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Impact of hybrid cooling approach on milling and surface morphological characteristics of Nimonic 80A alloy

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A R T I C L E I N F O

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Specific cutting energy
Burr formation
Grain growth

A B S T R A C T

Poor surface traits, short insert life, high manufacturing costs, and low productivity are associated with the machining of nickel alloys. Cutting fluids have well-known positive and negative effects on machinability performance. As a result, the machining industry has developed green cutting environments such as vegetable oil assisted minimum quantity lubrication (MQL) and cryogenic cooling. Despite the fact that MQL and cryogenic approaches can replace mineral oil-based flooding, their lack of lubrication and cooling properties at high speeds have prompted a search for a new hybrid approach (CO_2 + MQL) that provides adequate cooling/lubrication (C/L). Moreover, as of now, no information concerning the effects of hybrid cooling on milling of Nimonic-80A is existing. To test the viability, the machining of Nimonic-80A under hybrid C/L was compared to other cutting environments (MQL and cryogenic). As crucial machinability factors, temperature, power consumption, surface and subsurface characteristics were thoroughly examined. Hybrid condition curtailed the burr formation, which paves the way for a reduction in specific cutting energy (SCE). The experimental results indicate that the hybrid condition considerably decreases the temperature and SCE by 34–53% and 17–19% in comparison with the MQL condition. Peak widening and intensity reduction were seen in the XRD examination, but no phase transition was found. Smaller grain size shows the superiority of hybrid environment.

1. Introduction

Nickel alloys (NiA) are utilized in the development of aerospace components as a reason of top physical and metallurgical properties; the aerospace industries use about 50%of these alloys [1]. All classes of NiA have their strengths and drawbacks. Potential benefits of NiA are high strength [2], excellent resistance towards corrosion, and low modulus of elasticity [3]. NiA have meagre machinability as a reason of high chemical affinity towards cutter that results in chipping and premature tool failure. The temperature at the work material-tool juncture increases by reason of low conductivity of NiA while cutting, which directly affects the cutter life [4]. Machinability of Nimonic 80A is low on account of less conductivity and huge chemical reactivity consequences in degraded surface trait, quick cutter wear and more cutting forces [5,6]. Thus, there is a demand to apply cutting fluid (CF) to curtail the hotness and friction to enhance the surface trait [7–9]. The CF's

Abbreviations: a_e, Radial Depth of cut; BUE, Built-up edge; CO_2, Carbondi oxide; Cryo, Cryogenic; CF, Cutting fluid; C/L, Cooling/lubrication; DOC, Depth of cut; *f*, Feed rate; FG, Fine-grain; LN_2, Liquid Nitrogen; LOC, Length of cut; M_T, Milling temperature; MQL, Minimum quantity lubricant; PVD, Physical Vapour Deposition; *Ra*, Surface Roughness; SCE, Specific Cutting Energy; SEM, Scanning electron microscope; Vb, Flank wear; Vc, Cutting speed; VO, Vegetable oil.

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produces environmental and health problems and pollute land and water [10–12]. Green engineering is cutting-edge because it employs clean cooling technology in cutting operations. Noteworthy innovative cooling environments comprises minimum quality lubrication (MQL) and cryogenic cooling [13–15].

