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Investigation of the Effect of Machining Parameters and Graphene-Coated Tools on Cutting Temperature in Turning of AA7075 Using Taguchi Method

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ABSTRACT

Cutting temperature has a direct impact on tool wear, surface quality, dimensional accuracy, and overall process stability. Excessive heat generation in the tool-workpiece contact zone, particularly when machining high-strength aluminum alloys, can significantly degrade machining performance. In this study, the effects of cutting speed, feed rate, and depth of cut on cutting temperature during the turning of AA7075 alloy were investigated. The experiments were conducted using a TN-50B lathe and K20 grade tungsten carbide cutting tools. The experimental design was performed using the Taguchi method with cutting speeds of 3.534, 7.065, and 19.725 m/min, feed rates of 0.05, 0.07, and 0.09 mm/rev, and depths of cut of 2, 3, and 4 mm. The influence of machining parameters on cutting temperature was evaluated using Analysis of Variance (ANOVA). The results indicated that the depth of cut and feed rate depth of cut had the most significant impact on cutting temperature. Increasing either of these parameters led to a notable rise in temperature due to intensified plastic deformation and friction in the cutting zone. In contrast, cutting speed had a comparatively lesser effect. To improve thermal performance, a graphene coating was applied to the cutting tool surface. Comparative experiments demonstrated that the use of the coated tool, compared to the uncoated tool, resulted in an average reduction of 12.33°C in the measured cutting temperature. These findings confirm that graphene-coated tools are an effective approach for controlling temperature and improving the machining performance of the AA7075 alloy.

Keywords: Turning, AA7075 Aluminum Alloy, Cutting Tool, Graphene Coating, Cutting Temperature, Taguchi Method

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بررسی تاثیر پارامترهای ماشینکاری و پوشش گرافن بر روی دمای تراشکاری آلومینیوم ۷۰۷۵ با استفاده از روش تاگوچی

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چکیده

دمای برش تأثیر مستقیمی بر سایش ابزار، کیفیت سطح، دقت ابعادی و پایداری کلی فرایند دارد. تولید حرارت بیش از حد در ناحیه تماس ابزار و قطعه‌کار به ویژه هنگام کار با آلیاژهای آلومینیومی با استحکام بالا می‌تواند عملکرد ماشینکاری را به طور قابل توجهی تضعیف کند. در این پژوهش، اثر پارامترهای سرعت برش، نرخ پیشروی و عمق برش بر دمای برش در تراشکاری آلیاژ AA7075 مورد بررسی قرار گرفته است. آزمایش‌ها با استفاده از تراش TN-50B و ابزارهای برشی کاربید تنگستن درجه K20 انجام شد. طرح آزمایش‌ها با استفاده از روش تاگوچی و با سرعت‌های برش ۳/٥۳٤، ۷/۰٦٥ و ۱۹/۷۲٥ متر بر دقیقه، نرخ‌های پیشروی ۰/۰٥، ۰/۰۷ و ۰/۰۹ میلی‌متر بر دور و عمق‌های برش ۲، ۳ و ۴ میلی‌متر طراحی گردید. تأثیر پارامترهای ماشینکاری بر دمای برش با استفاده از تحلیل واریانس ارزیابی شد. نتایج نشان داد که عمق برش و نرخ پیشروی بیشترین تأثیر را بر دمای برش دارند. افزایش هر یک از این پارامترها باعث افزایش قابل توجه دما به دلیل تشدید تغییر شکل پلاستیک و اصطکاک در ناحیه برش شد. در مقابل، سرعت برش تأثیر نسبتاً کمتری داشت. برای بهبود عملکرد حرارتی، پوشش گرافنی بر سطح ابزار برشی اعمال شد. آزمایش‌های مقایسه‌ای نشان داد که استفاده از ابزار پوشش داده شده، در مقایسه با ابزار بدون پوشش، به طور میانگین باعث کاهش ۱۲/۳۳ درجه سانتی‌گرادی در دمای اندازه گیری شده برش شد. این یافته‌ها تأیید می‌کنند که ابزارهای پوشش داده شده با گرافن، روشی مؤثر برای کنترل دما و بهبود عملکرد ماشینکاری آلیاژ AA7075 هستند.

