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# Machinability of Inconel 718 in MQL turning using hybrid microwaved silicon nitride inserts

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KEYWORDS

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Dry turning

ABSTRACT

Machining Inconel 718 requires high strength inserts with high hot hardness and is challenging due to its high strength and thermal stability. Nonetheless, high wear rates, frequent tool change, extra time and increased tool cost are anticipated despite using large amounts of ecologically unfriendly synthetic cutting fluids. Several options on using vegetable oils and Minimum Quantity Lubrication (MQL) were explored but not with microwave treated inserts. This study intends to investigate using eco-friendly options such as dry and MQL turning on Inconel 718 with untreated and hybrid microwaved (HMW) treated $Si_3N_4$ inserts at 200°C for 15 minutes. The cutting speed (145 m/min), feed rate (0.08mm/rev) and depth-of-cut (0.1 mm) remained constant. The tool wear and surface roughness were measured and the efficacy of the HMW treatment was analyzed. In dry turning, $Si_3N_4$ (HMW) performs better with reduced flank wear by 13.85% than the $Si_3N_4$ (untreated) insert. Meanwhile, in MQL turning, the $Si_3N_4$ (HMW) had decreased flank wear by 30.53% when compared to the $Si_3N_4$ (untreated) insert. The surface roughness from MQL turning using the $Si_3N_4$ (HMW) was much lower (0.53μm) than the $Si_3N_4$ (untreated) (0.85μm). The $Si_3N_4$ (HMW) insert was found to be appropriate for MQL turning, but unsuitable for dry turning of Inconel 718 due to excessive tool wear.

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## 1.0 INTRODUCTION

Inconel 718 is a nickel chromium alloy with high-strength and high corrosion-resistance. It is widely used in defense, automobile, marine, and aerospace industries. Several studies, such as Kang et al. (2019), who explored its great strength, and Abdul Halim et al. (2020), who experimented on its high creep resistance and thermal stability, have demonstrated that this material is indeed difficult to machine (Kartheek et al., 2018). The machinability of Inconel 718 is negatively impacted by low thermal conductivity, properties at elevated temperatures, work hardening, and a tendency to adhere to cutting tools, as reported by Roy et al. (2018). Pusavec et al. (2011) state that poor tool life, low dimensional stability of the workpiece, and a poor surface finish are caused by the heat generated between the tool-chip interface.

With regard to its resilience to corrosion and extended durability, Inconel 718 is an attractive option for turbine engines used in high-temperature aerospace applications. However, conventional cutting tools like high speed steel have limitations. Nevertheless, substitutes like silicon nitride and titanium nitride make machining challenging because of Inconel 718's high hardness and the rapid temperature rise that occurs during the process. This causes the ceramic cutting tool to wear down significantly, necessitating frequent tool replacements that raise production costs and lengthen tool change times. It has taken a great deal of research and testing to determine the ideal cutting conditions for Inconel 718 using various cutting fluids (Misal & Sadaiah, 2017; Finkeldei et al., 2019; Sivaiah et al., 2020; Paturi et al., 2021).

Finding the conditions under which Inconel 718 can be cut most effectively has required a significant amount of investigation and experimentation. Ariff et al. (2018a) claim that silicon nitride cutting inserts have exceptional qualities particularly in post-sintering of $Si_3N_4$ inserts applying hybrid techniques, seem promising for hard to machine materials including nickel based super alloys, hardened steel and cast iron. When silicon carbide (SiC), graphite, and a mixture of SiC and graphite powders were utilized as susceptors for just 10 minutes at 200°C under the microwave, densification, hardness, and wear resistance were enhanced. Because there is a stronger interfacial bonding between all compositions of $Si_3N_4$ at elevated temperatures due to heat penetration increasing with decreasing conductivity, the mixture of SiC and graphite susceptors in the hybrid microwave treatment produced the highest improvement on the characteristics and machining performance of $Si_3N_4$ inserts (Chandrasekaran et al. 2013, Menendez et al. 2010).

Because of its hardness, significant tool wear is common, and synthetic cutting fluids have been used extensively, causing environmental harm and inspiring the development of numerous eco-friendly machining techniques. Teo et al. (2022) reported that when used as a cutting fluid for Inconel 718 machining, palm oil mixed with $Al_2O_3$ nanoparticles worked better than coconut and olive oils. Haron et al. (2019) conducted an experimental investigation on the wear processes of PVD TiAlN coated tungsten carbide inserts and found that, in both dry and cryogenic settings, turning Inconel 718 at high speeds might reduce the rate of tool wear and lengthen tool life through cryogenic machining. It was expected that the effective cooling provided by cryogenic $CO_2$ would lower the cutting temperature considerably and slow down the rate at which tool wear advanced.

