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Evaluation of Surface Roughness, Tool Wear and Chip Morphology during Machining of Nickel-Based Alloy under Sustainable Hybrid Nanofluid-MQL Strategy

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Abstract: Nickel-based super alloys exhibit high strength, oxidation and corrosion resistance; however, the machining of these alloys is a challenge that can be overcome with effective cooling/lubrication techniques. The use of a minimum quantity lubrication (MQL) technique is limited to lower cutting parameters due to the tremendous heat produced during the machining of Inconel 718. Sustainable and eco-friendly machining of Inconel 718 can be attained using MQL and lubricants based on nanofluids because of their improved heat transfer capabilities. For that purpose, the performance of hybrid nanofluid-MQL is examined. In this novel study, graphene and hexagonal boron nitride (hBN) nanoparticles are reinforced with palm oil and delivered to the machining interface using an MQL setup. The machining experiments are performed under the conditions of dry, wet, MQL and MQL with graphene/hBN deposited in palm oil. The machining performance under selected cutting conditions is assessed by analyzing the surface roughness, tool wear, chip morphology and surface quality of the machined workpiece. A comparison of results showcased the effectiveness of hybrid nanofluid-MQL with improvement in surface finish, reduction in tool wear and favorable chip forms concerning all other machining conditions.

Keywords: sustainable machining; hybrid nanofluid; MQL; hexagonal boron nitride; graphene; surface roughness; tool wear

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Citation: Makhesana, M.A.; Patel, K.M.; Bagga, P.J. Evaluation of Surface Roughness, Tool Wear and Chip Morphology during Machining of Nickel-Based Alloy under Sustainable Hybrid Nanofluid-MQL Strategy. *Lubricants* **2022**, *10*, 315. https://doi.org/10.3390/lubricants10110315

Received: 30 October 2022
Accepted: 16 November 2022
Published: 18 November 2022

1. Introduction

Nickel-based alloys are widely used in various high-performance applications due to their excellent properties at higher temperatures. Inconel 718 is one of the important materials from nickel-based alloys widely used in aerospace, nuclear, gas turbines and many other important applications [1]. Properties like excellent strength, corrosion and oxidation resistance make it the most famous candidate material, among others. However, besides its many advantages, the machining of nickel-based alloys presents many challenges due to low thermal conductivity and work hardening behavior, making it a difficult-to-cut material. Also, during machining, this material tends to adhere to the tool material, resulting in rapid tool wear and shorter tool life [2].

Conventional cutting fluids are widely utilized during machining with the objectives to provide cooling, lubrication and the removal of chips from the machining area. Hence, the role of cutting fluid becomes very crucial during the machining of nickel-based alloys [3]. However, the use of these cutting fluids possesses problems related to environmental pollution, effects on workers' health and an increase in total production costs due to the need of recycling and disposal costs. Considering this, metal-cutting industries and researchers are exploring alternatives to avoid the use of conventional cutting fluid. The use of minimum quantity lubrication (MQL) is one such response, as the small quantity of cutting fluid facilitates efficient heat removal and cooling compared to wet machining [4]. In contrast, few studies have discussed the inability of MQL application in providing efficient lubrication, especially during the machining of high-strength alloys [5].

In recent times, research has been focused on improving the performance of MQL with the use of nanofluid. Nanofluids are obtained by adding nanoparticles such as Al_2O_3, MoS_2, hBN, CNT, graphene, etc. into the base fluid, with the objective to increase the thermal conductivity and tribological characteristics of the lubricant mixture [6,7]. Besides improving tribological conditions, the nanofluids enable the formation of a thin film of lubricant between the machining interfaces, thus reducing friction. Yıldırım et al. [8] performed experimental investigations during the machining of Inconel 625 with nano-MQL by adding hBN nanoparticles compared to pure-MQL and dry machining. The results demonstrated the ability of hBN-nanofluid to improve the surface quality and tool life by retaining lubricant into the machining interface for a longer time and thus providing improved lubrication. Sirin et al. [9] investigated the role of mono/hybrid nanofluid with graphene and hBN nanoparticles and different surfactants during the drilling of Hastelloy X. Improved results in regard to cutting force, hole quality and cutting temperature were reported with the hybrid nanofluid application without surfactants. Danish et al. [10] examined the effect of graphene-reinforced sunflower oil applied under MQL during the machining of Inconel 718. Their findings showcased the effectiveness of nanofluid-MQL compared to dry and flood cooling approaches due to the ability of nanoparticles to create tribo-film between the machining interfaces and reduce friction, which led to improved surface quality and machining performance. Venkatesan et al. [11] conducted the machining of Hastelloy-X under dry and nanofluid-MQL conditions. The hBN nanoparticles with 0.25 wt.% and 0.50 wt.% were blended in coconut oil. Outcomes revealed the effectiveness of hBN-nanofluid with PVD-coated tools in the form of the reduction of the cutting force, surface roughness and coefficient of friction compared to dry machining. In a recent study, Babu et al. [12] performed the machining of Hastelloy C 276 under dry, MQL and nanofluid-MQL environments with varying cutting speeds and feeds. An average reduction of 66% in surface roughness was reported under nanofluid-MQL compared to dry machining. It was concluded that the application of nanofluids improves the machining performance through excellent dispersion, high thermal conductivity and heat transfer, surface wettability and tribological properties. Sarkar and Dutta [13] investigated the machining performance of Inconel 718 using coconut oil as base fluid and multi-walled carbon nanotubes under MQL. As reported, flank wear was significantly reduced under MQL and NMQL (nanofluid-minimum quantity lubrication) applications. Additionally, adhesion, abrasion and chip sticking were reported as tool wear mechanisms with MQL and NMQL applications.