کلیدواژه‌ها: تراشکاری، آلیاژ آلومینیوم ۷۰۷٥، ابزار برش، پوشش گرافن، دمای برش، روش تاگوچی

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1- Introduction

With the steady growth of industrial production and the rising intricacy of contemporary products, manufacturers are increasingly compelled to adopt a wider spectrum of fabrication routes to meet demanding performance and quality targets [1]. In this context, many sectors—most notably aerospace, automotive, and marine industries—continuously pursue advanced processes and improved material solutions that can deliver superior surface and structural quality, tighter dimensional tolerances, and more economical production, particularly under competitive and high-volume conditions [2-4]. Among the candidate materials for such applications, AA7075 has attracted substantial attention and sustained use. Owing to its high tensile strength, excellent fatigue performance, and generally favorable machinability, this alloy is considered a reliable choice for components that must combine low weight with robust mechanical capability in service. At the microstructural and compositional level, the presence of key alloying elements—especially copper and magnesium—plays an important role in tailoring the alloy's overall behavior. These additions contribute to improved ductility while also enhancing corrosion resistance, thereby supporting broader applicability in environments where both mechanical loading and environmental exposure are relevant [5, 6]. Consequently, AA7075 has been incorporated across a wide range of manufacturing operations, reflecting both its versatility and its importance in modern engineering systems. It is commonly used in forming processes where strength-to-weight considerations are critical [7], in welding-related applications where joining efficiency and joint integrity are essential [8, 9], and in additive manufacturing approaches that aim to combine design freedom with high-performance alloys [10]. In parallel, it remains a frequent choice in conventional subtractive routes such as machining, where productivity and achievable accuracy are central concerns [11], as well as in cutting operations where process stability and resulting quality directly affect downstream assembly and performance [12].

Because of the relatively low melting temperature of aluminum, its machining process may be accompanied by the formation of a built-up edge (BUE) and adhesion of material to the cutting tool, making the control of this phenomenon essential for achieving good surface quality and dimensional accuracy. The built-up edge phenomenon is one of the most important and undesirable issues in the machining of aluminum alloys. This phenomenon usually occurs due to the adhesion and accumulation of chips on the rake face of the cutting tool, forming a lump of material at the cutting edge [13]. The formation of a BUE can alter the effective cutting angle, increase friction between the tool and the workpiece, accelerate tool wear, and reduce the surface quality of the machined part. Furthermore, this phenomenon causes fluctuations in cutting forces and vibrations in the tool–workpiece system, negatively affecting dimensional accuracy, surface roughness, and tool life [14].

The formation of a BUE is influenced by various factors, each of which can affect its intensity and development [15]. Among the most important factors are cutting speed, rake angle, tool temperature, tool nose radius, and feed rate. Increasing cutting speed and tool temperature can soften the material and increase chip adhesion, while tool geometry (rake angle and nose radius) influences chip flow and pressure distribution in the cutting zone [16]. Feed rate also plays a key role in determining chip thickness and the degree of contact between the chip and the rake face, thereby affecting the likelihood of BUE formation [17]. In recent years, with the diversification of machining methods, numerous studies have been conducted to investigate and prevent built-up edge formation in machining processes.

Philip et al. [18], in a study involving cutting experiments on plain carbon steel using carbide tools and a device for rapid interruption of cutting, examined the mechanism of built-up edge formation. Their results showed that this phenomenon results from the accumulation of turbulent chip flows and subsurface layers on the rake face of the tool. Even at low cutting speeds, favorable conditions for BUE formation exist, although low temperature prevents its complete development. Their findings also indicated that the built-up edge grows with the advancing chip flow and the hardening of semi-deformed grains around the cutting zone, and it can form even within a critical temperature range. Yasin Syed Ahmad et al. [19] studied the effect of built-up edge formation on surface integrity and cutting forces during stable wear conditions of uncoated cutting tools in the machining of AISI 304 stainless steel. X-ray diffraction (XRD) was used to measure surface residual stresses, and scanning electron microscopy (SEM) was employed to analyze the surface and subsurface structure of the chips. Their results revealed that the built-up edge is an unstable, layer-by-layer phenomenon that forms gradually and detaches after reaching a critical size. This continuous cycle of formation and detachment can cause tool wear and microcracks at the cutting edge. However, under certain conditions, the presence of a BUE can reduce tool wear, improve surface quality, and decrease cutting forces. It was found that as the BUE height increases, the effective cutting angle decreases, leading to lower cutting forces and reduced fluctuations under steady conditions. Additionally, tensile residual surface stresses decrease with increasing temperature and BUE growth, indicating the direct effect of this phenomenon on the mechanical behavior of the machined surface.

