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Evaluation of cutting force and surface roughness in high-speed milling of compacted graphite iron

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Abstract. Compacted Graphite Iron, (CGI) is known to have outstanding mechanical strength and weight-to-strength ratio as compared to conventional grey cast iron, (CI). The outstanding characteristics of CGI is due to its graphite particle shape, which is presented as compacted vermicular particle. The graphite is interconnected with random orientation and round edges, which results in higher mechanical strength. Whereas, graphite in the CI consists of a smooth-surfaced flakes that easily propagates cracks which results in weaker and brittle properties as compared to CGI. Owing to its improved properties, CGI is considered as the best candidate material in substituting grey cast iron that has been used in engine block applications for years. However, the smooth implementation of replacing CI with CGI has been hindered due to the poor machinability of CGI especially at high cutting speed. The tool life is decreased by 20 times when comparing CGI with CI under the same cutting condition. This study investigates the effect of using cryogenic cooling and minimum quantity lubrication (MQL) during high-speed milling of CGI (grade 450). Results showed that, the combination of internal cryogenic cooling and enhanced MQL improved the tool life, cutting force and surface quality as compared to the conventional flood coolant strategy during high-speed milling of CGI.

1 Introduction

Grey Cast Iron (CI) has been widely used in the manufacturing of engine blocks and cylinder heads for so many years due to its mechanical and physical properties. However, the repetition of start-up and shut-down of engines can cause high mechanical loading and may lead to localized crack at the engine blocks and heads as a result of thermo-mechanical fatigue [1, 2]. From this aspect, researchers have found that Compacted Graphite Iron (CGI) is the best candidate in replacing CI. The graphite structure of CGI is interconnected with random orientation and round edges exhibits better mechanical strength than that of CI. Whereas graphite in the CI presents smooth surface flakes that easily propagates cracks resulting in weaker and brittle properties when compared to CGI as shown in Fig. 1. Table 1 shows the mechanical and physical properties of CGI in comparison to CI [3]. The tensile strength and fatigue strength of CGI are almost double than CI, the elastic modulus is 38% higher than CI, and the thermal conductivity is 8% smaller than CI. Owing to the improved properties, CGI is considered a suitable candidate to substitute the grey cast iron in various components for diesel engine; such as engine blocks, cylinder heads and cylinder sleeves [4].

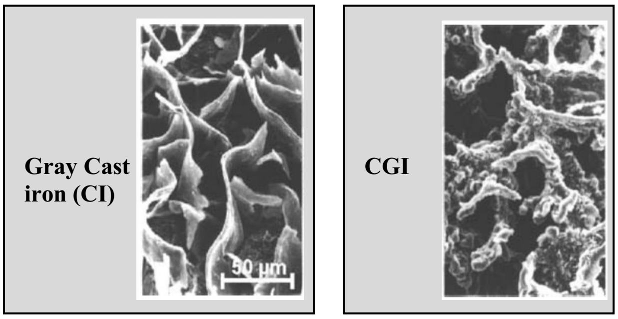

Fig. 1. Graphite particle shape of gray iron and compacted graphite iron [5]

Furthermore, the outstanding mechanical strength of CGI material enables the CGI-based engines to operate at higher temperature and cylinder pressure, which improved fuel consumptions, hence produce lower levels of emissions. In addition, CGI is lighter than CI as confirmed by Hyundai Motor Company whereby their CGI-based engine of 1.8L I-4 Diesel is 22 % lighter compared to the CI-based engine of the same kind [3].

Yang *et al.* (2015) studied the remanufacturing capability of automotive products by considering four different materials, used as engine block, namely Grey Cast Iron (CI) ASTMA48 Class 40, Aluminum A356-t6, Magnesium AMC SC1 T6 and CGI ASTM A482 Grade 450. The remanufacturing performance was ranked

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based on material's durability, clean-ability, restorability, environmental health and safety, material cost and material density. The authors found that CGI is more superior compared to CI in terms of remanufacturing performance. However, the poor machinability of CGI is the major barrier to the automotive industries in producing high performance engines with effective tool life, especially, when high-speed machining is applied to bore engine cylinders in an automated transfer line. According to [7], the tool life is decreased approximately by the factor of 20 when changing to CGI from CI for the same cutting condition. Whereas, [8] reported that when machining CGI the tool life reduced to 10% as compared to CI for both turning and milling process using PCBN and carbide tools. Da Silva *et al.* (2011) performed a tool life comparison between CGI and CI for high speed face milling. They found that, the flank wear was 100 % greater for CGI compared to CI at cutting speed of 600 m/min.

