superior performance under harsh conditions such as extreme temperature, oxidation, and corrosion, is widely used in the aviation and energy sectors but causes significant problems in machining due to its difficult machinability properties. This situation has brought up the need for alternative cooling strategies to reduce cutting forces and temperatures during machining, improve surface quality, and minimize environmental impacts. In this research, the impacts of varying cutting variables (depth of cut (Doc), feed rate (f), and cutting speed (Vc)) on cutting force (F_R), surface roughness (Ra), and cutting temperature (T) in the turning of Hastelloy X superalloy under three different machining environments (dry, vortex air, and compressed air) were experimentally investigated. The Taguchi L_9 orthogonal layout was utilized for the experimental design, and simultaneous optimization of multiple performance outcomes was carried out by the grey relational analysis (GRA) technique. According to the findings, the lowest F_R and Ra occurred in dry, compressed air and vortex air processing environments, respectively. The lowest values in terms of T were obtained in compressed air, vortex air, and dry machining environments, respectively. In summary, the effect of cooling conditions on T was not reflected in F_R and Ra. As a result of GRA optimization, where all performance criteria were evaluated together, the most suitable machining condition was determined to be a dry machining environment, an 80 m/min cutting speed, a 0.075 mm/rev feed rate, and a 0.8 mm cutting depth. Vortex air and compressed air environments have been evaluated as a strong alternative to dry environments.

1. Introduction

The need for materials that can perform reliably under harsh operating conditions such as high temperature, corrosion, and oxidation is increasing rapidly, especially in the aviation, space, energy, and chemical industries. Nickel-based superalloys, which are preferred in such applications, have gained an important place in recent years thanks to their superior mechanical properties and thermal stability. Among these alloys, Hastelloy X stands out with its properties, such as maintaining its strength at high temperatures and excellent oxidation and corrosion resistance, and is widely used in various high-tech applications, especially jet engines, gas turbines, and nuclear reactor components [1]. However, these superior properties also bring with them significant disadvantages in terms of workability. Structural properties such as high hardness, low thermal conductivity, and chemical stability cause problems such as overheating, high cutting forces, rapid tool wear, and poor surface quality during machining [2,3]. This makes the machining of superalloys such as Hastelloy X difficult and costly, thus necessitating the development of new cooling strategies to improve machining performance.

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In this context, in recent years, studies on environmentally friendly, energy-efficient, and cost-effective cooling techniques as an alternative to traditional cooling and lubrication methods have attracted attention. In a study conducted in the literature review for the turning process of a Hastelloy X workpiece, the dry environment and the minimum quantity lubrication (MQL) method at different rates were compared, and the superiority of the MQL method was expressed in terms of F_R, Ra, and tool wear (Vb) [4]. In a study conducted by Oschelski et al. the effects of dry, emulsion, and MQL methods on Ra values were investigated [5]. Sivalingam et al. investigated the effects of dry, emulsion, and cryogenic environments on main cutting force (Fc), Ra, and T [6]. Zhou et al. compared dry, MQL, and cryogenic environments in terms of Fc, Ra, Vb, and T [7]. Although the effects of these alternative cooling media on surface quality, cutting forces, and cutting temperature have been investigated on various materials, systematic and comparative studies, especially on Hastelloy X alloy, are quite limited. Although each of the traditional and alternative cooling/lubrication methods has the potential to improve machining performance, it also has certain limitations and disadvantages. Although dry machining is one of the cleanest methods from an environmental perspective, it accelerates tool wear and can negatively affect surface quality, especially in materials that generate high temperatures. Although emulsion-based cooling systems provide effective heat removal and lubrication, they cause harmful effects on operator health, such as toxic evaporation and skin irritation in the working environment, and the disposal of waste liquids increases environmental costs [8,9]. Although the MQL method aims to provide both lubrication and a limited cooling effect by using a low amount of liquid, it may be insufficient for materials exposed to high temperatures and may lose its effectiveness due to evaporation at high speeds [10,11]. Although cryogenic cooling greatly reduces the temperature in the cutting zone, its applicability on an industrial scale remains limited due to reasons such as high equipment costs, safety risks, and complexity of system integration [12,13]. In this context, the search for more balanced alternatives in terms of environmental, economic, and operational aspects has become a critical requirement for sustainable manufacturing processes. In recent years, vortex air and high-pressure compressed air systems, which are among the environmentally friendly and operationally viable alternative cooling methods, offer many advantages over traditional cooling techniques. Vortex tube technology rotates the compressed air, separating it into hot and cold air streams and providing effective cooling to the cutting zone with air that can be reduced to minus temperatures [14]. Similarly, high-pressure compressed air increases chip removal capability, prevents heat build-up in the cutting zone, and provides effective cooling, especially in narrow spaces [15]. Both methods stand out as strong alternatives for sustainable machining processes thanks to their compliance with clean production principles, low operating costs, easy integration, and operator health-friendly structure. For example, a vortex cooler was successfully used in the turning process of a Ti6Al4V workpiece, and its effects on Ra were investigated [16]. Similarly, the effects of 7.5 bar high-pressure air on Fc, Ra, and Vb were investigated in the turning process of Haynes 282 and Inconel 718 workpieces, and successful results were obtained [17]. Therefore, the vortex and high-pressure air method have the potential to improve output responses by improving the machining conditions in the turning process of the Hastelloy X workpiece.