Yazman et al. [20] investigated the effect of built-up edge thickness at different cutting speeds on surface roughness and cutting forces during the machining of austempered ferritic steel. Their results showed that variations in BUE thickness significantly influence cutting behavior; as its thickness increases, surface roughness and force fluctuations also change. Moreover, due to cutting forces and shear stresses, spherical graphite particles within the chip structure break and lose their original shape, leading to chip brittleness and instability. However, the presence of graphite in the cutting zone provides a localized lubricating effect, improving the tool–chip contact conditions.

Machining AA7075 presents several critical challenges that significantly affect process efficiency and part quality. One of the primary issues is the formation of a BUE. Due to the low melting point of aluminum and its high chemical affinity, workpiece material tends to adhere to the cutting tool edge, forming an unstable BUE. This phenomenon alters the effective tool geometry, increases cutting forces and vibration, and severely deteriorates surface finish. Another major challenge is heat generation and thermal management. The high plastic deformation and friction in the cutting zone generate substantial heat. While aluminum has high thermal conductivity, the localized temperature rise can still lead to thermal expansion of the workpiece, compromising dimensional accuracy, and accelerating tool wear. Consequently, controlling cutting temperature is essential, and the application of advanced coatings represents a promising strategy to mitigate these thermal issues and improve machining performance.

In machining metallic and non-metallic components, various types of cutting tools made from alloy steels, high-speed steels, hard metals, and ceramics are used. Tool coating is one of the most effective methods to improve mechanical properties and extend tool life. Such coatings typically consist of a thin wear-resistant layer applied to the tool surface. This study investigates the effect of applying a graphene coating on cutting tools on the formation of the built-up edge during the machining of AA7075.

The primary objective of this study is to experimentally investigate the thermal behavior and BUE formation during the dry turning of AA7075. While general machining parameters are well-documented, the specific interaction between the thermal field and the adhesive mechanisms leading to BUE in this high-strength alloy requires further elucidation. The innovation of this research lies in the application of an electrochemically deposited graphene coating on K20 carbide inserts to mitigate these thermal and tribological challenges. By identifying the critical cutting speed range that maximizes BUE and demonstrating the capability of graphene to reduce cutting temperature, this study offers a novel, practical solution for enhancing machining stability and tool life in industrial applications.

2-Materials and Methods

In this study, the turning process was performed on samples of AA7075 rods with a diameter of 50 mm and a length of 500 mm. Table 1 shows the chemical composition of AA7075.

Table 1 Composition of AA7075

Alloy	Cu	Mg	Cr	Zn	Mn
AA7075	1.26	2.13	0.134	4.38	0.061

The machining experiments were carried out using a TN-50B lathe machine manufactured by Tabriz Machine Manufacturing Company. In this research, a steel tool holder with a clamping angle close to 90 degrees and the ability to replace inserts was used. The selection of the cutting tool material was guided by the need for a robust baseline to evaluate the thermal effects of the graphene coating. K20-grade tungsten carbide was chosen due to its high toughness and excellent wear resistance, which ensure tool stability under the mechanical loads of machining. Furthermore, as a general-purpose grade, K20 provides a consistent and reliable substrate, allowing for a clear assessment of the coating's performance without the interference of complex multi-layered geometries found in specialized aluminum-specific tools.

The cutting temperature was measured using a FLIR thermal imaging camera with a measurement range of -20 °C to 550 °C. The camera was positioned at a fixed distance of one meter from the workpiece to capture the thermal images. It was configured to record the maximum temperature within the field of view, which was observed in the area near the cutting edge, specifically located on the rake face of the tool.

To investigate cutting temperature during the turning of AA7075, three main machining parameters—cutting speed, feed rate, and depth of cut—were considered as control variables. Each experimental test was conducted once. To ensure the accuracy and reliability of the measurements, the reported BUE height was calculated as the average of measurements taken at three different points along the cutting edge. The Taguchi method was employed for the design of experiments (DOE) and parameter analysis.

The Taguchi method is a structured approach used to determine the optimal combination of input factors for producing a product. It utilizes the signal-to-noise (S/N) ratio to evaluate the sensitivity of process output to uncontrollable factors in the experiment [21, 22]. In this study, three levels were selected for each of the parameters: cutting speed, feed rate, and depth of cut.

The selection of machining parameter ranges was based on preliminary experimental tests conducted to identify the conditions conducive to BUE formation. Through these initial trials, specific cutting speeds, feed rates, and depths of cut were determined to effectively induce the BUE phenomenon. Table 2 presents the levels of these parameters.

