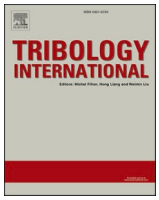
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Experimental research on sustainable drilling of Hastelloy X superalloy: Impact of hBN, GNP, LN_2 and hybrid eco-friendly cooling/ lubrication strategies

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ABSTRACT

In this study, the effect of sustainable cooling and lubrication strategies such as MQL, LN_2, LN_2 +MQL, LN_2 +hBN/GA, LN_2 +GNP/GA, LN_2 +hBN-GNP/GA on drilling nickel-based Hastelloy X alloy was examined. The environmental impacts and health risks of traditional petroleum-based cutting fluids used in drilling operations have led researchers to look for ecological alternatives. In this context, combinations of nanofluids enriched with minimum quantity lubrication (MQL), liquid nitrogen (LN_2), and nanosized hBN and GNP particles have been tested. The experiments were carried out at cutting speeds of 20 and 30 m/min and feed rates of 0.04 and 0.06 mm/rev. Nanofluids characteristics i.e., viscosity, Ph, thermal conductivity and wettability, and drilling performance were evaluated with criteria such as cutting force, surface roughness, hole quality and tool wear. The results obtained showed that the hybrid methods combining LN_2 and nanofluid-based MQL provided superior performance in terms of both cooling and lubrication, and the condition directly positively affected the processing outputs. This study contributes to the literature by revealing the potential of ecological cooling/lubrication methods in the sustainable production of difficult-to-machine materials such as Hastelloy X.

1. Introduction

Hole drilling is a metal cutting method that has a wider application area than other machining operations, especially in critical sectors such as the aviation and space industry. Drilling is a machining process that happens in a semi-enclosed area. That is why, it has some disadvantages compared to other metal removal methods such as turning and milling operations. The main disadvantages are the difficulty in evacuating the chip, sudden breakage of the drill caused by the jamming of chips, deviation from the size, poor surface quality, and high feed force. Friction and heat generation, especially during chip evacuation, reduce the quality of the drilled surfaces and can accelerate tool wear [1]. Moreover, these disadvantages can cause major problems in drilling difficult-to-cut materials, also known as heavy machining. Especially in drilling materials such as superalloys, which are employed widely in the space and aviation industries, machining efficiency is quite low. This situation challenges both manufacturers and researchers. Although superalloy materials have superior mechanical and thermal properties, their properties such as deformation hardening during machining, low thermal conductivity and abrasiveness put them in the class of materials that are difficult to cut [2]. Increasing the machining efficiency in drilling Nickel-based superalloys, which are widely used in the superalloy family, is important in many respects. Today, the use of cutting fluids is one of the most commonly used methods to increase machining efficiency. The use of cutting fluid, which is known to be important in turning and milling operations, has a much higher importance in drilling operations.

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Nomenclature

BUE	Built up edge.
CMM	Coordinate measurement machine.
EDX	Energy dispersive X-ray spectroscopy.
f	Feed rate (mm/rev).
hBN	Hexagonal boron nitride.
GNP	Graphene nanoplatelet.
GA	Gum arabic.
LN_2	Liquid nitrogen.
MQL	Minimum quantity lubrication.
MWCNT	Multi wallet carbon nanotube.
Ra	Average surface roughness.
SEM	Scanning electron microscope.
TiAlN	Titanium aluminum nitride.
Vc	Cutting speed (m/min).

Cutting fluids are an application that is used to minimize many problems caused by friction and heat. Cutting fluids play a vital role in increasing machining efficiency by minimizing tool wear, enhancing surface quality, and clearing chips from the cutting region, etc. [3,4]. However, the oil mist and residues created by the chemicals in petroleum-based cutting fluids used as classical cutting fluids lead to negative effects on the environment and employee health. Serious health problems such as dermatitis, skin cancer, asthma and lung cancer may occur when employees come into contact with cutting fluids through the skin and inhale liquid particles in the air [5–8]. Moreover, the use of high amounts of cutting fluid and disposal processes also increase production costs. [9]. For this reason, reducing the use of classical cutting fluid without reducing machining efficiency has always been a popular research topic for researchers and manufacturers [10,11]. One of these alternative methods is minimum quantity lubrication (MQL) method.

The MQL is a green cooling and lubricating technique that applies an aerosol mist to the cutting zone by combining a tiny quantity of cutting fluid with compressed air. A tribo-lubricating film layer is formed by tiny amounts of oil droplets on the tool/workpiece/chip contact. In this sense, it lowers production costs, cutting tool wear, losses from thermal shocks in the cutting tool, and heat at the tool/workpiece interface through efficient cooling and lubrication. In addition, almost all of these oil droplets evaporate, leaving no residue on the workpiece and chip [12,13]. MQL utilizes a very tiny quantity of cutting oil and these oils are biodegradable, it is a more desirable procedure in terms of both human health and the environment [14,15]. Many studies emphasize that the MQL method is an environmentally friendly method that increases processing efficiency and provides cleaner production [16–18]. However, some studies have emphasized that the performance of the MQL method is insufficient, especially under heavy processing conditions [19–22]. Increased heat generation, worse cutting conditions, and the emergence of new materials have all highlighted the need to make the MQL process more efficient. Nanosized solid lubricant particles with a high heat conduction coefficient are added to the cutting fluids to develop the MQL method's efficacy under heavy machining circumstances.

Nanofluids are prepared by adding solid nanoparticles, generally 1–100 nm in size, to the base fluid at different rates (by weight or volume) [23]. Different powders can be used as nanoparticles [24]. The basic liquids' lubricity and thermal conductivity are enhanced by these additional nanopowders [25]. In addition to improving the lubricating qualities of the base oil and increasing heat conductivity, sending nanoparticles to the cutting zone under high pressure with the cutting oil also forms a thin layer of protective lubricant film on the interface between cutting tool and workpiece [26]. It is possible to find many studies on nanofluids, some of them are summarized. Kıvak et al. [27] machined Ni-Hard on a lathe under dry, MQL, GNP and MWCNT-doped nanofluid machining environments. They claimed that GNP-added nanofluid cutting condition gave the best results on cutting temperature and surface roughness. Şirin and Kıvak [22] examined the effects of cutting conditions on machining performance by milling Inconel X-750 material under dry, MQL and hBN, Grpt, MoS_2 added nanofluid cutting conditions. Researchers have claimed that nanofluid cutting conditions provide superior performance. In another study, Şirin and Kıvak [28] examined the machining performance by milling Inconel X-750 alloy under hybrid hBN/Grpt, hBN/MoS_2 and Grpt/MoS_2 nanofluids. According to the results obtained from experimental data, they reported that hBN/Grpt hybrid nanofluid performed well in all conditions.

In line with these studies, studies on different ecological cooling methods continue. The biggest reason for this is that although the use of nanofluid provides good results in terms of lubrication, especially under heavy processing conditions, its cooling efficiency is low [29,30]. For this purpose, cryogenic cooling has become popular in recent years.

In cryogenic cooling, cooling is provided by sending cryogens i.e., Nitrogen, Carbon dioxide and Helium to the cutting zone. Liquid nitrogen (LN_2: melting and boiling points:−210 °C and 195.80 °C, respectively) is the most commonly used cryogen in cryogenic cooling operations [31]. LN_2 is a safe, non-toxic, and clean refrigerant that leaves no trace behind since it dissipates in the environment right away. Because of this, the cryogenic cooling process is regarded as being more cost-effective and ecologically benign than other approaches [32]. Khanna et al. [33] drilled Inconel 718 superalloy material under dry and LN_2 cutting modes and explored the effects of cutting conditions on machining performance. They achieved significant improvements in torque, tool wear, hole quality, chip shape and tool life criteria in LN_2 compared to dry environment due to temperature reduction. Ahmed and Kumar [34] analyzed the impacts of wet and LN_2 strategies on cutting force, torque, temperature, hole quality, surface roughness, tool wear and chip morphology when drilling Ti6Al4V alloy. As a result, they emphasized that cryogenic cooling gave better outputs with regard to cutting temperature, cutting force, torque, hole quality, tool wear and surface quality. Uçak and Çiçek [35] investigated the effects of cutting conditions on machining performance by drilling Inconel 718 under dry, wet and LN_2 modes. According to the study's findings, the wet cutting condition outperformed the cryogenic cutting condition in terms of cutting force, surface quality, and tool life, while the cryogenic cutting condition excelled in terms of temperature and hole quality.

Furthermore, some research suggests that the combination of MQL, nanofluid, and cryogenic cutting conditions, known as hybrid cutting conditions, can improve machining efficiency by better lubricating and cooling the cutting zone. For instance, Yıldırım [20] studied the effects of cutting circumstances on cutting temperature, surface roughness, and tool wear by turning Inconel 625 superalloy material under dry, MQL, LN_2 (liquid nitrogen), nanofluid, and nanofluid+LN_2 environments. It has been reported that nanofluid + LN_2 yield the greatest machining performance when turning Inconel 625 material. Yıldırım et al. [36] machined Inconel 625 material on a lathe under MQL, LN_2 and cryogenic plus MQL conditions. In the study, cutting temperature, surface roughness, surface topography, chip morphology and tool wear results were taken into consideration as performance criteria. According to the study's findings, processing outputs significantly improved under the cryoMQL cutting scenario. Şirin et al. [37] milled Inconel X750 under MQL, LN_2 and MQL+LN_2 environments and examined the impacts of cutting conditions on cutting force, cutting temperature, surface topography and tool wear. They asserted at the conclusion of the investigation that the MQL+LN_2 performed the best across all results. The Haynes-25 superalloy was machined by Şirin [38] in dry, GNP, MWCNT, N_2, and GNP/MWCNT+N_2 environments. According to the study's findings, the hybrid cutting condition outperformed the N_2 cutting condition in point of tool wear, surface roughness, and chip shape.

It is evident from an evaluation of the literature that there is

insufficient research, particularly when it comes to drilling operations. It has been observed that drilling studies, especially on Hastelloy X superalloy material, have not been researched sufficiently. Today, it is extremely important to carry out studies that highlight ecological cooling/lubrication methods in order to ensure sustainable production. The aim of present paper is to contribute to the literature by testing different ecological cooling/lubrication conditions in the drilling of Ni-based difficult-to-machine material. For this purpose, Different ecological cooling and lubrication conditions, such as MQL, LN_2, LN_2 +MQL, LN_2 +hBN/GA, LN_2 +GNP/GA, and LN_2 +hBN-GNP/GA, were used when drilling Hastelloy X superalloy. Thus, the goal is to determine the ideal cooling/lubrication condition for heavy machining circumstances, taking into account both these factors. The experimental procedure of the study, the findings and discussions of the findings are explained in the following sections.