Considering the foregoing literature, works have been reported to explore the influence of different cooling/lubricant strategies during the machining of Inconel 718 alloys. However, most of the studies have utilized single nanoparticles for nanofluid preparation, and the employment of hybrid nanofluid-MQL is limited. Considering these matters, the performance assessment of hybrid (graphene and hBN added with palm oil) nanofluid-MQL assisted machining is adopted with the aim to develop sustainable machining. Therefore, this work evaluates the efficacy of hybrid nanofluids by analyzing surface roughness, tool wear and chip morphology. As a result, the significance of this work can be justified as an effort to address the suitability to use the hybrid nanofluid-MQL and to emphasize the concept of sustainability in machining.

2. Materials and Methods

2.1. Preparation of Hybrid Nano-Green Lubricant

Graphene and hexagonal boron nitride (hBN) nanoparticles are used as an additive in pure palm oil to prepare the hybrid nanofluid mixture. Commercially available graphene with particle sizes ranging from 70 to 90 nm with a purity of 99.90% and hBN with particle sizes ranging from 70 to 90 nm with a purity of 99.85% are utilized. A two-step mixing procedure, as adopted by Danish et al. [9], is followed to prepare the nanofluids with graphene and hBN nanoparticles in palm oil. The hybrid nanofluid is prepared by adding 0.5 vol% + 0.5 vol% of graphene and hBN nanoparticles to the base fluid. The selected concentration of nanoparticles is considered based on the previous studies available in the literature [8,14]. In the initial procedure, the nanofluid is prepared by gradually adding nanoparticles in base fluid in a mechanical mixer. The prepared nanofluid mixture of graphene + hBN and palm oil is ultrasonicated (40 KHz, 100 w) for 45 min to attain the uniform dispersion of graphene nanoparticles in palm oil. The prepared lubricant mixture is stirred for 45 min at 800 rpm with a magnetic stirrer to ensure dispersion. For each experiment, fresh nanofluids are utilized to avoid sedimentation of nanoparticles in base fluid and for accurate results.

2.2. Machining Experiments

During machining experiments, Inconel 718 with a diameter of 50 mm and a length of 300 mm is selected as the workpiece material. The elemental composition of Inconel 718 is Ni 50–55%, Cr 17–21%, Ti 0.65–1.15%, Al 0.2–0.8%, Mo 2.8–3.3%, C 0.08%, Si 0.35% and S 0.015%. The material has superior thermo-mechanical properties, making it suitable for critical applications in various industries such as nuclear, aerospace, etc. A PVD-TiAlN/TiN coated carbide insert with a coating thickness of 2 μm and ISO designation CNMG 120408 manufactured by Widia is used, with specifications of rake angle: -6°, clearance angle: 0° and nose radius: 0.8 mm. A tool holder having ISO designation PCLNR2020K12 is utilized to hold the cutting tool rigidly on the machine. The machining experiments are performed on a lathe machine (make: HMT). The cutting speed of 90 m/min, feed of 0.2 mm/rev and depth of cut of 0.5 mm are selected as the machining parameters, considering the manufacturer's catalog, literature information and trial experiments. The turning experiments are performed under dry, wet, MQL and hybrid nano-green MQL environments. The MQL setup mounted on the machine is utilized to supply the lubricant mixture to the machining interfaces under MQL and nano-green MQL application. The MQL parameters, such as lubricant flow rate, air pressure and nozzle position, are kept constant in all the experiments. Based on preliminary experiments and literature review, 3 bar air pressure, 150 mL/h flow rate, nozzle angle of 30° and 20 mm distance from the machining zone are considered [8,14].