This study aims to fill this gap and investigates the effects of three different cooling media (dry, vortex air, and high-pressure air) on the machining performance with three levels of cutting variables (Doc, f, and Vc) during the turning process of Hastelloy X alloy. In the research, Taguchi L_9 orthogonal experimental design was preferred for planning the experimental processes; critical performance responses such as F_R, Ra, and T were measured and analyzed. Thus, it was aimed to determine the parameters that will optimize the cutting forces, cutting temperatures, and surface quality during machining and to present cooling strategies that minimize environmental effects.

In this context, the present study aims to contribute to the literature in several ways. First, it provides a comprehensive experimental comparison of dry, compressed air, and vortex air environments in the turning of Hastelloy X superalloy, a material known for its poor machinability. Unlike previous studies, this work explores the combined effects of these sustainable cooling/lubrication strategies on cutting force, surface roughness, and cutting temperature using a systematic experimental design. Second, it integrates a multi-response optimization method to determine the most effective cooling strategy considering multiple performance criteria simultaneously. Finally, the findings of this study are expected to support the development of more environmentally friendly and efficient machining practices for high-performance alloys in aerospace and energy applications.

2. Material and Method

In this study, turning operations were performed on Hastelloy X superalloy under dry, compressed air, and vortex air environments using a chemical vapor deposition (CVD)-coated carbide insert with the ISO designation WNMG080408-SU, manufactured by Sandvik Coromant. The insert, classified as AC6030M grade, features a trigon geometry with an 80° included angle and a 0.8 mm nose radius, and is specifically designed for medium to semi-finish turning applications. Its CVD coating enhances wear resistance and improves performance under demanding machining conditions. As a result of the experiments, the F_R, T, and workpiece Ra values were analyzed. In this context, the scope of the work is given in Figure 1. Experiments were conducted on a JOHNFORD TC-35 industrial CNC lathe. The CNC lathe used in the experiments is equipped with a maximum power capacity of 10 kW and a spindle speed control system that allows stepless adjustment up to 3500 revolutions per minute (rpm). The workpiece used in the machining tests was prepared from Hastelloy X material with a length of 250 mm and a diameter of 44 mm. The turning length was 15 mm in all experiments. Table 1 shows the material's chemical composition and mechanical characteristics.