2. Material and methods

2.1. Material, machine and cutting tool

The workpiece utilized in the drilling experiments was a superalloy called Hastelloy-X, which is based on Nickel. The test samples that were utilized in the studies have measurements of 100 × 150 × 13.5 mm. Table 1 provides the alloy's chemical composition, while Table 2 lists the alloy's mechanical and physical characteristics.

A Delta Seiki CNC-1050A vertical machining was utilized for the drilling experiments. Six distinct cooling conditions, including MQL, LN_2, LN_2 +MQL, LN_2 +hBN/GA, LN_2 +GNP/GA, and LN_2 +hBN-GNP/GA, were implemented for the experiments. In the drilling trials, two distinct cutting speeds (20, 30 m/min), two distinct feed rates (0.04, 0.06 mm/rev), and a constant drilling depth (about 14 mm) were employed as cutting parameters. Feed rate, cutting speed and depth of cut values were determined by literature, manufacturer recommendations and preliminary experiments. The cutting tools are high-quality TiAlN coated drills (TTT.7035.139.01) with a 5 mm diameter, 140° tip angle, and 30° helix angle (Ø5 ×26-Ø5H6 ×63), made by Taegu Tec. In the drilling experiments, a unique drill was employed for each experiment. To avoid vibration and run-out during the testing, the distance between drill bits and tool holder was maintained at 26 mm.

2.2. Drilling environment and parameters

The MQL is a green cooling/lubricating technique that involves applying aerosol mist vapor, or a tiny amount of cutting fluid (10–150 mL/hour) mixed with compressed air to the cutting zone. The fact that very little cutting oil is required and that these oils are biodegradable is a significant benefit for both environment and human health. Liquids were sent to the cutting zone using the LubriLean Vario model (Germany) MQL device. With a 2 mm diameter nozzle, 8 bar air pressure, and a 50 mL/h fluid flow rate, the external MQL method was used in the system for each experimental parameter. The cutting tool and the nozzle are positioned 20 mm apart and at a 30° angle.

Nanofluids were produced by mixing hBN and GNP nanoparticles with different volume fractions of 0.6 % into vegetable-based oil obtained from Belgin (Turkey). Vegetable-based fluid, which is biodegradable, can be considered environmentally friendly and ecological fluids. Hybrid mixtures were obtained by adding equal volumes of 0.3 % hBN + 0.3 % GNP to vegetable oil. The properties of oil and nanoparticles are provided in Table 3 and Table 4, respectively. In order to minimize surface tension and generate a homogenous mixture, surfactants or other extra chemicals can be added to the mixture during the creation of nanofluids. Surfactants hold nanoparticles in suspension, creating homogeneous and long-stable mixtures [39,40]. In this study, Gum Arabic (GA) surfactant was used as a surfactant. Surfactant has −325 mesh size and 99.95 % purity. Surfactant rate was used as 0.25 % wt, in parallel with literature. [41,42]. Scanning Electron Microscope (SEM) images of the nanoparticles and surfactant used in nanofluidic mixtures are presented in Fig. 1.

A two-step method was applied in nanofluid preparation. First, GA surfactant was added to the vegetable-based oil and mixed with a digital mechanical mixer (Daihan HS100D) at 750 rpm for 60 min. Then, nanoparticles were added, and the mixing process was continued with a mechanical mixer. After that, mixing was continued for 30 min with the help of an ultrasonic homogenizer (Bandelin Sonopuls HD3200) at a frequency of 200 W, 20 kHz. In the last step, the mixing process was completed after 120 min at 1500 rpm using a magnetic stirrer (Thermal N11151M). The obtained nanofluids were added to the MQL device without waiting and experiments were carried out. The nanofluid preparation stages can be seen visually in Fig. 2.

In the tests, cryogenic cooling with LN_2 at −196 °C was employed. An XL-45 HP type Taylor Wharton storage tank was utilized to store and consume LN_2. Cryogens were supplied to the cutting zone using a flexible vacuum pipe to reduce heat losses. Through a nozzle with an exit diameter of 3 mm, liquid nitrogen was sprayed at a 30° angle and 15 mm above the rake surface to reach the cutting zone. Test parameters are presented in Table 5.

The values used in this section were obtained from previous preliminary experiments and manufacturer company recommendations.

2.3. Characterization of nanofluids

Measurements were made of the fluids' viscosity, pH, thermal conductivity, surface tension, and contact angle. Using an AND SV-10 viscosity meter, the fluids' viscosity values were determined at 40 °C. A Sartorius PT-10 P pH meter with a measuring range of 0 to 15 pH and a measurement sensitivity of 0.01 was used to test the fluids' pH values. Utilizing the 5465 coded sensor, which is intended for liquids with a 3.2 mm radius, and the TPS 2500 S model (Hot Disk-Sweden) thermal constants analyzer instrument, thermal conductivity measurements were performed at constant temperature (23 °C).

The surface tension and contact angle were measured using a Theta Lite model (Sweden) equipment, which has an accuracy of 1 % for measuring angle values between 1–180°. The pendant drop technique was applied to measure surface tension, while the sessile drop technique was deployed to measure contact angle. The usual approach for quickly and accurately measuring wettability is the sessile drop technique [43].

2.4. Experimental measurement

The investigations employed a Kistler 9272–4 component piezoelectric dynamometer to identify force and torque. Using the Kistler 5070-A multi-channel amplifier and Kistler Dynoware software, signals from the dynamometer were translated to numerical values. The highest cutting temperature generated in the cutting zone was measured using an Optris PI450 infrared camera. The procedure adopted to measure the maximum temperature values involved drilling holes 0.5 mm from the surface of the workpiece. The infrared camera manufacturer's suggested emissivity value of 0.5 was chosen for Hastelloy X. Optris Connect software was implemented to record and show the cutting zone temperature online.

Table 1
Chemical composition of Hastelloy-X (wt%).

Ni	Cr	Fe	Mo	Ti	Al	Mn	Si	C	Cu	Co	Other
46.7	22.6	18.7	8.98	0.02	0.14	0.51	0.30	0.05	0.14	0.67	1.17

Table 2
Mechanical and physical features of Hastelloy-X.

Melting Range, (°C)	Young Modulus, (GPa)	Specific Heat, J/kg-K	Hardness, (HRB)	Tensile Strength, (mPa)	Yield Strength, (mPa)	Thermal Conductivity, W/m-K	Density, g/cm^3	Elongation, (%)
1260 −1355	207	486	87.1	732.2	319.2	9.1	8.22	54.4

Table 3
Vegetable based fluid's features.

Fluid name	Density (20 °C, g/mL)	Copper corrosion (3 h, 100 °C)	Refractive index (nD_{20})	Viscosity (40 °C, cSt)	Flash point (°C)	Appearance
CuttexSYN 5	0.895	1a	1.4600	5.16	170	Light yellow, clear

Table 4
Nanoparticles' features.

Type	Size (nm and μm)	Purity (%)	Density (g/cm^3)	Shape	Appearance
hBN	80	99.85	2.30	spherical	white
Graphene nanoplatelet	thickness. 5 nm diameter 30 μm	99.90	2.25	layered	gray

The roughness values on the hole surfaces were measured using a portable roughness tester, the Mahr Marsurf PS 10. The alloy was cut on an electro-discharge machine parallel to hole axis in order to quantify the surface roughness. The measurements were performed by calculating the mean of the Ra (average surface roughness) values obtained from three distinct places. Before every experiment, the instrument was calibrated via calibration blocks to guarantee the correctness of the results. Burr heights were measured using the Mahr DigimarCX1 device following the tests.

Tool wear and burr forms were measured with a DinoLite AM4113ZT digital polarized microscope. Circularity, cylindricity and diameter change measurements were made using the Dea Pioneer CMM device.

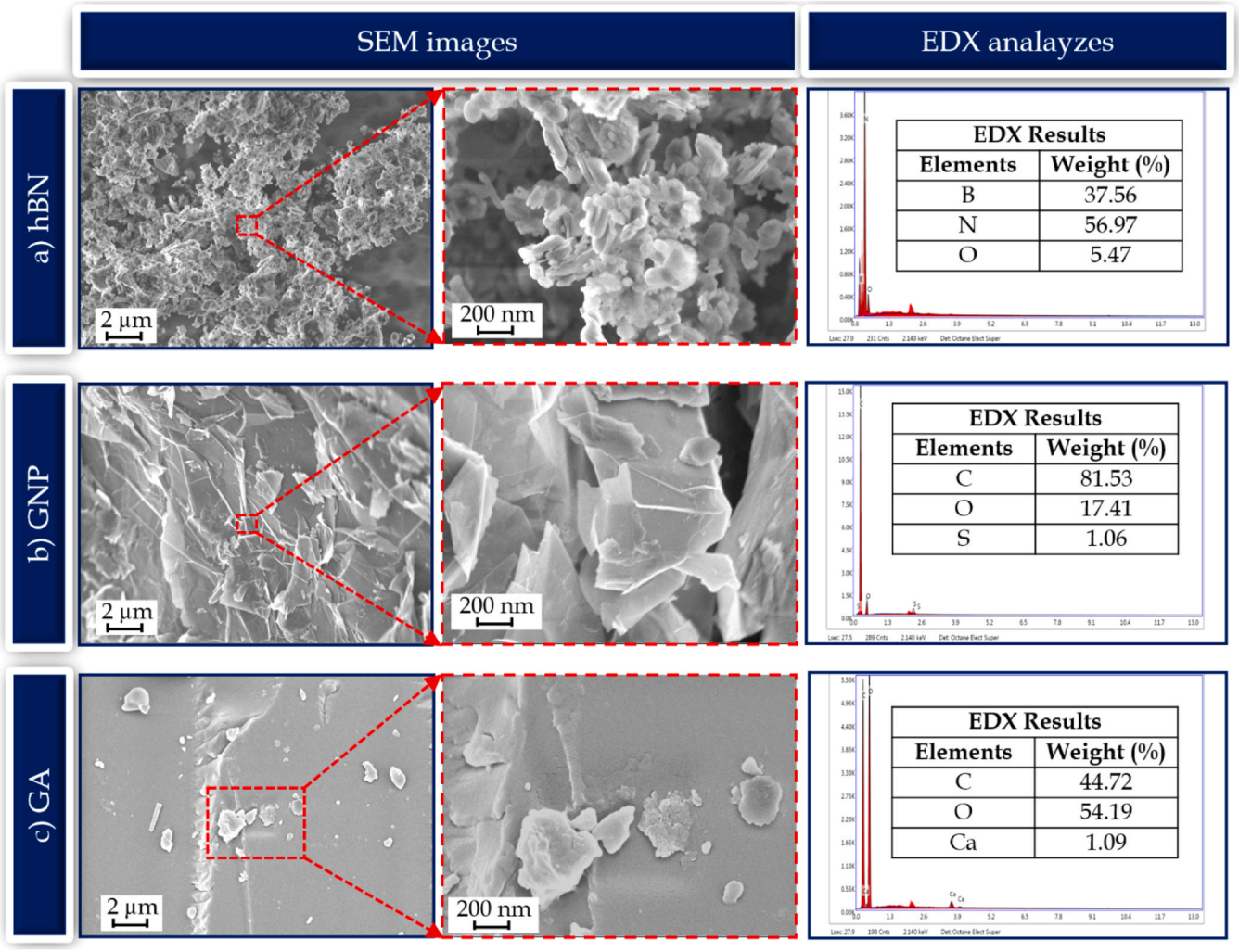


Fig. 1. SEM images of (a) hBN, (b) GNP nanoparticles, and (c) GA surfactant.