2.3. Measuring Equipment and Procedure

The machining response is analyzed by evaluating surface roughness, tool wear and chip morphology. Surface roughness is one of the important indicators during machining, as it governs tribological performance. The surface roughness (Ra) is determined as per ISO4287 [15] using Mitutoyo SurfTest (resolution of 0.01 μm). The sampling and evaluation lengths are considered 0.8 mm and 4 mm, respectively. Measurements are taken at three different locations of the machined workpiece by rotating it along the axis, and an average value is considered for comparison. During machining, different types of tool wear can be seen. However, flank wear is mostly considered and analyzed, as it can be easily measured by the Tool maker's microscope. Therefore, in this work, the maximum flank wear VBmax is considered, and the progression of tool wear is measured as per ISO 3685 standard [16] by utilizing a Tool maker's microscope (30× to 150× and 5 μm resolution) equipped with an image analysis software. A scanning electron microscope (Make: Jeol, 6610 LV) is used to analyze the tool wear mechanism. The chips produced are collected at the end of each experiment, and the chip morphology is analyzed by capturing the images of the chips. The methodology adopted for the work is presented in Figure 1.

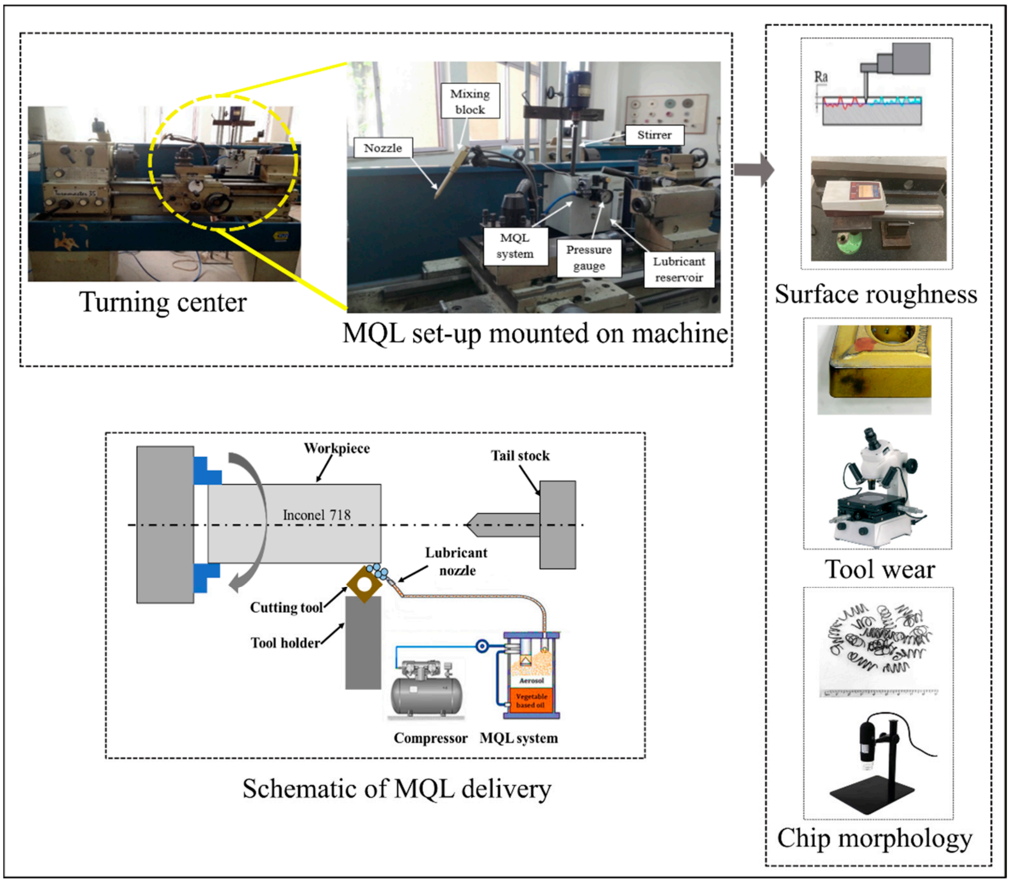

Figure 1. Experimental methodology adopted.