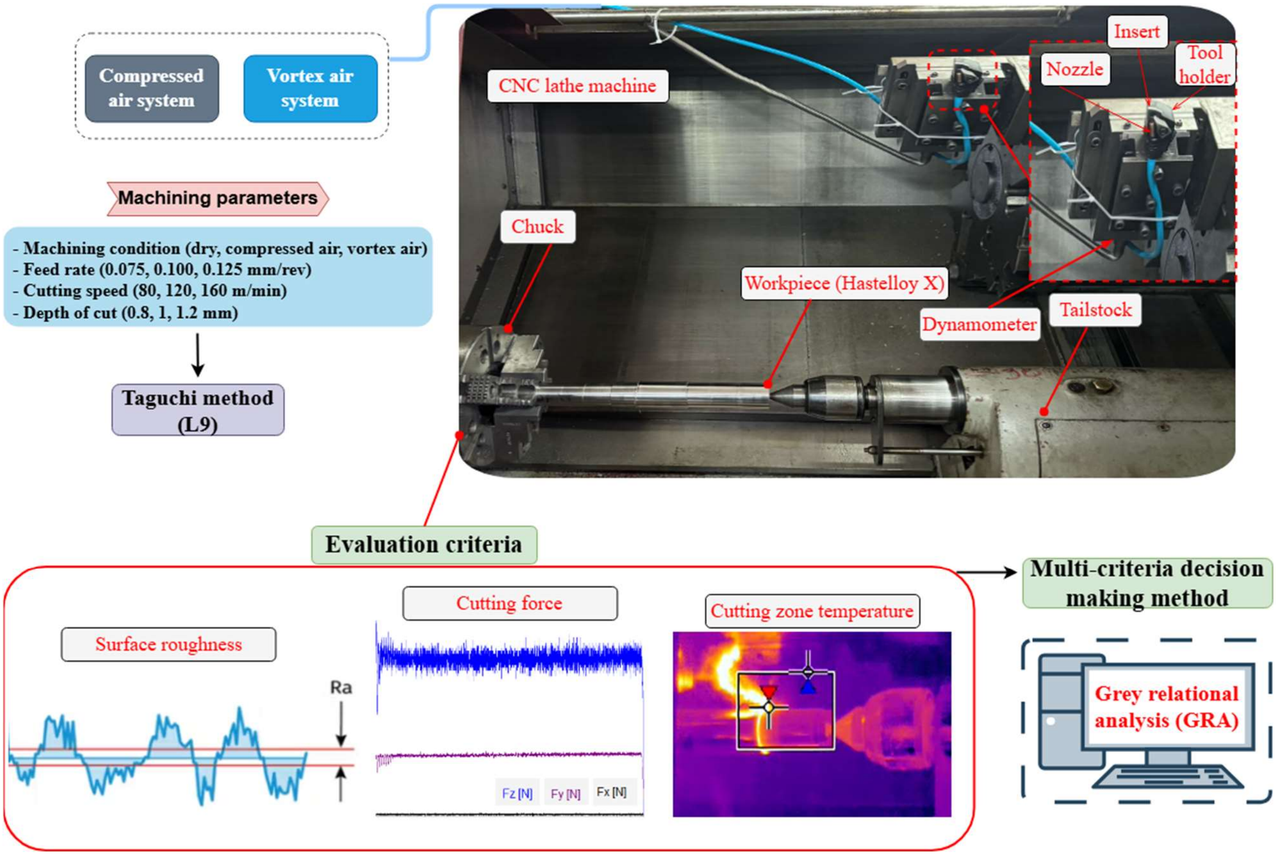

Figure 1. Steps followed in the experimental study

Table 1. Chemical composition and mechanical characteristics of Hastelloy X superalloy [18]

Chemical structure									
Element	Cr	Mo	Co	W	Mn	Fe	C	Si	Ni
Weight (%)	22	9	1.5	0.6	1	18	0.1	1	47
Mechanical characteristics									
Density (g/cm³)				8.22					
Thermal conductivity (W/mK)				9.1					
Tensile strength (MPa)				754.97					
Yield strength (MPa)				385.42					
Elongation (%)				45					

The experiments were conducted under three different machining conditions (Mc) (dry, compressed air, and vortex air), using three levels of f (0.075, 0.100, and 0.125 mm/rev), three Vc (80, 120, and 160 m/min), and three Doc (0.8, 1, and 1.2 mm). The experimental design was made according to the Taguchi L_9 orthogonal experimental design, which aims to obtain maximum information with the minimum number of experiments. The levels of cutting parameters used were determined in accordance with the recommendations of the cutting tool manufacturer. In the literature, it is emphasized that limited advancements have been made regarding tool wear, cutting forces, and surface quality in the machining of nickel-based superalloys such as Hastelloy X, and that moderate cutting speeds along with shallow cutting depths should be preferred. Additionally, the technical data provided by Sandvik Coromant and the recommended operating ranges by the tool manufacturer were also considered in selecting these parameters. Preliminary experiments were conducted to observe the effects on tool durability and chip formation, and parameter combinations at three optimal levels were chosen, taking process stability into account. Experiments were conducted under three processing conditions: dry air, compressed air, and vortex air. Sustainable and environmentally friendly alternatives, such as dry machining, compressed air, and vortex air methods, were preferred. This selection was made to reduce the environmental impacts of conventional cooling techniques (e.g., emulsion or lubrication) and is based on eco-friendly machining strategies increasingly highlighted in recent literature. Moreover, within the scope of this study, the effects of the vortex air method on Hastelloy X were systematically investigated for the first time, aiming to contribute to the literature in this regard. The dry turning process was done without using any coolant or lubricant. A specially designed air cooling system is used in compressed air-assisted turning operations. In this system, airflow directed to the cutting area with a constant pressure of 14 bar was used. In this way, regional cooling is provided. In vortex air-assisted turning operations, airflow was provided at -5°C temperature at 10 bar pressure with an Acgreiff brand vortex tube. The air nozzle used in both cooling methods is positioned 15 mm away from the cutting tool tip and directed directly to the cutting area. As a result of the experiments, the F_R, T, and Ra values occurring during the tool and workpiece interaction were measured and analyzed. Cutting forces were measured with a Kistler brand (9257B) three-axis dynamometer (Fx, Fy, Fz). In this study, F_R, which is the resultant of the three axis components, was evaluated according to the processing parameters. T was determined by a FLIR T440 thermal camera positioned 50 cm away from the cutting area. Surface roughness measurements were made with a Mitutoyo SJ-210 brand roughness device. Surface roughness values were determined by averaging the measurements taken from three different regions located at both the entry and exit sections of the workpiece after each experiment. In this study, Ra was evaluated.

2.1. Grey relational analysis (GRA)

In recent years, GRA has become one of the most widely preferred methods in multi-parameter optimization studies due to its ability to simultaneously optimize multiple performance characteristics [19-22].

