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Effects of Minimal Quantity Lubricants Reinforced with Nano-Particles on the Performance of Carbide Drills for Drilling Nickel-Titanium Alloys

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ABSTRACT:

Drilling of NiTi alloys under two lubricant-coolant strategies; namely flood and minimal quantity nanolubricant; two types of carbides drills, and three cutting speeds was investigated. Progressive tool wear, tool-life, drilling thrust force, surface finish quality, and dimensional accuracy were considered. Experimental results suggest that the application of minimal quantity nanolubrications with coated carbide drills outperformed the flood lubrications with uncoated carbide drills. These results were pronounced for cutting speed of 10 to 20 m/min, whereas, accelerated tool wear, high thrust force, and low tool life were experienced for 30 m/min cutting speed. Despite of some promising results obtained from the supply of minimal quantity nanolubricants, this approach was found to be ineffective towards improving surface roughness and hole diameter accuracy.

KEYWORDS: *NiTi Alloys; Drilling; Tool Wear; Thrust Force; Tool Life; Surface Roughness; Hole Accuracy; and Minimal Quantity Nanolubrications*

1.0 INTRODUCTION

Recognitions of shape memory alloys (SMAs) among reseachers and industry players have been steadily up surging in the last few decades. Unique properties of SMAs suited them as excellent materials for several noteworthy applications. This includes sensors and actuators for automotive parts; vibration dampers and retractable landing gear for aerospace components; as well as implants and stents for biomedical domains or applications [1–3]. Research and development of this unique material cover from high temperature shape memory alloys, magnetic shape memory alloys, thin film shape memory materials, and shape memory polymers. Basic working condition of these alloys is relatively simple, in which, the metal alloys can be readily deformed through applications of external forces, as claimed by Jaronie et al. [1]. The authors also explained that SMAs can contract or recover to its original form after being heated beyond a certain temperature level either by external or internal heating; or through other relevant stimuli such as magnetic fields [1]. These intrinsic properties, along with the shape memory effect and the pseudoelasticity behaviours have made these materials highly exclusive than other engineering alloys counterparts [2].

Among many existing SMAs, NiTi alloys are most demandable materials and gain a substantial attention by a number of researchers. This is mainly due to their remarkable mechanical properties, which include high superelasticity, shape-memory effects, good corrosion resistance and high ductility with excellent mechanical strength [1,4,5]. Besides, these alloys also hold a unique capabilities of “remembering” and “returning” to their original conditions [1,5]. These properties provide benefits for biomedical engineering applications, especially in human body such as artificial organs and implants, since human body experiences stress changes during daily activities. Nonetheless, Hsieh et al. asserted that impediments toward a comprehensive development of NiTi alloys are attributed to difficulties in manufacturing process, particularly during machining or cutting processes [6]. Many of previous approaches through non-conventional machining processes such as laser forming, electro-discharge machining, waterjet machining, and electronic chemical machining have been successfully studied and implemented for cutting and shaping of the NiTi components [3,6–9]. Despite of these research outputs, Kaynak et al. stressed that industrial implementation of non-conventional processes for every component made from NiTi alloys may not always be achievable due to cost implications and lack of technological capabilities [10,11]. In that sense, conventional machining is still inevitably for material removal of these alloys into a range of geometrical shapes and sizes as well as dimensions.

Previous experimental studies on conventional turning of NiTi alloys showed that rapid tool wear and low cutting tool life expectancy are dominant machinability factors that need to be fully addressed [10,12]. For example, Kaynak et al. demonstrated that cryogenic cooling had a profound effect on controlling and reducing the accelerated tool wear rate as compared to minimal quantity lubrication (MQL) and dry cutting [10,11]. Similar authors further explained in Refs. [13,14] that in cryogenic machining, the grain boundaries of NiTi alloy were deformed into martensitic state, in which onset of deformation occured at a relatively low stress. Work material hardening was small or negligible for the first couple percent strain due to twinning mechanisms. The reseachers also claimed that these properties along with extremely low cryogenic temperature were favourable toward a proper chip formation due to smaller tool-chip contact length [13]. Kaynak et al. emphasised that, unlike in cryogenic machining, chip deformation behaviours in dry and MQL cutting were highly complex. It was also stressed that a combination of slip, deformation twinning, and unrecoverable stress-induced martensite formation existed, which were less favourable toward a proper chip forming processes [13,14].

Even though tool wear alone can be considered as one of the parameters affecting machining processes, it has a notable and direct impact on overall machining performance and product quality such as surface roughness and surface integrity. For instance, Weinert and Petzoldt [2] claimed on surface hardness integrity improvements of the NiTi alloys through the application of optimum cutting speed and tool coating in drilling the alloys despite a rapid tool wear that occured. As asserted by the authors, a reduction of cutting force in the shear cutting zone was substantiated since friction between tool and workpiece was alleviated by the hard coating on tool substrate [2]. However, a contradicting result was later reported by Guo et al., when the researchers studied the influence of cutting speed and feed rate on surface integrity characteristics of NiTi alloys during milling process [15]. The results showed that there was a lower hardness near the machined surface (which was attributed to the surface roughness) as compared to that of the white subsurface layer (which was resulted from changes in the austenite phase of cubic hard and rigid geometry) [15]. In a recent reported literature, machinability of nickel–titanium (Nitinol) shape memory alloy was discussed in term of optimum cutting speed that led to the minimum Von Mises and shear stresses criteria [16]. ANSYS/LS-DYNA R15 was applied in the finite element simulation through the implementation of SOLID164 3D element. The authors reported that resultant stress was in the lowest amount of 3.6 x 10^9 N/m^2, when the cutting speed reached 109 m/min. As claimed by the researchers, that a slight difference of 9% between finite element simulations with experimental data existed, which was a clear indication of a very good fit [16].

Among many conventional machining processes, drilling on NiTi alloys is an equally and increasingly important for fabrications of biomedical components. Holes are required on spinal rods, spinal vertebral spacers, implants, extension springs, etc [3]. These components are typically assembled to other main parts, and hence, drilled holes should not have any burrs for such applications. However, a previous study reported that while machining nickel titanium alloys, a large amount of materials were not separated from the workpiece and appeared as several layers of material or burrs [17]. Shyha and his colleagues also found in their study that a large exit burr was formed as a result of drilling an unsupported specimen of Kovar shape memory alloys [18]. Optimum burr size was obtained when smaller tool diameters and lower feed rates were used, whereas very limited impact was observed when increasing the cutting speed [18]. The exit burr heights were reported to be within the values of 0.44 – 2.42 mm and 0.14 – 0.75 mm, respectively for unsupported and supported Kovar shape memory plates. From these results, it is obvious that smaller burrs were obtained when the Kovar shape memory alloys were supported at the back-end during drilling process.

Due to temperature dependent and stress induced phase transformation of the NiTi alloys during machining, it must be stressed that cooling and lubricating conditions; apart from machining parameters and tooling factors, should be carefully considered due to rapid tool wear. Our previous studies have reported a significant and positive effects of minimal quantity nanolubrication on progressive tool-wear, tool life, and surface roughness during machining of AISI 1050 and titanium alloys, Ti-6Al-4V [19,20]. Apart from these studies, Dambatta et al.

showed that the application of MQL with silicon dioxide suspended nanoparticles had a profound effect in reducing grinding forces, workpiece surface roughness, surface damage, and wheel wear [21]. The authors attributed these results to a formation of thin tribo-film on the surface of grinding, which allowed better slewing action and material removal. Therefore, it is hypothesised that similar effect for the nickel-titanium alloys can be attained. However, scientific experimental data on drilling of these NiTi alloys under minimal quantity nanolubrication are still lacking or underreported. In this current study, the focus lies in the experimental investigation on the effects of lubricating conditions such as flood and minimal quantity nanolubrication on the progressive tool-wear growth of coated and uncoated carbide drills, as well as drilling thrust force. Surface roughness and dimensionally accuracy of the drilled hole were subsequently determined for evaluation of the drilling quality of the NiTi alloys.

2.0 EXPERIMENTAL PROCEDURE

2.1 Workpiece material

The material used in this experiment was NiTi alloy of 50.2 and 49.8 (at%) from Nickel and Titanium elements, respectively. The alloy was acquired from Kellog's Research Lab, USA and it was received as a plate of 500 x 150 x 10 mm in length, width and thickness, respectively. A wire electrical-discharge cutting process was used to trim the plate into drilling specimens with approximate size of 94 x 70 mm. This was done so that the sample can accommodate the working space of the cutting force dynamometer and can be securely fixed in a specially fabricated channel jig. The alloy was used or drilled as received without any heat treatment carried out on it.

2.2 Cooling and lubricating conditions

A number of research studies have reported on the suitability of adding nanoparticles in a base fluids for various machining processes such as grinding, milling and turning. Frequently used nanoparticles, as reported in the literature, include molybdenum disulphide, copper oxide, silicon dioxide, and aluminium oxide. In this study, aluminum oxide (Al_2O_3) nanoparticles of < 50 nm particles size were chosen. 0.4 wt% of the particles were prepared and mixed with a water soluble cutting oil (SolCut). The mixing of the cutting oil with the nanoparticles was performed at a temperature of 18-23 ºC using an ultrasonic liquid processor for a duration of 4 hours. 1% of sodium dodecyl benzene sulfonate (SDBS) was included into the nanolubricant in order to alleviate any agglomeration in the mixture. This was found in our previous studies when turning AISI 1050 hardened steel and titanium alloys as stated in Refs. [19,22]. To ensure a uniform mixing, the ultrasonic processor was set at 100 kW output power with an amplitude frequency of 25%. The prepared nanolubricants were delivered to cutting or drilling area under near dry condition using a UNIST Minimal Quantity Lubrication system at a flow rate of 50 ml/hr, which was a typical setting used and recommended in several studies reported earlier [19,22–24]. One nozzle was placed near the tip of the drill, wheras the other one was close to the drill cutting edges so that the lubricants can be deliverd efficiently near the tool-chip interface. For comparison purposes, flood lubrications using Solcut (water soluble fluids) were also considered in the experimentation.