Minimum quantity lubrication (MQL) is an economical and environmentally friendly technique that regulates temperature and offers sufficient lubrication (Kumar et al., 2022). Additionally, MQL reduces surface roughness when turning Inconel 718 (Siddique et al., 2023). Xavier et al. (2016) achieved successful machining of Inconel 718 using MQL machining with a Cubic Boron Nitride (CBN) insert. The researchers observed minimal tool wear at a higher cutting speed of 125 m/min, using a feed rate of 0.15 mm/rev and a larger depth of cut of 0.6 mm. It is worth noting that this outcome was not attainable with a carbide tool insert, which is only suitable for lower cutting speeds such as 60 m/min. A study comparing different cooling techniques was carried out by Husshini et al. (2022), who discovered that the combination of MQL and cryogenic/chilled air provides effective cooling and lubricating capabilities in lowering temperature generated during machining, which improves surface quality. As a result, MQL and chilled air result in reduced surface roughness, increased cost-effectiveness, and enhanced sustainability. Following the resolution of machining difficulties, manufacturers can take benefit of Inconel 718's special qualities for a range of applications.

In this paper, the machining performance in terms of tool wear and surface roughness is investigated in dry and MQL turning of Inconel 718 using hybrid microwave (HMW) treated $Si_3N_4$ inserts at 145 m/min using a constant feed (0.08 mm/rev) and depth of cut (0.1mm). The hybrid microwave treatment applied on the $Si_3N_4$ inserts is at 200°C for 15 minutes with a mixture of silicon (IV) oxide ($SiO_2$) and graphite powders as susceptors. The main aim of this paper is to determine if the hybrid microwave treated $Si_3N_4$ inserts have lower wear rates and improved surface finish under dry and MQL turning conditions in machining Inconel 718.

## 2.0 EXPERIMENTAL PROCEDURE

### 2.1 Hybrid Microwave Treatment

A small alumina crucible with a diameter of 30 mm (Figure 1(a)), was used for holding the uncoated $Si_3N_4$ insert (Euromax RNGN 120700) and was later covered with a lid. The inserts with a diameter of 12.7 mm and thickness of 7.9 mm were used. As indicated in Figure 1(b), the smaller crucible was then inserted into a larger crucible that had an opening of 65 mm in diameter and plunged into the susceptor powder containing a mixture of 25 $cm^3$ silicon (IV) oxide ($SiO_2$) and 25 $cm^3$ graphite (G) powders as susceptors as shown in Figure 1(b). This is to assure that the insert experiences uniform volumetric heating. To facilitate rapid hybrid microwave heating, susceptor powders (Alfa Aesar) with a size of 0.5 μm ($SiO_2$) and about 300 mesh (G) of 99.9% purity were employed in the HMW treatment. There was also a lid covering the bigger crucible as well. After that, using a magnetron operating frequency of 2.45 GHz in a domestic microwave oven (Panasonic NN-CD997S), the crucibles were heated to 200°C for 15 minutes.

(a) (b)

Figure 1: (a) $Si_3N_4$ insert inside the small crucible; (b) Small crucible submerged inside the susceptor ($SiO_2$ and graphite) powders.

### 2.2 Density and Hardness Test

An electronic density tester (Dahometer DH-300) was used to measure the densities of the $Si_3N_4$ insert from the HMW treatment. The Vickers Hardness Tester (Innovatest Falcon 400) was then used in micro-Vickers mode to conduct a hardness test. The average reading was recorded after tests were conducted three times. The $Si_3N_4$ (untreated) insert was used to compare results.

### 2.3 Scanning Electron Microscope

Using the Scanning Electron Microscope (SEM) (JSM-IT100), the microscopic structure of the $Si_3N_4$ (untreated) and $Si_3N_4$ (HMW) inserts were observed. Due to its non-metal nature, silicon nitride required to be coated with a gold-palladium coating using a Quorum Sputter Coater (SC7620) prior to being inserted into the SEM, as illustrated in Figure 2. Electron Dispersive X-ray Spectrometer (EDS) was performed on the $Si_3N_4$ (untreated) and $Si_3N_4$ (HMW) inserts to ascertain the elemental distribution of the composition through the mapping diagram. The EDX spectrums from an area scan was performed on the inserts. These EDX spectra reveal the peak of every element detected. This was further verified with the X-Ray maps to clearly see the distribution of Si, Al, O and N in the $Si_3N_4$ inserts.

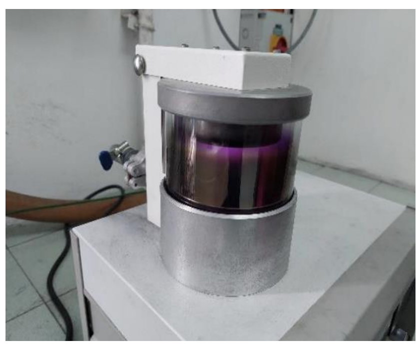


Figure 2: Coating using the Quorum Sputter Coater (SC7620).

