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REGULAR PAPER

Sustainable Machining of Hardened Inconel 718: A Comparative Study

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Abstract

Recent trends in metal cutting shows the increasing of demand at the global stage for the application of eco-friendly machining approaches in order to eliminate the adverse effects of conventional cutting fluids. Thus, this experimental work was conducted to evaluate the performance of sustainable cooling techniques of cryogenic carbon dioxide (CO_2), Minimum Quantity Lubrication (MQL), cryogenic liquid nitrogen (LN_2) and dry cutting on machinability of Inconel 718. For the cryogenic CO_2 approach, a new concept of cryogenic cooling technique was introduced for efficient and consistent cooling performance. The findings displayed cryogenic CO_2 as a promising coolant since it resulted in slower tool wear rate compared to cryogenic LN_2 and dry cutting, while being more effective in decreasing cutting forces and surface roughness compared to other approaches. Its adequate and consistent cooling efficiently disperses the generated heat and creates an ideal cutting condition for the tool and workpiece to interact with each other during cutting. In contrast to MQL cutting, the usefulness of CO_2 was supplanted due to the resulting shorter tool life. As such, the MQL approach is preferred as it extends the tool life longer by 67.2% with the maximum volume of material removal as compared to cryogenic CO_2. Its lubrication impact shows effectiveness in diminishing the tool wear rate than the cooling effect by the cryogenic CO_2. However, from the viewpoint of sustainability, MQL could be less preferable due to unpleasant odour and settling of MQL mist around the cutting area.

Keywords Sustainable machining · Inconel 718 · Cryogenic · MQL · VMR · Dry cutting

1 Introduction

For over a decade, conventional water or oil-based cutting fluids in flood condition have played an important role in metal cutting. Basically, its main functions are to remove heat which is inherently generated due to shearing of the material and to reduce friction at chip-tool and tool-workpiece interfaces while the metal is being cut. However, its lower cooling capacity and poor penetration ability results in heat accumulation which increases the cutting temperature [1]. Thus, its application is restricted to low cutting speeds in order to avoid severe tool wear [2]. Furthermore, the application of conventional cutting fluids has been surrounded by many undesirable issues, including worker's health and safety, environmental concerns as well as the maintenance of the fluid which make it impractical to be used. The handling and disposal of cutting fluids requires extra effort and cost particularly when adhering to a strict environmental protection policy [3]. With increasing global pressure on environmental requirements and workers' welfare, many countries, through the Occupational Safety and Health Act (OSHA), have revised their regulations and manufacturing practices to prevent the disposal of cutting fluid waste. Due to this, sustainable machining approaches such as dry, near-dry and cryogenic cutting have emerged with continuous growth in demand.

Dry cutting is a machining method which operates in the absence of cutting fluids, lubrications or cooling media during the cutting process [4]. This method emphasized a great concern on environmental due to no coolant emissions and meeting the environmental regulations. It also creates a clean and healthy working environment. Moreover, this method has a significant cost reduction, as there is no cost for cooling lubricant, fluid maintenance and fluid disposal. Thus, this method is also economically attractive as it helps to reduce the costs of production which is always to be the

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main goal of any manufacturers. However, the absence of cooling and lubrication effects in most cases results in adverse effects on the tool life and surface integrity due to elevated temperatures at the cutting zone. This is particularly so when cutting difficult-to-cut materials such as Inconel 718, which has a very low heat conductivity (11.4 W/m/K) where the dry cutting worsens its heat dissipation and increases the cutting temperature. Inconel 718 also tends to work-harden at elevated temperatures which increases its hardness as well as the tool wear rate through induced heat mechanisms, such as adhesion and diffusion, which makes it unsuitable to be cut in dry condition [5]. However, it is still possible to obtain better machining performance with dry cutting. For instance, a study by Devillez et al. [5] found that dry cutting of Inconel 718 using coated carbide tools is preferable in terms of surface roughness and cutting force at an optimized cutting speed, in comparison to flood cutting. Besides that, Musfirah et al. [6] and Shokrani et al. [7] studied the effect of dry cutting on the tool life in high speed milling of Inconel 718 in comparison with cryogenic cooling using liquid nitrogen (LN_2). They reported that the cryogenic cutting significantly increases the thermal shock at the cutting tool edge during the cutting process resulted in shorter tool life. This is due to the extreme cool of LN_2 cause tool experienced massive temperature changes repeatedly along the intermittent cutting of milling process, lead to fatigue and proneness to cracks that retard the tool life. Even though the surface roughness under cryogenic cutting is better, however, it was expected to be higher than dry cutting after a specific machining length due to rapid tool wear [7]. Thus, the effectiveness of dry cutting is believed to be achievable by the appropriate selection of cutting parameters, cutting conditions, the type of cutting tool, as well as the workpiece [8]. Due that, dry cutting remains as one of the most preferred cutting approaches to be tested, and being complementary to the major advances in cutting tools technology.

An alternative to dry cutting is the near-dry technique known as Minimum Quantity Lubrication (MQL). It is an environmentally-friendly approach since it consumes only a very small amount of cutting oil of 6–100 mL/h at the cutting zone, as compared to 1000 L/min in flood cutting [8]. As suggested by Kyung et al. [9] and Kaynak [10], MQL offers an efficient lubricating effect and at the same time cooling the cutting interface to reduce friction. As a result, there are significant reductions in temperature, wear rate, cutting force and surface roughness. As of today, the MQL cutting has drawn the attention of researchers and industrial practitioners. Rigorous studies on MQL application for turning process have been conducted such as by Kaynak [10] and Pereira et al. [11], while Kasim [12] and Yaogang [13] performed the MQL research on milling and grinding process, respectively. Interestingly, all of the researchers agreed that MQL is an attractive alternative for a sustainable mode of cooling and lubrication in metal cutting which results in better machining performances. However, Madhukar et al. [14] highlighted the possibility of the lubricants to leave unpleasant smell and oily marks on the machined surface and machine parts. Thus, for the purpose of environmental preservation, non-toxic biodegradable oils such as vegetable-based cutting fluids which are not resinate and easy to clean off were more preferred.