2.3 Setup and drilling parameters

A three-axis CNC milling machine was used for the drilling experimentations. As depicted in **Figure 1**, each of the through holes were drilled on a rectangular NiTi plate. To avoid any vibration or chatter, the plate was securely and tightly clamped onto a specially designed channel jig. Drilling process was carried out under three cutting speeds of 10, 20 and 30 m/min with a constant feed of 0.02 mm/rev. A preliminary test revealed that cutting speed of higher than 30 m/min led to a rapid failure of the drill bit due to excessive chipping and loss of the main cutting, chisel edges as well reaching the tool wear criteria or limit of within the first two drilled holes. Lower speed than 10 m/min was deemed unsuitable with respect to machining productivity. A constant feed was used due to smaller or negligible influence of this parameter towards the growth of tool wear. Uncoated tungsten carbide drills and coated tungsten carbide with TiAlN coatings were used for performance purposes. It is imperative to be noted that these two typical tool coatings are commonly tested and compared in previous research studies of drilling titanium, nickel based alloys as well as NiTi [12,25]. With respect to the drilling performance evaluative factors; the tool wear growth, surface roughness, and induced thrust force were measured in this study.

The growth of wear on the drills was monitored using Xoptron XST60 stereomicroscope at 35x optical magnifications. The measurement of flank wear was made for every hole that was drilled until the flank wear length has reached an average value of 0.2 mm wear limit or criteria, as recommended by Rival [26]. The IMT Mini image processing software assisted in measuring the wear length and it was determined from the average value of each of the drill cutting edges. As far as the surface roughness is concerned, this output parameter was measured using a portable surface roughness measurer, after all drilling experimentations have completed. Measurements were made at four equi-distant locations along the hole surface and average value was taken. A traverse speed of 8 mm/min was employed for the stylus pick-up. The trend of surface roughness for all of the drilled holes were reported, so that the effects of tool wear on the surface roughness can be elucidated. Dimensional accuracy of the drilled hole diameter was evaluated using Mitutoyo coordinate measurement machine. An average dimensional accuracy was obtained from the measurements of hole diameter at the entrance, middle and exit locations. Finally, a stationary Kistler® dynamometer was used to acquire the induced thrust force at sampling rate of 1–2kHz. This sampling rate was taken so that any minor variation in the force signals can be detected.

3.0 RESULTS AND DISCUSSION

3.1 Tool wear progress and tool life

Progress of flank wear on both uncoated and coated carbide drills for feed rate of 0.02 mm/rev and cutting speeds of 10, 20, and 30 m/min against drilling time and number of drilled holes are depicted in **Figure 2 and 3,** respectively. In this study, the flank wear growth on both of the main cutting edges of the drills were measured at several locations and an average flank wear length was determined. It is evident that the average wear length for uncoated carbide drills were initially very high, with flank wear reaching 0.1 mm within only a few seconds of drilling or within the first two holes, especially for the speed of 20 and 30 m/min. Whereas, the wear rate for the coated carbide drills displayed a consistent run-in period and was lightly stabilised after drilling 10 holes. These general observations revealed that the coated drills exhibited superior performance than the uncoated ones in terms of wear resistance due to presence of harder coatings of TiAlN on the carbide drills. This result is in agreement with the findings obtained by Weinert et al. [12] when the researchers investigated the drilling of NiTi alloys with Titanium Carbo-Nitride/Titanium Nitride (TiCN/TiN) multicoating tools. The authors claimed that an optimum cutting speed of 30 m/min was suitable for the aforementioned drilling investigations. Machining surface quality was also reported to improve with a measured surface roughness of up to 5.9 μm.

The findings from this study clearly exhibited that coated drills outperformed those uncoated drills in terms of the tool life criteria. This was assessed in term of the wear length reaches a maximum flank wear of $VB_{max} \leq 0.2$ mm after a certain drilling duration (which is measured in seconds or certain number of holes). Drilling time to attain this specific tool wear criteria was estimated to be 1965 and 785 seconds, respectively for the speed of 10 m/min and 20 m/min. It is to note that these results were attained when using TiAlN coated drills under minimal quantity nanolubrications. However, when flood lubrications were employed, a slightly lower drilling time of 1800 and 725 seconds were recorded, respectively for the same drilling speeds. It appears that Al_2O_3 nanoparticles play an important role to enhance lubricity and improve friction coefficients of the base fluids compared to that of the flood conditions. These results are in agreement with Park et al. [27], in which the authors reported that nanographene-enhanced vegetable oil fluids provided superior results in terms of wettability and a reduced friction coefficient, which improved tool wear and edge chipping resistance. In addition, Sharma et al. explained that the nano-sized particles in nanolubricant have a tendency to interact with friction and they are deposited on the contact surface to form a physical tribo-film that compensates for the loss of mass due to friction [28]. Hence, it can be concluded that the nanoparticles inclusion in the SolCut base fluids was equally beneficial in improving the coolant properties with that of the flood conditions. The use of minimal quantity lubrication for the nanolubricants adds to the advantage of a cleaner production or machining environment.

However, as depicted in **Figure 2 and 3**, it is evident that the development of flank wear progressed highly rapid, especially for the highest cutting speed of 30 m/min when using the TiAlN coated drill. This was observed from the 1st hole until the failure of drill at the 6th hole. Drilling time of only 118 seconds was recorded to reach the aforementioned number of holes. This concludes that speed of 30 m/min could be the threshold to drill the NiTi alloys under the minimal quantity nanolubrications. Surprisingly, coated drill sustained a longer tool life of 338 seconds or 16 holes for the same cutting speed when flood lubrication was employed. This shows that the water soluble cutting fluids under flood conditions was able to penetrate closer or nearer to the drilling cutting zone to alleviate friction and tool wear for the highest cutting speed employed in this study. As far as uncoated drills are concerned, results shown in **Figure 2 and 3** depicted that the uncoated carbide drills were unsuitable for drilling these extremely hard NiTi alloys due to aggressive tool wear. For the cutting speeds of 20 and 30 m/min, the uncoated drills can only be used for less than 180 seconds, which was equivalent to less than 6 drilled holes. This was discovered regardless of whether flood or minimal quantity nanolubrication was employed.

Nevertheless, drilling time can reach 870 seconds with 13 drilled holes when the lowest cutting speed of 10 m/min was employed. This is consistent with common understanding that low cutting speed will lead to longer tool life. With respect to the tool wear mechanisms, it was observed that abrasion was the main mechanism for both types of carbide drills, **Figure 4(a-b)**. This can be identified by parallel grooves or scratches in the direction of the material flow during drilling process. On the other hand, **Figure 4(c-d),** revealed a large built-up layer or edge (BUE) on each of the drill cutting edges, apart from some severe chipping and cracking on the main and chisel edges. All of these phenomenon contributed to the tool failure mode and these observation are in good agreement with the results in Refs [13,14]. It is to note that the measurement of the flank wear was extremely difficult and could led to possible measurement errors with the presence of BUE and chipping on the cutting edges. As a consequence, measurement of flank wear was repeated to ensure consistency and validity.

3.2 Taylor's tool life equation

A tool life in drilling process is often described by the number of holes produced or drilled prior to the tool failure. A tool life can also be described as the time a drill reaches a predefined wear criterion. Previous section discussed the growth of flank wear that leads to an estimation of tool life with respect to drilling time. **Figure 5** shows a comparison of the tool life values obtained for the two lubricating and cooling conditions investigated under the given drilling parameters depicted in **Table 2**. It is clear that coated drills and minimal quantity nanolubrications outperformed the uncoated drills in term of the tool life. For instance, when drilling at an intermediate cutting speed of 20 m/min, an increment of 88% in tool life was achieved by the coated carbide drills as compared to that of uncoated drills with minimal quantity nanolubrication. In a meantime, the well established Taylor's tool life equation was subsequently employed to determine the relationships between tool life and the considered machining parameters. The development of this equation also allows prediction of tool life while drilling the NiTi alloys.

Consistent with the existing metal cutting theory, tool wear was found to increase substantially with a higher cutting speed as shown in the Taylor's tool life model, $VT^n = C$, where V is the cutting speed (in m/min), *T* is the tool life (in seconds), *n* and *C* are empirical constants. Using statistical analysis, the Taylor's tool life equations derived as a function of cutting speed, *V* are given as:

$VT^{-0.661} = 1455$, $R^2 = 0.99$ ………………… (1) (*Coated drill under flood condition*)

$VT^{-0.363} = 182$, $R^2 = 0.88$ ………………… (2) (*Coated drill under MQL nano*)

The Taylor's tool life equations derived herein were specifically for the coated drills. This is due to the fact that performance of coated carbide drills was significantly better than the uncoated ones in terms of drilling time as well as the number of drilled holes, as explained earlier. From the two equations shown above and judging from the R^2 values of 0.99 and 0.88, it can be concluded that the derived empirical equations can describe experimental trend highly well. Empirical constant, *n*, for both equations are also very close to the reported values in the literature for similar type of tool/ work material combination, i.e. titanium or nickel alloys with tungsten carbide cutting tool [29,30].