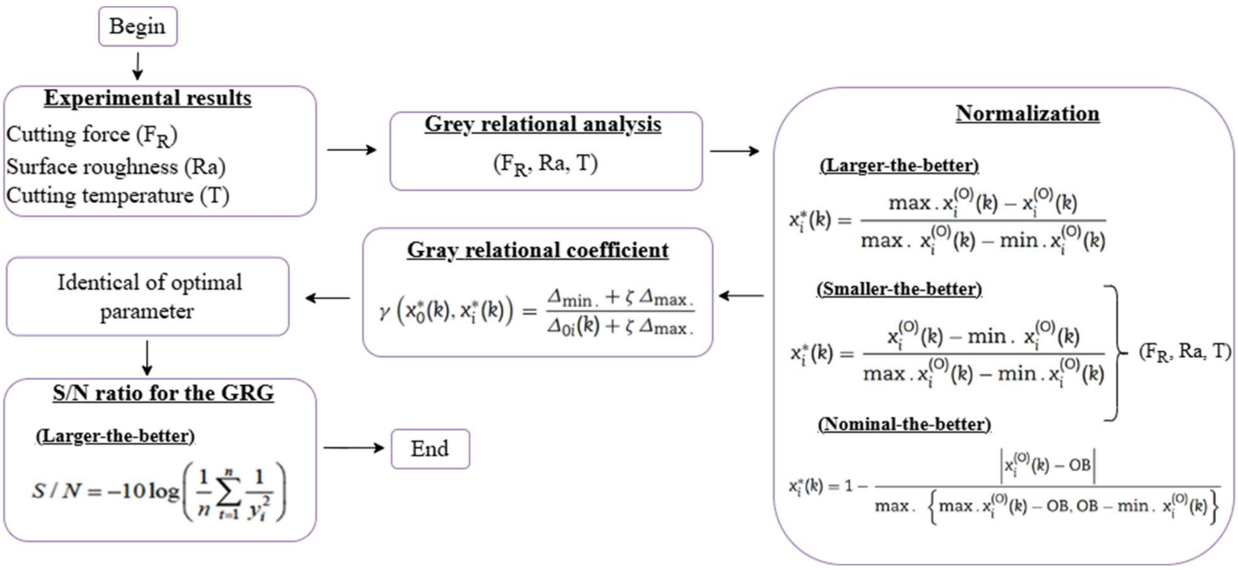

Figure 2. Steps followed in the optimization process

In this research, it was aimed to optimize the cutting force, surface roughness, and cutting temperature outputs during the turning of Hastelloy X superalloy by using a Taguchi-based GRA approach. The steps followed in the GRA method are given in Figure 2.

3. Experimental Results and Discussion

3.1. Evaluation of cutting force

Figure 3 presents the impacts of turning parameters on F_R. No significant differences were observed in F_R values in terms of processing conditions. While the lowest F_R value was obtained in dry machining conditions, the highest value was obtained in machining with vortex air. A similar trend has been observed in the literature [23]. This situation is explained by the fact that the air directed to the cutting zone creates a cooling effect, increasing the tendency of the material to resist cutting. As the amount of advancement increases, F_R values increase significantly. This is an expected result. As the feed rate rises, the material removal volume also grows, which in turn enhances the interaction between the material and the tool, leading to an increase in cutting force [24].