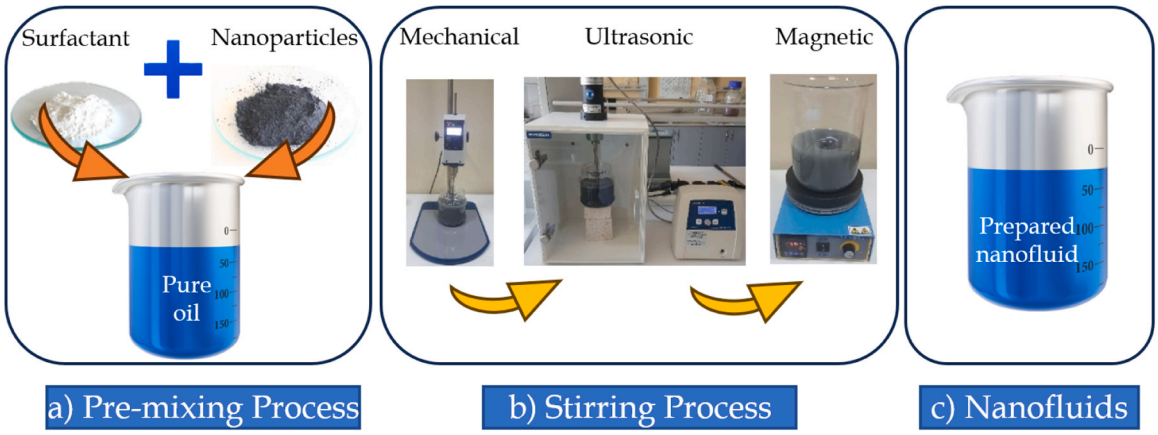


Fig. 2. Preparation process of nanofluids, processes of (a) pre-mixing, (b) stirring, and prepared (c) nanofluids.

Table 5
Experimental parameters.

CNC vertical machine	DELTA SEIKI CNC-1050 A
Workpiece	Hastelloy X (100 × 150 × 13.5 mm)
Cutting tool	Ø5h6 × 26 × 63 mm
Cutting parameters	Cutting speed: 20, 30 m/min; feed rate: 0.04, 0.06 mm/rev; drilling depth: 13.5 mm
Conditions	MQL[1], LN_2[2], LN_2 +MQL[3], LN_2 +hBN/GA[4], LN_2 +GNP/GA[5], and LN_2 +hBN-GNP/GA[6]
Cutting oil	Cuttex SYN 5 (Viscosity 5.16 mm^2/s, density 0.895 g/mL, Flash point 170 °C)
MQL	SKF LubriLean Vario, pressure 8 bar, flow 50 mL/h, nozzle diameter: 2 mm
Nanofluid and surfactant	hBN, GNP, and GA
Cryogenic cooling	LN_2, Taylor Wharton XL45 HP, capacity: 165 L, pressure: 15 bar, nozzle diameter: 3 mm

These measurements were made at different distances from the surface throughout the hole depth and average values were taken. Wear on the drills was measured with FEI Quanta SEM with energy dispersive X-ray spectroscopy (EDX). Details about the experimental procedure are seen in Fig. 3.

3. Results and discussion

3.1. Evaluation of nanofluids characteristics

3.1.1. pH and viscosity of nanofluids

The homogeneity, heat transfer, and lubricating effects of nanofluids can be inferred from properties including pH, viscosity, thermal conductivity, and wettability. Viscosity is particularly crucial in the MQL system so that the oil can be more effectively ground up by the device and produced as an oil mist. It is commonly acknowledged that low viscosity nanofluids offer more efficient lubrication and improved cutting zone penetration [22,44].

Nanofluid pH values demonstrate the stability and uniformity of the mixes. It has been noted that high pH nanofluids are more uniform [45]. Nanoparticles added into the base liquid increase the viscosity and thermal conductivity [44]. In this study, the viscosity and pH results obtained as a result of the measurements made on nanofluids are provided in Fig. 4.

As seen in Fig. 4, the base fluid has a pH of 5.76 and a viscosity of 5.16 MPa.s. The viscosity and pH of the liquids increased with the addition of nanoparticles and surfactants to base liquid. For example, it was determined that the viscosities of hBN/GA, GNP/GA and hBN-GNP/GA nanofluids were 21.89 %, 23.64 % and 26.74 % higher than base fluid, respectively. Similarly, the pH of hBN/GA, GNP/GA and hBN-GNP/GA nanofluids increased by 12.5 %, 16.49 % and 11.97 %, respectively, compared to base fluid. The lower viscosity and pH of hBN-added nanofluid compared to other nanofluids are associated with the properties of hBN nanopowders in spherical structure [46,47]. It is thought that the fact that hBN-GNP/GA hybrid nanofluid has the highest viscosity (6.54 MPa.s) and lowest pH (6.45) value among fluids is due to the effect of hBN and GNP nanoparticles with specific geometrical shapes and surfactant. According to the literature, the pH and viscosity of nanofluids obtained by adding nanoparticles to the base liquid increase [22,45,48]. The viscosity and pH levels of nanofluids are elevated by weak Van der Waals bonds and brown random force. Brown random force ensures that nanoparticles in nanofluids move continuously, which promotes their stability. Brown random force is especially effective on nanoparticles below 100 nm in size [49].

Brownian random motion is inversely proportional to the size of nanomaterials, meaning that smaller particles are affected by more thermal energy and move more [50] Van der Waals forces between nanoparticles in the nanofluid can cause the particles to stick together and form larger aggregates in the liquid [51]. This may lead to an increase in the viscosity of the fluid. In studies in the literature, it has been stated that Van der Waals forces affect the dispersion stability and viscosity of particles in the fluid [52]. Brownian random force and Van der Waals bonds have different effects on nanofluid pH and viscosity, and the nanofluids used in this study were predicted to be affected by these effects.

3.1.2. Thermal conductivity of nanofluids

The ability of cutting fluids to quickly remove heat produced in the cutting zone is strongly correlated with their thermal conductivity. To increase the thermal conductivity of cutting fluids, nanoparticles are used [24]. The thermal conductivity value also increases due to the increase in energy between the nanoparticles and the base liquid as a result of the Brownian movement, which occurs in the suspended particles in the nanofluids [44,53]. Thermal conductivity results of nanofluid mixtures are given in Fig. 5.

The addition of nanoparticles into base liquid results in an increase in the thermal conductivity values of the nanofluids, as seen in Fig. 5. The hybrid hBN-GNP/GA cutting condition produced the maximum thermal conductivity value (0.1904 W/mK), whereas the base fluid produced the lowest thermal conductivity (0.16771 W/mK), as shown in Fig. 5. The addition of surfactant and nanofluid to the base fluid is seen to boost its thermal conductivity value. For instance, in comparison to the base fluid, the thermal conductivity values of the hBN/GA, GNP/GA, and hBN-GNP/GA nanofluids rose by 11.96 %, 10.77 %, and 13.94 %, respectively. Compared to GNP/GA nanofluid (0.1851), hBN/GA nanofluid has a better thermal conductivity value (0.1871). The