3.3 Drilling thrust force

Effects of cutting speed on the development or growth of the thrust force against drilling time and number of drilled holes are denoted in **Figure 6 and 7,** respectively. Within the early stage of drilling experiment, i.e. from the first to the fifth holes, induced thrust forces were in the range of 160 N to 250 N under the minimal quantity nanolubrications and coated carbide drills. Further drilling of above the fifth hole led to a fairly gentle increment in the induced thrust force for all considered drilling speeds. Under the lowest cutting speed of 10 m/min, the TiAlN coated carbide drills induced a maximum drilling thrust force of 327 N. However, unlike the result from 10 m/min of cutting speed, a lower drilling thrust force of 255N was generated when highest cutting speed of 30 m/min was tested. Apparently, the induced thrust force exhibits a declining trend of about 22% when cutting speed was raised. These results are in-agreement with previous research of machining nickel-based alloys [31] and titanium alloys [32]. In Ref [31], the authors claimed that the results were attributed to the low heat dissipation in the cutting zone, which indirectly reduced the hardness of the material to enhance material removal process. Meanwhile, authors in Ref. [32] conceived that a thin boundary film was formed between the tool–workpiece interfaces when MQL was used, which presented a significant thrust force reduction.

In our case, application of minimal quantity nanolubricants contributed towards a reduced coefficient of friction between the tool-workpiece interface. As a matter of fact, the presence of nanoparticles in the base fluids could facilitate the polishing or rolling effects of the nanoparticles between two contact surface, apart from the formation of thin protective film, similar to the claim by Sayuti et al. [33]. This mechanism leads to lesser friction between surface of the drill and NiTi workpiece. Hence, it attributed towards a significant reduction in the thrust force, as depicted in **Figure 6 and 7**, for the cutting speed of 30 m/min. This is despite the accelerated tool wear under this cutting speed, as shown earlier in **Figure 2 and 3**. Contrary to the preceding discussions, application of flood conditions in drilling the NiTi alloys for the same drilling speeds has resulted in a significantly high induced thrust force. The magnitude of thrust force was in the order of 2 to 4 times higher than those from minimal quantity nanolubricants. It is believed that the flood coolants were not be able to ease extreme heat generation in the cutting zone, which was the main cause for the high thrust force. Likewise, similar trends of high thrust force were observed for the uncoated drills as compared to the coated ones, regardless of whether minimal quantity nanolubricants or flood coolants were applied.

3.4 Surface roughness and dimensional accuracy

Condition of machined component surface is vital as it can directly influence fatigue and functional performances of the component during in-service. Very often, drilling process can induce surface and subsurface alterations on the finished part. Whereas, impact of the aforementioned progressive tool-wear towards dimensional accuracy of the NiTi (i.e. hole diameter and hole roundness) is equally important aspect to be fully understood. **Figure 8** represents average surface roughness values over the number of drilled holes for flood and minimal quantity nanolubrications. As apparent, uniform and consistent roughness values in the range of 0.7 μm to 1.2 μm were observed regardless of the drilling speeds, cooling and lubricating conditions, as well as the type of coating on the drills. However, it was quite a surprise that the values of surface roughness were marginally or slightly high under minimal quantity nanolubrications as compared to that of the flood conditions, **Figure 8**. This is incongruent with results from past researchers that employed MQL conditions to cut NiTi alloys and other materials. For instance, Kaynak et al. claimed that MQL machining of NiTi alloys had resulted into smallest variation of R_a values over some machining duration [13]. Similarly, Dambatta et al. reported an improvement of surface roughness and surface damage during grinding of Si_3N_4 ceramic materials with silicon dioxide nanoparticles suspended MQL [21]. Debates are still highly ignited due to mix of results produced by researchers in machining difficult-to-cut materials with MQL, as claimed by Boswell and his co-authors [34].

Figure 9 further reveals the average surface roughness values for each of drilling speeds employed. Herein, the applications of minimal quantity nanolubrication resulted in a slightly higher surface roughness values as compared to the flood conditions. For example, at cutting speed of 10 m/min, the measured surface roughness were 0.959 μm and 0.987 μm, respectively for flood and minimal quantity nanolubrications. Likewise, for cutting speed of 30 m/min, surface roughness of 0.834 μm and 0.938 μm were recorded under flood and minimal quantity lubrication, respectively. Although previous section has emphasised some encouraging effects of nanolubrications toward reducing drilling thrust force, however, inclusion of nanoparticles in the SolCut base cutting fluid has detrimental effect on surface roughness. In fact, the Al_2O_3 nanoparticles could probably influence the surface roughness due to the rubbing effects of these hard particles against the workpiece surface. Sayuti et al. asserted that chemical reactions occurred on the thin film Al_2O_3 nanolubricants could also lead to the formation of welded zone on the NiTi surface [33]. It was conceived that the oxide welded zone has a slightly higher hardness profile, which explained why there was an incremenet in the surface roughness [33]. High cutting temperature generated during drilling process could lead to an intensive formation of Al_2O_3 protective film, which was then peeled off due to aggressive cutting action to produce rougher machined surface. As a result, the drilled surfaces were inspected under a high power microscope in order to identify in detail any surface structure defects resulted from the application of Al_2O_3 nanoparticles in the base cutting fluids. **Figure 10** depicts the poor surface qualities with a number of defects, specifically cracks and uneven surfaces due to material adhesions. A relatively smoother surface was obtained under flood condition as shown in **Figure 11**.

Meanwhile, average hole diameter accuracies, which were measured at three depth locations, are shown in **Figure 12 and 13**. These results demonstrated that diameter accuracy of the drilled holes were significantly influenced by the choice of cooling and lubricating conditions as well as the type of drill coatings. Diameter of the drilled NiTi alloys were comparatively high when minimal quantity nanolubrication with coated drills was employed in the drilling experiments. This is fairly in-line with the outcome of surface roughness discussed previously. Apparently, the presence of rough surface finish attributed to a larger hole diameter of 6 to 103 μm variation from the nominal value of 6.0 mm. It is believed that similar mechanisms that was discussed for the surface roughness are valid to explain the deviation in hole dimensional accuracy. Unlike in the minimal quantity nanolubrications, flood conditions with uncoated drills contributed to a superior hole diameter accuracy with a variation in the range of 12 to 50 μm from the nominal diameter.

4.0 CONCLUSIONS

This work considered tool-wear, tool-life, thrust force, surface roughness, and dimensional accuracy aspects of drilling NiTi shape memory alloys. Experiments were evaluated with respect to minimal quantity nanolubrication and flood conditions, with two types of carbide drills; namely, uncoated and TiAlN coating, and under three different cutting speeds. The following concluding remarks can be drawn from the results discussed earlier:

1) The nanoparticles inclusion in SolCut base cutting fluids was beneficial in improving the minimal quantity coolant-lubricant properties while drilling the NiTi alloys. Al_2O_3 nanoparticles play an important role to enhance thermal conductivity and improve heat transfer coefficients of the base fluids.

2) In specific, coated drills exhibited superior performance than the uncoated ones in terms of tool progressive wear rate, especially under the application of minimal quantity nanolubricants. A consistent and stablised run-in period were displayed until the tool-life expentency has reached. However, it was showed that the minimal quantity nanolubricants were only deemed suitable to control the rate of tool wear within the cutting speed range of 10 to 20 m/min.

3) As for the drilling thrust force, similar decreasing trends were displayed under the minimal quantity nanolubricants due to polishing or rolling effects and formation of thin protective film of the nanoparticles between contact surface of tool and NiTi alloys.

4) Nonetheless, this minimal quantity lubrications approach was found to be ineffective towards surface quality and dimensional accuracy as compared to that of the flood lubrications for all cutting speed employed and type of coated drills used. Microscopic inspection of the drilled surface revealed a number of surface structure defects which attributed towards poor surface roughness and high dimensional tolerance of the hole diameter.

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List of Tables

Table 1: Experimental details

Items	Descriptions
Machine Tool:	
CNC milling machine	Tongtai EZ-5A
Data Acquisition Equipment:	
Microscope	Xoptron Stereo Microscope XST60
Dynamometer	Kistler Type 9129A with 9070 Charge Amplifier
Portable surface roughness	HandySurf E-35B
Workpiece:	
Material	Nickel-Titanium (NiTi)
Dimensions	94 mm x 70 mm x 10 mm
Cutting Tools:	
Material	Tungsten carbide (WC–Co)
Type of drill	Twist drill
Diameter	6 mm
Point and helix angle	30°, 135°
Coatings	Uncoated and TiAlN coated
No. of flutes	2

Table 2: Drilling parameters

Parameter level	1	2	3
Cutting speeds (m/min)	10	20	30
Feed rate (mm/rev)		0.02	

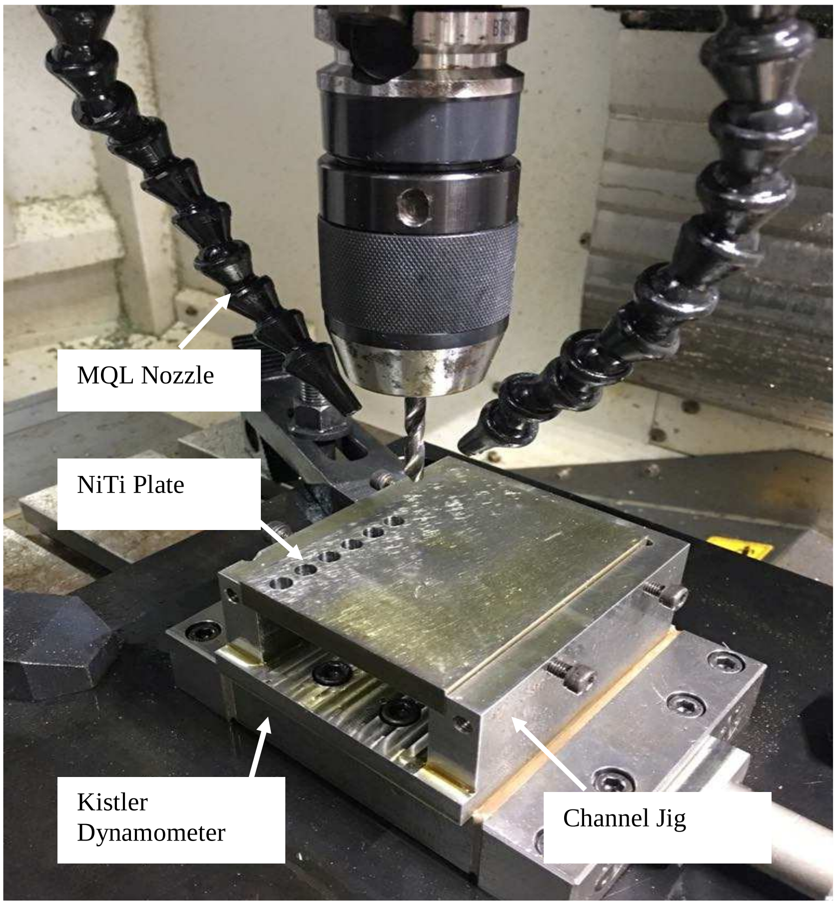


Figure 1: Drilling experimental setup consists of Kistler force dynamometer, channel jig and lubrication nozzles