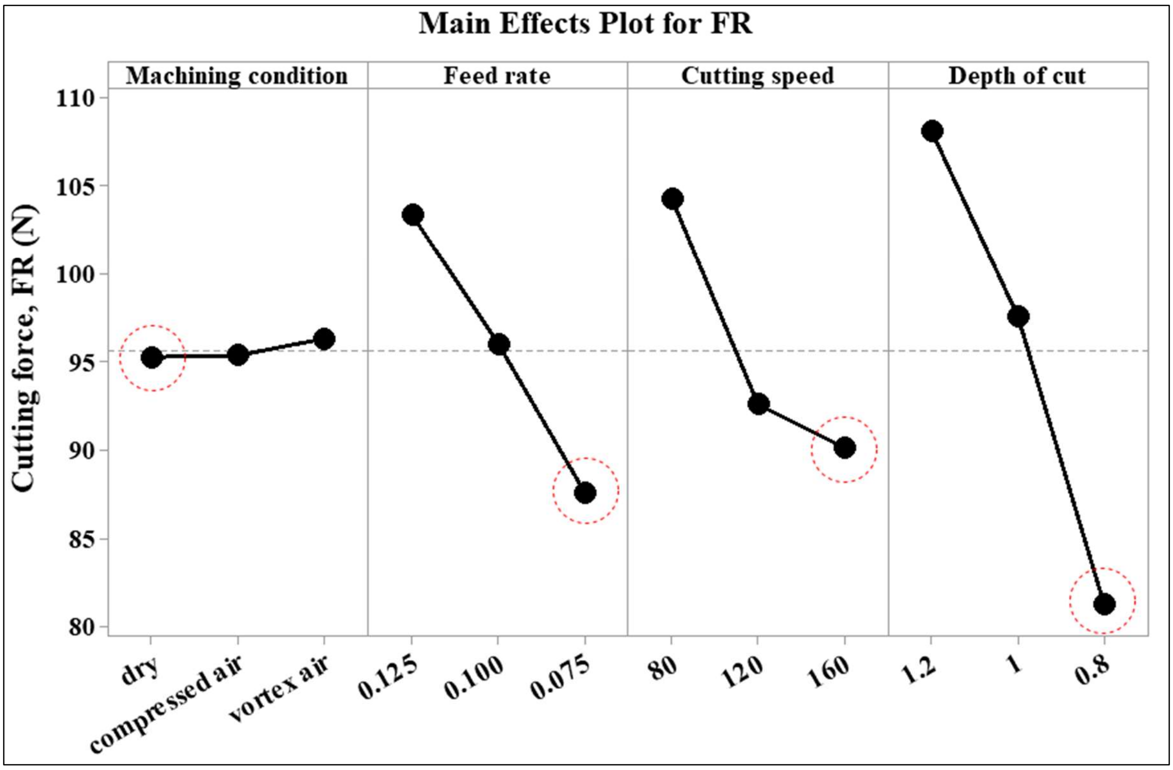

Figure 3. Effect of processing parameters on F_R

The effect of cutting speed on F_R showed an opposite trend to that of feed. In other words, as the cutting speed increased, F_R values decreased. In general, it is frequently reported in the literature that the rise in cutting speed has a decreasing effect on the cutting force [25]. This trend is attributed to the rise in temperature in the cutting zone with increasing cutting speed, which consequently enhances the plasticity of the machined material, making it easier to deform. The lowest F_R value was obtained at 0.8 mm cutting depth. A significant increase in F_R values was observed with increasing cutting depth. As frequently emphasized in the literature, this phenomenon is attributed to the fact that increasing the depth of cut enlarges the contact area between the workpiece and the tool, as well as the volume of workpiece removed [26].

3.2. Evaluation of surface roughness

In Figure 4, the impacts of turning variables on Ra are given. In the graph, it is seen that the lowest Ra occurs in dry, compressed air and vortex air processing conditions, respectively. Air sent to the cutting zone under high pressure can cause sudden temperature drops on the workpiece and tool surface. This may lead to microstructural changes and local hardening in the cutting zone. These hardened or solidified areas make it difficult for the tool to penetrate the workpiece, causing an increase in cutting forces [23]. Therefore, the high cutting forces occurring in compressed air and vortex air processing conditions are also reflected in the surface roughness. It has been reported in the literature that dry machining conditions give better results than vortex machining conditions in terms of surface roughness [16]. Ra rises with feed rate. The minimal Ra value occurred at a feed rate of 0.075 mm/rev. As the feed rate rises, the tendency of the cutting tool to leave marks on the surface also rises, leading to surface waviness and higher Ra values [27]. It is observed that Ra values show a non-linear change depending on the cutting speed parameter. While the lowest Ra was obtained at 80 m/min and 160 m/min cutting speeds, the highest Ra value was reached at 120 m/min cutting speed. This situation indicates that the relationship between cutting speed and surface quality cannot be explained solely by thermal effects; interactions with tool wear, chip formation, and other machining parameters also play a decisive role in surface roughness. The lowest Ra value occurred at 0.8 mm cutting depth. Studies in the literature have shown that a rise in cutting depth leads to a significant rise in both F_R and Ra values [28]. The primary reason for this is stated to be the vibrations and deviations that occur in the tool with the increasing cutting load.