Based on the selected parameter levels, an experimental design matrix consisting of nine tests was generated using the Taguchi method. All other process parameters were kept constant during the experiments. The process temperature was also measured using a thermal imaging camera. In the second step, to evaluate the coating effect, the machining process was performed using the parameters of the test design table and using the coated tool.

Table 2 Levels of Experimental Design Parameters

Parameter	Symbol	Level 1	Level 2	Level 3
Cutting speed (m/min)	V	3.534	7.065	19.725
Feed rate (mm/rev)	F	0.05	0.07	0.09
Depth of cut (mm)	D	2	3	4

The tool coating process was carried out electrochemically, with controlled parameters such as electrolyte composition, temperature, current, and time to achieve the desired coating characteristics. In this study, the coating process was conducted using a potentiostat device, model VERTEX-One. The inserts were used as substrates and coated with graphene nanoparticles deposited from a 1% acetonitrile aqueous solution. The electrolysis process was performed at room temperature with an applied voltage of 10 V. Based on preliminary trials to determine the optimal deposition conditions, the process duration was fixed at 4 hours for all cutting tools used in the experiments. Figure 1 shows the potentiostat device model VERTEX-One used in this study.

Fig. 1 Potentiostat device model VERTEX-One

3- Results and Discussion

In this study, the measured temperature were considered as the output responses in the experimental design table. Table 3 presents the results obtained from the measurements process temperature.

Table 3 Cutting temperature in tests

Test no.	F	D	V	$T_{\text{With uncoated tool}}$ (°C)	$T_{\text{With coated tool}}$ (°C)
1	0.05	2	3.534	189	165
2	0.05	3	7.065	196	187
3	0.05	4	19.725	221	207
4	0.07	2	7.065	191	186
5	0.07	3	19.725	207	200
6	0.07	4	3.534	203	193
7	0.09	2	19.725	212	195
8	0.09	3	3.534	202	191
9	0.09	4	7.065	217	203

Figures 2 and 3 show the temperatures measured by the thermal camera during the experiments conducted according to the experimental design matrix using the uncoated and coated tools, respectively.