Table 1. Mechanical and physical properties of CGI (GJV) compared to conventional grey cast iron (GJL).

Properties	Units	GJV 450	GJL 250	GJL 300
Ultimate tensile strength	MPa	450	250	300
Rotating-bending fatigue (20 ºC)	MPa	210	110	125
Rotating-bending fatigue (225 ºC)	MPa	205	100	120
Elastic modulus	GPa	145	105	115
Elongation	%	1-2	0	0
Thermal conductivity	W/m.K	36	46	39
Thermal expansion	µm/m.K	12	12	12
Density	g/cc (CGS	7.7	7.1	7.1
Brinell hardness	BHN 10-3000	215-255	190-225	215-255

It is well known that, the decreased in tool life is due to the absence of Manganese-Sulfide (MnS) layer, which acts as a protective surface to avoid adhesion at the tool-chip interface in the case of machining CI [5, 10]. The most significant difference between CI and CGI is the sulfur content. CGI consists of almost 90% less sulfur content compared to CI. In machining CI, sulfur reacts with manganese to form MnS inclusions that forms a thin layer and acts as lubrication on the cutting edge surface. The MnS layer may also reduce the cutting temperature, hence decreases the oxidation and diffusion rates [10]. To demonstrate this effect, [8] compared the tool life by using different cutting speeds for machining both CGI and CI. As cutting speed increased to 400 m/min, a built-up layer containing MnS began to form on the cutting edge and the thickness of the layer increased as the cutting speed was raised to 800 mm/min. In contrast, with the same cutting condition applied to CGI, the tool suffered from abrasive flank wear with increasing cutting speed. Bazdar *et al.* (2009) attempted to increase the sulfur content on the graphite aspect ratio of a commercial CGI in order to improve the machinability. However, the tensile properties of the modified CGI decreased as compared to the commercial CGI.

The main purpose of this study is to investigate the effectiveness of various cooling/lubrication strategies in high-speed milling of CGI. The performance of uncoated carbide tool was tested at three different cutting speeds (400, 600 and 800 m/min) and two feed rates (0.1 and 0.2 mm/tooth). The progression of tool wear under various cooling/lubrication was recorded and analyzed. In order to evaluate the effectiveness of each different cooling/lubrication strategy, cutting force and surface roughness were measured at all conditions investigated. First, an experiment with conventional flood coolant (WET) was employed and the tool wear progression was used as the benchmark for other cooling/lubrication strategies, such as; Minimum Quantity Lubrication (MQL) with added nano-particles (nMQL), nano-MQL with combination of external cryogenic cooling (nMQL + ExtCryo), and nano-MQL with combination of internal cryogenic cooling (nMQL + IntCryo). Then, the respective cutting forces were acquired in real-time and surface roughness was measured at the end of each experiment. Finally, the tool wear was measured using a confocal laser microscope. The worn tools were analyzed under a Scanning Electron Microscope (SEM) and Energy Dispersive X-ray to examine the predominant type of wear mechanisms and chemical characterization, respectively.

Cooling and lubrication play an important role in metal cutting process for transferring excessive heat at the tool/workpiece engagement region and reducing tool wear. In addition, these applications are able to reduce the power consumption and at the same time improve the surface quality and productivity. In a conventional machining of most metals, a flood coolant system is preferable due to the effective cooling and ease of the application. However, flood coolant is less effective when working with difficult-to-cut and low thermal conductivity materials such as CGI. To deal with extremely high cutting temperature when machining these materials, several studies were conducted by employing cryogenic cooling with liquid nitrogen (LN2). It has been proved that cryogenic cooling results in a better tool-life [12, 13] and lower cutting force [14] when machining titanium alloys. Due to the low temperatures below -180 ºC, liquid nitrogen has been used in a wide variety of application for cooling purposes. In addition, LN2 is odorless and more environmental friendly compared to the conventional flood coolant [15]. Nevertheless, reports on the performance of cryogenic cooling when machining of CGI are very limited. It was very common that an external spray nozzle is used to supply LN2 to the cutting tool as shown reported by many researchers since year 2001 until now [13, 16-20]. By this way, the surface hardness of the workpiece material may increase due to the excessive LN2 spray. Fig. 2 shows the hardness of CGI Grade 450 with respect to testing temperature, and the effect of the excessive cryogenic cooling using conventional external spray. It is clearly showed that the hardness can be easily increased to 16%, due to the effect of excessive LN2 of the external cryogenic cooling. Similarly, [21] reported that the hardness of Ti-6Al-4V increases from 32HRc to 42HRc due to the exposure of LN2. Therefore, in order to solve the excessive spray effect, a specially designed tooling kit (as shown in Fig. 3) was used in this study which enables the supply of liquid nitrogen to the cutting tool internally. The performance of the newly designed tooling kit was evaluated accordingly.