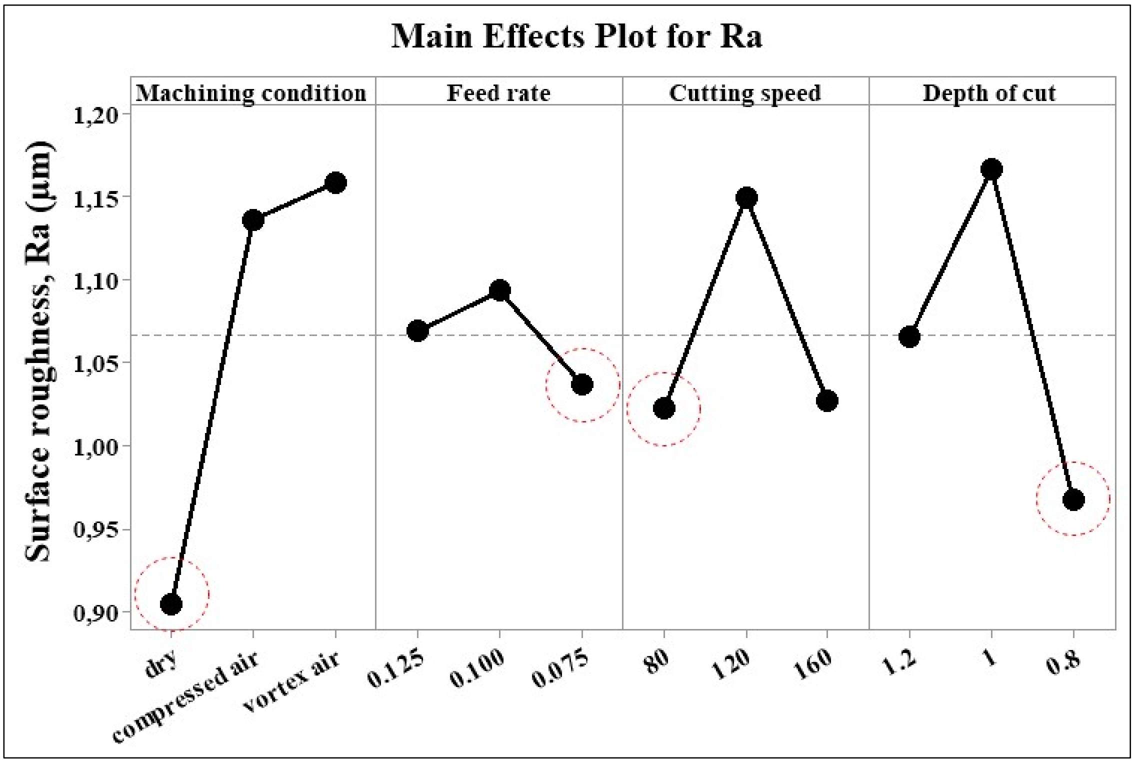

Figure 4. Effect of processing parameters on Ra

3.3. Evaluation of cutting temperature

In Figure 5, the impacts of turning parameters on T are given. In the machining experiments conducted with compressed air and vortex air applied to the cutting medium, a significant decrease in T values was observed, particularly under the compressed air condition. This result is expected due to the intense cooling effect of compressed air and vortex air applied directly to the cutting zone.

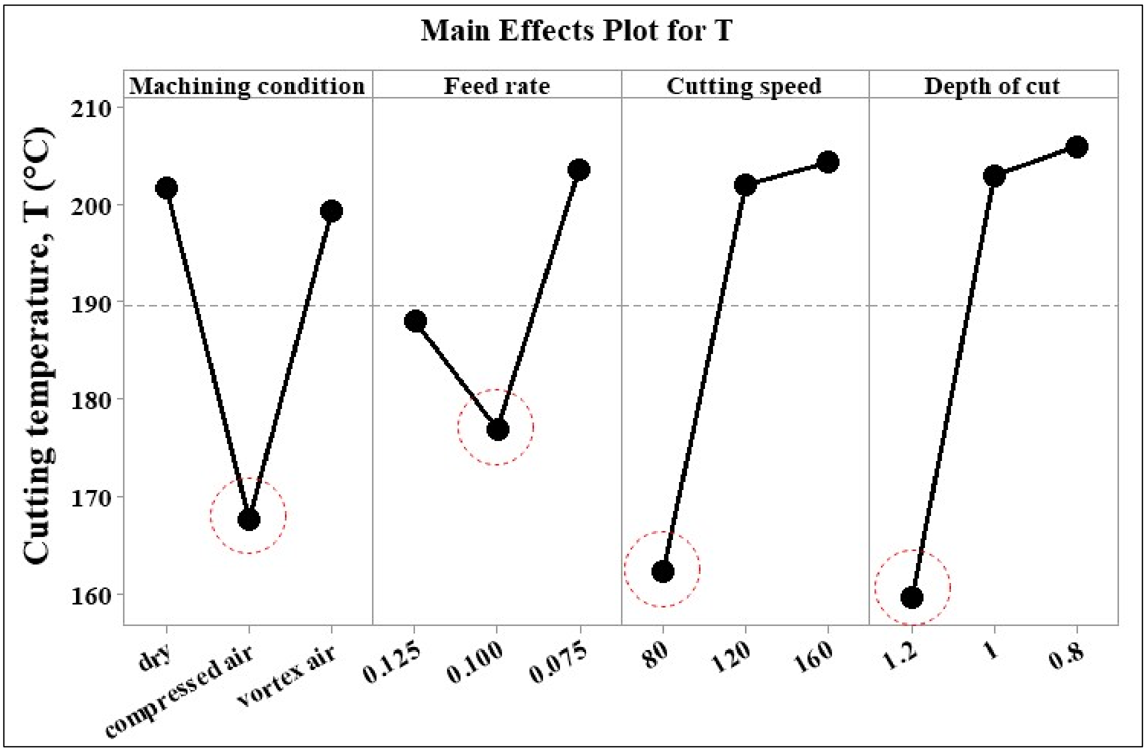

Figure 5. Effect of processing parameters on T

In an experimental study, it has been stated that the vortex air machining condition positively affects the cutting temperature values compared to dry machining [29]. The T value reached its highest value at the lowest feed rate of 0.075 mm/rev. Although this result is not commonly encountered in the literature, it can be explained within the framework of thermal diffusion time. At low feed rates, the cutting tool remains at the same point for a longer period, resulting in a longer heat dissipation time. This can cause more heat to build up in the cutting zone. As the cutting speed increases, an increase in T values is observed. This can be attributed to the increased plastic deformation and friction occurring at high cutting speeds, which generate more heat [30]. T values decreased with increasing cutting depth. A larger cutting depth increases the material removal volume, allowing a greater portion of the generated heat to be carried away by the chips. It has been stated that, with the increase in chip volume, a large portion of the heat in the cutting medium is transported by the chips, which can reduce the temperature of both the workpiece and the tool [31].