3. Results and Discussion

3.1. Surface Roughness

The quality of the machined part is assessed through the surface finish produced on the machined workpiece. A higher surface finish is always desired, and it reduces the rejection of the machined parts. For this purpose, the average surface roughness (Ra) produced during different machining environments has been comprehended. In the current investigation, the highest surface roughness is observed under dry machining, followed by MQL, wet and nano-green MQL conditions, respectively, and presented in Figure 2. As expected, the higher surface roughness in dry machining is produced due to the thermal distortion of the workpiece material in the absence of cooling/lubrication and rapid tool wear due to the excessive temperatures being produced [7]. Though the cooling ability of the supplied lubricant mixture during wet machining is good, the lack of lubricating effects makes chip removal difficult and adversely affects the surface finish. The improved performance of MQL, as compared to dry and wet machining, is attributed to the penetration of cutting fluid into machining interfaces, which reduced the temperature and friction in the cutting region. Also, the application of compressed air during MQL has facilitated easy chip removal and thus helped reduce surface roughness [12]. It is evidenced by the comparison that the application of hybrid nanofluid played a significant role in improving surface finish by reducing the thermal effects and tool wear. The application of hybrid nanofluid-MQL resulted in a reduction in surface roughness by almost 40%, 28% and 14% compared to dry, wet and MQL conditions, respectively. Many significant factors have played an important role in the enhanced machining performance with mono and hybrid nanofluid applications. The addition of graphene and hBN has enhanced the lubricant mixture's thermal conductivity and improved heat dissipation from the machining zone [10]. In addition, the improved tribological condition with lubricant film formation at the machining interface has reduced friction at the tool-work and chip-tool interfaces [17]. In a study conducted by Şirin and Kıvak [14], the nanofluid with MoS_2, graphene and hBN was applied during the machining of an Inconel alloy and obtained an improved surface finish with hBN-nanofluid MQL with a reduction in temperature and tool wear for the selected machining conditions. The lamellar structure of the solid hBN nanoparticles and the weak van der Waals bonds between their atoms have contributed to an effective lubricating effect and reduced friction in machining interfaces. Additionally, the application of nanofluids enabled the formation of tribo-film through their mending, polishing, and rolling bearing mechanism [18]. Furthermore, graphene and hBN-added hybrid nanofluids enable the filling of micro-channels on the workpiece surface and are able to improve the surface finish compared to mono nanofluids.

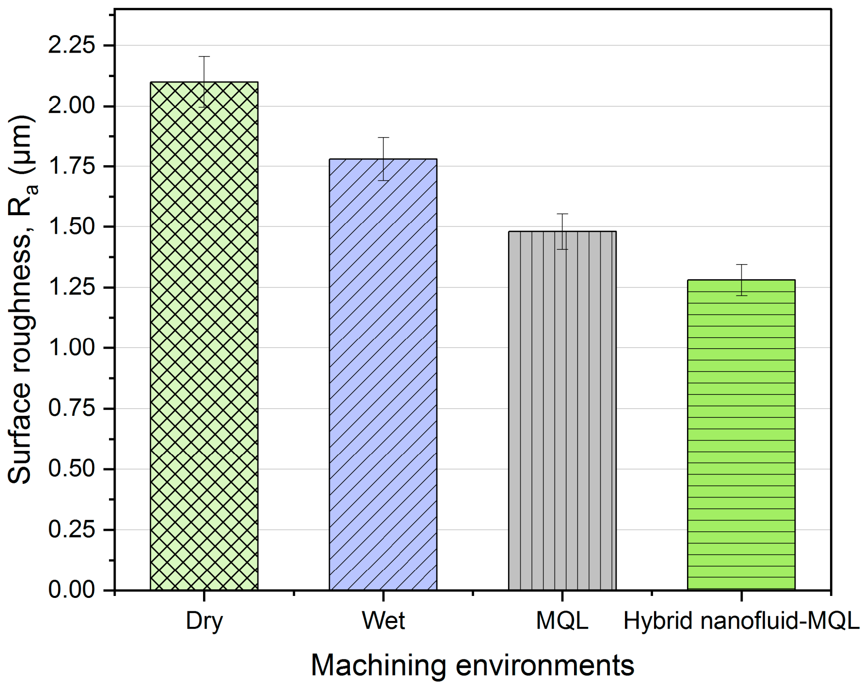

Figure 2. Surface roughness produced under different machining environments.

3.2. Tool Wear

The condition of the cutting edge of the tool during machining governs the machining ability. The amount of tool wear occurred during machining is considered to determine the cutting efficiency of the tool. The tool wear and thus the tool life are affected by many factors; however, the workpiece material plays an important role in tool wear, especially during the machining of nickel-based alloys. Generally, flank wear, which occurs on the side of the tool, is considered an important indicator of the tool wear and thus the tool life. In this work, the maximum flank wear VBmax is analyzed and compared for the selected machining environments and illustrated in Figure 3. Following the trend observed in surface roughness, maximum flank wear occurs under dry machining due to insufficient cooling and lubrication. Early fracture of the tool and thus rapid tool wear occurred due to the high temperatures produced during dry machining. The application of MQL with the spray of a small quantity of cutting fluid to the machining zone with compressed air has significantly controlled the tool wear. The ability of MQL in terms of heat removal and reduction in friction in the machining interfaces is discussed in previous studies [8]. Besides improving machining performance, the application of MQL is an environment-friendly approach with fewer negative effects on workers' health, as vegetable oil-based cutting fluid is used in this study. Additionally, the cutting oil applied with MQL gets consumed by means of evaporation and thus does not possess the requirement of recycling or disposal of waste, like in the case of conventional flood cooling. This is one of the important criteria in the development of sustainable machining. The tool wear is reduced, with the application of vegetable-oil-based MQL attributed towards the efficient heat removal form the cutting zone by the oil mist along with compressed air and reduction of friction with the addition of nanoparticles [19]. The significant reduction in tool wear with the hybrid nanofluid-MQL application is due to the improved tribological and thermal properties of the lubricant mixture with nanoparticles. The tool wear under hybrid nanofluid-MQL is reduced by almost 50%, 38% and 29% compared to dry, wet and MQL conditions, respectively. The presence of nanoparticles considerably reduces friction and increases specific heat capacity, thus enabling efficient heat dissipation from the cutting zone. Similar findings about the ability of nanoparticles to reduce tool wear are reported in previous studies [8]. Graphene and hBN exhibit weak van der Waals forces, thus creating a low shear plane and enabling them to develop a thin film of lubricant on the surface. In the current study, the enhanced tool life is achieved with the use of graphene and hBN nanoparticles blended in a lubricant mixture. The presence of nanoparticles improves the retention of oil particles and prevents the immediate release from the cutting zone, thus improving the lubricating action. Furthermore, the selected concentration of nanoparticles in mono and hybrid nanofluid applications resulted in higher heat absorption capacity and penetration ability and retained lubricant mixture for a longer time. Thus, it is important to use the correct concentration of nanoparticles, as an increase in concentration beyond a certain ratio results in the increased viscosity of the lubricant mixture and lowers the lubricating ability [20].