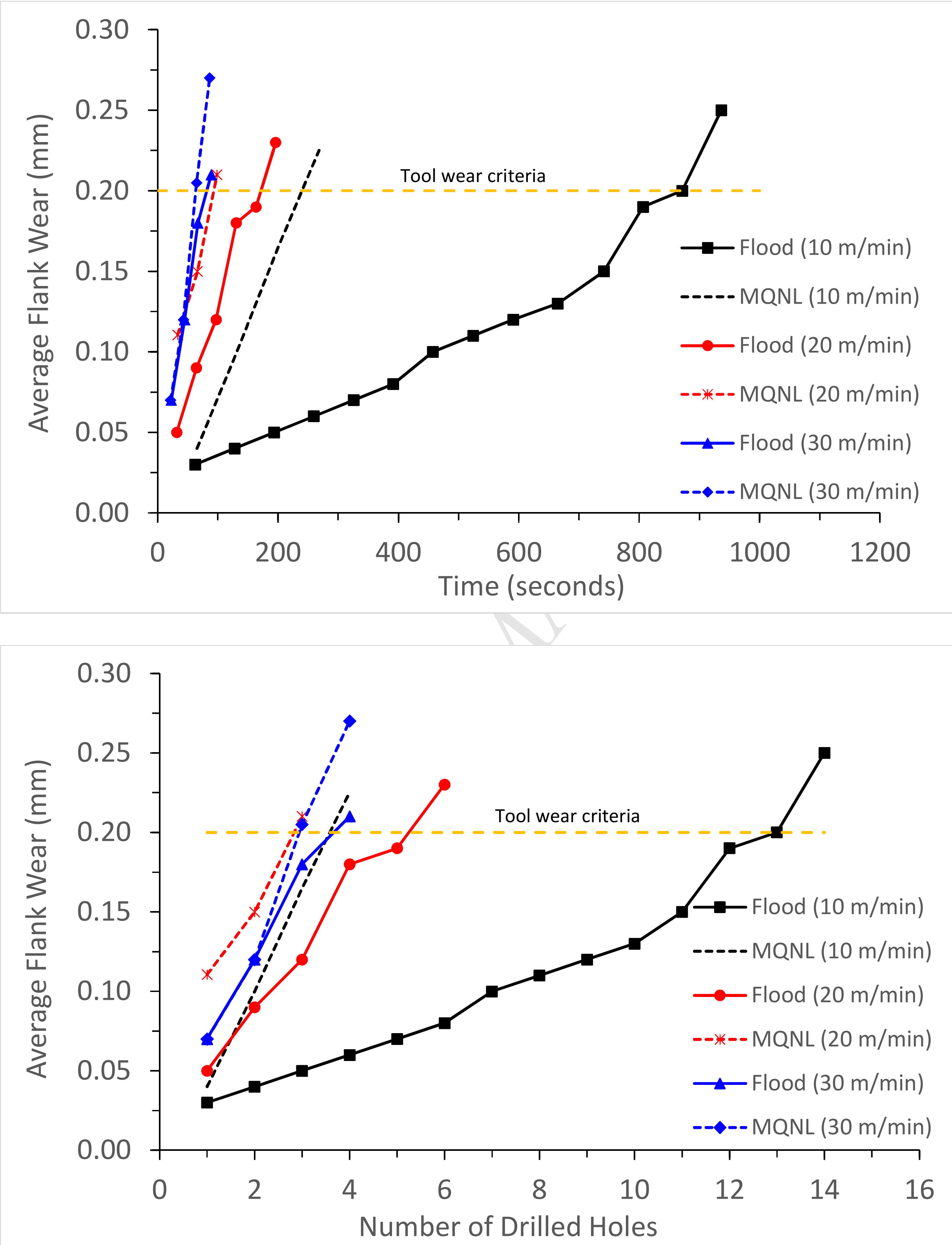


Figure 2: Average of flank wear on the uncoated drills against (a) time in seconds and (b) number of drilled holes for respected experimental conditions

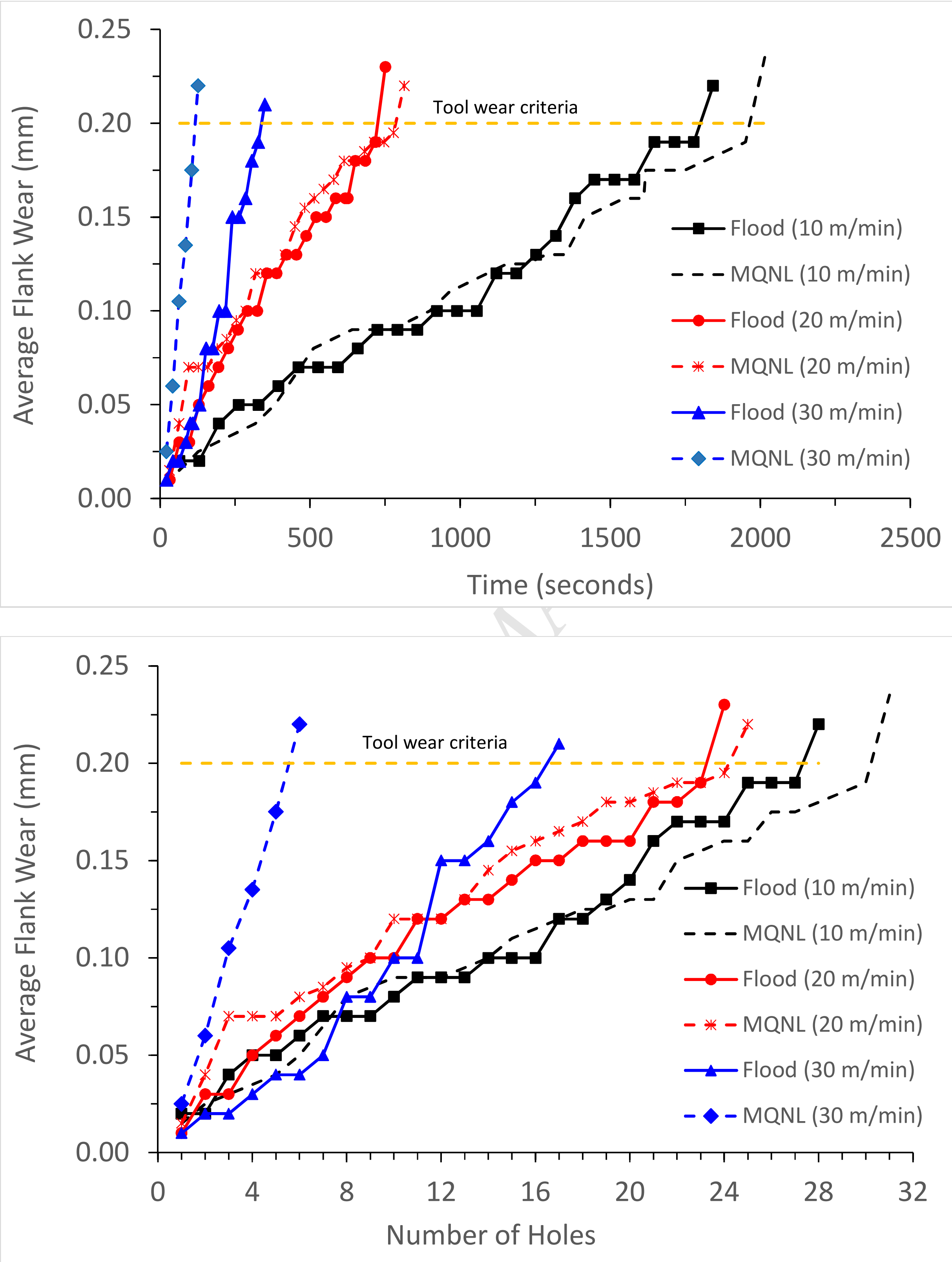


Figure 3: Average of flank wear on the coated drills against (a) time in seconds and (b) number of drilled holes for respected experimental conditions