The effects of the turning parameters on F_R, Ra, and T have been comprehensively analyzed. However, based on the evaluations, it was determined that the effects of the turning parameters on F_R, Ra, and T differ. Therefore, multi-criteria decision-making (MCDM) methods are required to simultaneously optimize all performance criteria and identify the most suitable combination of machining parameters.

3.4. Optimization results

In this part of the study, it is aimed to determine the optimum parameters by using the grey relational analysis method. For this purpose, all data were normalized between 0 and 1 in order to evaluate the performance criteria with different units together. Since lower values of F_R, Ra, and T are desired in terms of machining performance, the "smaller is better" approach was applied during the normalization. After the normalization process, grey relational coefficients (GRC) were calculated to determine the degree of similarity between each alternative and the reference (ideal) series. Finally, the general grey relational grades (GRG) were calculated by taking the arithmetic average of the GRC. The computational results obtained through the mathematical equations presented in Figure 2 are provided alongside the experimental data in Table 2.

Table 2. Processing parameters, experimental and optimization results

Exp. no	Machining parameters				Experiment results			Normalized values			Coefficients			GRG	S/N	Rank
	Mc	f	Vc	Doc	F_R	Ra	T	F_R	Ra	T	F_R	Ra	T			
1	dry	0.125	160	1.2	109.870	0.867	185	0.172	0.722	0.275	0.377	0.642	0.408	0.476	-6.452	6
2	dry	0.100	120	1	94.500	1.115	215	0.557	0.210	0.025	0.530	0.388	0.339	0.419	-7.556	7
3	dry	0.075	80	0.8	80.440	0.732	205	0.909	1.000	0.108	0.846	1.000	0.359	0.735	-2.674	1
4	compressed air	0.125	120	0.8	85.610	1.123	195	0.779	0.194	0.192	0.694	0.383	0.382	0.486	-6.262	4
5	compressed air	0.100	80	1.2	116.760	1.118	98	0.000	0.204	1.000	0.333	0.386	1.000	0.573	-4.836	3
6	compressed air	0.075	160	1	83.750	1.168	210	0.826	0.101	0.067	0.742	0.357	0.349	0.483	-6.327	5
7	vortex air	0.125	80	1	114.540	1.217	184	0.056	0.000	0.283	0.346	0.333	0.411	0.363	-8.790	9
8	vortex air	0.100	160	0.8	76.790	1.047	218	1.000	0.351	0.000	1.000	0.435	0.333	0.589	-4.591	2
9	vortex air	0.075	120	1.2	97.650	1.212	196	0.478	0.010	0.183	0.489	0.336	0.380	0.402	-7.925	8

The analysis findings related to the GRG values are presented in Table 3. In this table, the maximum GRG value obtained for each parameter level represents the optimum level of the corresponding parameter. Additionally, by utilizing the S/N ratio graph for the GRG shown in Figure 6, the optimum combination of turning parameters can be determined.

Table 3. Response table for the GRG

Level	Machining parameters			
	MC	f	Vc	Doc
1	**-5.561**	-7.169	**-5.434**	-6.405
2	-5.809	-5.661	-7.248	-7.558
3	-7.102	**-5.642**	-5.791	**-4.509**
Delta	1.541	1.526	1.815	3.049
Rank	3	4	2	1

Bold indicates optimum variable values

As a result of the optimization analysis conducted within this scope, the optimal machining parameters were identified as dry machining conditions, a 0.075 mm/rev feed rate, an 80 m/min cutting speed, and a 0.8 mm cutting depth.