### 2.4 Machining

The tool wear rates for the $Si_3N_4$ (HMW) and $Si_3N_4$ (untreated) inserts were measured in this dry and MQL machining experiment using an Inconel 718 cylindrical rod with a diameter of 75 mm and a length of 450 mm. As seen in Figure 3, the rod was divided into 5 segments of equivalent lengths (71 mm) and machined using a turning operation on a lathe (HARRISON M390). Despite Xavier et al. (2016) using higher cutting parameters in the machining of Inconel using a CBN tool at a speed of 120 m/min, a feed rate of 0.15 mm/rev, and a depth of cut of 0.6 mm, it appears that the feed rate and depth of cut were excessively high for the $Si_3N_4$ inserts and considered unsuitable due to tool failure. Therefore, the investigation at a higher cutting speed was performed with a lower feed rate and depth of cut. The machining parameters were kept constant, cutting speed (145 m/min), feed rate (0.08 mm/rev) and depth of cut (0.1 mm). Figure 4 shows the MQL device that was used (Foshan Yong Sheng He-Teo 2551A-nP10LB) with parameters 0.2 ml/pulse, pulse rate 1.2, air pressure 4-6 bar and lubricant used per segment per turning was 26.4 ml. The MQL Lubricant (OLCUT 105A) was used for this purpose.

Figure 3: The segmented Inconel 718 clamped in the lathe machine (HARRISON M390).

Figure 4: MQL Device (Foshan Yong Sheng He-Teo 2551A-nP10LB).

After each segment was machined, the flank wear was measured under a microscope (Meiji Techno FU 1010). To determine the tool wear rates for the $Si_3N_4$ (HMW) and $Si_3N_4$ (untreated) inserts under dry and MQL cutting conditions, the data was recorded and plotted into graphs.

## 2.4 Surface Roughness Measurement

As seen in Figure 5, the surface roughness of Inconel 718 on the machined segments was measured using a surface roughness tester (PCE-RT 11). In order to observe the performance of the $Si_3N_4$ inserts under dry and MQL cutting conditions, measurements were carried out after each machining.


Figure 5: Measuring the surface roughness on the machined surface of Inconel 718.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Density and Hardness

Figure 6 shows the $Si_3N_4$ samples that were utilized in this experiment. After being treated with hybrid microwave energy for 15 minutes at 200°C, there are no changes at all in the dimensions or physical appearance. The density (3.41 g/cm$^3$) stayed constant because of the weight (4.41 g) remaining constant. Comparing the HMW treated insert to the untreated insert, however, shows a significant improvement in hardness of up to 70%. Table 1 displays the results for the hardness and density.

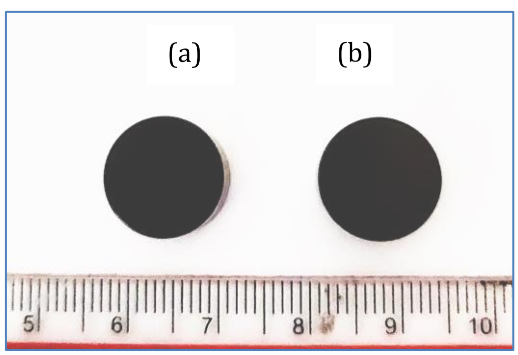



Figure 6: The $Si_3N_4$ samples (a) Untreated (b) HMW treated.

Table 1: The density and hardness of the $Si_3N_4$ samples.

| Sample | Density (g/cm$^3$) | Hardness (HV) |
|---|---|---|
| Untreated | 3.41 | 429 |
| HMW | 3.41 | 729 |

The enhanced hardness of the $Si_3N_4$ (HMW) insert can be attributed to the increased heat generated by the micro plasma (spark effect) of graphite, which is efficiently transported to the $SiO_2$ particles. The improved quick heating is a result of the absorption of heat from $SiO_2$ and microwave energy from graphite. Therefore, the mixture's heating rate is higher than that of the pure graphite and $SiO_2$ susceptor alone. Because heat permeates the skin deeper and faster with decreasing conductivity, it is believed that when both $SiO_2$ and graphite are used as susceptors, there is a stronger interfacial bonding between all the compositions of $Si_3N_4$ at elevated temperature even as low as 200°C.

### 3.2 Microstructural Observation

Figure 7 shows the SEM images taken for the $Si_3N_4$ (HMW) and $Si_3N_4$ (untreated) inserts. The images reveal that there are no significant changes in the microstructure and the HMW treatment at 200°C for 15 minutes did not alter the microstructure. Both inserts exhibit similar observations, with the presence of pores shown by the red circles. The pore size of $Si_3N_4$ (HMW) appears to be smaller than that of $Si_3N_4$ (untreated) inserts. Nevertheless, the $Si_3N_4$ inserts exhibit similar appearances with a homogeneous and uniformly distributed grain structure, which accounts for the identical density results.