Aside from dry and MQL cutting approaches, researchers are exploring new opportunities and benefits that may be gained from what has been termed as cryogenic cutting. Recent research has shown that its application has raised interest among researchers [15–17]. This approach uses liquid gases such as liquid nitrogen (LN_2), carbon dioxide (CO_2), helium (LHe) or argon to cool the cutting area which is exposed to the highest temperature during cutting. Its neat-cooling approach is somewhat similar to the dry cutting approach as it is free from any contamination and offers a clean and healthy working environment for the operators [18]. Once it is used, the coolant evaporates into the atmosphere automatically without the need for any treatment, cleaning process and additional costs. As for manufacturing practices, cryogenic cooling has a direct influence on the overall cutting performance. A study conducted by Kaynak [10] has shown a substantial reduction in tool wear due to low cutting temperatures which in turn increases the material removal rate. Most of the research done in literature applied LN_2 as the coolant since it offers almost zero contamination because it is colourless, odourless, tasteless, non-toxic, as well as being non-combustible and has the highest cooling capacity (at -196 °C) [19]. In milling Inconel 718, cryogenic LN_2 helps to drastically decrease cutting temperature by almost 70% compared to dry cutting, as reported by Musfirah et al. [6]. Meanwhile, Aramcharoen and Chuan [20], observed an almost 50% reduction of cutting temperature when compared to dry and flood oil-based coolant. This leads to lower tool wear rate and better machined surface, as reported by Kaynak [10]. Despite having impressive benefits, contrasting machining results were also reported by Musfirah et al. [6], Shokrani et al. [7] and Iturbe et al. [21] when conducting high speed cutting of Inconel 718. They found that excessive cooling results in adverse impact on both the cutting tool and workpiece. It generates tool edge frittering or chipping around the insert noses due to thermal shock and at the same time causes the workpiece to become harder and stronger due to cold work hardening, which accelerates tool wear rate and increases cutting forces. Nevertheless, an approach by Debnath et al. [3] could be considered where they applied a specially designed nozzle with a powerful jet of cutting fluid to allow better penetration of the coolant into the tool-workpiece and chip-tool interface. At the same time, it reduced the amount of coolant approaching the machined surface and controlled the consumption at very low level.

Past research has shown an emerging trend in the application of CO_2 as a good alternative to LN_2 based on its encouraging performance in high cutting speed machining [22–24]. It offers an environmentally benign approach which is safe and economical compared to conventional coolants. It is also cheaper and available in massive amounts since it is generated from a primary process where it is reused instead of being released into the atmosphere [25]. Thus, it can be said that the environmental impact due to the emission of CO_2 in this application does not increase. In terms of cooling effect, CO_2 has lower cooling capacity than LN_2 which leads to less work-hardening effect on the workpiece during cutting, with a significant improvement of the overall machining performance [11]. When compared to LN_2, a study by Dilip and Pradeep [26] reported CO_2 in turning of AISI 1045 steel performed better in terms of resistance to wear, cutting force and surface roughness, when compared to wet and LN_2 machining. The results were in parallel with Çakır et al. [27] who mentioned that CO_2 has a lower friction coefficient than LN_2 which results in lower cutting force, better surface finish and chip control as well as the highest reduction in tool wear.

For better performance of cryogenic CO_2, O. Pereira et al. [25] introduced an injection system which could control the phase transition of the CO_2 by controlling its pressure. Theoretically the liquid CO_2 transforms into 60% gas and 40% snow or dry ice at a temperature of approximately -78.5 °C when sublimates at the ambient temperature. This is a result of the Joule–Thomson effect [24]. By using the injection system, the phase transition can be controlled to ensure a smooth supply of the coolant deep into the cutting zone without any blockage in flow by the dry ice. This concept is in line with Dilip and Pradeep [26], who suggested the application of a gaseous form of cryogenic coolant for better coolant penetration. Machai and Biermann [23] also highlighted the limitation of CO_2 snow, when they found that a chemical reaction occurred between titanium and the tool material which was believed to be due to high cutting temperature as the coolant did not have efficient penetration deep into the tool-chip interface.

As such, this paper evaluates the machinability of Inconel 718 when conducting high speed milling using carbide coated milling inserts under cryogenic CO_2 condition. A new concept of CO_2 cooling system was applied for more sufficient and consistent cooling flow direct to the cutting zone. The performance of this environment-friendly machining strategy was then compared with other eco-friendly approaches which were MQL, cryogenic LN_2 and dry cutting. The analyses were based on cutting tool life, cutting force and surface roughness. For evaluating the machining productivity, it was measured based on the volume of material removal (VMR) for each experiment conducted.

2 Experimental Setup

The workpiece used in this study was a block of grade AMS5663 Inconel 718 that had been age-hardened and solution-treated. Its hardness ranged within 42 ± 2 HRC and its chemical composition is shown in Table 1. A grade ACK 300 Sumitomo carbide-coated ball nose milling insert as shown in Fig. 1a was applied to run the experiment. The insert is a multi-coated type with alternate layers of TiAlN and AlCrN until it achieved a total coating thickness of 3 µm for higher oxidation resistance and hardness [28]. The dimensions of the insert were: outer diameter of 10 mm, relief angle of 11°, radial rake angle of 0°, axial rake angle of 3° and approach angle of 90°. The insert was attached to a BIG Hi-power milling chuck with a nominal cutter diameter of 16 mm and an overhang length of 30 mm, as shown in Fig. 1b. The down-milling process was performed using a CNC milling machine model DMG 635, V Eco with an ability to mill at a maximum speed of 8000 rpm.

Three experiments were conducted based on three different sets of parameters, with the control factors and cutting conditions as shown in Table 2. The first and second parameters were the optimized parameters from previous researches conducted by Kasim [12] and Hadi [29], respectively. Meanwhile, the third parameter was run at a cutting speed of 120 m/min as the mid-level between experiment 1 and 2. The performances of the three selected parameters were compared under different cutting conditions. Under condition 1, all the three experiments were performed under cryogenic CO_2 condition. For condition 2, the first and second experiments were done previously by Kasim [12] and Hadi [29] under MQL and cryogenic LN_2 approaches

Table 1 Nominal chemical composition of Inconel 718 in wt%

Ni	Cr	Fe	Nb	Mo	Ti	Al	Co
53.00	18.30	18.70	5.05	3.05	1.05	0.49	0.30
Mn	Si	C	Cu	B	P	S	
0.23	0.08	0.051	0.04	0.004	< 0.005	< 0.002	

respectively. They were conducting the high speed milling of Inconel 718 in a similar machine and setting (cutting tool, machine, workpiece and parameters) and the same measurement procedures. Meanwhile, the third experiment was conducted under dry condition.