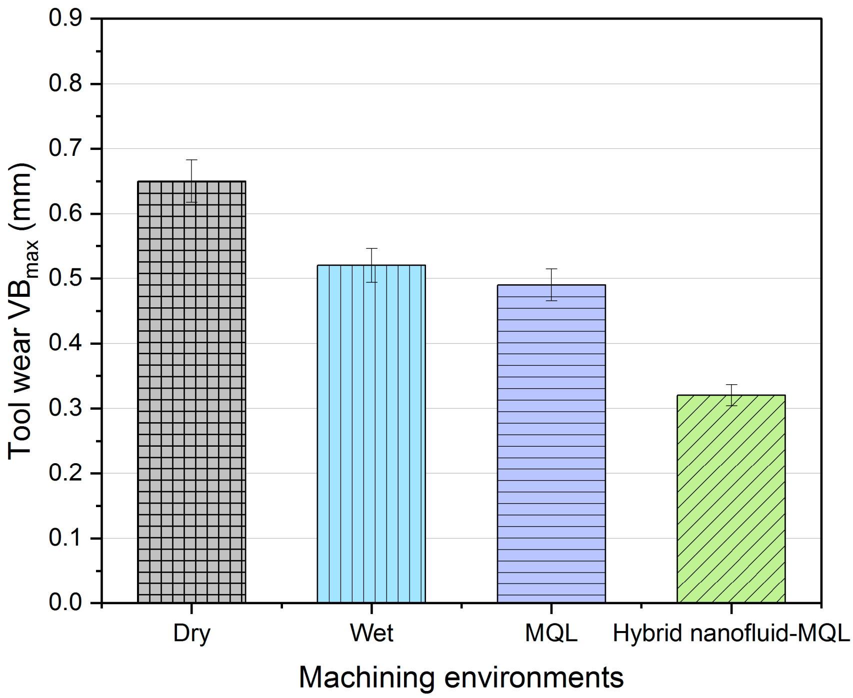

Figure 3. Tool wear produced under different machining environments.

The effect of the considered lubricating conditions on the mechanism of tool wear is analyzed and presented in Figure 4. From the analysis, adhesion and abrasion are found to be active wear mechanisms in all cutting inserts. The EDX analysis of the rake surface of the tool also confirms the adhesion as the wear mechanism as the composition of work material is observed. The higher temperature produced during machining leads to the chance of workpiece and chip material being welded on the tool surface and causing built-up edges and layers, which is common during the machining of nickel-based alloys [21]. The wear marks parallel to the direction of chip flow on the flank and rake surfaces of the tool define the abrasive wear. Figure 4 shows the abrasion as the active wear mechanism observed during dry machining. On the other side, abrasive wear is observed during wet and MQL machining due to the rubbing action of the tool with the workpiece and chips during machining. The application of hybrid nanofluid-MQL showed a considerable reduction in the abrasive wear of the tool. It is believed that the presence of nanoparticles enabled the development of an oil layer and controlled the friction and thus tool wear. Abrasive wear, being one of the most common wear mechanisms during the machining of nickel-based alloys, is reported in previous studies [22,23]. The EDX analysis of worn cutting tool inserts is presented in Figure 4. It is noticed from the EDX spectrum that material composition is found on the cutting tool insert due to adhesion. The presence of workpiece material on the tool insert being observed in the EDX spectrum confirms adhesion as the wear mechanism during dry machining. This is mainly due to the poor heat conductivity and chemical reactivity of the workpiece material. It is also confirmed that the presence of material composition is also evidenced on the tool insert utilized for wet, MQL and hybrid nanofluid-MQL conditions. The dominant wear mechanism is found to be adhesion in all cutting conditions. This confirms the previous results reported in various literature mentioning adhesion as the active wear mechanism during the machining of difficult-to-cut materials [24].