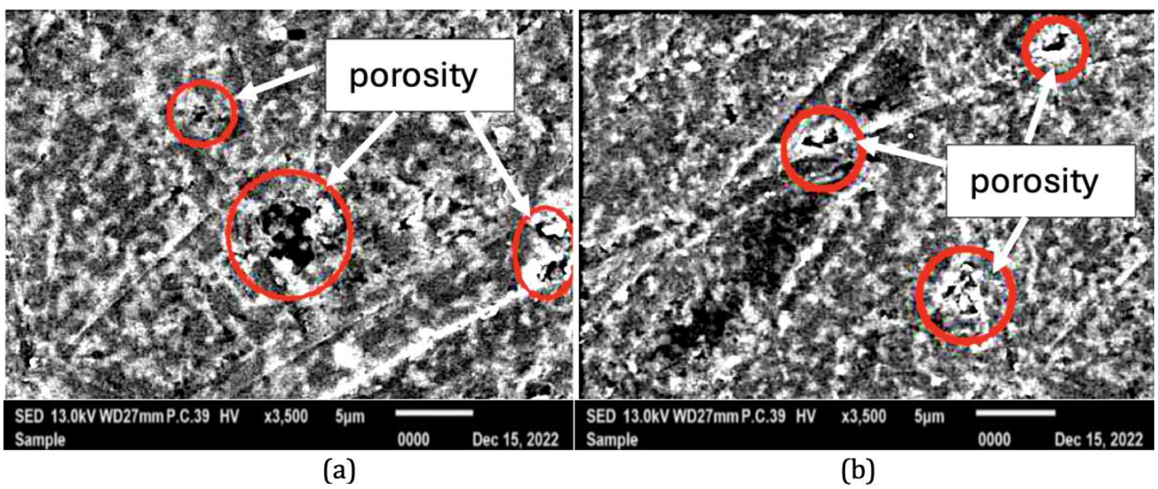
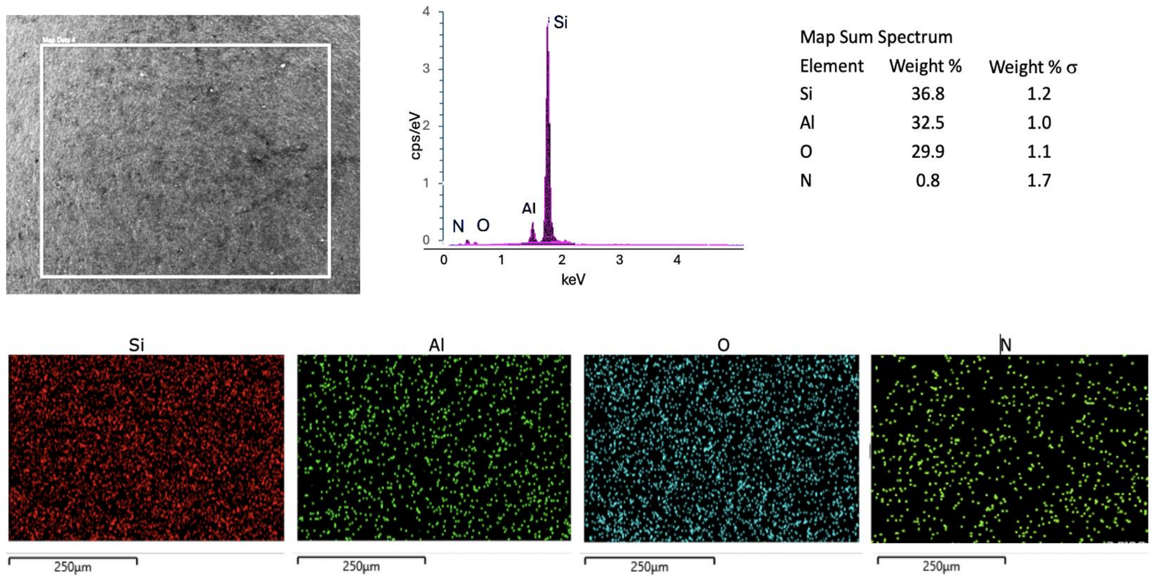
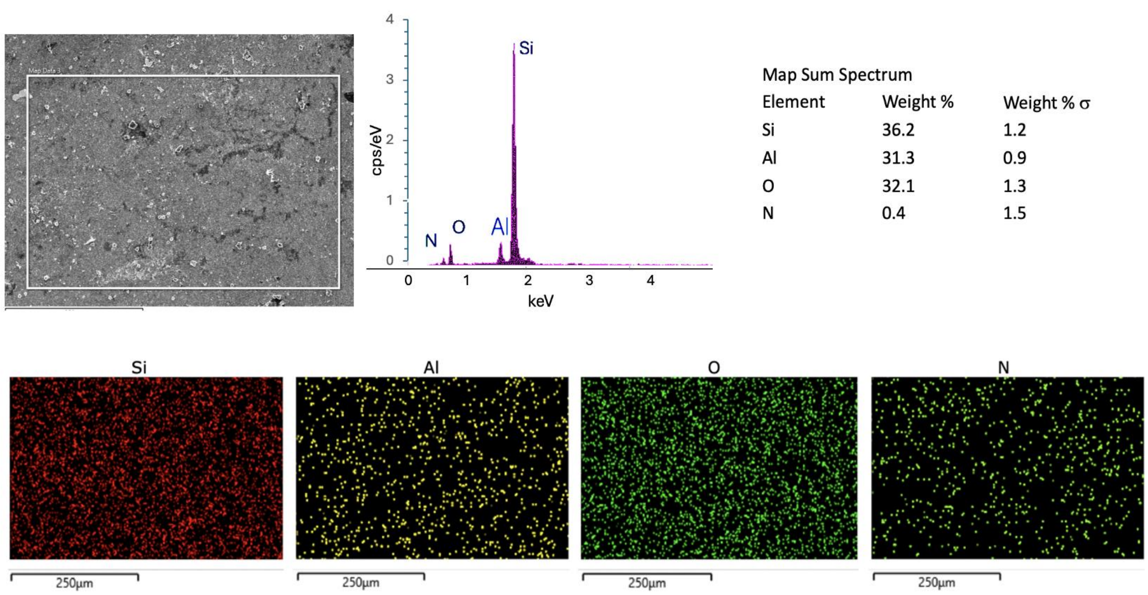