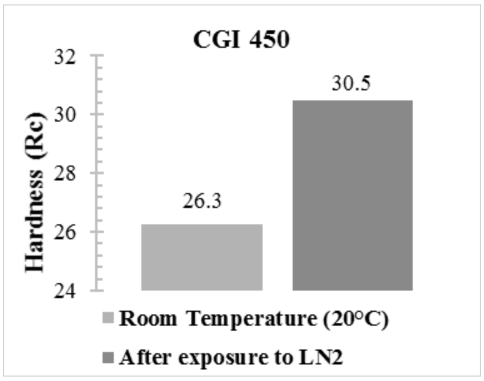

Fig. 2. The effect of the excessive cryogenic due to the conventional external spray of CGI 450

Minimum quantity lubrication (MQL) is well known for its capability to cool and lubricate the cutting tool simultaneously. However, MQL is less effective under high-speed machining as the sprayed oil simply evaporates as soon as the spray contacted the high temperature tool. In this study, a nano-particle is added with the vegetable-based oil, similar to that study conducted by [22]. It their study, it has been proved that, the enhanced exfoliated nano-graphene (xGnP) vegetable-based oil performed better in terms of reducing the tool wear of a ball-milling process compared to the traditional MQL vegetable oil. The added nano-particles provide additional lubrication to the cutting tool even when the MQL spray already evaporates. This is due to the nano-particles is arranged in a multiple-layer structure. With the same interest, [23] did a comparative study on the effectiveness of added nano-particle MQL by xGnP and Hexagonal Boron Nitride (hBN). They reported that, the mixture of hBN particles reduced the flank wear and central wear of a ball-milling process better than xGnP mixture.

This study investigated the effectiveness of MQL with added nano-particle using MQL with added hBN nano-particle when machining CGI. In addition, the combination of both external and internal spray of cryogenic cooling and enhanced nano-hBN lubricant was also performed.

2 Experimental methodology

The experiments were performed on a three-axis vertical milling center, Mori Seiki NVD-4000-DCG-HSC with Fanuc CNC controller. The cutting tool used in the machining test was an indexable end-milling cutter with designated code R390-016A16L-11L with two cutting edges. The tool diameter was 16 mm. The insert used was uncoated carbide (grade H13A) from Sandvik-CoroMill 390. Its helix angle was 21° and the corner radius was 0.8 mm.

The workpiece material is a commercially CGI (grade GJV 450) with size of 100 x 100 x 300-mm block from SinterCast. The mechanical and physical properties of the workpiece are shown in Table 1. Table 2 presents the chemical composition of the workpiece according to the material producer. The cutting parameters was defined according to the standard production line and also based on previous published work. The machining conditions are shown in Table 3.

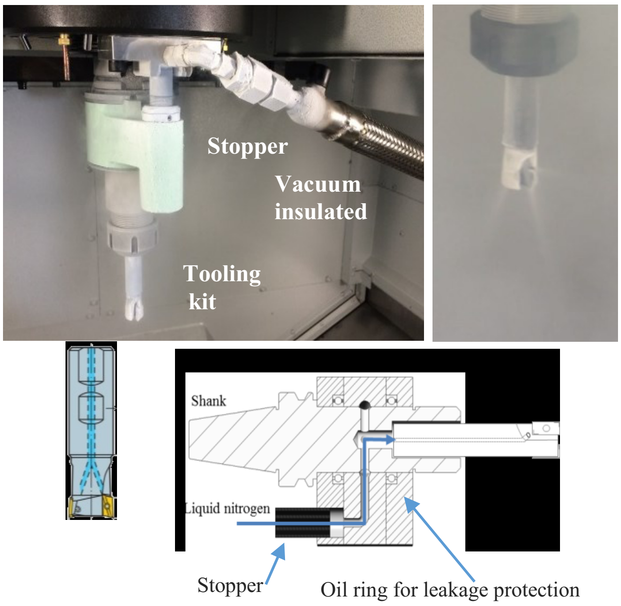

Fig. 3. Custom designed of internal cryogenic cooling tooling kit.