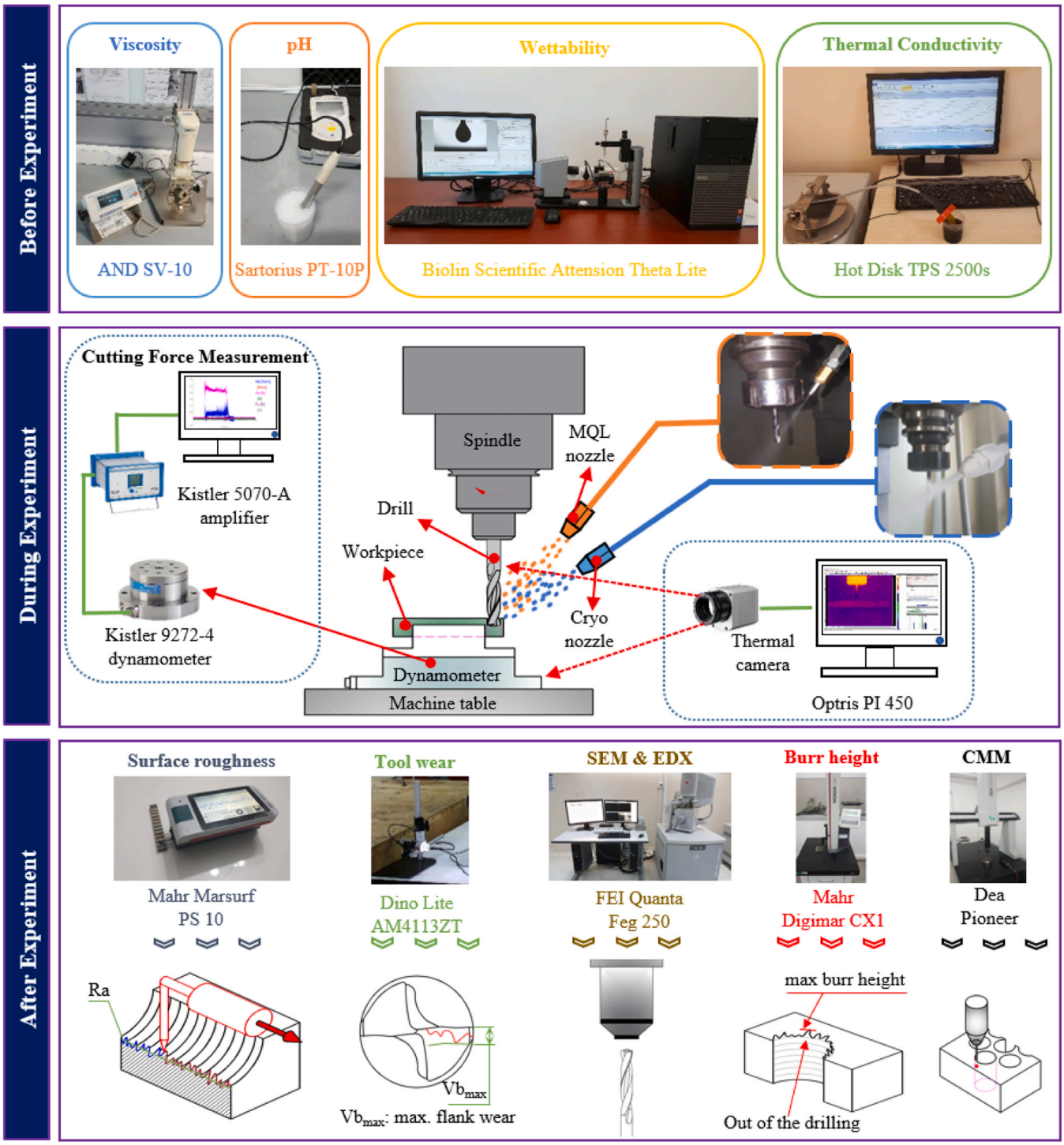


Fig. 3. Experimental setup and measurements.

spherical structure and low Van der Waals force of hBN nanopowders are assumed to be the cause of this condition [54,55].

3.1.3. *Wettability of nanofluids*

The processing performance of liquids is influenced by wettability. The cutting fluid's capacity to coat the surface and establish a layer between workpiece and cutting tool is known as the wettability characteristic [56]. Cutting fluids are supplied to the cutting zone as high-pressure droplets in the MQL process, where they serve as lubricant and cooling agent. The contact angle describes how far apart these drips are on the surface. The size, shape, characteristics, and mixing ratio of the nanoparticle can all have an impact on the contact angle. More lubricant droplets are distributed throughout the surface when the contact angle value is low [57]. Surface tension influences the wettability characteristics of nanofluids by its interaction with contact angle. The drop in surface tension observed in nanofluids indicates a small contact angle between the liquid and the surface. Similarly, it has been highlighted that nanofluids with a poor contact angle disperse across a larger surface area, lowering surface tension and facilitating better lubrication and cooling [40,58]. Fig. 6 shows the surface tension and contact angle for nanofluids.

Fig. 6 illustrates that the base fluid has the lowest contact angle value

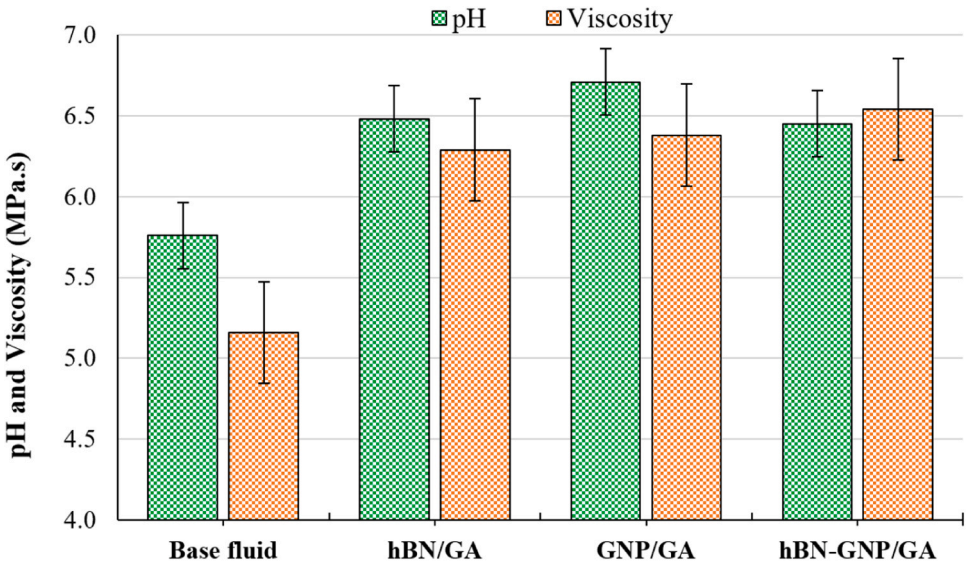


Fig. 4. pH and viscosity results of fluids.

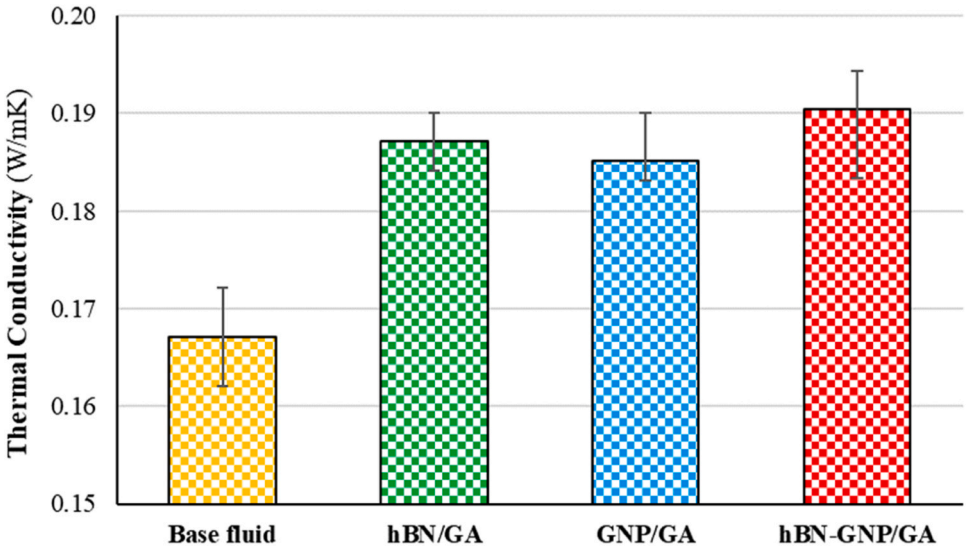


Fig. 5. Thermal conductivity of fluids.

(18.75°), while the hybrid nanofluid hBN-GNP/GA has the highest contact angle (22.26°). The contact angles of the hBN/GA, GNP/GA, and hBN-GNP/GA based fluids are seen to be greater than those of the base fluid by 14.72 %, 19.28 %, and 20.25 %, respectively. The contact angle can vary depending on the properties and mixing ratio of the nanoparticle. According to Sadri et al. [59], adding GA surfactant to nanofluids increased the mixture's stability and raised its thermal conductivity value. Furthermore, the surface tension values rose when surfactants and nanoparticles were added to the base liquid. As shown in Fig. 6, the GNP/GA nanofluid had the highest surface tension value (34.85 mN/mm) while the base liquid had the lowest surface tension value (32.21 mN/mm). The surface tension of the hBN/GA, GNP/GA, and hBN-GNP/GA nanofluids rose by 11.15 %, 11.66 %, and 11.47 %, in comparison to base fluid.

Nano-sized particles with lubricant properties and high thermal conductivity can exhibit different mechanisms in the fluid. For example, tribo film layer formation, mending effect, exfoliation, polishing effect, sliding effect, interlayer sliding effect (especially in hybrid nanofluids), cushioning effect, etc [60]. These effects help the fluid to adhere to micro and nano level surfaces and show tribological lubricant effect thanks to the particles in these effects. In some studies, in the literature, it is stated that the surface contact angle of the fluid decreases with the addition of nanoparticles [61,62]. However, nanofluids delivered at high speed in the cutting process settle at the cutting tool-workpiece-sawdust interfaces and form nanofluid mechanisms [63,64]. This reveals that effective lubrication can be supported not only by wettability but also by boundary lubrication.

3.2. Evaluation of cutting force and torque

Drilling process efficiency is influenced by aspects such as force and torque values. Power consumption and overall manufacturing costs rise with increasing cutting force and torque levels [65].

In present work, the LN_2 +hBN-GNP/GA environment yielded the lowest thrust force (468 N) at 20 m/min and 0.04 mm/rev drilling parameters, as shown in Fig. 7. At 20 m/min and 0.06 mm/rev parameters, the LN_2 condition produced the maximum force of 840 N. In comparison to the LN_2, the force value achieved in the LN_2 +hBN-GNP/GA cutting condition is 44.28 % lower. This condition can be linked to the hBN-GNP/GA cutting condition's greatest thermal conductivity value.

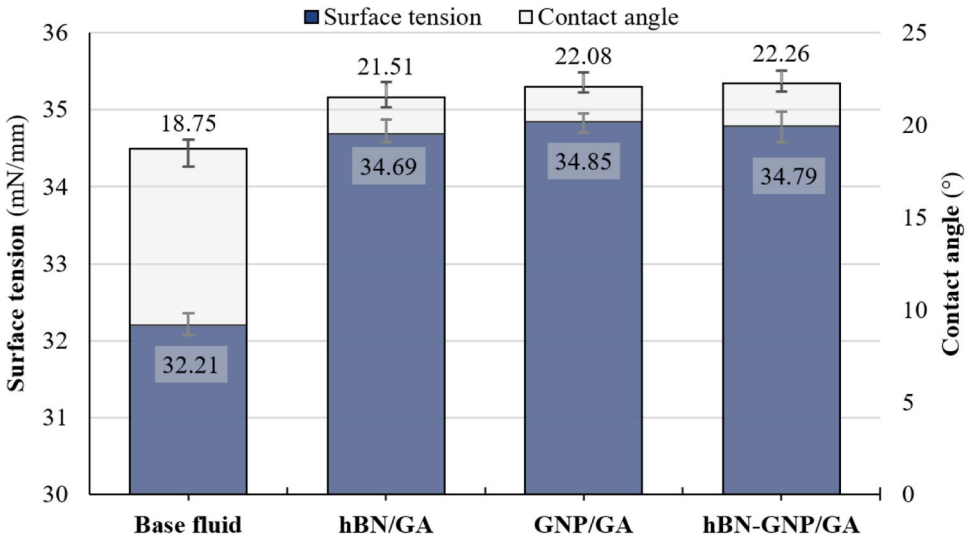


Fig. 6. Graphical expression of nanofluids contact angle and surface tension.