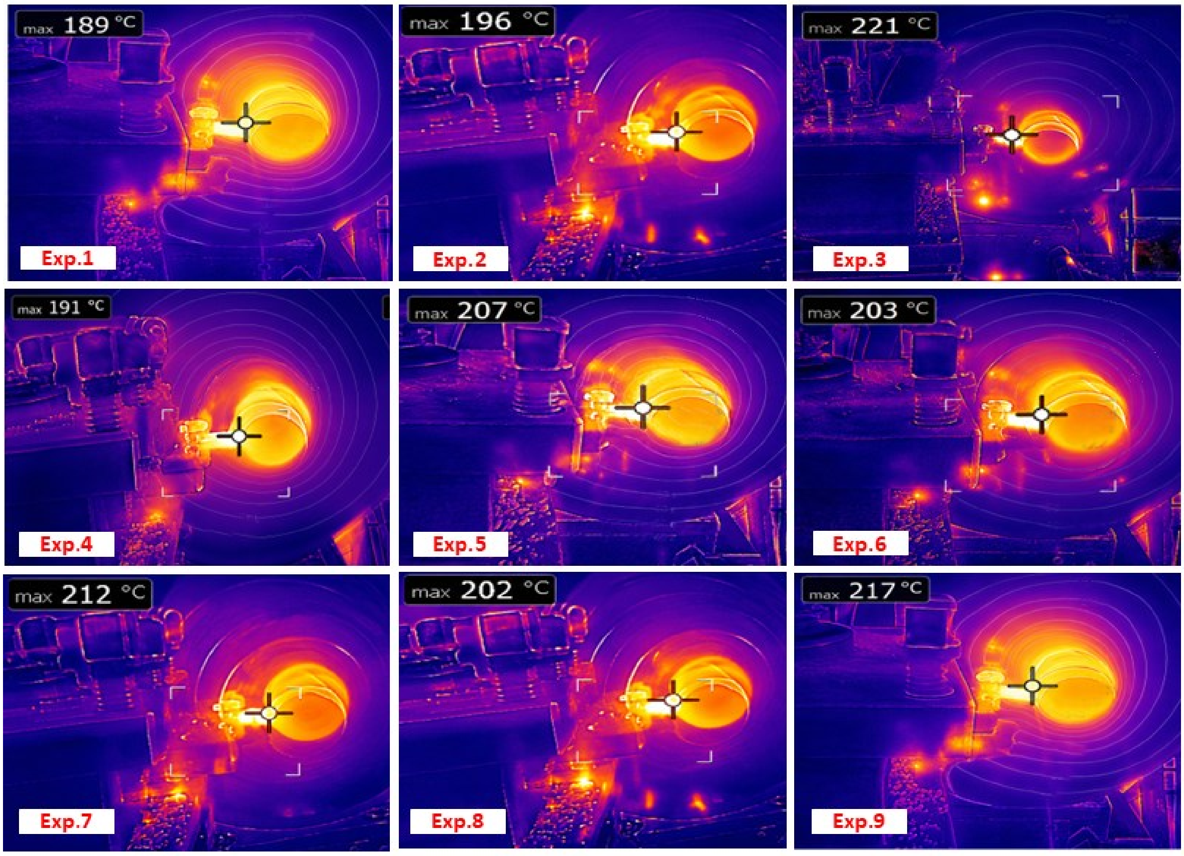

Fig. 2 Temperature measured by the thermal camera with the uncoated tool.

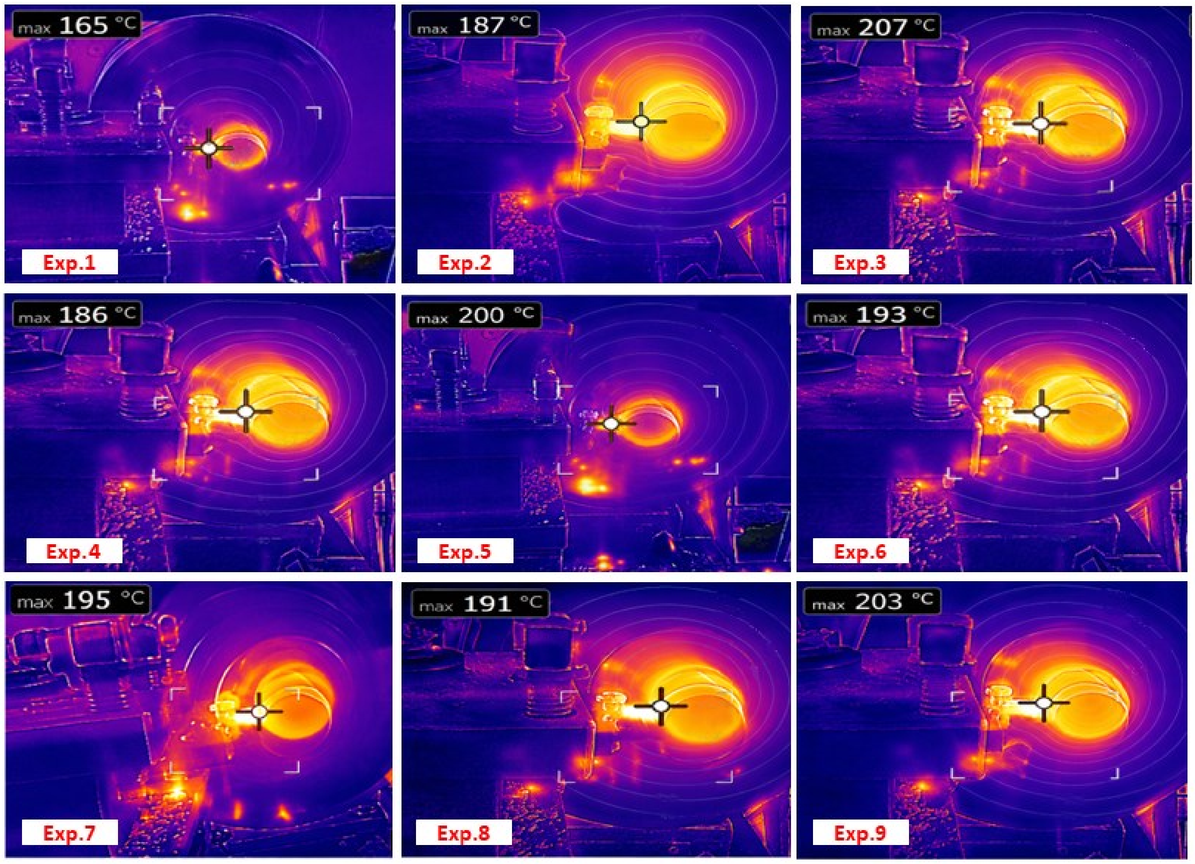

Fig. 3 Temperature measured by the thermal camera with the coated tool.