For each experiment, a 3D laser scanning microscope (CLSM), Model: Keyence VK-X200 with a magnification of 10X, has been used to capture the image of corresponding tool wear. Measuring software, known as 'VK Analyzer', has been used to measure the average flank and crater wear from the captured image. The worn tools were analyzed in a scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) in order to identify the predominant type of wear mechanisms and to measure the chemical weight percentage adhere on the tool.

Due to the irregular shape of the workpiece stock from the as-cast effect, a layer of approximately 2 mm was removed by face milling before the actual experiment starts. A total of 24 experiments were

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conducted which consists of different 6 combinations of cutting parameters for each cooling/lubrication method.

Table 2. Chemical composition of CGI, GJV 450.

Component	wt. %
C	3.55
Si	2.25
Mn	0.40
S	0.0065
Cr	0.029
Cu	0.81
Mg	0.009
Sn	0.075
Ti	0.009

Table 3. Machining conditions

Condition	Description
Cutting speed, Vc	400, 600 & 800 m/min
Feed per tooth, fz	0.1 & 0.2 mm
Axial depth of cut	2 mm
Radial depth of cut	5 mm
Cutting length	375 mm

3 Results and discussion

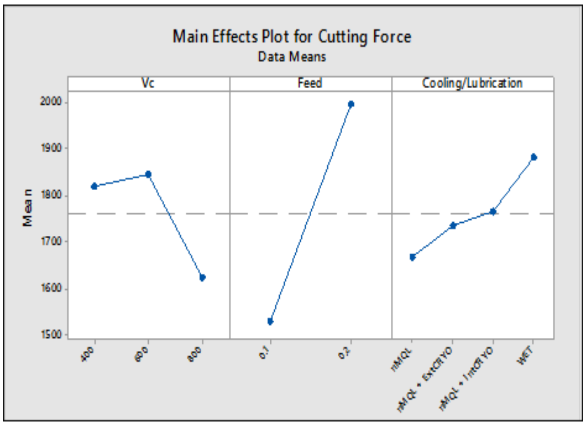
Fig. 4 presents the main effects of cutting force, surface roughness and average flank wear with respect to different cutting speed (Vc), feed-per-tooth (fz) and cooling/lubrication methods. Results show that, there is no significant effect on the cutting force for the change of Vc from 400 to 600 m/min. But, cutting force is decreased as Vc increased to 800 m/min, similar to the findings by Oxley [24], cutting force decreased as the cutting speed increases until at certain point before increased back due to material's strain characteristics. However, cutting force increased significantly with increase in feed rate (fz), due to the double increment of material removal rate from 7.95 cm^3/min to 15.91 cm^3/min. Meanwhile, WET condition, consumed the highest cutting force compared to other cooling and lubrication methods. This is due to the inefficient cooling of the conventional flood coolant method. For that reason, WET strategy appears to suffer from the worst tool life as shown in Fig. 4(c). Fig. 5 reveals the EDX analysis of the tool flank face under WET strategy. Due to inefficient cooling, the EDX spectra reveals that, the tool material for WET strategy exhibits a strong adhesion of workpiece material. A highest concentration of iron, carbon, silicon, manganese and copper was observed under all cutting conditions using WET strategy as cooling/lubrication method. These chemical elements are the main element of the workpiece material. As an example, for Vc = 800 m/min and fz = 0.2 mm (Fig. 5), the weight percentage of iron for WET are 86% followed by 84%, 78% and 76% for NanoMQL, NanoMQL+ExtCryo and NanoMQL+IntCryo, respectively. Perhaps, the cutting tool from WET strategy suffers thermal cracks at the tool cutting edge. These cracks are caused by cycling variation of temperature and frequently happen perpendicular to the cutting edge. The thermal cracks damage only appears after machining at cutting speed of 600 and 800 m/min under WET strategy as reported by Silva et al. [9]. Severe cracks may cause frittering hence causing poor surface finish and excessive flank wear as shown in Fig. 6.