For the cryogenic CO_2, the coolant used was a mixture of CO_2 in liquid and gaseous forms together with compressed air where the pressure of each of them was upheld at 11 bars, 6 bars and 4 bars, respectively. A custom-designed cryogenic CO_2 cooling system as illustrated in Fig. 2 was employed to control the liquid–gas-solid/snow phase changes of the CO_2 along the flow of the coolant in an insulated hose and exiting through a nozzle. Through this, the minimum temperature of the coolant could be maintained at approximately − 55 °C. The temperature had been confirmed by using a type K, contact rod thermometer. The nozzle has an inner diameter of 1.3 mm and it was bent to have the right angle and distance in order to jet out the coolant right to the very tip of the cutting zone. It was attached to the spindle to provide relative movement of the cutting tool with respect to the workpiece. The main function of this system was to have a high-pressure flow of coolant without the risk of CO_2 dry ice or snow to

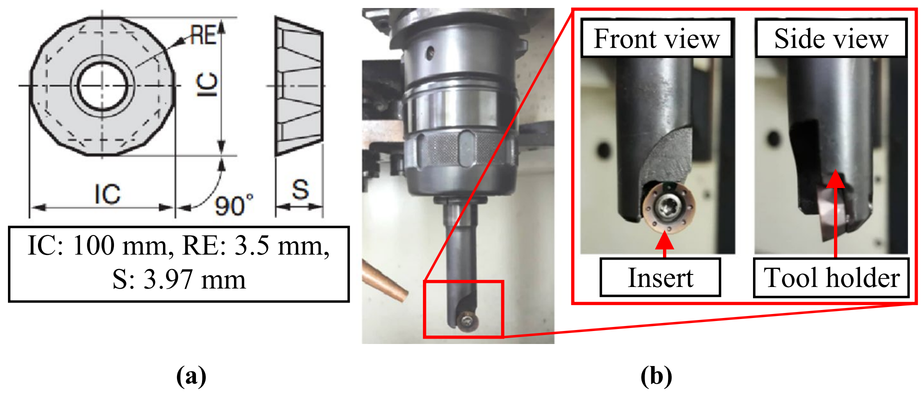

Fig. 1 **a** The geometry of the ball nose insert [28]; **b** the insert attached to the milling clamping chuck

Table 2 Experiment design

Experiment number	Cutting speed, *Vc* (m/min)	Feed rate, *fz* (mm/tooth)	Axial depth of cut, *ap* (mm)	Radial depth of cut, *ae* (mm)	Machining condition	
					Condition 1	Condition 2
Exp. 1	100	0.15	0.50	0.66	Cryogenic CO_2	MQL [12]
Exp. 2	143.79	0.15	0.3	0.35	Cryogenic CO_2	Cryogenic LN_2 [29]
Exp. 3	120	0.15	0.4	0.6	Cryogenic CO_2	Dry

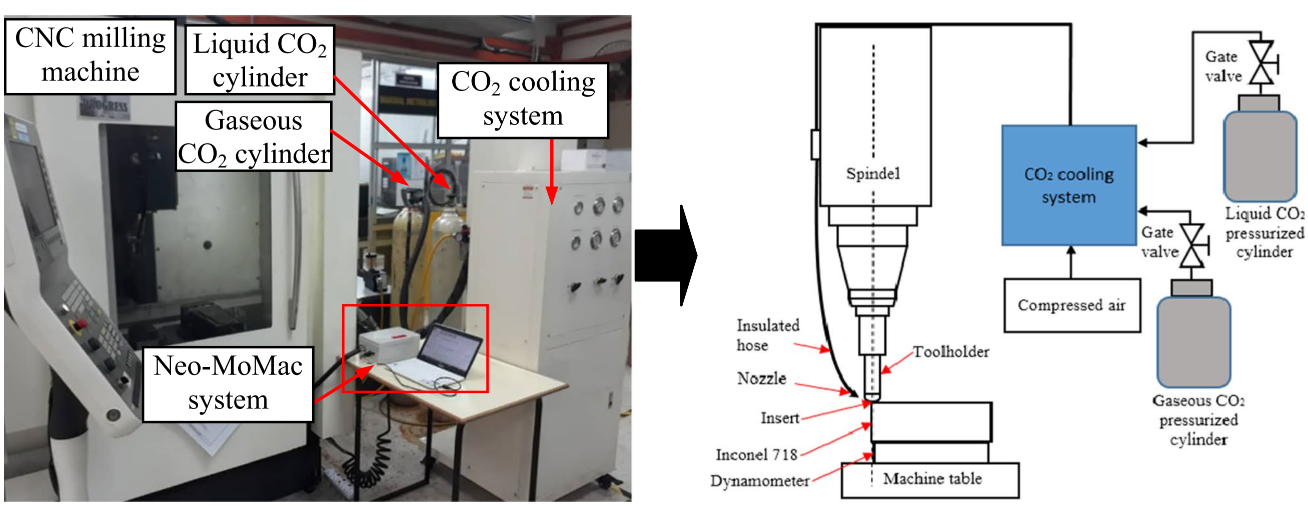

Fig. 2 Experimental milling setup under cryogenic CO_2 condition and its schematic system

block the flow. It was also expected to minimize the consumption rate of the coolant and its contact area with the machined surface. Thus, the effect of cold work hardening could be reduced, which is responsible for the increasing of the workpiece hardness. This CO_2 cooling approach is considerably different from other researchers such as Cordes et al. [24], and Machai and Biermann [23], which directly supplied the liquid CO_2 from the pressurized cylinder to the cutting zone without controlling the pressure. Meanwhile, the delivering methods of the MQL and LN_2 are shown in Fig. 3a, b respectively with the details with reference to Kasim [12] and Hadi [29].

Assessment of tool life was determined based on the localized tool wear on the insert flank face (*VBmax*). The milling process was interrupted at specific intervals to identify the wear patterns and measure the wear rate by using a Mitutoyo toolmaker's microscope and a holding jig to hold the insert at a consistent position (as in Fig. 4a). The cutting process was continued until the tool wear met one of the failure criteria: (1) average flank wear (*VBavg*) reaching 0.3 mm, (2) localized flank wear (*VBmax*) reaching 0.5 mm, or (3) catastrophic failure, which was based on ISO 8688-2 for the end milling process [30]. Figure 4b shows how the flank wear rate was measured. For tool wear mechanisms, a Field Emission Scanning Electron Microscope (FESEM), model SUPRA 55VP was employed to thoroughly observe the worn tool area. Meanwhile, the surface roughness was measured by the contact technique using a Mitutoyo Surf-test profilometer. The stylus travel distance was set at the cut-off length of 0.8 mm in accordance with ISO 4288 1996. The measurement was conducted along the direction of the feed and recorded thrice at the beginning of each run. The average values of Ra (the arithmetic average of the absolute values) were measured for further analysis.