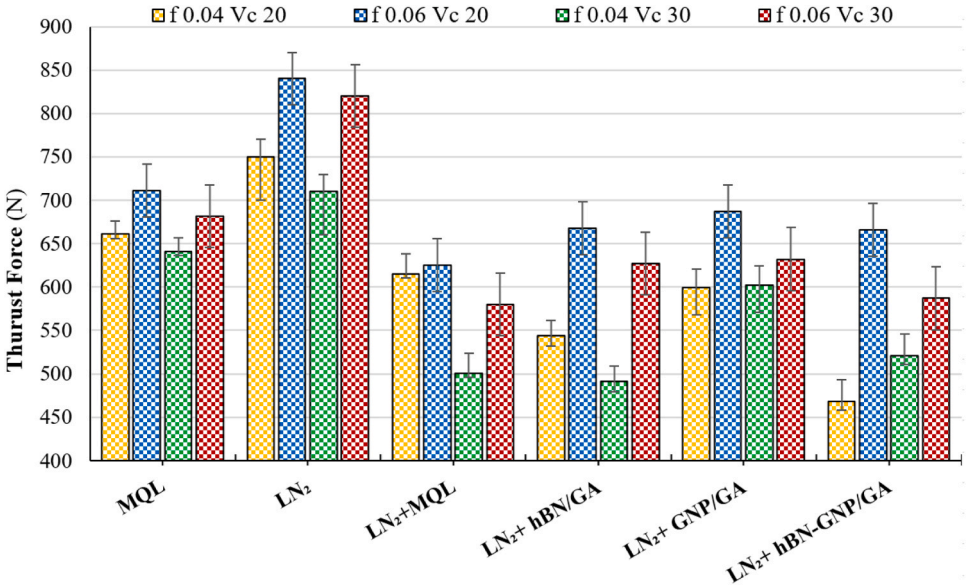


Fig. 7. Thrust force vs cutting environments.

Furthermore, because of the greater cooling of the cryogenic cutting state, nanofluids offer superior lubricity, wettability, and some tribological mechanisms i.e., mending, polishing, rolling, interlayer sliding effect, etc. In this case, a synergistic impact in the hybrid nanofluids made the repairing actions of nanoparticles and the rolling interlayer sliding effects of spherical-structured hBN nanoparticles between GNP nanoparticles with lamellar structure more effective. By forming a thin oil film layer on the tool/chip interface, the lubrication feature of the cutting conditions employed lowers friction, and the cooling feature lowers the temperature in the cutting zone [48,59]. Furthermore, cryogenic cooling applied at low temperatures (−196 °C) causes the workpiece material to become brittle and therefore its strength increases. For this reason, forces tend to increase under cryogenic conditions [66]. Similarly, Ucak and Çiçek [35] found that cryogenic cutting condition increased cutting forces due to effective cooling.

The thrust force rose with an increase in feed, but it reduced as the cutting speed increased. The decrease in the tool-chip contact area and the rise in cutting zone temperature, which lowers the material's yield strength, are the causes of the forces' drop with increasing cutting speed. The feed value has a direct bearing on the size of the axial force produced during drilling [67]. It is feasible to conclude from this investigation that feed has a greater influence on force than cutting speed.

The axial force and torque changes throughout the drilling operation are parallel to one other. Fig. 8 displays torque values as a function of feed and cutting speed variations during drilling under various cutting situations.

The torque and cutting force changes in Fig. 8 are parallel to each other. At 0.04 mm/rev and 30 m/min drilling parameters, the LN_2 +hBN-GNP/GA condition produced the lowest torque result (2.90 Nm). In LN_2 cutting conditions, the maximum torque of 6.30 Nm was recorded at 0.06 mm/rev and 30 m/min parameters. In the LN_2 +hBN-GNP/GA cutting condition, the torque value decreased by 53.96 % compared to LN_2 cutting. This is explained by the fact that, particularly under hybrid (cryogenic+hBN-GNP/GA) cutting conditions, nanofluids reduce friction by generating bearing rolling effect mechanisms between drill bits and material. In addition, the Gum Arabic surfactant additive increased the stability by creating a more homogeneous mixture and had an impact on this situation. These obtained values are parallel to pH (Fig. 4)

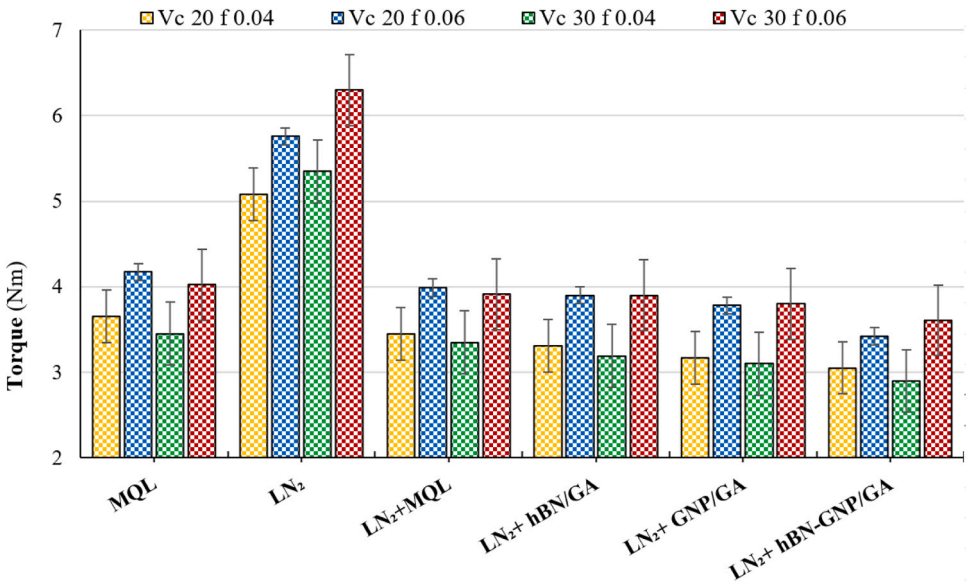


Fig. 8. Torque vs cutting environments.

and thermal conductivity values (Fig. 5). Moreover, it can be attributed to the combined use of cryogenic condition with superior cooling performance.

As with thrust force, torque values decrease as cutting speed increases (Fig. 7). This is because the material's yield strength is lowered by high temperatures in the cutting zone. The increased thickness and area of the chips are assumed to be the cause of the torque values that rise with the feed value.

3.3. Evaluation of cutting temperature

Cutting temperature is one of the parameters that affects tool life and surface roughness in metal machining operations. Cutting temperature can positively affect machining up to a point, as it favors plastic deformation. Cutting temperature becomes even more important, especially in difficult operations such as drilling, which take place in a semi-closed environment. Failure to quickly evacuate the chips formed in a closed area causes the temperature in the cutting area to increase. Due to the increase in temperature, chip sticks to the drill surfaces, increasing friction and adhesion mechanism formation [68]. Cutting temperature values obtained when drilling Hastelloy X super alloy at different feed rates and cutting speeds under different drilling environments are given in Fig. 9.

Accordingly, in LN_2 cutting condition, the lowest temperature value is 250 °C at 0.04 mm/rev and 20 m/min parameters; in MQL, the highest cutting temperature value is 491 °C at 0.06 mm/rev and 30 m/min parameters. When comparing the LN_2 to the MQL, the cutting temperature value dropped by 49.08 %. In comparison to other hybrid cutting conditions, the LN_2 +hBN-GNP/GA cutting condition produced the greatest results. This situation can be associated with the thermal conductivity results (Fig. 5). Fig. 9 shows that in terms of cutting temperature, cryogenic cooling performs better than nanofluid cutting circumstances. Liquid nitrogen forms a lubricating gas shield between cutting tool and chip during cryogenic cooling because it rapidly evaporates after absorbing heat [69]. Furthermore, the MQL method's cooling function is inadequate in comparison to cryogenic cooling because of the extremely

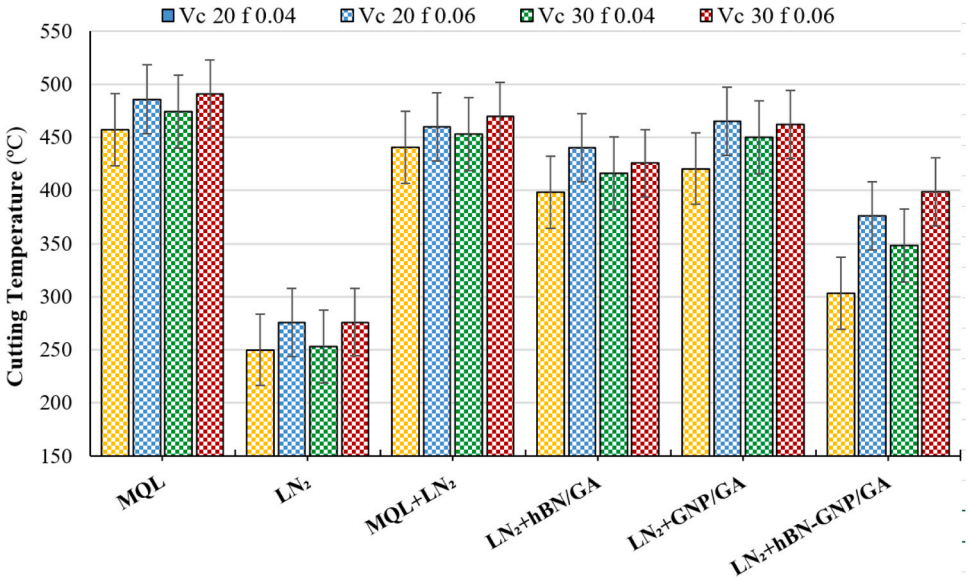


Fig. 9. Cutting temperature vs cutting environments.

little amount of cutting oil utilized in it [20].