The results for surface roughness (Fig. 4 (b)) for the whole set of experiments were fund to be below 1.0 micron, which is within the acceptable range for rough milling process. The main effects diagram showed that at Vc = 600 m/min, the finest quality was recorded below the average surface quality for both MQL and MQL + Internal Cryogenic cooling, compared to MQL + ExtCryo cooling and WET which produced the worst surface roughness value. There was no significant effect on surface roughness for the change of feed, fz.

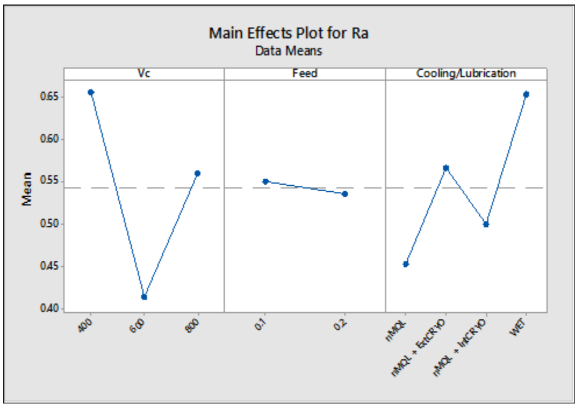
The main effect for average flank wear (Fig. 4 (c)) reveals that flank wear is at smallest amount when cutting speed was at 600 m/min. The average flank wear is improved when higher feed was applied. More importantly is the effects of cooling/lubrication methods. The results show that WET, Nano-MQL and NanoMQL+ExtCryo has the worst tool life compared to NanoMQL+IntCryo. As mentioned before, under WET condition, the tool suffered from thermal cracks and excessive adhesion of workpiece material. As for Nano-MQL, the tool flank wear recorded the worst roughness value due to inability of MQL to penetrate outside the region of slipping, between the primary and secondary zone. This also may be due to effect of higher cutting speed and higher feed employed.

As shown in Table 4, the burn mark increased as cutting speed increased for both feed rates under MQL strategy. For NanoMQL+Ext Cryo, even though cryogenic cooling promises an excellent cooling capability, however due to the excessive amount of liquid nitrogen being exposed to the workpiece, it causes the hardness of the workpiece to increase, similar to the study reported by Park et al. [25]. It was evident that cryogenic cooling using the proposed tooling kit devise is able to control the cryogenic spray from spreading to the workpiece hence increases the hardness. As a result, NanoMQL+IntCryo was found to outperform other cooling/lubrication methods in improving the tool life. Furthermore, similar result was achieved in previous study [26] that was conducted on machining Ti-6Al-4V. It was evident that proper application of cryogenic is able to provide 93% reduction in tool wear compared to dry machining when utilizing the same research apparatus as in this study.

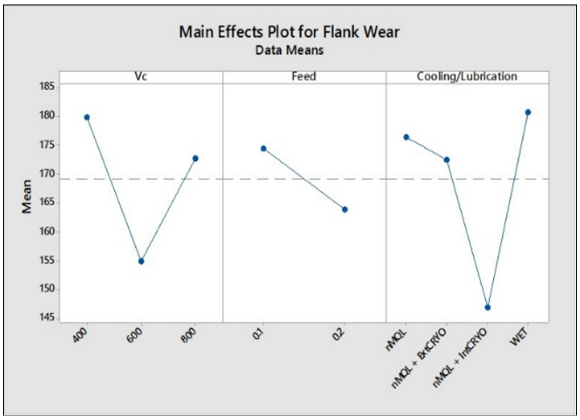
Since the main effect only shows the effect of one independent variable on the response variables by ignoring the effects of other independent variables, the potential of making error conclusion may occur. Hence, Fig. 7 shows the interaction effects for the cutting force and surface roughness. A statistical interaction occurs when the effect of one independent variable on the dependent variable changes depending on the level of another independent variable.



a) Cutting force



b) Surface roughness



c) Average flank wear

Fig. 4. Main effects of cutting force, surface roughness and average flank wear

From Fig. 7, it can be concluded that, there is no interaction for all the main effects for cutting force (Fig. 7 (a)). As for the surface roughness (Fig. 7 (b)), there is no interaction effect except for Vc and fz. Instead, a cross over interaction effect was observed for Vc and fz on surface roughness, which implies both variables have no influence on surface roughness. So, the variation of surface quality is solely dependent on the application of cooling/ lubrication methods.