For the cutting force, it was measured and recorded throughout the first cutting path using the Neo-MoMac system which was developed by UKM Tech. Malaysia. This measurement system consisted of a strain gauge-based dynamometer, data acquisition (DAQ) and graphical user interface (GUI) computer display. The workpiece was fastened onto a dynamometer, which was mounted on the machine working table and connected to the DAQ to capture and store the real-time signals in the form of *x*, *y*, and *z* axes (as shown in Fig. 5a). The resultant force (*Fr*), which consisted of three cutting force components; tangential force (F_X), radial force (F_Y) and axial force (F_Z), was measured using Eq. (1) [31]. Figure 5b illustrates the direction of each force component acting on the ball nose insert in the milling process [32].

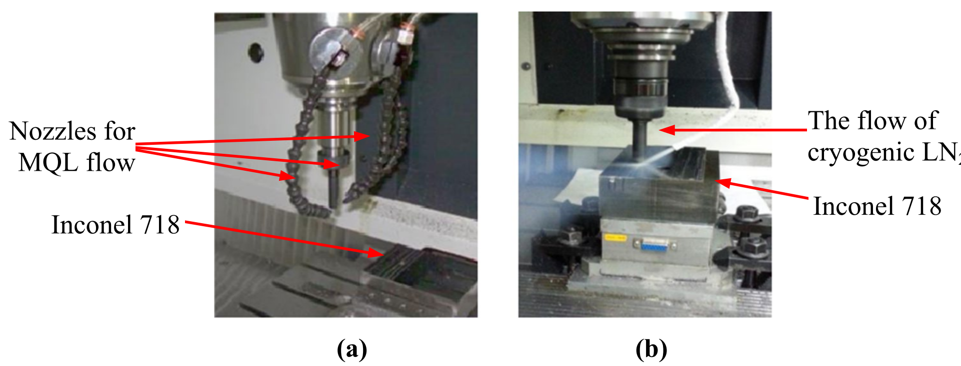

Fig. 3 Experimental milling setup; **a** MQL conducted by Kasim [12], and **b** cryogenic LN_2 conducted by Hadi [29]

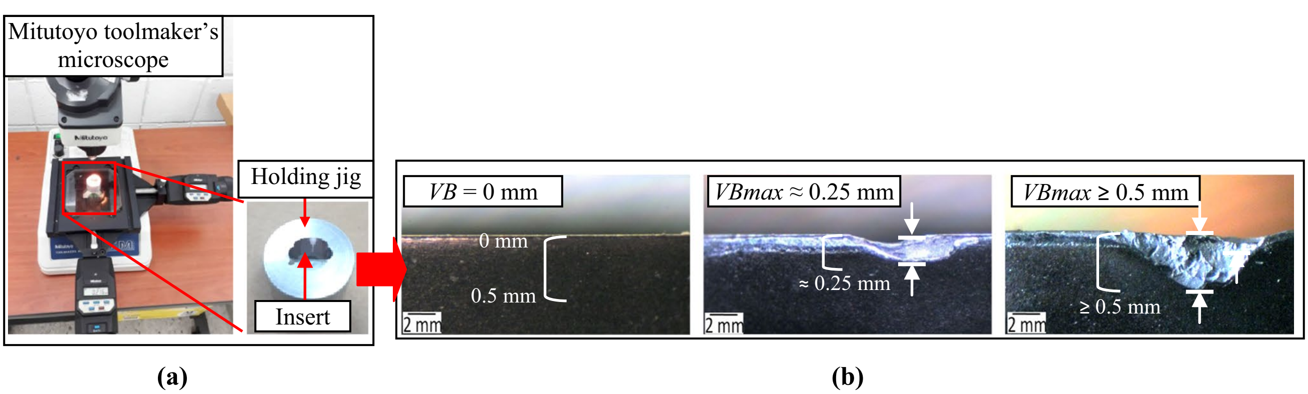

Fig. 4 **a** The Mitutoyo toolmaker's microscope and the holding jig used, **b** the measurement process

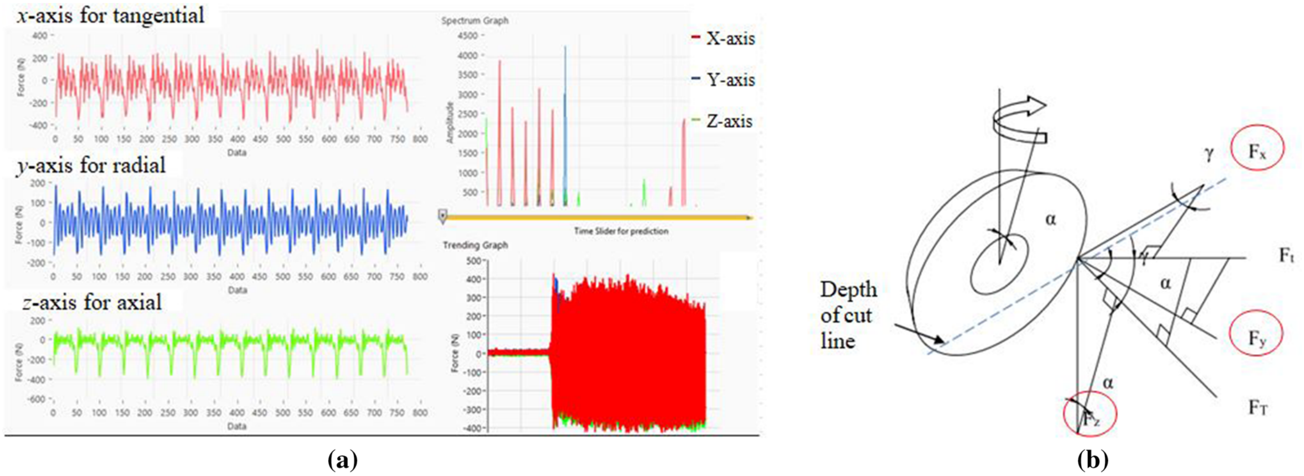

Fig. 5 **a** The graphical user interface (GUI) of each cutting force component recorded by the Neo-MoMac system, **b** direction of cutting force components in milling with ball nose insert [32]