3.4. Evaluation of hole quality

3.4.1. Evaluation of surface roughness

Surface quality in drilling is of critical importance in production and engineering processes. However, due to the unique nature of the drilling operation, achieving good surface quality is a challenge. Since drilling operations take place in a closed area, the difficulty of chip evacuation and the jamming of chips in the hole may cause deterioration of surface quality and even breakage of the drill [67]. In this sub-section, surface roughness was measured to analyze the hole quality in drilling Haynes X alloy under different conditions and the results are given in Fig. 10.

Accordingly, the highest surface roughness value was found to be 1.875 μm under the LN_2 cutting condition and 0.06 mm/rev and 20 m/min parameters, while the lowest surface roughness value was 1.052 μm under the LN_2 +hBN-GNP/GA environment at parameters of 0.06 mm/rev and 30 m/min. The Ra value obtained by using the cryogenic cutting condition alone is 78.23 % higher than hybrid environment of LN_2 +hBN-GNP/GA with GA surfactant addition. In drilling operations, all nanofluid cutting conditions showed better performance than MQL and LN_2 modes. The formation of a tribo-film layer and the reduction of friction in the cutting zone are facilitated by tribological processes such as bearing rolling, mending, polishing, and cushioning effect produced by nanoparticles [22,27,48]. Especially in the drilling process, the cushioning effect exhibited by nanoparticles can prevent wear of the drill cutting edges by acting as a protective cushion between the drill and the workpiece. It is thought that the drill produces better surface quality by preserving surface integrity thanks to the cushioning effect under nanofluid cutting conditions. It can be concluded that surface roughness values decrease as a result of the outstanding characteristics of lamellar and spherical nanoparticles combined in hybrid nanofluids.

Since LN_2 +hBN-GNP/GA was coupled with the cooling and lubricating processes, which lower the cutting temperature and friction, it performed well in hybrid cutting conditions. The concurrent action of lubrication and cooling had a favorable impact on surface quality in the hybrid cutting state.

As the cutting speed increased, the surface roughness values decreased due to high temperatures in cutting zone. It is thought that low surface roughness values are obtained due to the decrease in built-up edge (BUE) form, especially at high cutting speed values. Moreover, cutting forces and therefore surface roughness also increases depending on increasing feed value [35].

3.4.2. Evaluation of hole diameter

Usually, a second operation is required to bring precision holes to exact measurement. Since these operations increase machining costs, it is important to ensure measurement accuracy in drilling operations without the need for an additional operation. In this subsection, hole diameter values measured after drilling Hastelloy-X under various environments are presented in Fig. 11.

When Fig. 11 is examined, The MQL mode produced the largest hole diameter (5.039 mm) at 0.06 mm/rev and 30 m/min parameters; the LN_2 +hBN-GNP/GA delivered the lowest hole diameter value (5.011 mm) at 0.04 mm/rev and 20 m/min parameters. It was identified that the diameter deviation value obtained by using LN_2 +hBN-GNP/GA hybrid cutting condition showed a 71.79 % improvement compared to LN_2 mode. This is similar to the thermal conductivity and cutting temperature findings. Once the diameter changes for hybrid cutting conditions are listed from largest to smallest, they are LN_2 +MQL, LN_2 +GNP/GA, LN_2 +hBN/GA and LN_2 +hBN-GNP/GA. Low hole diameter values under hybrid cutting environments are assumed to be caused by the simultaneous application of the cryogenic environment's efficient cooling feature and the superior lubricating qualities of nanoparticles with various forms and attributes.

The diameter changes grow with increasing cutting speed. The phenomenon was linked to the hole size degradation because of rising vibration that varied with cutting speed. Likewise, the reason for the increase in hole diameters as feed rate increases is associated with the cutting force and axial loads on the tool [67,70]. The cutting force (Fig. 7) and torque values (Fig. 8) results obtained in this study support this hypothesis.

3.4.3. Evaluation of circularity

The difference between the biggest and smallest radius measured from a particular center point is used to illustrate deviation from circularity. The ISO 6318 standard states that the "Least Square Circle (LSC)" technique can be used on the CMM instrument to measure deviation from circularity [71]. Circularity deviation values measured after drilling are given in Fig. 12.

When Fig. 12 is examined, the results of deviation from circularity show a similar trend to the hole diameter graph in Fig. 11. In Fig. 12, the

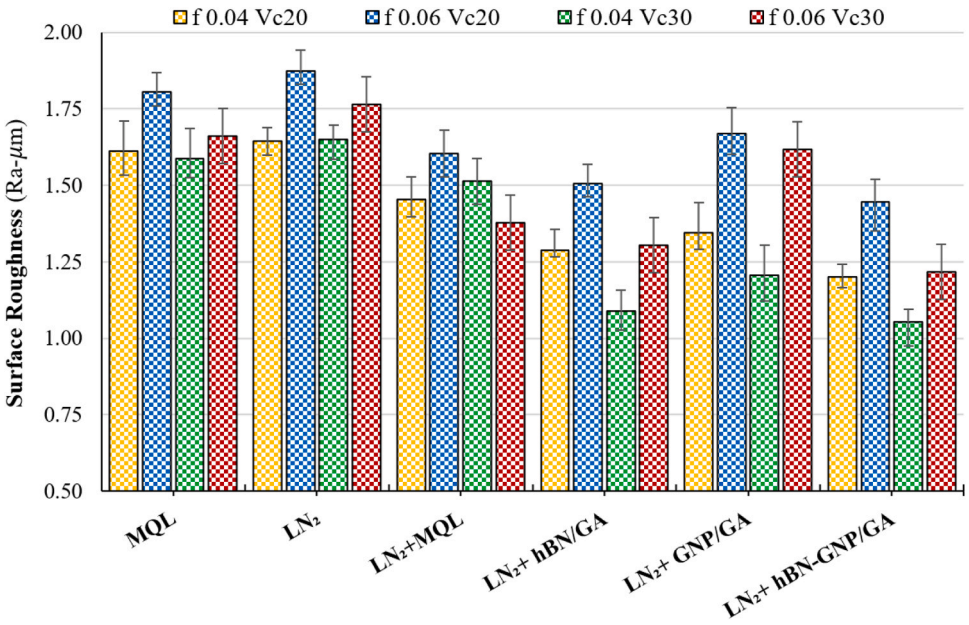


Fig. 10. Surface roughness vs cutting environments.

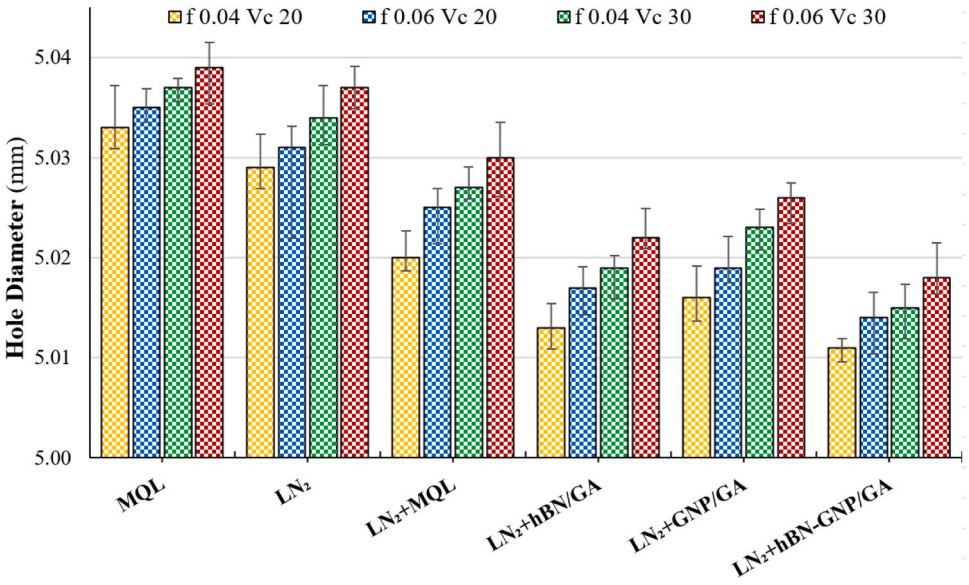


Fig. 11. Hole diameter vs different environments.

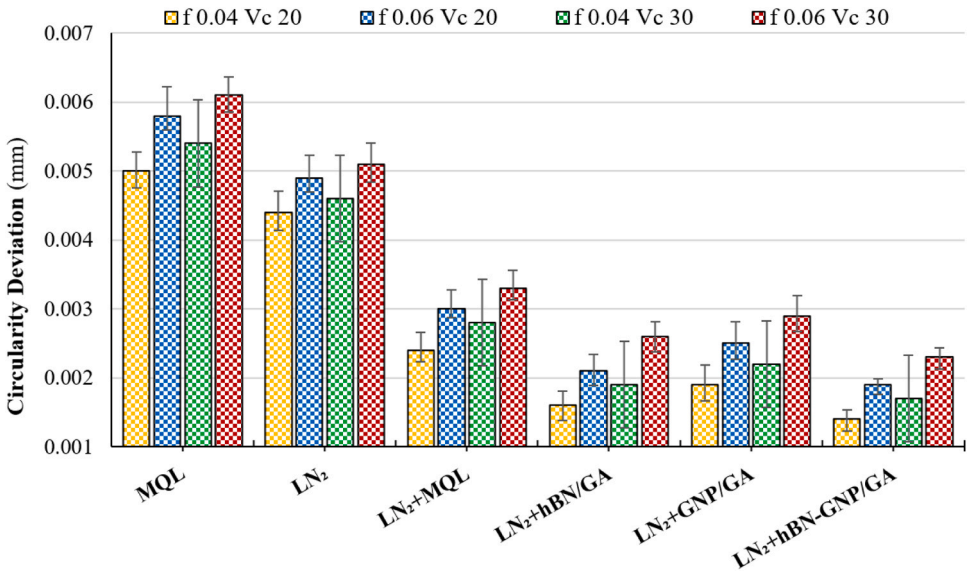


Fig. 12. Deviation from circularity vs different environments.

highest circularity deviation value (0.0061 mm) was found under MQL cutting condition at 0.06 mm/rev and 30 m/min, while the best deviation from circularity value (0.0014 mm) was reached under LN_2 +hBN-GNP/GA at 0.04 mm/rev and 20 m/min. In terms of the performances of the cutting conditions, the deviation from circularity values, when listed from largest to smallest, are MQL, LN_2, LN_2 +MQL, LN_2 +hBN/GA, LN_2 +GBN/GA and LN_2 +hBN-GNP/GA. High hole diameter and circularity deviation values were detected due to thermal distortions at high temperature values. Deviation from circularity values, which increased more at high temperature values, decreased on the contrary under hybrid cutting conditions.