Table 4. Tool flank face captured for average flank wear measurements

Cutting Condition		**Coolant/lubrication Methods**	
Vc	Fz	Nano-MQL	Nano-MQL+IntCryo
400	0.1		
600			
800			
400	0.2		
600			
800			

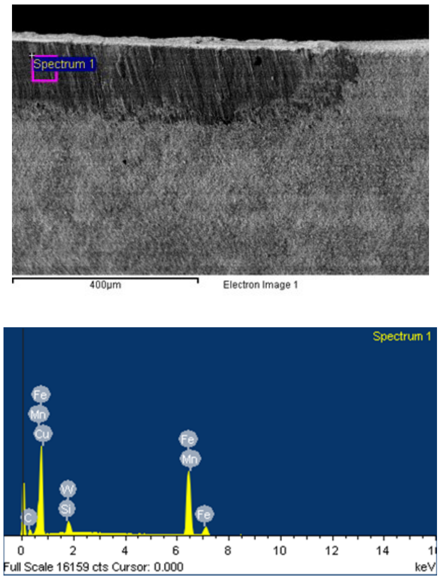


Fig. 5. EDX at the flank face after machining CGI at Vc = 800 m/min and fz = 0.2 mm with WET strategy

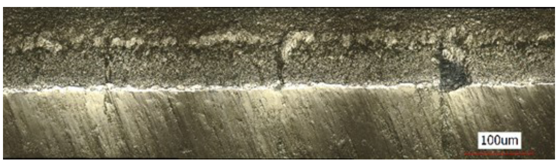
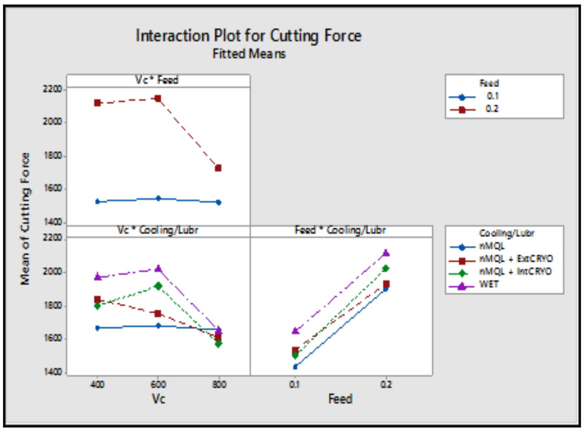
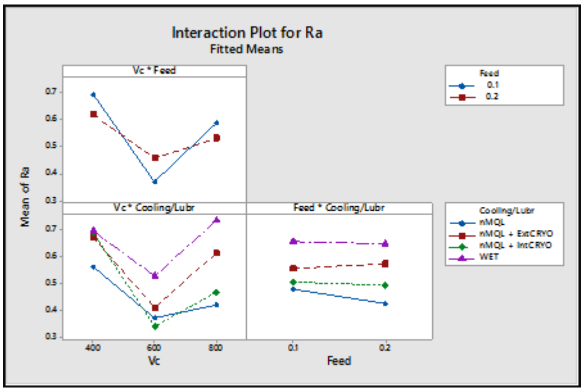


Fig. 6. Tool cutting edge for WET strategy for cutting coondition of Vc = 600 m/min and fz = 0.2 mm



a) Cutting force



b) Surface roughness

Fig. 7. Interaction effects of cutting force and surface roughness

Results indicated that MQL and MQL + Internal Cryogenic cooling were able to produce the best surface quality while WET and external cryogenic cooling produced the worst surface quality. From the overall performance it can be concluded that, increase in cutting speed and feed do not affect the surface roughness, due to the acceptable range of surface roughness reading obtained for all cooling/lubrication methods which is below than 1.0 micron.

4 Conclusions

From the investigation conducted, it can be suggested that:

1. Cutting force is inversely proportional to the cutting speed. In addition, cutting force increased significantly when higher feed is employed.
2. NanoMQL has the worst tool life even though consumed lowest cutting force. This effect was due to thermal softening of the tool and workpiece. The combination of heat and shear stress at the primary and secondary zones resulted in high temperature and stress generation at the cutting zone.
3. The proposed tooling kit was able to efficiently transfer the cryogen to the cutting zone and effectively cool the tool without increasing the workpiece hardness. Hence, the tool life for Nano-MQL+Internal Cryogenic method outperformed other cooling/lubrication strategies.
4. Cutting speed and feed per tooth do not influence the surface roughness. The surface roughness was significantly affected by the application of cooling and lubrication methods. However, all experiments present acceptable surface roughness values of below 1.0 micron.

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