Figure 7: SEM images of (a) $Si_3N_4$ (untreated) (b) $Si_3N_4$ (HMW) inserts (3500X).

EDS analysis results for the $Si_3N_4$ (untreated) and $Si_3N_4$ (HMW) inserts in Figure 8 show a very small effect of oxidation at the surface in using hybrid microwave energy at 200°C, with the peak value of O before and after heating changing from 29.9% to 32.1%, while the other elements being relatively consistent. This is a very insignificant increase that is very much expected to be seen in a low temperature setting. Furthermore, the X-Ray maps reveal that the distribution of the Si, Al, O and N elements are all uniformly distributed for both the $Si_3N_4$ (untreated) and $Si_3N_4$ (HMW) inserts.




(a)




(b)

Figure 8: EDS report and X-Ray maps for (a) $Si_3N_4$ (untreated) (b) $Si_3N_4$ (HMW) inserts.

### 3.3 Tool Wear

Figure 9 shows the $Si_3N_4$ tool wear progression for the dry machining. When compared to the $Si_3N_4$ (HMW) inserts, the untreated $Si_3N_4$ (untreated) inserts exhibit a considerably higher flank wear trend during dry turning of Inconel 718. The wear rate of $Si_3N_4$ (untreated) is 0.093 mm/min, whereas the wear rate of $Si_3N_4$ (HMW) is 0.087 mm/min. Even though there is not much of a difference in terms of wear rates between both inserts. Nonetheless, it is clear that even in dry turning, the hybrid microwave treatment at 200°C for 15 minutes positively affects the performance of the $Si_3N_4$ insert resulting in a lower wear rate.

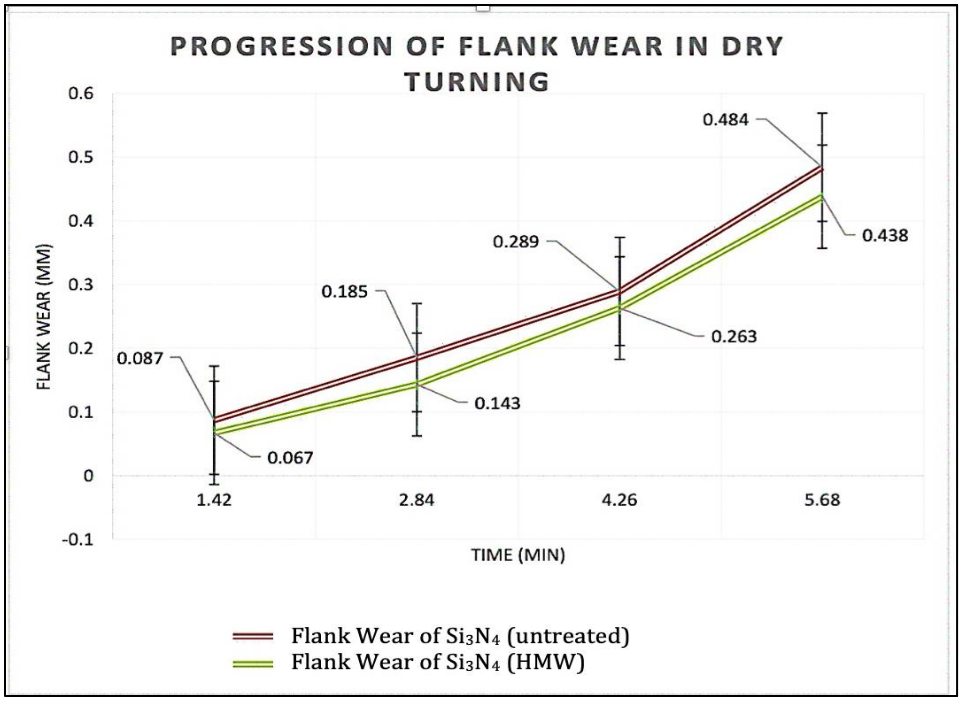



Figure 9: Flank wear of $Si_3N_4$ in dry turning of Inconel 718.