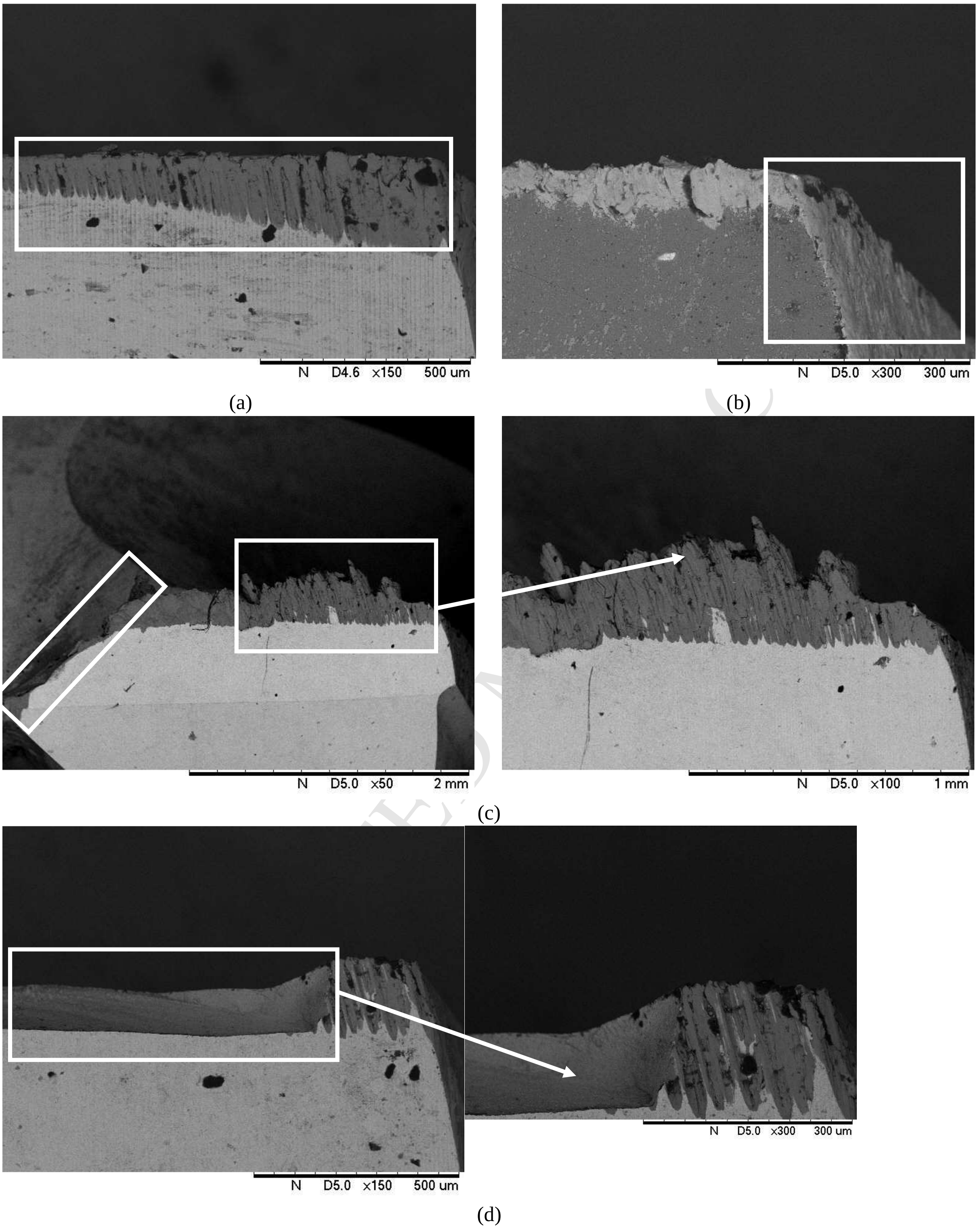


Figure 4: (a) Abrasion on uncoated carbide drill at 10 m/min under flood lubricating condition, (b) abrasion on coated carbide drills at 20 m/min under minimal quantity nanolubrication condition, (c) formation of built-up edge (BUE) and chipping on coated carbide drill at 30 m/min under flood lubricating condition, and (d) catastrophic failure on uncoated carbide drill under flood lubricating condition

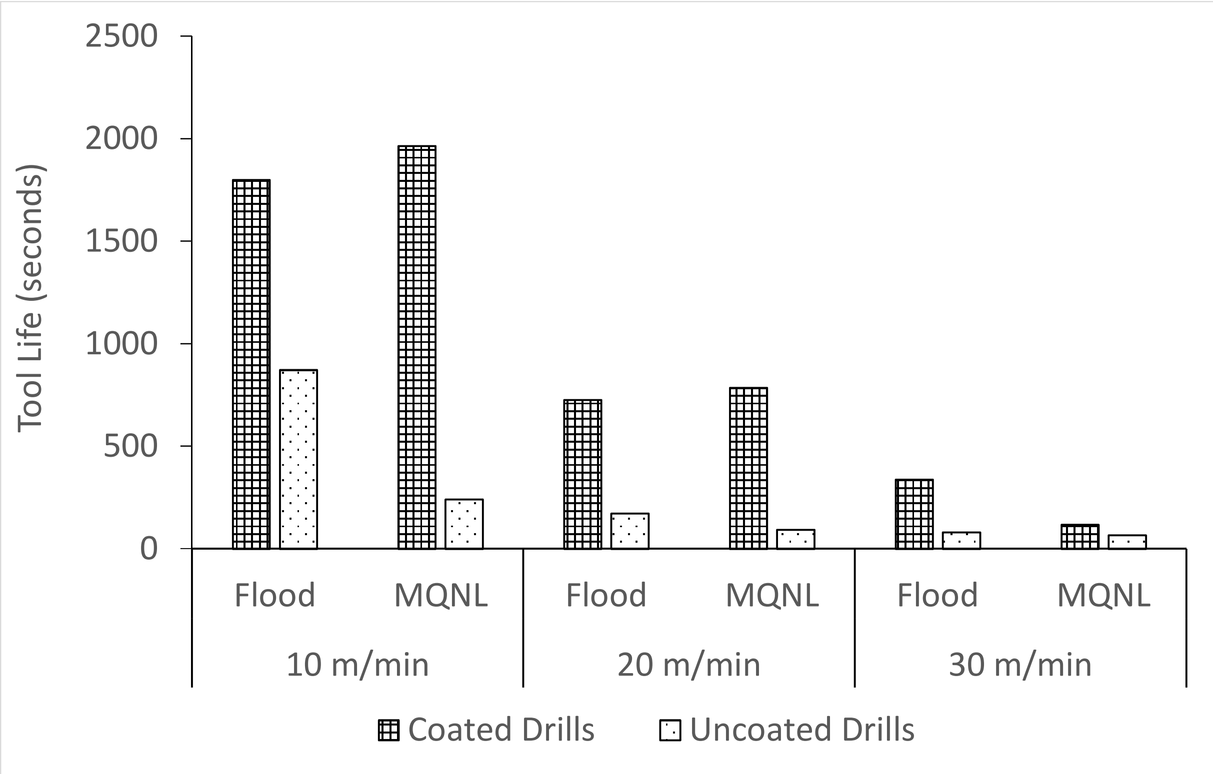


Figure 5: Tool life for uncoated and coated carbide drills with respect to experimental conditions