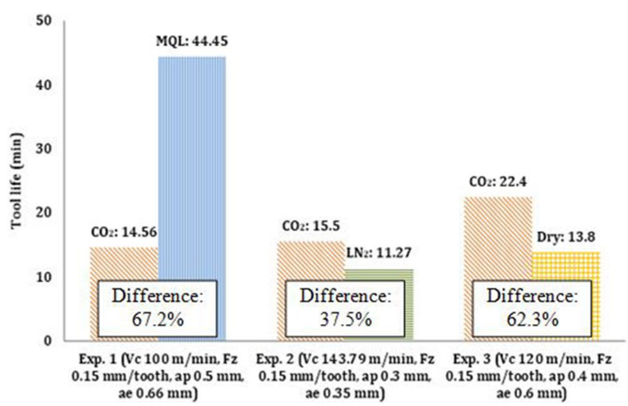

Fig. 6 Comparison of tool life

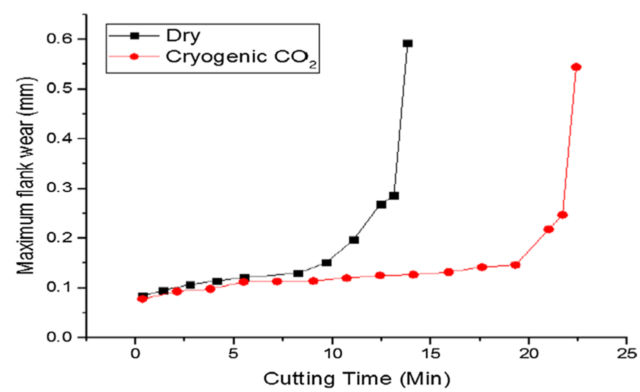

Fig. 7 The tool flank wear progress under cryogenic CO_2 and dry condition (experiment 3)

$$Fr = \sqrt{\left(F_X^2 + F_Y^2 + F_Z^2\right)} \tag{1}$$

For surface roughness and cutting force, only data produced by new or sharp cutting tools was used. This was to avoid the excessive tool wear effect on the workpiece surface due to the higher cutting temperature. For experiments 1 and 2, the results of tool life, cutting force, surface roughness, temperature and productivity under MQL and cryogenic LN_2 were in accordance with the results obtained by Kasim [12] and Hadi [29], respectively.

3 Results and Discussion

3.1 Tool life

Figure 6 compares the influence of different cutting conditions on tool life under experiments 1, 2 and 3. In experiment 1, the tool life under CO_2 was considerably shorter by 29.89 min compared to that under the MQL condition. This result exhibited the effectiveness of the lubricating effect by the MQL to reduce friction at the tool-workpiece and tool-chip interface, hence slowing down the wear rate. As mentioned by Kasim [12] and Kanak [10], the formation of a thin film layer between the tool and the chip in the MQL cutting provided the lubrication effect which significantly reduced the wear rate. Pereira et al. [11] similarly found longer tool life under MQL than cryogenic CO_2 when milling Inconel 718.

Nevertheless, the cryogenic CO_2 cooling system managed to supply the pressurized coolant deep into the cutting edge with great heat conduction such that it rapidly reduced temperature. As revealed in Fig. 7, the tool flank wear under cryogenic CO_2 progressed steadily for almost 20 min at *VBmax* less than 0.2 mm compared to dry cutting. At the same time, Dilip and Pradeep [26] believed the cryogenic coolant also provided a cushioning effect that was able to reduce friction at chip-tool and tool-workpiece interface with significant reduction of the wear rate. However, as discussed by Courbon et al. [33], the lubricating effect by the cryogenic coolant might be effective at low contact friction in relation to the contact geometry and low loads used. Thus, under extreme contact friction of worn tool, the lubrication cannot be relied on due to poor coolant penetration at the contact interface. Significantly, by referring to Fig. 7, once the *VBmax* exceeded 0.2 mm, the wear rate rose dramatically and promptly retarded the tool life. This phenomenon happened due to the intense contact friction force by the worn tool which hindered the coolant penetration and caused high heat generation which rapidly increased temperature as well as the tool wear rate.

Observation of the tool wear patterns identified that it was initiated with a smooth abrasive; by a continuous rubbing and sliding friction at the contact surface between the tool and hard carbide particles in Inconel 718, and pitting; by the repetitive cyclic load of intermittent milling, around the cutting edge, as shown in Fig. 8. It then progressed into chipping at the tool edge which then enlarged to form notch wear and flaking near to the depth of cut line. As shown in Fig. 9, the FESEM micrograph at the worn tool area under cryogenic CO_2 consists of abrasive, fracture and notch wear at flank face, flaking and groove at rake face, and BUE at depth of cut line, that changed the shape of the insert. It confirmed that tool wear was greatly affected by the mechanical effects which were abrasion and adhesion rather than thermal effect. Even though the tool wear rate under MQL was slower, Kasim [12] reported slightly similar tool wear patterns with cryogenic CO_2. Figure 10a shows some FESEM images of worn tool conditions at flank and rake face from the study. It is also important to note that the synthetic mist oil used in MQL left unpleasant odour and residue due to the settling of the oily mist on the workpieces and machine parts, as has also been highlighted by Madhukar et al. [14]. Thus, the MQL approach can be considered as less sustainable as compared to cryogenic CO_2 machining where once the coolant is used, it completely sublimates to the air and leaves workpiece, chips, cutting tool and inner machine area clean and dry.

Further from experiment 2, the tool life under cryogenic CO_2 was 4.23 min which is 37.5% longer than cryogenic LN_2. As explained by Musfirah et al. [6], rapid tool wear rate in cryogenic LN_2 was due to cold work hardening effect on the workpiece which increased its hardness. By referring to Hadi [29], the highest micro-hardness recorded was 455 HV at 100 μm beneath the machined surface, which is 7.3% harder than the bulk hardness of the workpiece. Concurrently, the mechanical shock which occurred at the tool edge due to the interrupted milling process was believed to have worsened in cryogenic LN_2. The tool experienced huge changes in temperatures which forced it to contract (when

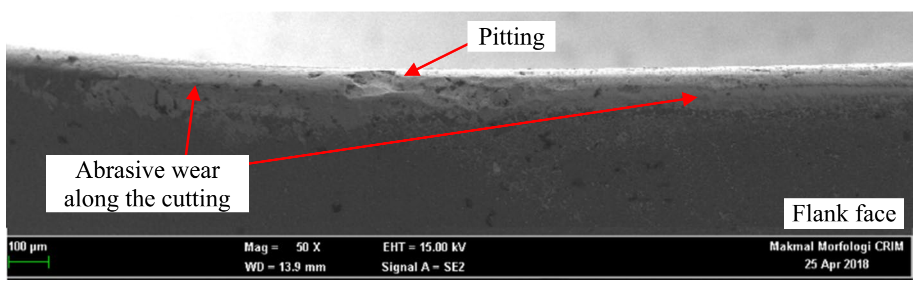

Fig. 8 Pitting and abrasive wear at tool cutting edge under cryogenic CO_2 condition (experiment 2)