As for the cutting parameters, it has been determined that the most effective factor on the deviation from circularity values is the feed compared to the cutting speed. It is thought that these deviations are caused by the increase in runout in the drill due to the increase in feed. This result coincides with the result found by Şirin et al. [57].

3.4.4. *Evaluation of cylindricity*

Cylindricity refers to the distance between hole surface points and a common axis. [72]. Fig. 13 shows the values of deviation from cylindricity against different cutting conditions.

When Fig. 13 is examined, the cutting condition with the highest deviation from cylindricity is MQL, while the condition with the lowest is the LN_2 +hBN-GNP/GA hybrid cutting environment. With the effect of effective lubrication and cooling in the LN_2 +hBN-GNP/GA cutting condition, a 70.37 % improvement in deviation from cylindricity values was observed compared to the MQL cutting condition. It is thought that the axial forces occurring during the drilling process affect the deviation values from cylindricity. This situation was encouraged by the high cutting force (Fig. 7) and torque (Fig. 8) occurring during drilling. It is believed that elevated temperatures brought on by high cutting speeds have a detrimental effect on the workpiece's and the cutting tool's mechanical stability and raise the values of cylindricity deviation. Increasing axial forces with increasing feed rate also negatively affected the deviation from cylindricity [73].

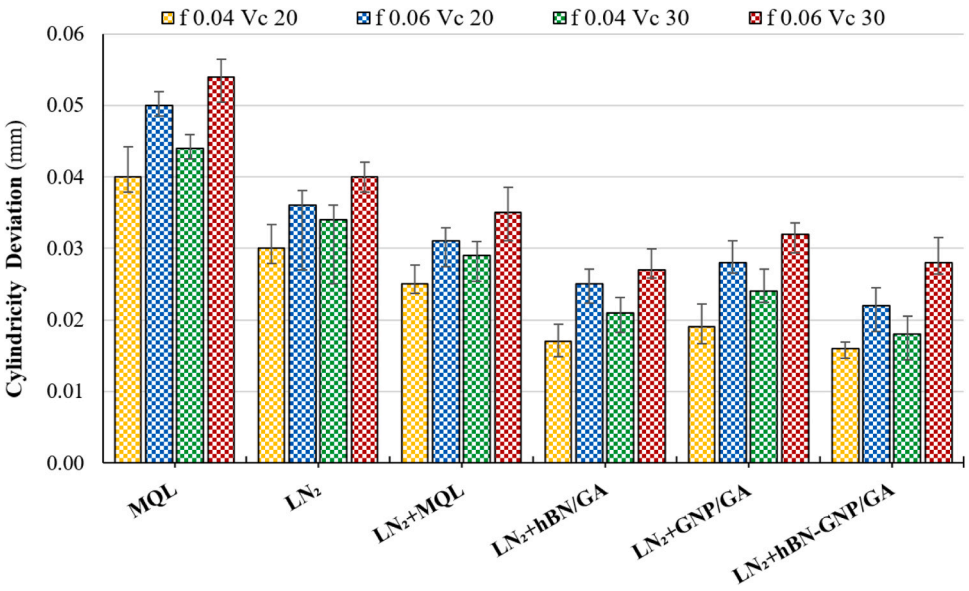


Fig. 13. Deviation from cylindricity vs different environments.

3.5. Evaluation of burr height

Burr at the entry and exit of the hole during drilling operations is a condition that needs to be taken into account since it has an adverse effect on the dimensional accuracy and hole surface quality [74,75]. Fig. 14 shows the changes in burr height values depending on cutting conditions and drilling parameters.

Accordingly, the highest burr height was 0.370 mm under MQL cutting condition with machining parameters of 30 m/min and 0.06 mm/rev. The reason for this situation seems to be that the temperature values occurring in the drilling process are high in the MQL. The poorest burr height as 0.192 mm occurred in the LN_2 +hBN-GNP/GA cutting condition at 30 m/min and 0.04 mm/rev drilling parameters. In the LN_2 +hBN-GNP/GA hybrid cutting condition, the burr height occurring at 30 m/min and 0.04 mm/rev parameters decreased by 28.88 % compared to MQL. The reason for this situation is that, as explained in the previous sections, both lubrication and cooling performance of hybrid environment are better than others.

3.6. Evaluation of tool life and tool wear

Since tool life is a critical indicator that affects machining performance, workpiece surface properties and operating costs, it is important to examine it. Especially since the drilling process takes place in a semi-closed environment, it is challenged to remove the cutting heat and chips from the cutting area, which causes rapid wear and even breakage of the drill bits. Fig. 15 shows the maximum tool wear values obtained after sixty holes drilled under different environments at 20 m/min and 0.06 mm/rev parameters. When Fig. 15 is examined, after ten holes drilled under dry conditions, the cutting tool flank wear reached 0.281 mm and the tool life was completed. It is thought that the absence of any means of cooling/lubrication in dry conditions promotes excessive elevation of temperature and friction and jamming of chips, which in turn accelerates tool wear [57]. In the MQL condition, with the effect of lubrication, the amount of wear decreased by 8.18 % compared to the dry condition. According to Fig. 15, the lowest tool wear was found in the LN_2 +hBN-GNP/GA condition. This was followed by LN_2 +hBN/GA,

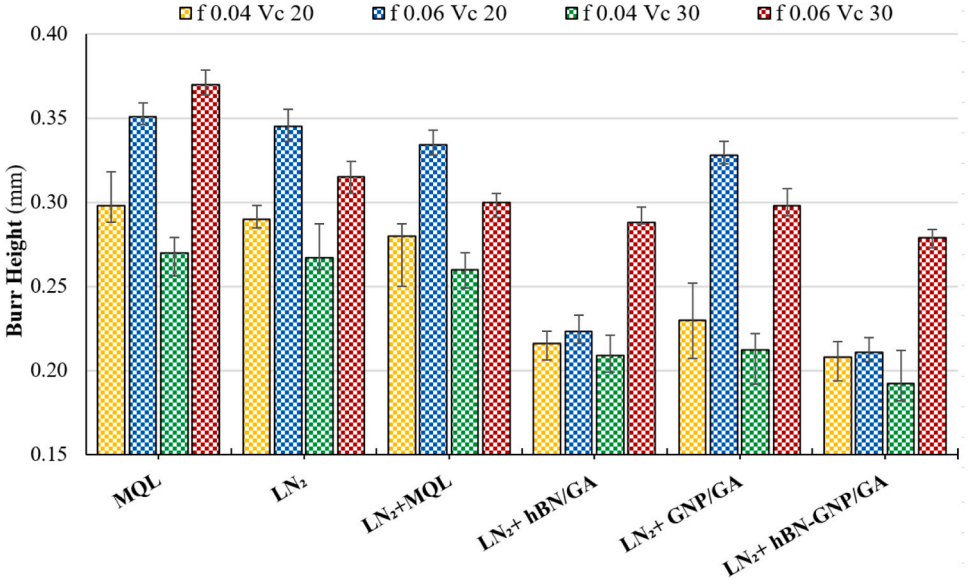


Fig. 14. Burr height values under different cutting conditions.

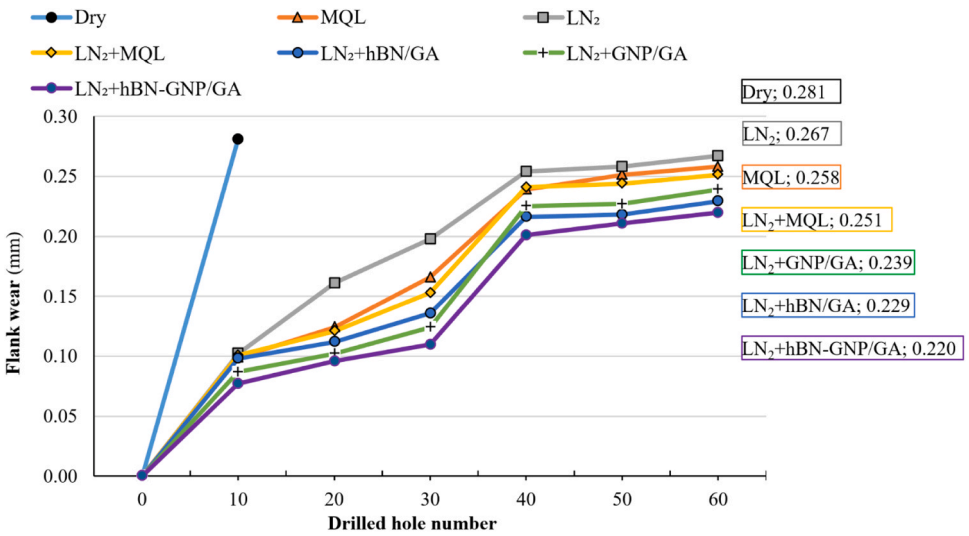


Fig. 15. Flank wear values at 20 m/min-0.06 mm/rev parameters under different conditions.