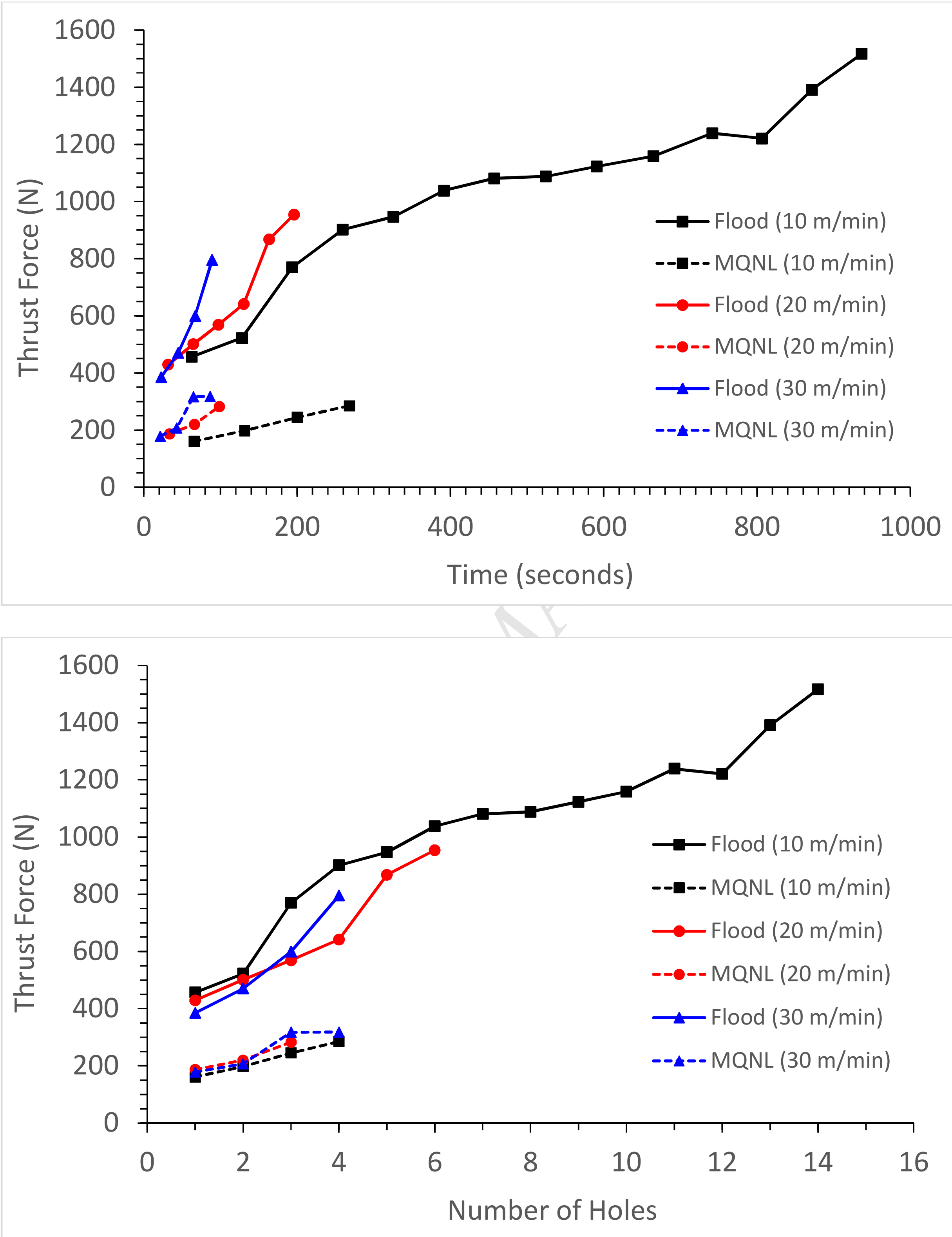
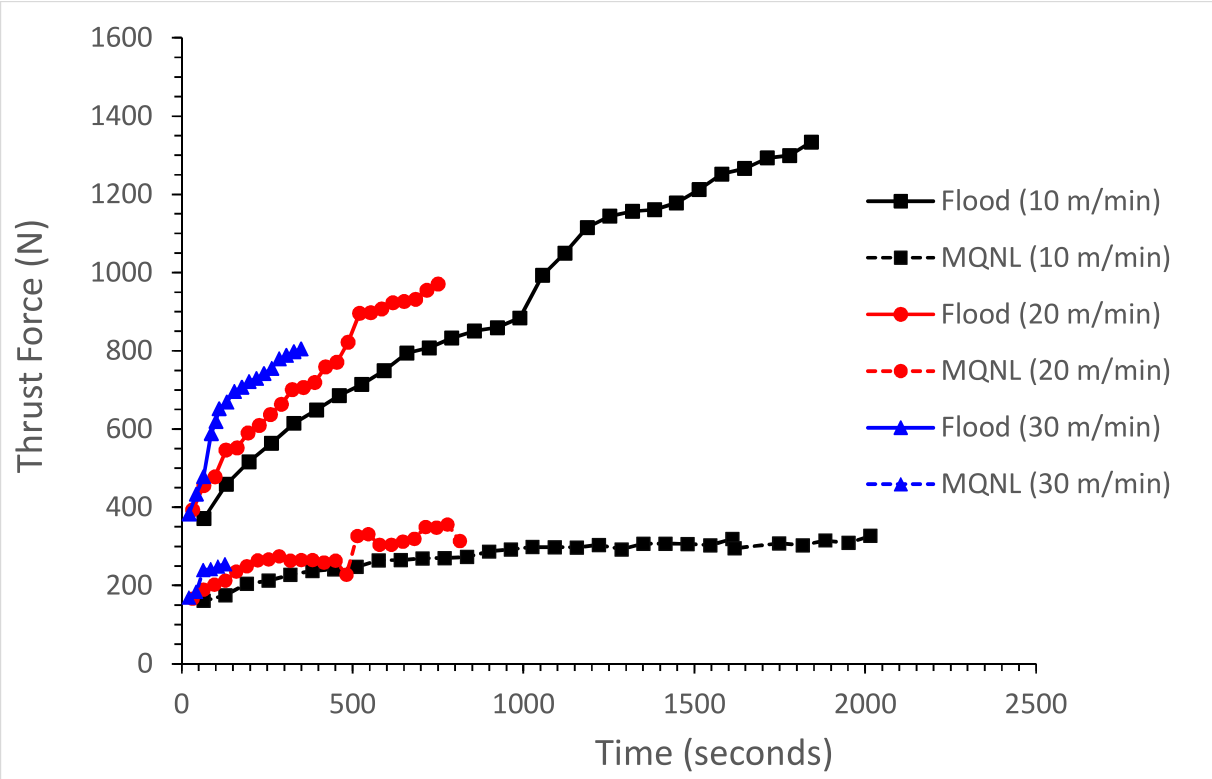


Figure 6: Development or growth of drilling thrust force for uncoated drills against (a) time in seconds and (b) number of drilled holes for respected experimental conditions



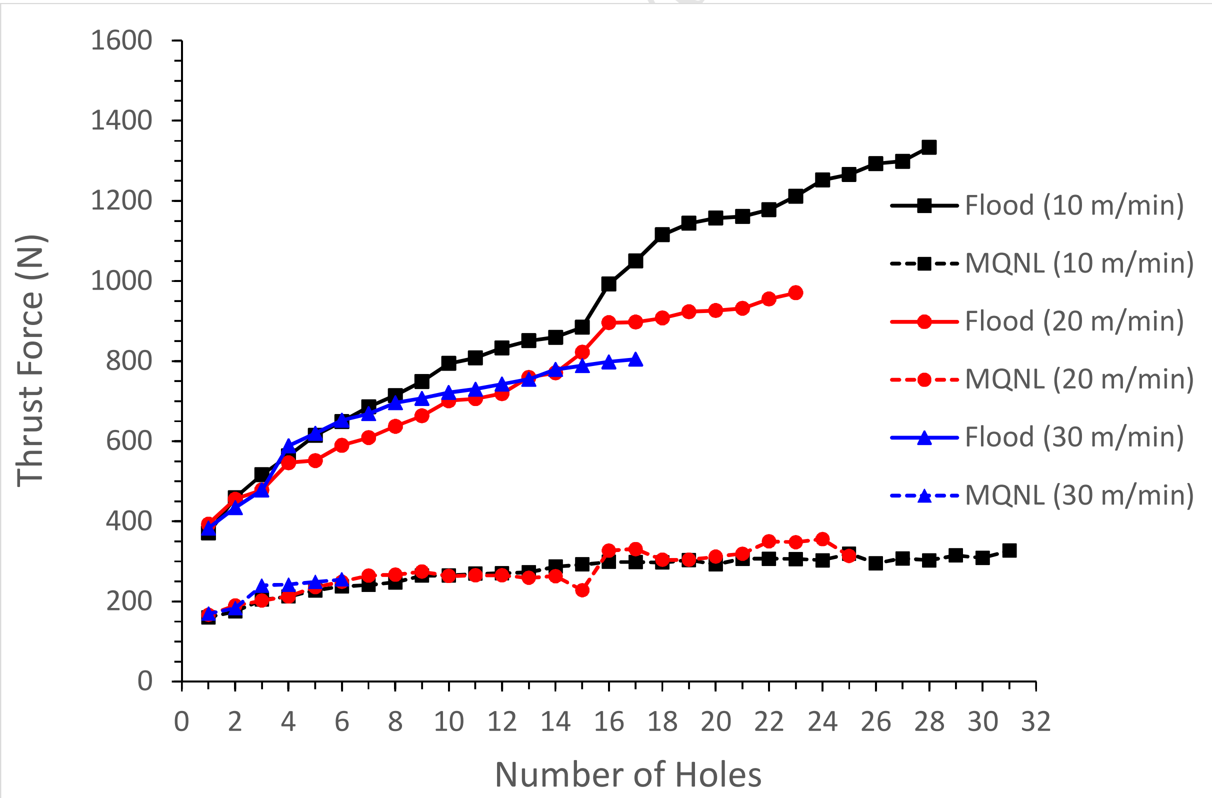


Figure 7: Development or growth of drilling thrust force for coated drills against (a) time in seconds and (b) number of drilled holes for respected experimental conditions