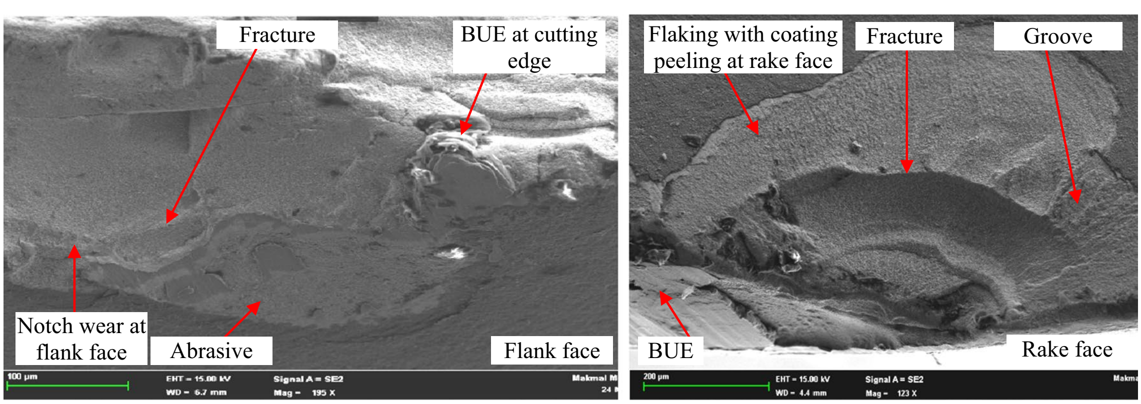

Fig. 9 Tool wear pattern at flank and rake face under cryogenic CO_2 condition (experiment 2)

exposed to the extreme cold of LN_2) and expand (during removal of chips) repetitively and caused thermal cycling at the tool edge which then resulted in thermal cracks due to thermal fatigue (as shown in Fig. 10b) and thermal shock which resulted in abrupt tool failure. This predicament did not happen in cryogenic CO_2 since the coolant offered a more controlled cooling effect on the workpiece, which led to less work-hardening effect; thus, making it suitable to be used in the machining of Inconel 718. Nevertheless, this result is in agreement with the results reported by Dilip and Pradeep [26] in turning of AISI 1045 steel bar.

When compared with the dry condition under experiment 3, it is obvious that the use of cryogenic CO_2 resulted in longer tool life by approximately 62.3%. This result was also in parallel with the findings of Pereira et al. [17]. The right and consistent cooling effects of cryogenic CO_2 efficiently reduced the cutting temperature and slowed down the tool wear rate at the cutting edge as shown in Fig. 7. In addition, the high flow of CO_2 coolant helped to flush chips away from the cutting zone; thus, reducing the tendency of chips from being deposited into the tool edge and developing BUE as illustrated in Fig. 11. However, under dry condition, the absence of cooling and lubricating effects significantly increased the temperature and friction between tool and workpiece and accelerated tool wear as shown in Fig. 7. Further in Fig. 12, the adhesion of chips at cutting-edge occurred aggressively from the beginning of cut and became more severe with the increment of flank wear. This is because Inconel 718 has a strong adhesive property at high temperature which causes the residual chips to easily adhere to the hottest area of cutting edge and form BUE [34]. Whereas, under cryogenic CO_2, the presence of BUE was

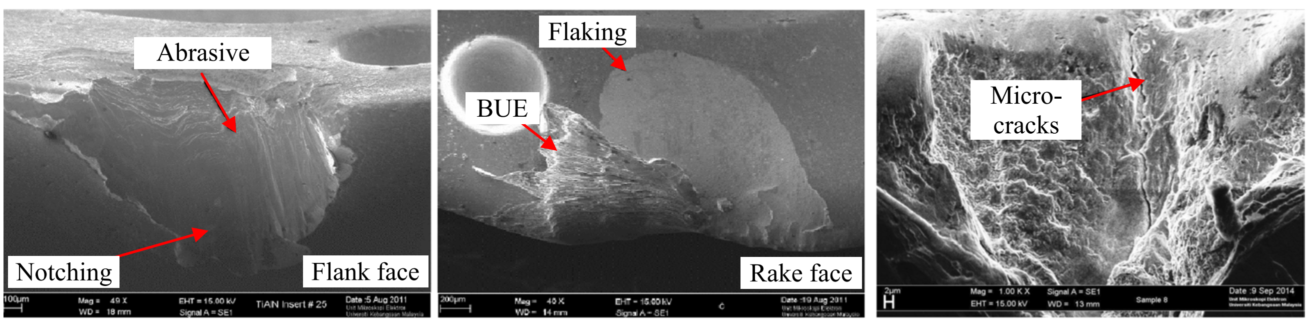

Fig. 10 **a** Under MQL condition (experiment 1) [12], and **b** Under cryogenic LN_2 condition (experiment 2) [29]

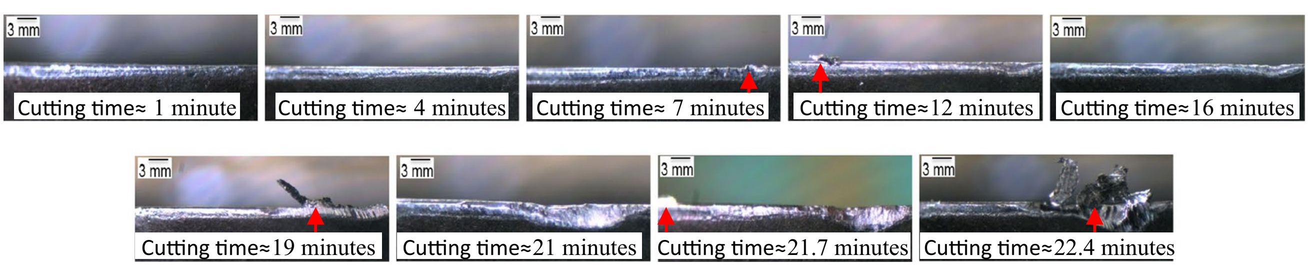

Fig. 11 The occurrence of BUE in the cryogenic CO_2 cutting (experiment 3)