To evaluate the validity of the proposed model and method, normal probability plots, residual scatter plots, histograms, and residual versus time plots were used. These plots were generated using Minitab software. The absence of any specific pattern or distinct shape in the residual scatter plots indicates equality and homogeneity of variances. Figures 4 and 5 show the remaining four charts for the temperature measured with the uncoated and coated tools, respectively.

To examine the effects of cutting speed, feed rate, and depth of cut on the measured temperature, the coefficient tables obtained from the analysis of variance (ANOVA) were used. Tables 4 and 5 show the ANOVA results for the temperature measured with the uncoated and coated tools. When the p-value is less than 0.05, the effects of the input process parameters on the output responses are considered statistically significant.
Regarding thermal behavior, Figure 6 shows that increasing the depth of cut, feed rate, and cutting speed leads to a significant increase in process temperature due to the increased material removal rate and enhanced frictional interactions in the cutting zone [23, 24]. As shown in Figures 6 and 7, increasing all input parameters in the process leads to an increase in the measured temperature. Among them, the Depth of cut has a greater influence on the measured temperature in the process with both uncoated and coated tools.

One of the most important statistical methods for data analysis is linear or multiple regression analysis. In this method, the output responses of a process can be logically related to the independent input parameters. Equations (1) and (2) represent the regression equations for the measured temperature with the uncoated and coated tools, respectively, in the machining process.

$$T_{\text{With uncoated tool}}\ (^\circ C) = 155.56 + 208.3\ F + 8.17\ D + 0.947\ V \quad (1)$$

$$T_{\text{With coated tool}}\ (^\circ C) = 135.95 + 250\ F + 9.50\ D + 0.983\ V \quad (2)$$

To better examine the behavior of the coated tool, scanning electron microscope (SEM) images were used. The FE-SEM images of the graphene-coated tool are shown in Figure 8. According to Test No. 3, in the machining process with the uncoated tool, the measured temperature was 221 °C. This test was conducted with a cutting speed of 19.725 m/min, a depth of cut of 4 mm, and a feed rate of 0.05 mm/rev. For this test, the BUE height was also measured, which was 0.52 mm. Figure 9 shows the image of the formed BUE on the tool.

Statistical analysis based on the ANOVA results indicates that the cutting temperature during the turning of AA7075, using both uncoated and coated tools, is significantly influenced by the depth of cut and feed rate, which together account for more than 78% of the observed temperature variations. An increase in the feed rate intensifies plastic deformation and frictional interactions at the tool-chip interface, leading to greater heat generation in the cutting zone. Similarly, increasing the depth of cut increases the volume of material removed and the contact area, thereby increasing the thermal load on the cutting tool. In contrast, the cutting speed showed a relatively smaller and statistically insignificant effect on the cutting temperature within the selected parameter range. The observation of minimum cutting temperature at intermediate cutting speeds suggests the existence of an optimal thermal regime, where reduced tool–workpiece contact time balances the rate of heat generation.
Figures 6 and 7 respectively show the effects of the independent input parameters on the the measured temperature with the uncoated and coated tools in the machining process.