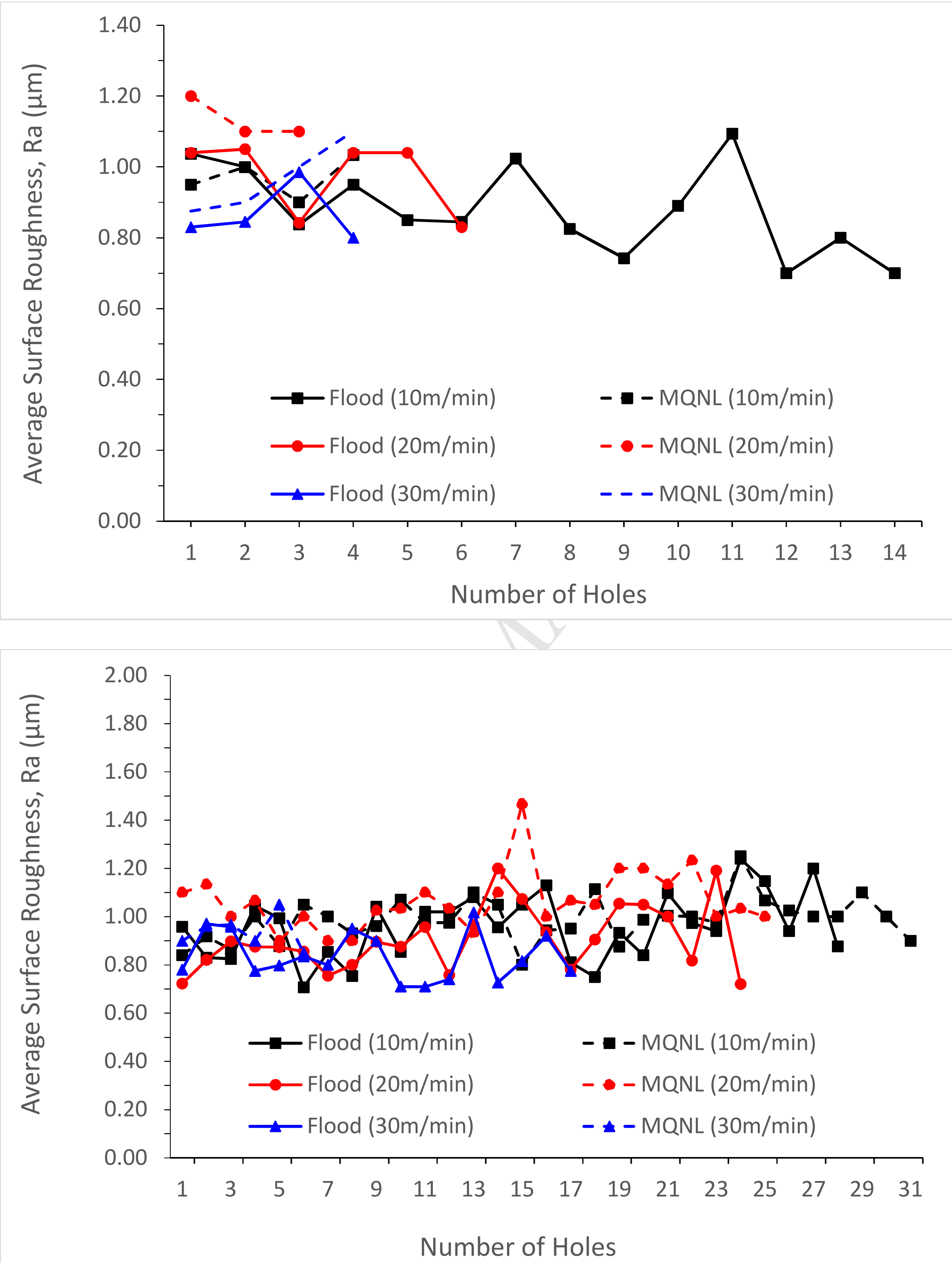


Figure 8: Average surface roughness of (a) uncoated drills (b) coated drills against number of drilled holes for respected experimental conditions

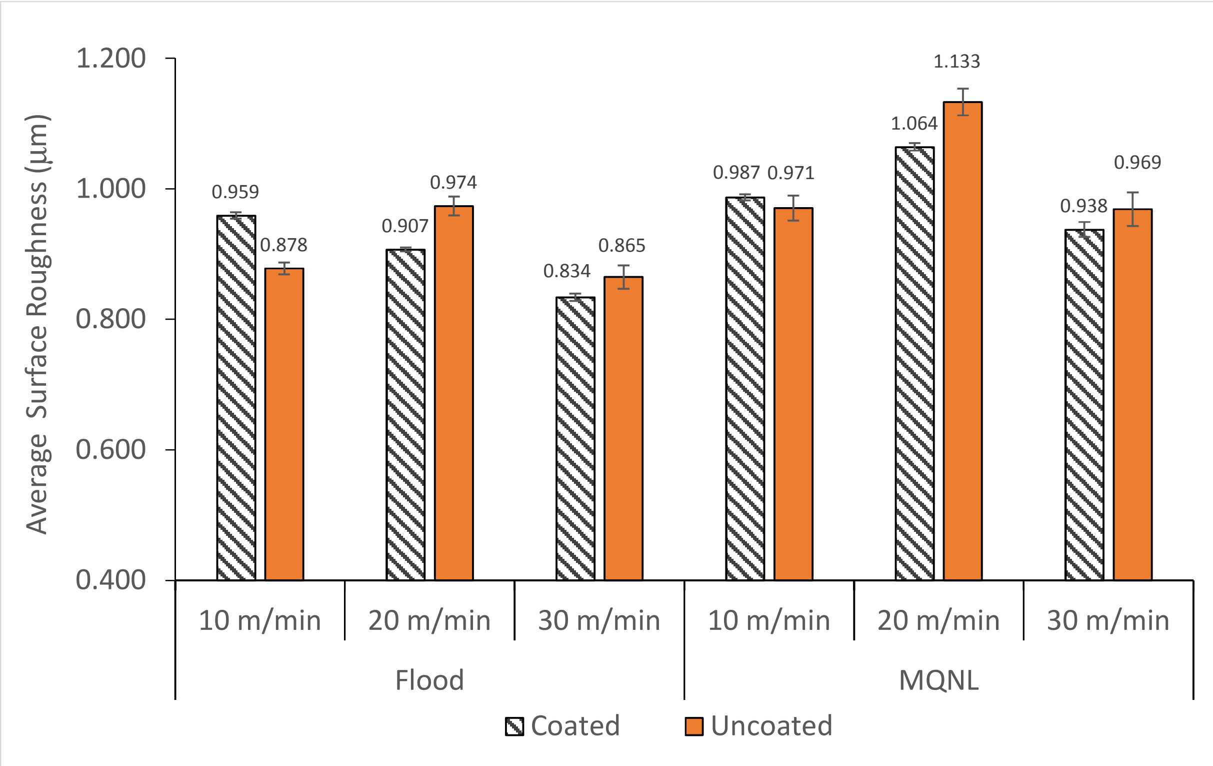
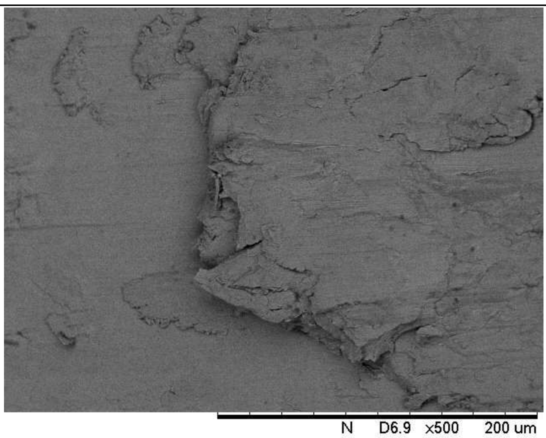
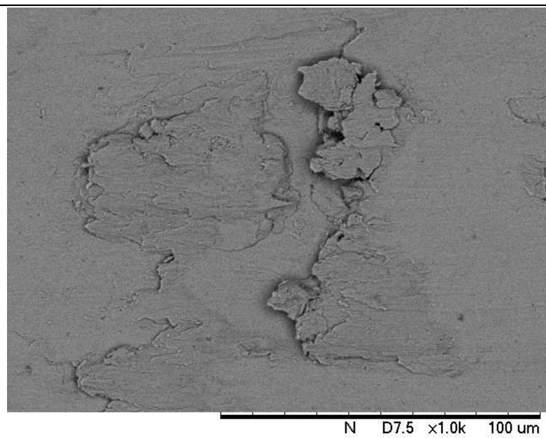


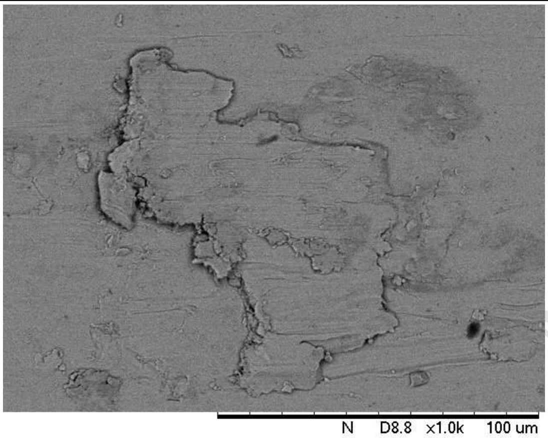
Figure 9: Average of surface roughness with respected experimental conditions



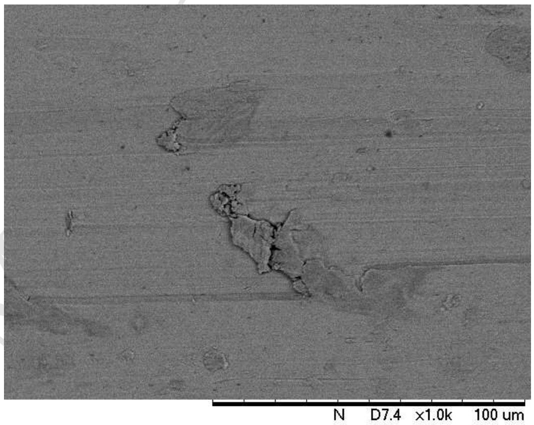
(a) uncoated drill at 10 m/min



(b) coated drill at 10 m/min



(c) uncoated drill at 30 m/min



(d) coated drill at 30 m/min

Figure 10: Surface structure defects for different drill types, cutting speed and MQL nanolubrication conditions