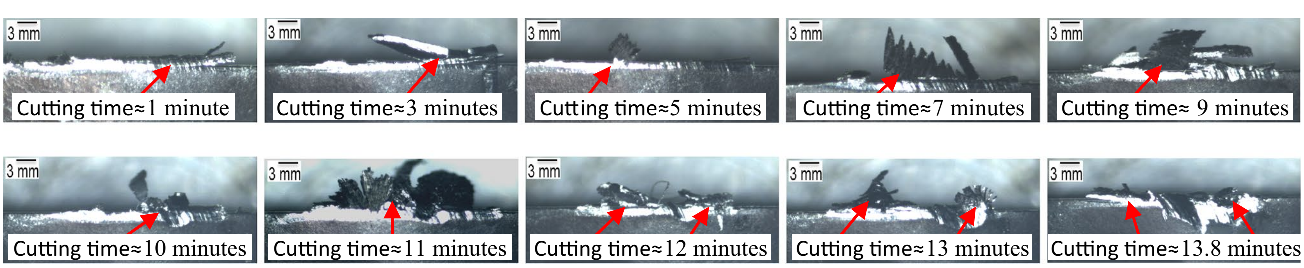

Fig. 12 The occurrence of BUE in the dry cutting (experiment 3)

found less often as well as being smaller in terms of size. Nevertheless, the BUE is undesirable since it is responsible for the rapid development of notching and flaking at cutting edge which accelerates tool failure.

It was also found in Fig. 6 that the tool life under cryogenic CO_2 was longer at a cutting speed of 120 m/min (experiment 3) and a shorter tool life was observed at the lowest cutting speed (experiment 1). This result exhibited the effectiveness of cooling by CO_2 at a higher speed, as has been discussed by Dilip and Pradeep [26].

3.2 Cutting force

The comparison of cutting forces variations with respect to machining conditions is represented in Fig. 13a. Experiment 1 found that the cutting force under MQL and cryogenic CO_2 was slightly different with the MQL, higher by only 5.2%. For MQL, this result proved the remarkable role of the lubrication oil attributing to the reduction of friction at tool-chip and tool-workpiece interfaces, thus reducing forces [12]. As explained by Y. Kaynak et al. [35], the ability of the MQL lubricant to slip into the cutting edge aided in reducing friction, adhesion and temperature gradients at the sliding contacts, with a significant reduction in forces. Comparing the cryogenic CO_2 with LN_2 and dry cutting, a significant difference was observed in which the cryogenic CO_2 managed to reduce the cutting force by almost 55% and 57.5% respectively. This result is in line with reports by Dilip and Pradeep [26] and Aramcharoen and Chuan [20] who mentioned that when using the coolant in the primary shear zone, the cold work-hardening effect on the workpiece by the LN_2 caused more forces to produce stress for material deformation. Meanwhile, in dry cutting, higher forces were obviously associated with the formation of BUE at the tool cutting edge as in Fig. 12. The BUE was responsible for the increase of coefficient of friction at the sliding contact between tool-workpiece interface which in turn increased forces [36]. At the same time, the effect of high cutting temperatures of dry cutting (which is below the critical temperature of the workpiece) also contributed to the increase of machined surface hardness and toughness and resulted in higher cutting forces.

Alauddin et al. [31] have stated that the cutting force has a close relationship with axial depth of cut (DOC) and feed rate because increasing of both factors will significantly increase the cutting force which is due to the increased chips load and size of cut per tooth. It is particularly in parallel with the findings of cryogenic CO_2 cutting in which at constant feed rate, the cutting forces increases with axial DOC. Referring to Fig. 13a for experiment 1, maximum force was produced at the highest axial DOC, which was similar to the finding of Kasim [12] in MQL milling of Inconel 718.

3.3 Surface Roughness

Figure 13a compares the average roughness from the experimental works. It is evident that cryogenic CO_2 exhibited the lowest surface roughness values compared to others. When compared with MQL, the CO_2 cooling improved the surface roughness by 41.4%. But there was only a slight difference between cryogenic CO_2 and LN_2 which clearly showed that cryogenic cutting was capable to produce a better surface finish. Thus, it can be said that the cooling effect by the cryogenic coolant provide significant influence on the surface quality as it is heat-dependent. This is parallel with Pusavec et al. [37], mentioned that the mechanical and chemical degradations of the machined surface could be prevented by the cooling effect of cryogenic cutting which in turn improve surface roughness. In addition, Kaynak et al. [38] stated that the workpiece sensitivity to temperature being one of the main reasons for local chatter on the machined surface which increase surface roughness. Meanwhile, in experiment

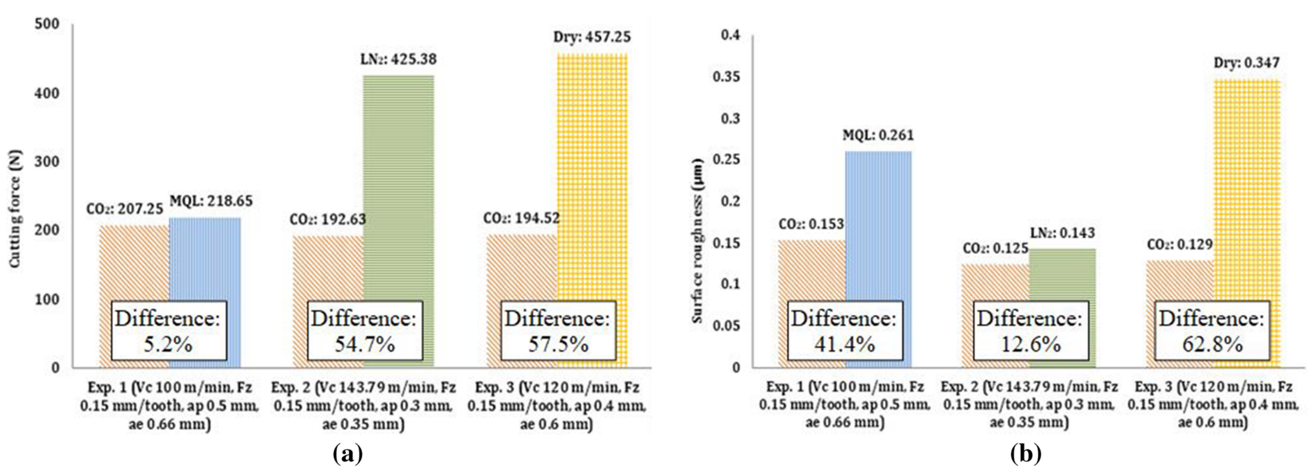

Fig. 13 Results comparison; **a** cutting force, and **b** surface roughness

3, visibly dry cutting resulted with higher surface roughness than cryogenic CO_2. It is believed that the present of BUE in dry cutting as shown in Fig. 12 has a prominent role in influencing the roughness. The BUE is responsible to increase friction between workpiece-tool interfaces which in turns increase roughness of the machined surface. This is in line with Thakur and Gangopadhyay [39] which suggested to diminish BUE in order to reduce surface roughness and surface defect.