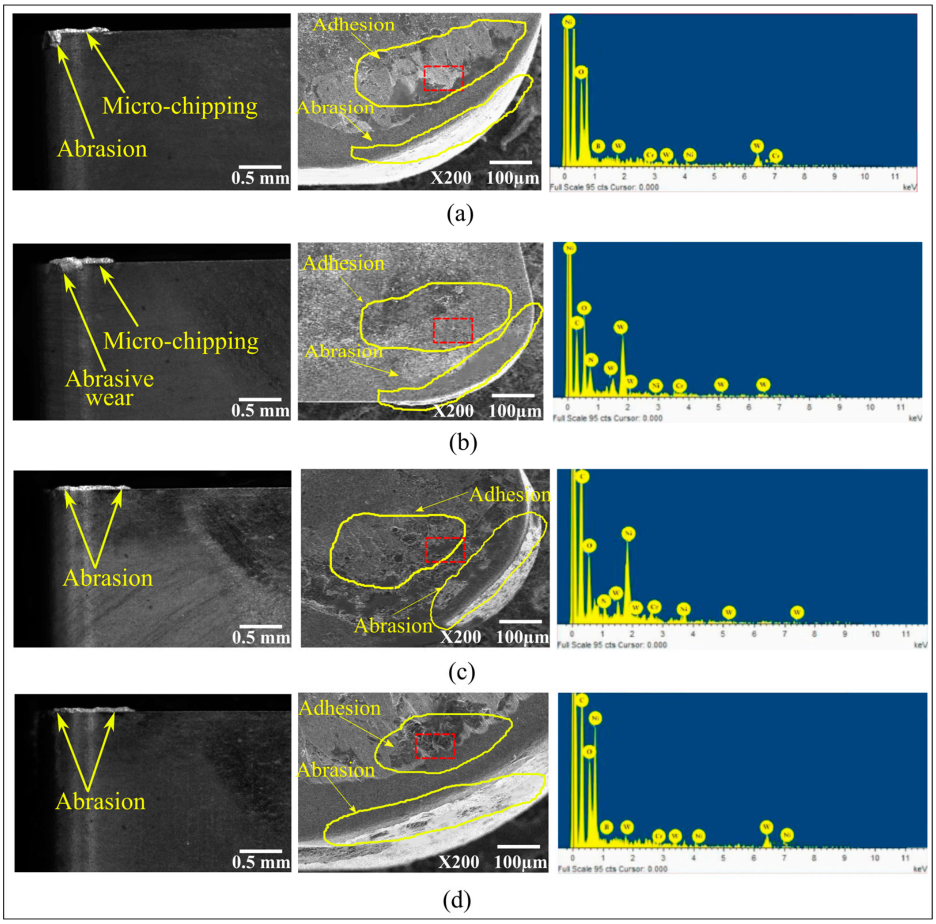

Figure 4. Tool wear produced and EDX analysis under (**a**) dry (**b**) wet (**c**) MQL (**d**) hybrid nanofluid-MQL conditions.

3.3. Chip Morphology

Chips are produced from the workpiece surface due to plastic deformation caused by the actions of the cutting tool during machining. The morphology of chips produced during machining reveals the quality of the machining and the effectiveness of the cooling/lubricating medium. Additionally, the shape and size of the chip produced is affected by the amount of friction produced between machining interfaces [25]. Generally, machining nickel-based alloys with low thermal conductivity results in continuous and serrated chips due to non-uniform plastic deformation. This may result in surface damage to the workpiece and tool material [26,27]. With this view, in the current work, the morphology of chips produced under different cutting environments is analyzed and compared. The macroscopic analysis presented in Figure 5 shows that long, irregular and highly non-uniform chips are produced under dry machining. This is due to the higher temperatures in the primary and secondary zone and the increased chip-tool contact length. The application of wet machining produced continuous spiral chips due to a lack of lubrication in the machining zone, whereas MQL and hybrid nanofluid-MQL enable the formation of shorter and fractured chips. This is mainly attributed to the reduction of chip-tool contact area with pressurized airflows and better cooling and lubrication. Figure 5 shows the micrographs of the front side of the chips produced during dry, wet, MQL and hybrid nanofluid-MQL conditions. The formation of serrated chips is observed in all the considered machining environments. When closely observed, chips with large serrations are produced during dry and wet machining, while MQL and hybrid nanofluid-MQL result in small, serrated chips. Chips with shorter lengths and a large curl radius are produced during wet machining. The availability of cutting fluid at machining interfaces improves the chip morphology with fine lamella. The application of MQL along with compressed air facilitated easy chip removal from the machining zone and resulted in chips with a low curl radius and shorter lengths. The effectiveness of hybrid nanofluid-MQL can be noticed with the production of shorter chips with fine lamella compared to dry and wet machining. The effective penetration of nanofluids in the machining interface resulted in better lubrication and heat dissipation, leading to a reduction in tool wear and easy chip formation [28]. Sen et al. [19] reported chips with a small curl radius produced under MQL-nanofluid application during the machining of Inconel 690. Generally, chip curl is mainly affected by the friction force on the rake face of the tool. The higher friction with improper cooling/lubrication acts as a restrictive force and prevents the chip curl, thus producing a large curl diameter [29]. The reduction in the heat produced and the friction at the cutting zone produces chips with fine lamella. During hybrid nanofluid-MQL application, the cutting fluid with nanoparticles penetrates effectively between chip-tool interfaces and lowers the friction, thus improving chip morphology. The application of compressed air with MQL and hybrid nanofluid-MQL makes chip removal easy. The reduction in friction with enhanced lubrication results in an improved chip-breaking effect and produces chips with smaller lengths and curl radii. This signifies the effectiveness of MQL and hybrid nanofluid-MQL in improving the machining performance by facilitating easy chip removal due to enhanced cooling and lubrication.