The progression of flank wear under MQL machining is shown in Figure 10. The $Si_3N_4$ (untreated) has a wear rate of 0.008 mm/min, which is higher than the wear rate of 0.005 mm/min for the $Si_3N_4$ (HMW). As a result of the improved wear resistance properties, it is evident that $Si_3N_4$ (HMW) flank wear advances considerably more slowly and at a constant rate will that lead to a longer tool life.

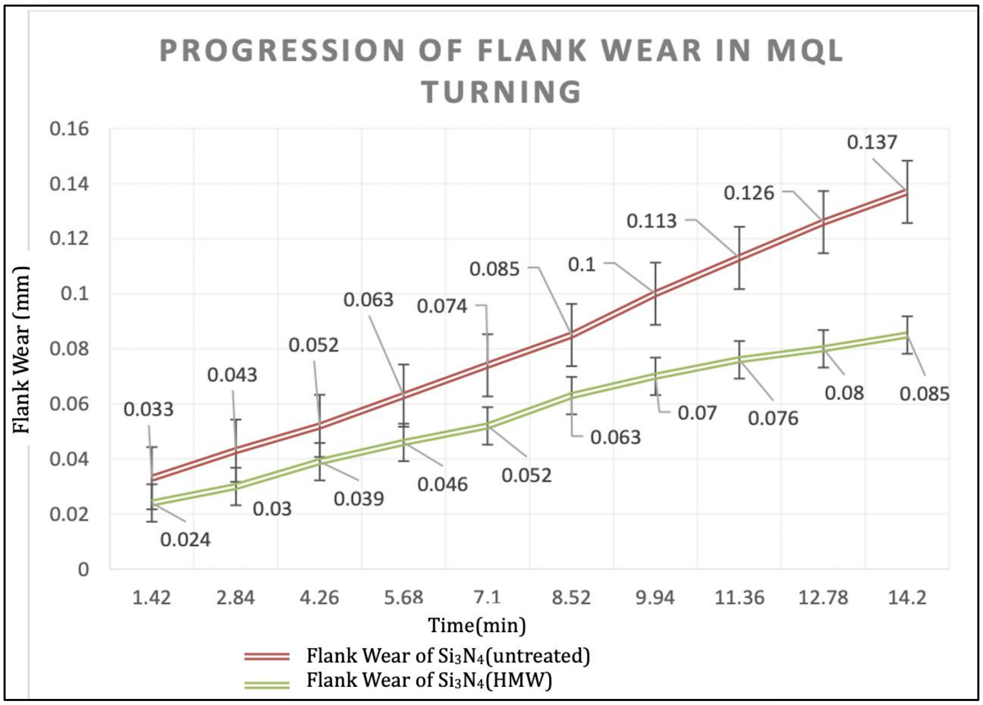
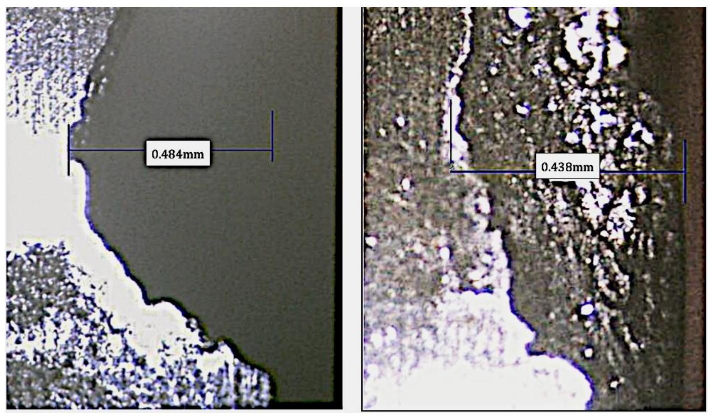


Figure 10: Flank wear of $Si_3N_4$ in MQL turning of Inconel 718.

The wear resistance property of the $Si_3N_4$ (HMW) insert increased as a result of its increased hardness. Consequently, it is noticeable from both dry and MQL turning. Even under dry turning, $Si_3N_4$ (HMW) insert has reduced wear rates, the significant friction and temperature rise make it impossible to continue machining in this circumstance, and thus makes it inappropriate. Conversely, under MQL turning, the increased hardness appears to have a beneficial effect. Under this environmentally friendly machining initiative, the higher wear resistance from the HMW treatment does reduce the wear rate and eventually will increase the tool life. MQL can be seen as a better option and an alternative to traditional flood cooling methods that cause more harm than good to the environment in machining Inconel 718.