Furthermore, by comparing the surface roughness obtained under cryogenic CO_2 condition, it indicates that a low cutting speed resulted in a rougher machined surface. The greatest achievement of surface roughness was produced at the highest cutting speed of experiment 2. This could be due to the effect of more heat being generated at higher speeds, thus help to reduce the degree of work hardening of the material by the extreme cold of cryogenic CO_2.

3.4 Productivity

To evaluate the productivity of each cutting condition, the forms of Material Removal Rate (MRR) and Volume of Material Removal (VMR) were used. The MRR was calculated for the milling process using Eq. 2 [40].

$$MRR = (ap \times ae \times Vf) \quad (2)$$

meanwhile, the VMR was calculated using Eq. 3, as also applied by Ginting et al. [41] and Kasim [42].

$$VMR = MRR \times TL \quad (3)$$

where TL is the total tool life (min), ap is axial depth of cut (mm), ae is radial depth of cut (mm) and Vf is table feed (mm/min).

The calculated MRR and VMR values for each experiment are presented in Table 3 while Fig. 14 illustrates the comparison of results for each experimental work. In Experiment 1, the VMR under MQL was 67.2% more than cryogenic CO_2. The main achievement of MQL condition was the extension of tool service life which resulted in the higher VMR. As for experiments 2 and 3, cryogenic CO_2 produced higher VMR which surpassed cryogenic LN_2 and dry cutting due to its prolonged tool life. This was in parallel with the findings of Cordes et al. [24] who found that cryogenic CO_2 produced as much as 63% longer of tool life when compared to dry cutting and increased the MRR by 72% to produce a better surface finish.

It was also observed that cryogenic CO_2 produced the maximum VMR at the speed of 120 m/min which resulted

Table 3 The productivity of each cutting conditions

Experiment No.	Cutting condition	Cutting parameter				MRR (mm^3/min)	Tool life (min)	VMR (mm^3)	% Difference
		Vc (m/min)	*fz* (mm/tooth)	*ap* (mm)	*ae* (mm)				
1	CO_2	100	0.15	0.5	0.66	152	14.56	2213	67.2
	MQL						44.45	**6756**	
2	CO_2	143.79	0.15	0.3	0.35	77	15.50	**1194**	37.5
	LN_2						11.27	868	
3	CO_2	120	0.15	0.4	0.6	139	22.40	**3114**	62.3
	Dry						13.80	1918	

Bold indicates the highest value of VMR from each experiment

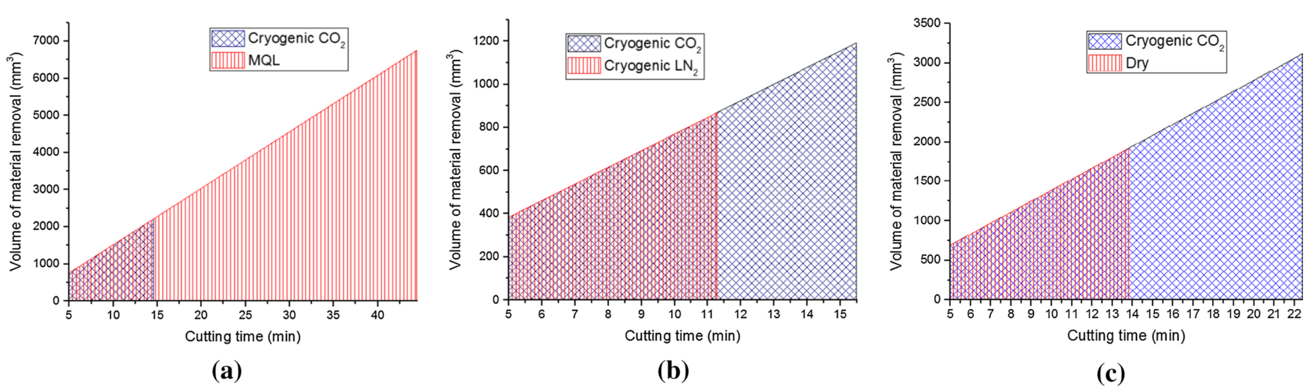

Fig. 14 Comparison of volume of material removal (VMR) for; **a** experiment 1, **b** experiment 2 and **c** experiment 3

in the longest tool life. This confirmed that under cryogenic CO_2 condition, the effective cutting speed for machining Inconel 718 was at 120 m/min. It can be seen in Table 3 that each experiment generated similar MRR for different cutting conditions which reveals that MRR analysis alone is not adequate to investigate the efficiency of tools under different cutting conditions. This is due to the reason that its measurement is merely based on cutting parameters and does not consider the performance of each cutting condition in extending tool life. Thus, as also discussed by Ginting et al. [41] and Kasim [42], the VMR approach is more applicable for industries in deciding the exact cutting condition that can increase productivity and monitor the consumption rate of tools based on the machining schedule.

4 Conclusion

This study investigated the performance of a new concept of cryogenic CO_2 cooling system, a sustainable machining approach, on machinability when conducting high speed milling of Inconel 718, which required the measurement of cutting tool life, cutting force, surface roughness and productivity. The machining performance was compared with other green machining procedures which were MQL, cryogenic LN_2 and dry cutting, each in different machining parameters. The findings from the experimental results showed the efficiency of cryogenic CO_2 system in directly providing adequate and consistent cooling to the cutting edge, resulting in longer tool life compared to cryogenic LN_2 and dry cutting. It also produced a major impact on other heat-dependent responses, which were cutting force and machined surface quality, since cryogenic CO_2 showed superior improvement. However, the lubrication effect in MQL cutting exhibited its ability in reducing the tool wear rate; hence, it prolongs the cutting tool longer than cryogenic CO_2 as well as maximizes the volume of material removal which is always the goal of top industries. On the other hand, cryogenic LN_2 and dry cutting demonstrated disappointing outcomes compared to cryogenic CO_2 because of their propensity to work-harden the workpiece which adversely impacted the overall machining performances. From the sustainability point of view, MQL was less preferred due to unpleasant odour and oily residue due to the settling of the oily mist on the workpiece, cutting tool and machine parts. As such, it can be concluded that the combination of both sustainable cooling and lubricating effects is required for a higher machinability and sustainability of high speed cutting Inconel 718. Nevertheless, the benefits and eco-friendliness of these machining approaches require more in-depth studies so as to prove their performance economic and practical aspects since some approaches entail a substantial initial system investment.

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