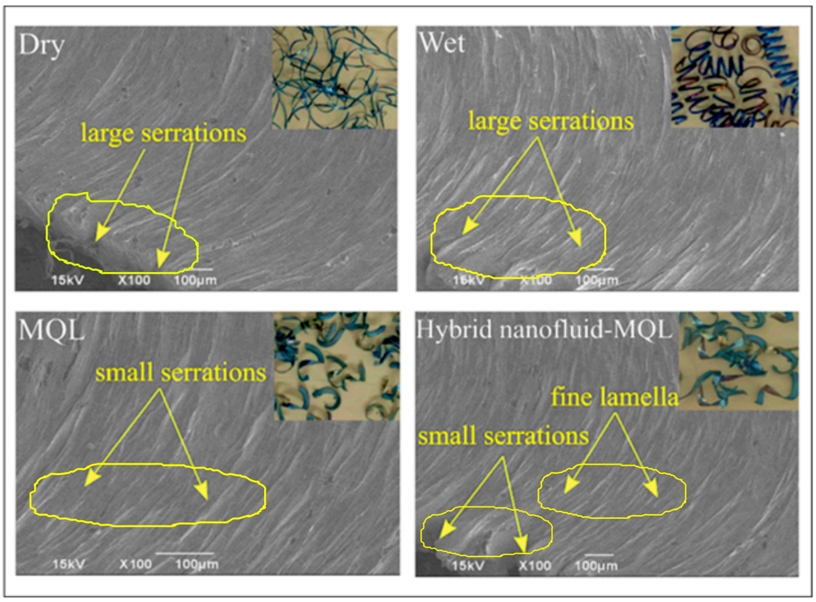

Figure 5. Chip morphology produced under different machining environments.

3.4. Analysis of Hybrid Nanofliud-MQL Performance

It has been observed from the comparative analysis presented in previous sections that the application of hybrid nanofluid-MQL improved the machining performance with the improvement in surface finish and reduction in tool wear. It is believed that the application of graphene and hBN with oleophilicity and palm oil with higher polarity has enabled the formation of tribo-film in the machining interfaces and resulted in a reduction in friction. Additionally, graphene and hBN exhibit weak van der Waals forces with low shearing power. The nanoparticles in nanofluid resulted in layered deformation and reduced the contact area between the tool and workpiece, thus improving surface quality and machining performance. Though the workpiece material and palm oil possess low thermal conductivity, the addition of graphene and hBN with higher conductivity improved the thermal conductivity of the nanofluid mixture. Figure 6 illustrates pictures of the surfaces produced under different machining conditions. It is observed that the dry machining resulted in surface deterioration and the formation of an irregular surface texture due to the absence of cooling/lubricating action. Wet machining has resulted in visible feed marks due to a lack of lubrication. On the other side, MQL exhibited mild feed marks on the surface, attributed to better lubrication and less chip flow damage with the compressed air application. Finally, applying hybrid nanofluid-MQL resulted in a smooth surface with minor feed marks. Danish et al. [9] reported similar observations in the form of enhanced surface morphology and machining efficiency with the use of graphene nanoparticles. This confirms the efficient cooling and lubrication provided by hybrid nanofluid-MQL with improved machining performance.