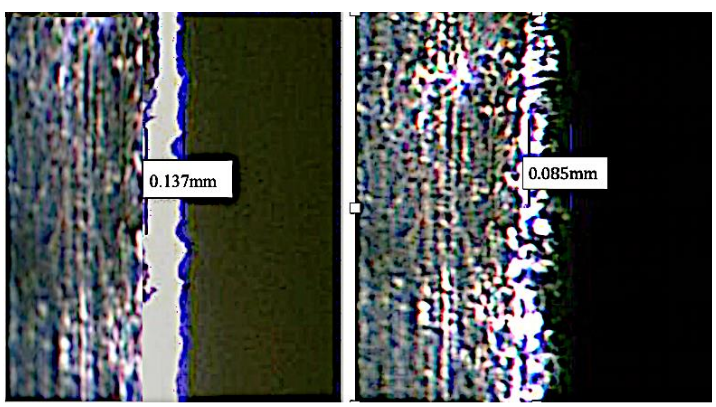
It is anticipated that the reduction of cutting speed in MQL machining will lead to improvements in tool wear rates and surface roughness. According to the findings provided by Ariff et al. (2018b), Jeyapandiarajan and Xavier (2019), and Bertolini et al. (2021), the machining of Inconel 718 results in reduced tool wear and enhanced surface roughness while operating at lower cutting speeds. This research offers an opportunity for additional investigation into the feasibility of achieving higher cutting speeds for machining Inconel 718 using conventional carbide or ceramic tools, which were previously believed to be unattainable due to catastrophic failure. However, it is evident that the utilization of hybrid microwave treated inserts is promising. Nevertheless, it should be noted that increased cutting speeds (higher than 145 m/min) may not be favorable for enhanced tool wear performance and surface roughness. This is mostly attributed to the increased frictional forces and subsequent temperature rise at the cutting zone.

Figures 11 and 12 show images of tool wear in dry and MQL turning, respectively. In relation to dry turning, it was observed that both $Si_3N_4$ (untreated) and $Si_3N_4$ (HMW) exhibited an affinity for chipping after a machining duration of 5.68 minutes. This can be attributed to the presence of higher friction and a consequent increase in temperature inside the cutting zone, which is due to the absence of a cutting fluid. In contrast, $Si_3N_4$ (untreated) and $Si_3N_4$ (HMW) did not detach during MQL turning due to the cooling effect of MQL fluids on the cutting zone and the lubricating effect on the machining process. The extent of flank wear remains negligible even after a machining duration of 14.2 minutes, in contrast to the dry machining process. The microscopic images reveal that the $Si_3N_4$ (HMW) exhibits a progressive and much slower wear rate compared to the untreated $Si_3N_4$.




(a) (b)

Figure 11: The micrograph for the insert after 5.68 mins in dry machining (a) $Si_3N_4$ (untreated) (b) $Si_3N_4$ (HMW).




(a) (b)

Figure 12: The micrograph for the insert after 14.2 mins in MQL machining (a) $Si_3N_4$ (untreated) (b) $Si_3N_4$ (HMW).

### 3.3 Surface Roughness

The surface roughness values of the machined Inconel 718 for the dry and MQL turning are displayed in Figures 13 and 14 respectively. Although the $Si_3N_4$ (HMW) has lower Ra values for dry turning, the values are similar to the $Si_3N_4$ (untreated) after it reaches 5.68 minutes of machining. Conversely, even after 14.2 minutes of machining, the Ra values for the $Si_3N_4$ (HMW) under MQL turning are significantly lower (0.53 μm) than the untreated $Si_3N_4$ (0.85μm). The enhanced hardness and wear resistance of the $Si_3N_4$ (HMW) insert resulted to the improved surface quality of the machined Inconel 718 under MQL turning. The HMW treatment at 200°C for 15 minutes can be an inexpensive and quick method to increase the hardness of $Si_3N_4$ inserts rapidly, which also increases tool life and eventually lowers the cost and frequency of tool replacements.