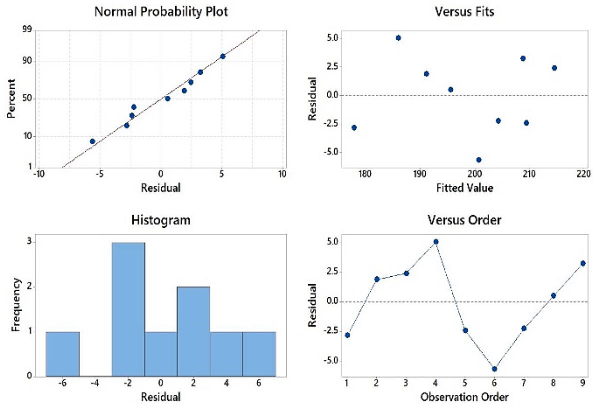

Fig. 4 Four residual plots for the measured temperature with the uncoated tools

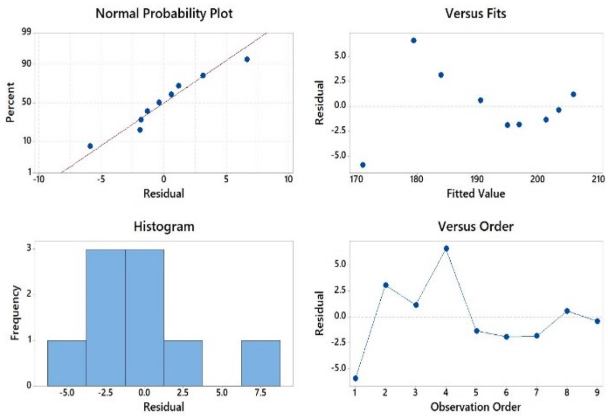

Fig. 5 Four residual plots for the measured temperature with the coated tool

Table 4 Analysis of variance of measured temperature with the uncoated tools

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Regression	3	894.56	90.04%	298.19	15.06	0.006
V	1	104.17	10.48%	104.17	5.26	0.070
D	1	400.17	40.28%	400.17	20.21	0.006
F	1	390.22	39.28%	390.22	19.71	0.007
Error	5	99.00	9.96%	19.80	-	-
Total	8	993.56	100.00%	-	-	-
R-sq					90.04%	

Table 5 Analysis of variance of measured temperature with the coated tools

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Regression	3	1111.81	91.82%	370.60	18.70	0.004
V	1	150.00	12.39%	150.00	7.57	0.040
D	1	541.50	44.72%	541.50	27.33	0.003
F	1	420.31	34.71%	420.31	21.21	0.006
Error	5	99.08	8.18%	19.82	-	-
Total	8	1210.89	100.00%	-	-	-
R-sq					91.82%	

consistent performance across the cutting edge. The primary mechanism behind the observed temperature reduction is the excellent tribological properties of graphene.

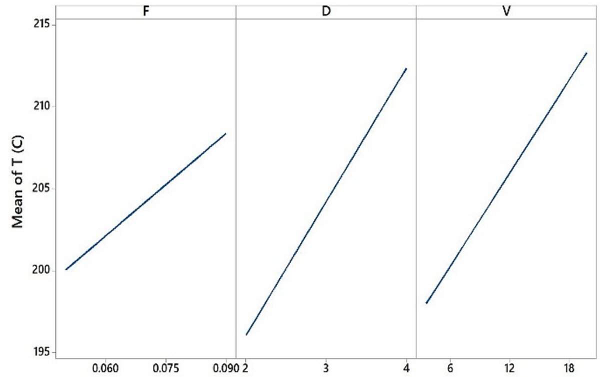

Fig. 6 Effects of input parameters on temperature with the uncoated tools

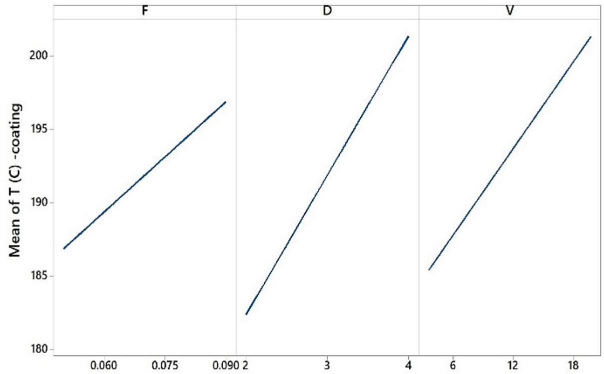

Fig. 7 Effects of input parameters on temperature with the coated tools

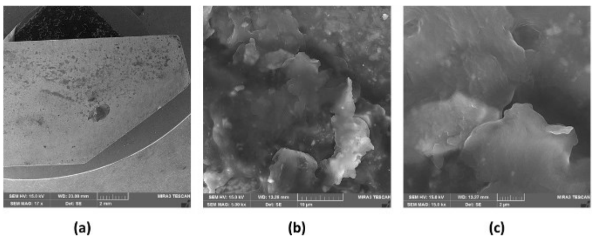

Fig. 8 (a) Coated tool image; FE-SEM images of the graphene coating surface at (b) lower and (c) higher magnifications.