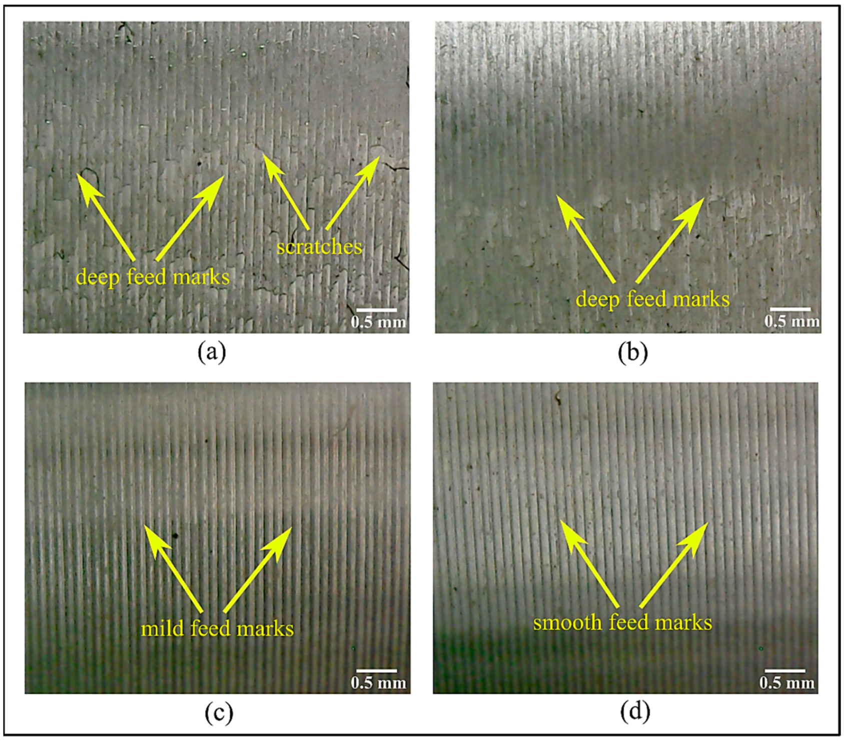

Figure 6. Images of machined surface produced under (**a**) dry (**b**) wet (**c**) MQL (**d**) hybrid nanofluid-MQL conditions.

4. Conclusions

The work demonstrated the machining of Inconel 718 under dry, wet, MQL and hybrid nanofluid-MQL environments. The novelty of the work is the application of hybrid (graphene and hBN) nanofluid-MQL to assess the machinability of Inconel 718. The machining performance is investigated by analyzing the surface roughness, tool wear, chip morphology and surface quality of the machined workpiece. The work reveals the following important conclusions:

1. Improved surface quality is achieved under hybrid nanofluid-MQL application while the highest surface roughness is observed under dry machining. Hybrid nanofluid-MQL resulted in a reduction in surface roughness by almost 40%, 28% and 14% compared to dry, wet, and MQL conditions, respectively. This is attributed to the retention of cutting fluid particles for a longer time, along with nanoparticles, and thus improved the lubrication and enhanced surface finish.
2. The minimum flank wear is observed with hybrid nanofluid-MQL followed by MQL, wet, and dry machining. The hybrid nanofluid-MQL has reduced tool wear by almost 50%, 38% and 29% compared to dry, wet and MQL conditions, respectively. It is found that for tool wear, adhesion and abrasion is the dominant wear mechanism under all the machining environments.
3. The chip morphology revealed that chips with large serrations are produced during dry and wet machining, while MQL and hybrid nanofluid-MQL resulted in small, serrated chips. Also, the chips with shorter lengths and a smaller curl radius produced under hybrid nanofluid-MQL showcased better lubrication and penetration of fluid in machining interfaces.
4. The presence of graphene and hBN in the lubricant mixture led to the improvement in tribological conditions in machining interfaces, which led to a reduction in tool wear and improved surface quality and machining performance.

In summary, the superior cooling and lubricating ability of hybrid nanofluid-MQL can be considered a feasible approach for improved machinability of nickel-based alloys. The same can be an effective alternative to the use of conventional flood when the machining economy and sustainability are considered prime concerns. In future, machining-induced tribological characteristics under different cooling/lubrication conditions can be studied.

Author Contributions: Conceptualization, M.A.M.; Data curation, K.M.P. and P.J.B.; Formal analysis, K.M.P.; Investigation, M.A.M.; Methodology, M.A.M. and K.M.P.; Resources, M.A.M. and P.J.B.; Writing—original draft, M.A.M.; Writing—review & editing, K.M.P. and P.J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All the data available in main text.

Acknowledgments: Authors would like to acknowledge the resources provided by Nirma University to carry out the research work.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

MQL	Minimum quantity lubrication
NMQL	Nano-fluid Minimum quantity lubrication
Al_2O_3	Aluminum oxide
hBN	Hexagonal boron nitride
CNT	Carbon nanotube
MWCNT	Multi-walled carbon nanotubes
MoS_2	Molybdenum disulphide
PVD	Physical vapor deposition
TiAlN	Titanium aluminium nitride
TiN	Titanium nitride
Ra	Average surface roughness
VBmax	Maximum flank wear
ISO	International Organization for Standardization
SEM	Scanning electron microscope
EDX	Energy dispersive X-Ray

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