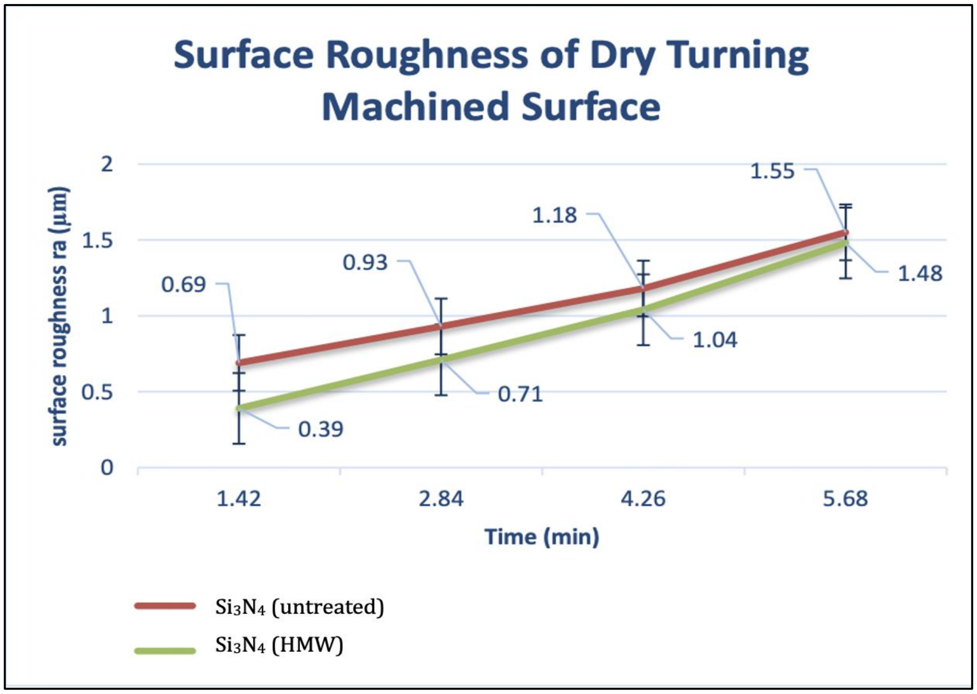



Figure 13: Surface Roughness of Inconel 718 under dry turning.

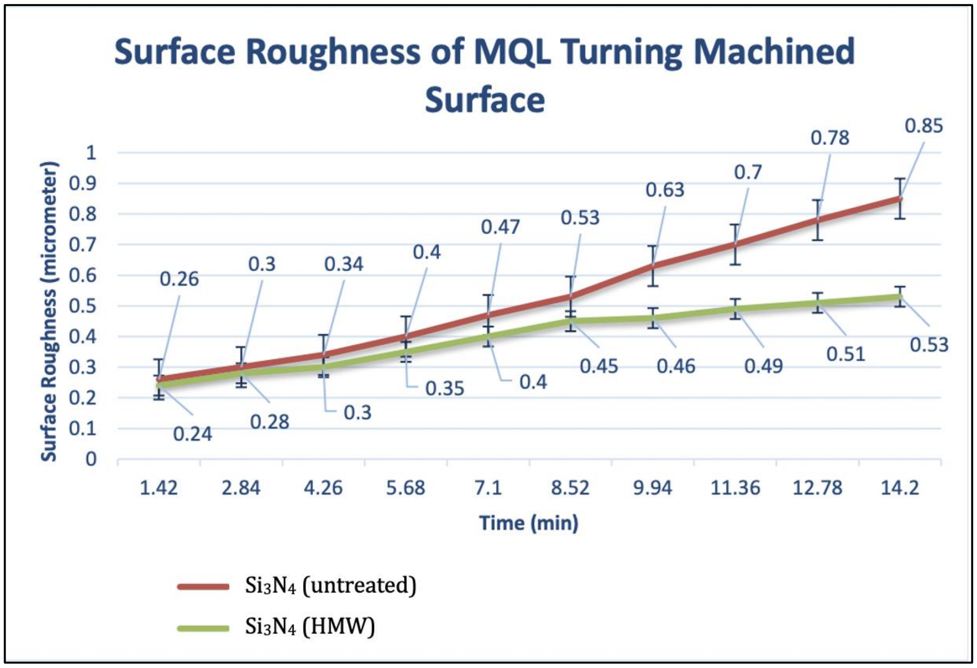



Figure 14: Surface Roughness of Inconel 718 under MQL turning.

**CONCLUSIONS**

Uncoated $Si_3N_4$ inserts are generally used for machining cast iron and hardened steel. However, the efficiency and possible application of hybrid microwave treated $Si_3N_4$ inserts in MQL turning of Inconel 718 have been effectively established by this study, operating at a cutting speed of 145 m/min, feed rate of 0.08 mm/rev, and depth of cut of 0.1 mm. The following conclusions are drawn from the findings of the experiments which are encouraging and may be useful for future research:

a. The density of $Si_3N_4$ inserts remained constant following hybrid microwave treatment.
b. Hybrid microwave treatment increased the hardness of $Si_3N_4$ inserts by 70%.
c. The increased hardness of $Si_3N_4$ (HMW) inserts leads to improved performance in dry and MQL turning, with decreased tool wear.
d. Hybrid microwave treatment under MQL turning of Inconel 718 resulted in lower tool wear rate of 0.005 mm/min as compared to 0.087 mm/min under dry turning.
e. The best surface roughness was achieved in MQL turning with the $Si_3N_4$ (HMW) insert (Ra = 0.52 μm).

Hybrid microwave treatment of $Si_3N_4$ inserts at 200°C for 15 minutes is effective for MQL turning of Inconel 718 due to its reduced tool wear and ability to maintain excellent surface roughness over time. Nonetheless, hybrid microwave treatment of $Si_3N_4$ inserts in dry turning of Inconel 718 is not recommended due to rapid tool wear and poor surface roughness.

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