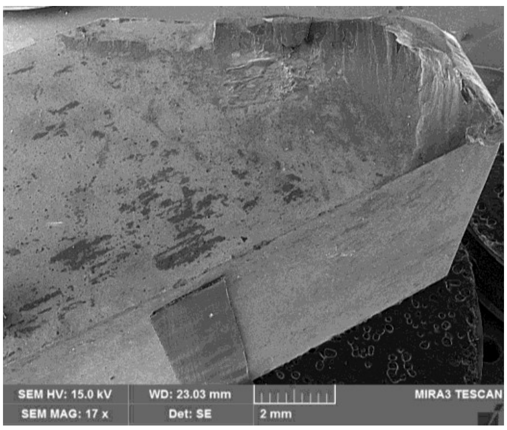

Fig. 9 FE-SEM micrograph of the tool with BUE formation

The application of the graphene coating significantly influenced the thermal behavior of the machining process, as evidenced by the reduction in cutting temperature. Figure 8 presents the FE-SEM images of the coated tool surface at different magnifications. As observed in Figure 8(b) and (c), the graphene nanoparticles have formed a relatively uniform and continuous layer over the tool substrate. This homogeneous coverage is crucial for ensuring Known as an effective solid lubricant, the graphene layer creates a low-shear interface between the tool and the chip, significantly reducing the coefficient of friction. This reduction in frictional force minimizes the heat generated at the secondary shear zone. Furthermore, graphene possesses exceptionally high thermal conductivity. This property allows the coating to act as a thermal bridge, rapidly dissipating heat away from the localized cutting zone and distributing it more evenly throughout the tool body. Consequently, the accumulation of heat at the tool tip is mitigated. Additionally, the protective nature of the coating reduces direct adhesive contact between the aluminum workpiece and the carbide tool, thereby lowering the ploughing forces and the associated thermal energy. According to Table 3, the maximum temperature reduction of 24 °C is observed in machining process 1 due to the use of the graphene-coated tool. This occurs due to a combination of reduced friction, enhanced heat dissipation, and protection against adhesive wear.

4-Conclusion

In this study, the effects of machining parameters and graphene-coated cutting tools on cutting temperature during the turning of AA7075 were experimentally investigated using the Taguchi design method and ANOVA analysis. Cutting speed, feed rate, and depth of cut were selected as the primary control parameters, while cutting temperature was considered the main response variable due to its direct influence on tool performance and machining stability. The experimental results demonstrated that depth of cut and feed rate are the most influential factors affecting cutting temperature. Increasing these parameters resulted in a significant rise in temperature due to intensified plastic deformation and friction in the cutting zone. In contrast, cutting speed showed a comparatively smaller and statistically insignificant effect on temperature variation. The lowest cutting temperature was observed at moderate cutting speeds, indicating the presence of an optimal speed range in which heat generation is minimized.

Based on the experimental design table, the use of the coated tool, compared with the uncoated tool, resulted in an average reduction of 12.33°C in the measured temperature. This improvement can be attributed to the excellent thermal conductivity and solid lubrication properties of graphene, which reduce friction and heat accumulation at the tool–chip interface. The reduced cutting temperature contributed to improved machining stability and enhanced tool performance. Overall, the results confirm that combining optimized machining parameters with graphene-coated cutting tools is an effective strategy for controlling cutting temperature and improving the machining performance of aluminum alloy AA7075.

In summary, the findings of this study confirm that the proposed approach extends by introducing a validated strategy for thermal management in aluminum machining. The innovative aspect of this research is the successful application of a graphene coating via electrochemical deposition, which demonstrated a significant reduction in cutting temperature and improved tribological performance. The integration of experimental data provided clear evidence of the coating's uniformity and its role in reducing friction at the tool-chip interface.

Future studies may focus on investigating the long-term wear behavior and durability of graphene-coated cutting tools under extended machining conditions. Given the significant influence of coating thickness on thermal performance, it is essential that this parameter be carefully considered and measured in future research. Additionally, evaluating the combined effects of graphene coatings with different tool geometries, cooling strategies, or hybrid lubrication methods could provide further insights into thermal and tribological performance. Numerical modeling and finite element simulations may also be employed to predict temperature distribution and validate experimental findings. Finally, extending the proposed approach to other aluminum alloys and difficult-to-machine materials would help assess the broader applicability of graphene-based coatings in industrial machining processes.

Ethics Approval:

The scientific content of this article is the result of the authors' research and has not been published in any Iranian or international journal.

Statement on the use of artificial intelligence:

The authors have used artificial intelligence tools in the process of translating the text and editing the images.

Author contributions

A.F. Project administration, Writing original draft. Y.Y. Project administration, Writing - Review & editing. H.A. Investigation, Visualization, Resources, Formal analysis.

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Conflict of Interest:

There are no conflicts of interest to declare.

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