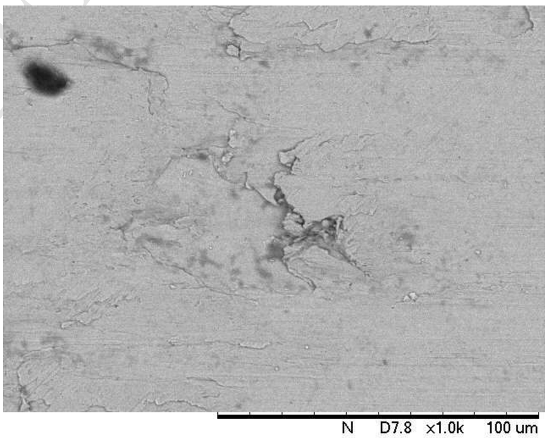
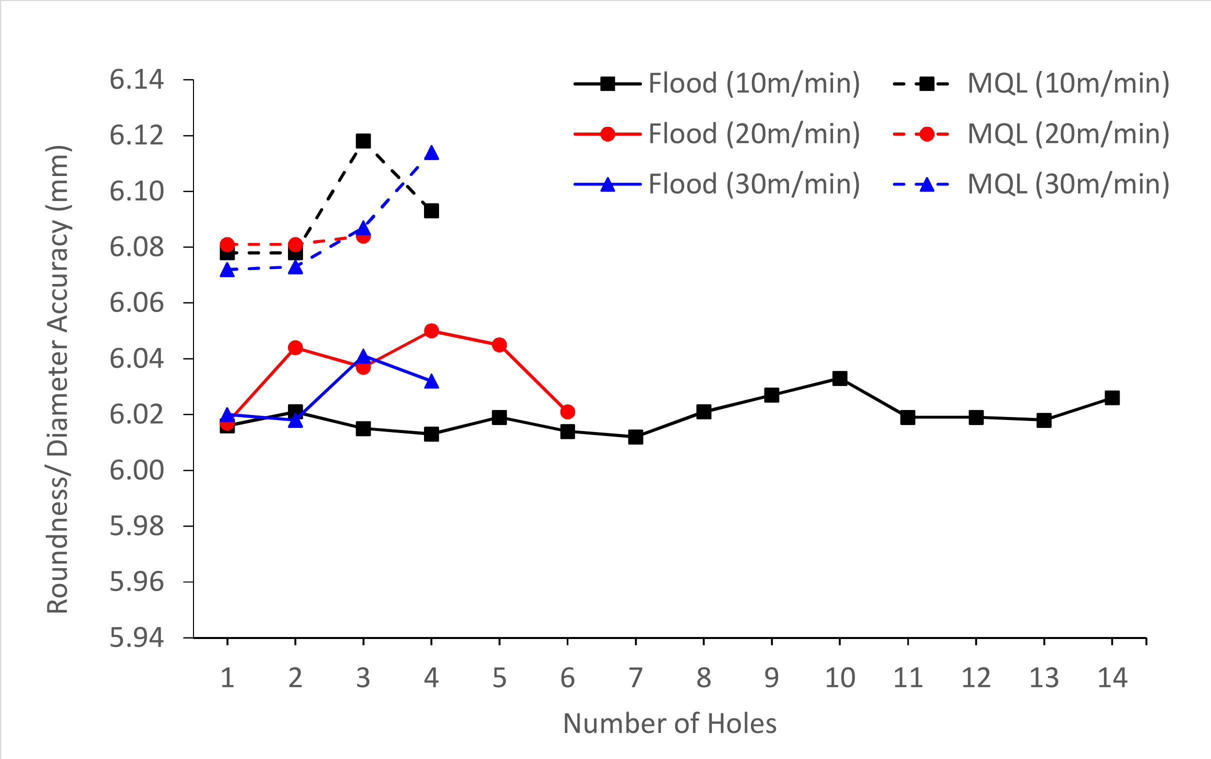


Figure 11: Surface morphology under flood lubricating conditions for uncoated drill and 10 m/min


Roundness/ Diameter Accuracy (mm)
6.14
6.12
6.10
6.08
6.06
6.04
6.02
6.00
5.98
5.96
5.94
Flood (10m/min)
MQL (10m/min)
Flood (20m/min)
MQL (20m/min)
Flood (30m/min)
MQL (30m/min)
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Number of Holes

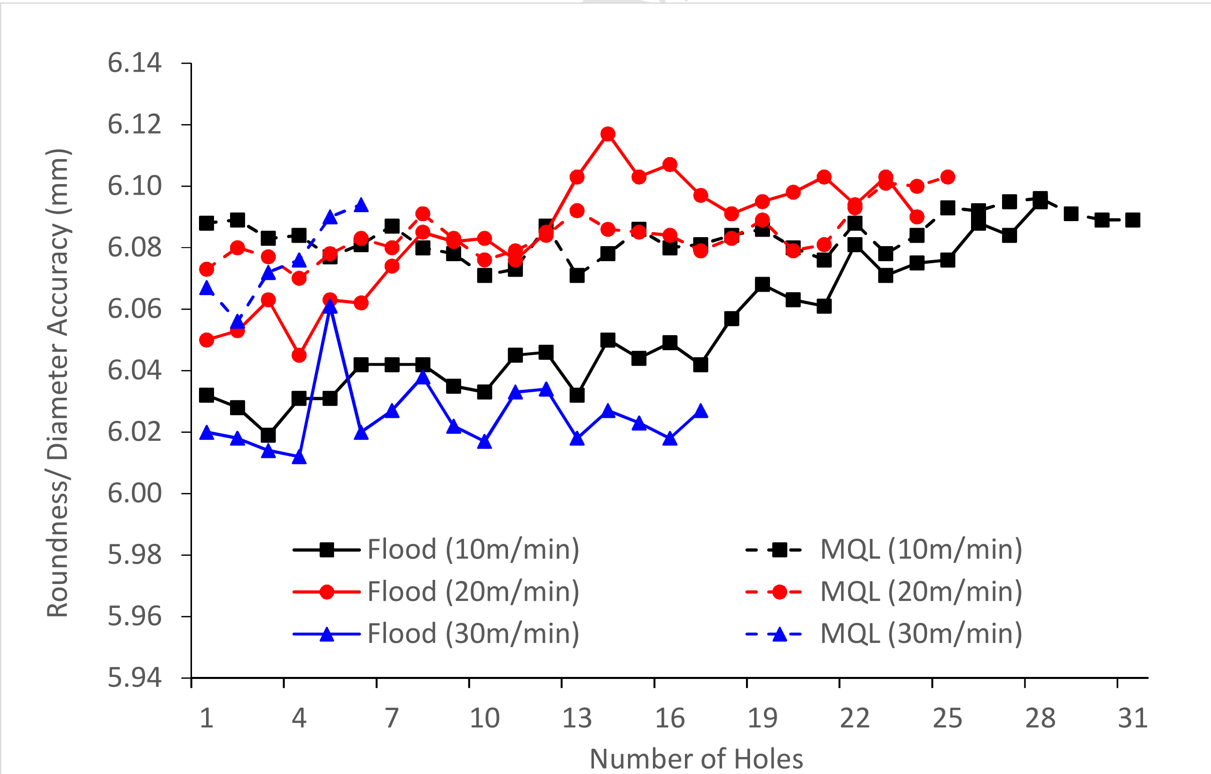

Roundness/ Diameter Accuracy (mm)
6.14
6.12
6.10
6.08
6.06
6.04
6.02
6.00
5.98
5.96
5.94
Flood (10m/min)
MQL (10m/min)
Flood (20m/min)
MQL (20m/min)
Flood (30m/min)
MQL (30m/min)
1 4 7 10 13 16 19 22 25 28 31
Number of Holes

Figure 12: Average roundness/ hole diameter accuracy of (a) uncoated drills (b) coated drills against number of drilled holes for respected experimental conditions

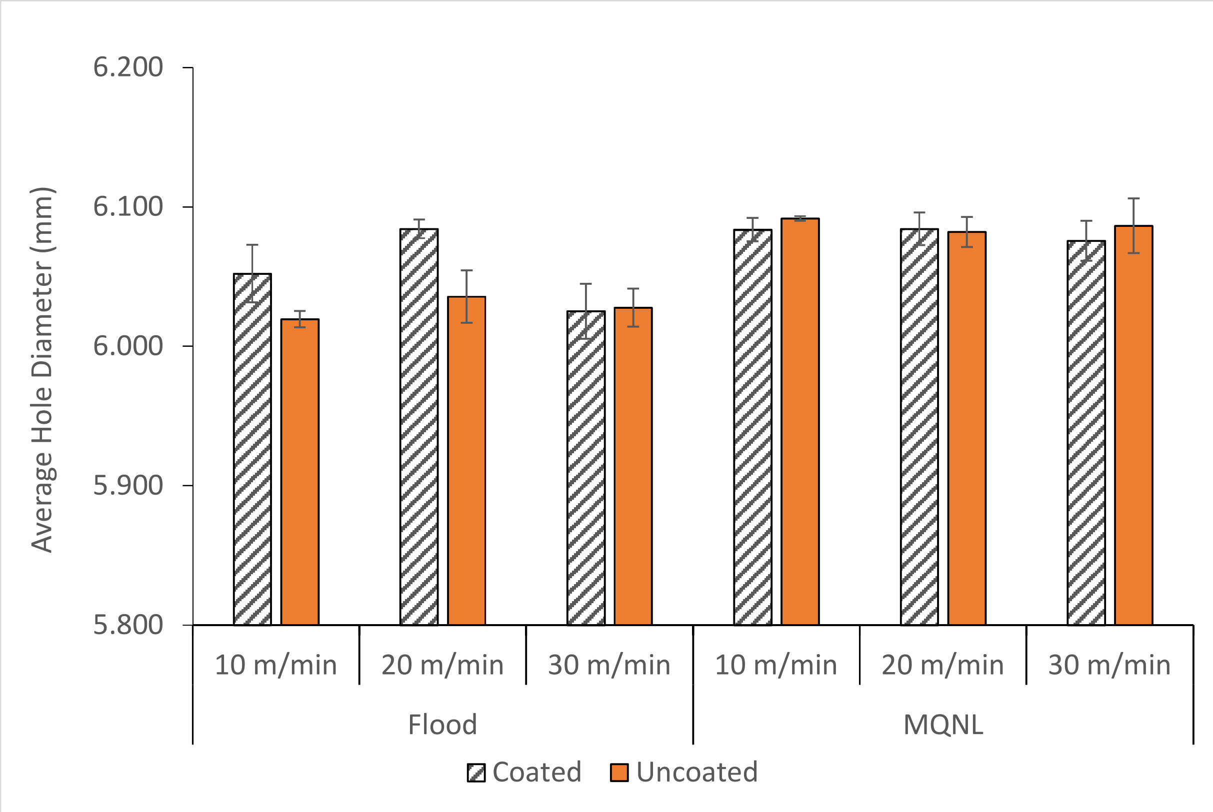


Figure 13: Average of hole diameter with respected experimental conditions

Highlights

- Drilling performance of minimal quantity lubricants reinforced with nano-particles was evaluated
- Al_2O_3 nanoparticles inclusion in SolCut base cutting fluids was beneficial in improving tool wear resistance of coated carbide drills
- Surface finishes were substantially affected by the application of the minimal quantity nanolubrication