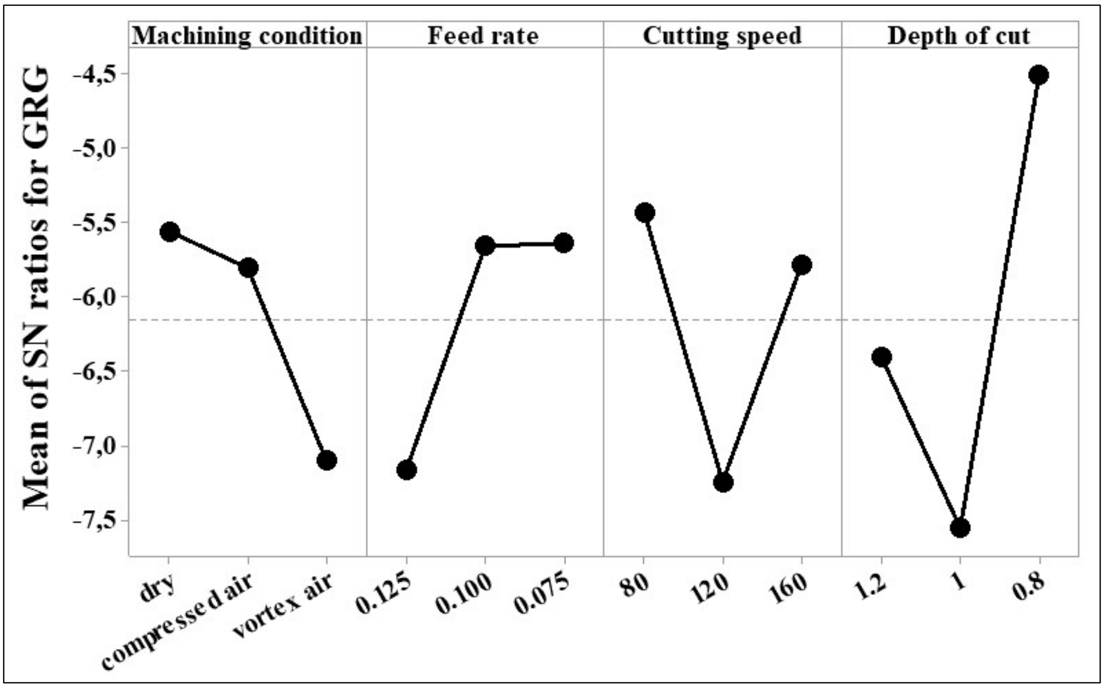

Figure 6. S/N ratios graphics for the GRG

Due to the nature of the Taguchi experimental design method, the number of experiments, which would normally require

81 trials, was limited to 9. When evaluating the results of the experiments based on the material removal rates (MRR), the dry environment emerged first with an MRR of 4800 mm^3/min, followed by the vortex air with an MRR of 12800 mm^3/min, and the compressed air with an MRR of 9600 mm^3/min. Therefore, based on the findings, it is concluded that vortex air and compressed air environments could be strong alternatives to dry machining, as they allow for the removal of a greater volume of material per unit of time.

4. Conclusions

In this research, the performances of three different cooling methods (dry, vortex air, and compressed air) and three levels of cutting parameters (Doc, f, and Vc) on F_R, Ra, and T were experimentally evaluated during the turning of Hastelloy X superalloy. The obtained data indicate that both the applied cooling environment and the cutting parameters significantly influence machining performance. The findings derived from this study are summarized below.

The experimental findings clearly demonstrate the effects of different machining environments and cutting parameters on machining performance. In terms of cutting force (F_R), the lowest value was obtained under dry machining conditions, which aligns with reports in the literature suggesting that elevated temperatures in dry cutting contribute to chip softening [32]. However, the highest F_R value was observed under vortex air conditions, which may be attributed to the excessive cooling effect increasing the surface hardness of the workpiece, thereby raising resistance to cutting. Similarly, Taha et al. [33] reported that overcooling could lead to increased mechanical resistance during machining. The observed reduction in F_R with increasing cutting speed is generally associated with thermal softening in the cutting zone at higher speeds, while increases in feed rate and depth of cut lead to higher cutting forces due to greater material removal volume and tool load, consistent with findings reported in previous studies [34].

Regarding Ra, the lowest Ra value was recorded under dry machining conditions and at the minimum feed rate of 0.075 mm/rev. This can be explained by the fact that lower feed rates tend to reduce tool vibration and surface deformation. However, the highest Ra value was obtained at a cutting speed of 120 m/min, indicating a non-linear relationship between cutting speed and Ra. In terms of cutting temperature, the lowest temperature was observed under compressed air machining, while vortex air also showed a temperature-reducing effect compared to dry cutting. This result is in agreement with previous studies indicating that compressed and directed airflows can effectively dissipate heat from the cutting zone [23].

Optimization using the GRA method identified the optimal machining parameters as a dry environment, 0.8 mm depth of cut, 80 m/min cutting speed, and 0.075 mm/rev feed rate. This parameter combination is considered to offer a balanced solution in terms of both machining performance and environmental considerations. Finally, with respect to material removal rate (MRR), vortex and compressed air environments provided significantly higher material removal capabilities per unit time compared to dry machining, indicating that they may serve as strong alternatives in sustainable machining applications where energy efficiency and environmentally friendly cooling strategies are desired.

In future studies, existing and alternative cooling conditions can be investigated in greater depth across different material groups, machining methods, and optimization techniques, aiming to develop more sustainable and environmentally friendly cooling environments.

Conflict of Interest Statement

The authors declare that there is no conflict of interest

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