LN_2 +GNP/GA, LN_2 + MQL, MQL and LN_2 condition, respectively. While the wear value was reached to 0.281 mm after ten holes drilled in dry condition, the amount of flank wear was 0.220 mm in LN_2 +hBN-GNP/GA, although the number of holes drilled increased to sixty. This decrease can be attributed to the fact that hBN nanoparticles with spherical structure penetrate between the GNP nanoparticles with

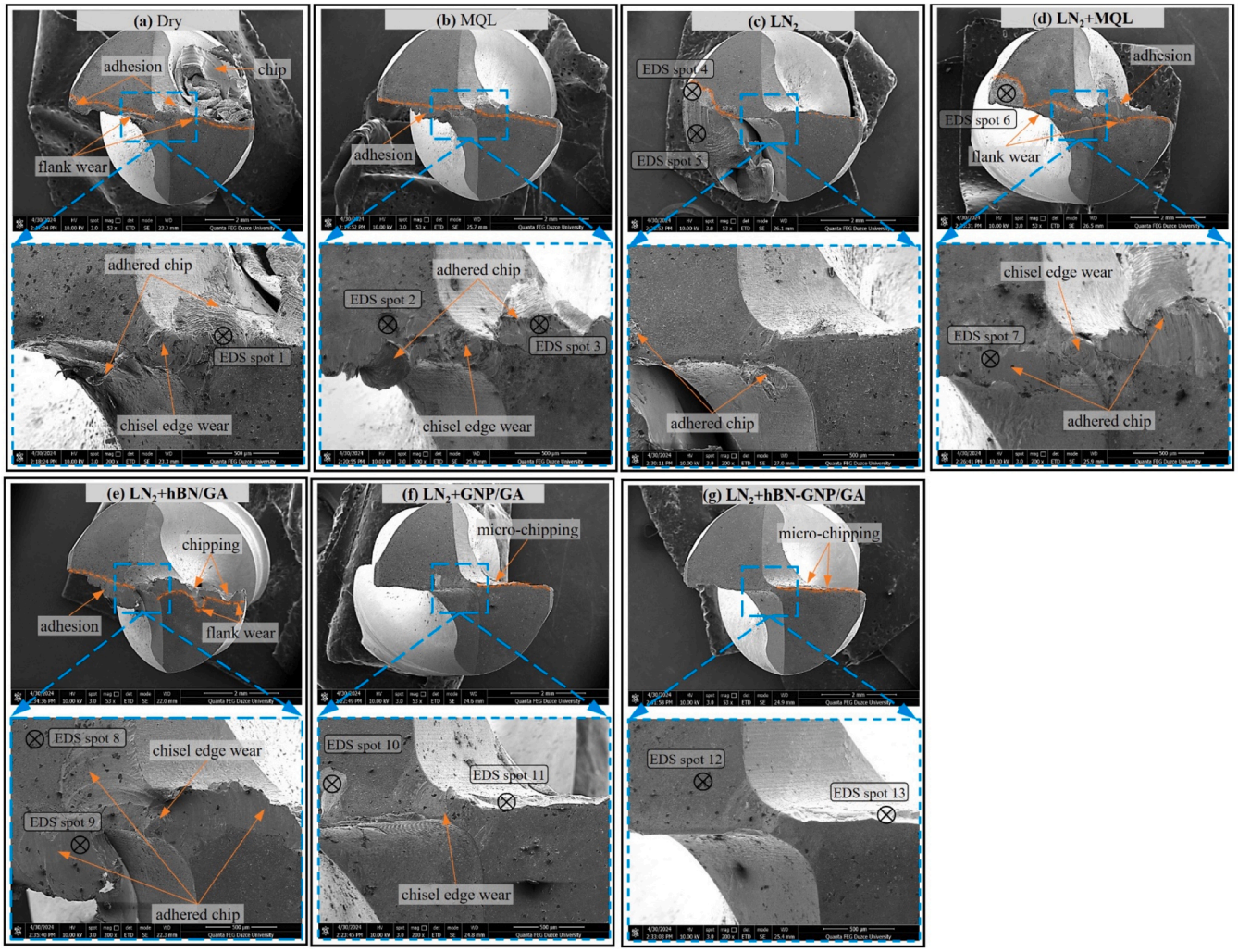


Fig. 16. SEM images of worn drill bits under (a) dry, (b) MQL, (c) LN_2, (d) LN_2 +MQL, (e) LN_2 +hBN/GA, (f) LN_2 +GNP/GA, and (g) LN_2 +hBN-GNP/GA *(Drilling details: Fig. 16a: Image after 10 drilling operations; Figures b-g: Image after 60 drilling operations, 20 m/min cutting speed and 0.06 mm/rev feed rate)*.

layered structure, creating an interlayer sliding effect. Thanks to the properties contained in nanoparticles, nanofluids create repairing, rolling, polishing, interlayer sliding and cushioning mechanisms [57]. It is thought that GA surfactant added to nanofluids relatively strengthens the efficiency of nanofluids by creating a homogeneous mixture. In the cryogenic condition, the highest wear as 0.267 mm was obtained after the dry condition. The increase in the strength of the alloy under cryogenic cooling is thought to be the main reason explaining this situation [66]. In hybrid (cryogenic+nanofluid) conditions, where lubrication and cooling effects are performed simultaneously, lower tool wear values were obtained compared to other environments. It can be stated that while cooling is provided with the LN_2 condition, effective lubrication with the nanofluid condition delays the flank wear mechanisms in the cutting tool and thus the tool wears less. The effective lubrication of the hBN-GNP/GA) can be clarified by the viscosity, pH, thermal conductivity and wettability properties.

SEM images taken after drilling 60 holes of TiAlN coated cutting tools at 20 m/min and 0.06 mm/rev parameters are presented in Fig. 16 and EDX analyzes taken from Fig. 16 EDS points are provided in Table 6. According to Fig. 16, it can be seen that the dominant wear mechanisms was flank wear, chisel edge wear, adhesion, built-up-edge (BUE), chipping. It has been clearly determined that the worn area is larger in dry mode. Since there is no lubrication or cooling agent present while dry drilling, chips stick to the drill bit surface, lowering both the tool life and surface quality. This perspective is supported by the alloy elements found on the cutting tool in the EDX analyses. When the EDS points are examined, the high density of workpiece elements on the cutting tool proves that adhesion wear is more dominant in the LN_2 condition (Fig. 16-c).

The adhering-welding ability of the workpiece rises when the temperature in the cutting zone reaches high levels during machining since this promotes the chemical affinity between alloy and cutting tool [36]. Chipping and micro-chipping wear were observed on the cutting tool used under hybrid LN_2 + nanofluid environments. Generally, the adhesion wear mechanism is assumed to be the source of chipping on the cutting edge of the tool [76]. Depending on the cooling condition, the cutting tool needs more cutting force to remove chip at temperatures below the plastic deformation temperature. The resulting chips cannot move away from the cutting region and stick to the cutting tool. Especially during the removal of these adhering chips, particles breaking off from the tool cause chipping wear. This challenge can often be encountered in the processing of Ni-based materials [77–79]. The wear seen in the LN_2 + hBN-GNP/GA cooling condition is micro-chipping wear. Additionally, compared to other circumstances, the tool wear area and quantity were reduced in the LN_2 + hBN-GNP/GA cooling condition (Fig. 16-g).

4. Conclusion

In this study, the performance of different ecological cooling and lubrication methods (MQL, LN_2, LN_2 +MQL, LN_2 +hBN/GA, LN_2 +GNP/GA, LN_2 +hBN-GNP/GA) while drilling Hastelloy X superalloy was experimentally investigated. The important findings of the study can be summarized as follows:

- Hybrid cooling/lubrication strategies, particularly combinations of LN_2 and MQL, have provided distinct advantages over methods used alone in drilling operations. The cooling capacity of LN_2 and the lubricating effect of MQL significantly reduced surface roughness, force, torque and tool wear, thus extending tool life.
- The use of LN_2 effectively kept cutting temperatures under control even at elevated cutting speeds and feed rates during machining.
- The use of nanofluids containing hBN and GNP, when combined with MQL method, increased the lubrication performance in drilling operations and further reduced cutting forces and torque. These nanofluids improved the surface quality and hole quality and minimized tool wear, thanks to their low friction coefficient and high thermal conductivity.
- While the cutting tool life was completed after ten holes drilled under dry environment, up to sixty holes were reached thanks to hybrid cooling/lubrication methods.
- In experiments conducted under 20, 30 m/min and 0.04, 0.06 mm/rev parameters, it was observed that LN_2 and nanofluid combinations provided optimum performance even at elevated cutting speeds. Especially at low feed and cutting speed, hybrid cooling/lubrication methods have a positive effect on the dimensional accuracy, circularity, cylindricity and burr height of the hole, enabling more homogeneous and high-quality holes to be obtained.
- SEM and EDX analyzes performed on the cutting tool proved that the dominant wear mechanism is adhesion. Adhesion wear promoted chipping formation on the drill cutting edge.
- The environmental impact of hybrid methods is significantly lower than traditional petroleum-based cutting fluids. Additionally, the use of these methods reduces operating costs and increases the safety of the working environment by reducing the amount of waste cutting fluid.

In conclusion, this study demonstrated the effectiveness of ecological cooling/lubrication methods in drilling Hastelloy X superalloy and showed that hybrid strategies offer a strong alternative for sustainable machining. Hybrid methods obtained by combining LN_2 and MQL optimized drilling performance at appropriate cutting speeds and feed rates. Nanofluids enriched with nano-sized hBN and GNP particles played an important role in increasing drilling efficiency by increasing surface lubrication performance. Furthermore, these findings also

Table 6
EDX quants results from EDS spots from Fig. 16.

EDS Spot	Element weights%											
	Ni	Fe	Cr	Co	Si	W	Mo	C	Ti	Al	N	O
1	27.5	11.7	15.1	0.6	0.8	-	7.5	14.5	0.8	2.1	-	14.5
2	3.3	1.4	2.2	-	0.5	41.8	-	32.5	-	-	-	13.1
3	42.8	16.6	20	1.2	0.7	-	8.6	7.8	-	-	-	2.6
4	-	-	0.9	8	-	64.8	-	-	-	-	-	26.3
5	35.1	14.1	19.9	0.4	0.5	-	6.3	8.5	-	-	-	15.3
6	-	-	1.8	4.5	-	61.7	-	12.4	-	-	-	19.6
7	38.4	15.7	18.7	1.1	0.7	-	8.5	9.2	0.5	1.2	-	6.1
8	-	-	3.2	-	-	-	-	29.1	23.2	17.5	23	4
9	42.9	16.2	20.1	0.7	-	-	6.7	9.8	-	-	-	2.9
10	-	-	-	7	-	72	-	16.8	-	-	-	4.3
11	-	-	0.6	3.6	-	67.4	-	20.9	-	-	-	7.5
12	-	-	3.2	-	-	-	-	6.8	30	24.8	35.2	-
13	2.7	1.3	1.8	3.7	-	54.2	-	27	-	2	-	7.4

highlight the importance of promoting industrial applications of ecological cooling and lubrication techniques to achieve sustainable production goals.

Statement of originality

As the corresponding author, I hereby confirm on behalf of all authors that:

The paper has not been published previously, that it is not under consideration for publication elsewhere, and that if accepted it will not be published elsewhere in the same form, in English or in any other language, without the written consent of the publisher.

The paper does not contain material which has been published previously, by the current authors or by others, of which the source is not explicitly cited in the paper.

CRediT authorship contribution statement

Şenol Şirin: Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Turgay Kıvak:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Çağrı Vakkas Yıldırım:** Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition. **Emine Şirin:** Writing – original draft, Resources, Methodology, Investigation, Formal analysis. **Murat Sarikaya:** Writing – review & editing, Visualization, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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