MQL is one crucial alternate technique in relation to no coolant and flood cutting strategy [16,17]. It uses least volume of oil [18–21] and produces less pollution as compare with flood cooling [22,23]. The vegetable oil (VO) employed through MQL are regarded as a best substitute to traditional CF's [24]. MQL with vegetable oil lessens the chipping on the cutting tip, which is a noteworthy cause for less tool rejection [25]. Specific cutting energy (SCE) has a straight authority over surface trait. Therefore, a model was developed, which was in reasonable concurrence with the experimental values. The expansion inflow and pressure throughout the employment of MQL lessened the SCE [26]. Chetan et al. [27] studied the performance of MQL, cryogenic, cryo-treated and untreated cutting approaches while cutting Nimonic-90. MQL method of cutting outpaced other machining approaches relative to roughness at high speeds. Günay et al. [28] machined Nimonic-80A utilising a variety of cooling techniques with coated tools. MQL cooling method prolonged the tool life in the cutting of low thermally conductive material. Response Surface Methodology (RSM) is engaged to demonstrate the Material Removal Rate (MRR) to quantify the insert wear. The utilization of rice bran oil is assessed against coconut oil while cutting AISI 304 stainless steel. Rice bran oil was found to be outshined coconut oil and produced a better-machined face by suppressing the friction [29]. Zaman and Dhar [30] developed a twin nozzle to boost the MQL efficacy. Dry and single jet MQL machining was conducted to evaluate the performance of the dual jet MQL nozzle. In case of heat reduction and cutter wear, the dual jets outscored the other cutting strategies. Yildirim et al. [31] examined the wear behaviour of Waspaloy while using PVD and CVD coated cutters under disparate cutting environments. The outcome achieved by flood cooling was close to the MQL environment. As a result, the MQL method is recommended for Waspaloy milling, considering the environment, employee well-being and production costs. Nimonic 80A was machined with the coated cutter to evaluate the performance of disparate cooling strategies. At a higher cutting speed, flood coolant outperformed the MQL environment even though it performed well under average working speed [32].

Cryogenic (cryo) environment when cutting seems to be cleaner because there is no need for disposable after the use [9,33]. The prominently used cryogenic gases are carbon dioxide (CO_2) and liquid nitrogen (LN_2) [34]. Furthermore, no clumsy usage of CF's obstructs the working environment and harms workers' health [8,35]. Cryogenic environment aided cutting is regarded as a viable cooling strategy in this regard [36]. Furthermore, surface integrity has substantially enhanced, particularly at the peak pressure and flow rate. Ayed et al. [37] explored the impact of variables on surface topography and cutter wear when cutting Ti-6Al-4 V. To modify the pressure and flow rate, a variety of nozzle hole sizes were used. At the maximum pressure and flow rate, the surface integrity has substantially improved. Owed to the sporadic nature of milling action, there have been some controversies in the literature about the impact of cryo environment on milling performance. Cryo LN_2 has no impact on the effectiveness of AISI 304 material, in comparison to no coolant when milling [38]. CO_2 as a cutting medium recognised less wear on the coated insert when finishing titanium alloy, instead of using traditional CFs. Cakir et al. [39] evaluated the performance of LN_2, O_2, and CO_2 conditions. The outcomes revealed that cutting with CO_2 snow yielded less cutting force and low roughness on the machined face than cutting by dry or flood environment. The CO_2-snow approach was deployed to evaluate the performance of CF in threading and parting operations. According to the experimental outcomes, a CO_2 flow rate of 6 g/s is suitable for threading and parting of stainless steel [40]. Jerold and Kumar [41] executed cutting of Ti-6Al-4V and compared it with LN_2, CO_2, flood and dry cutting strategies. CO_2 produced 2–12% fewer cutting forces and 2–14% more surface uniformity than cryo LN_2 environment. The application of CO_2 confirmed improved chip control and cutter wear reduction than other cutting environments. Khanna et al. [42] used PVD coated inserts to investigate the effects of 15-5 PH stainless steel under various cooling settings. Cryogenic machining outperforms conventional machining in terms of power consumption and subsurface microhardness. The relatively finer grain size was produced in the cryogenic machining. Iqbal et al. [43] analysed the milling orientation, helix angle of the cutter, varied cutting speed, and the impact of CO_2 cooling on Ti-6Al-4V cutting. The outcome demonstrated that down-milling outpaced up-milling concerning cutter wear and machined face quality. Cryogenics demonstrated minor impacts during the machining of several materials as well as when varied cutting conditions were used. The question is: why cryogenic coolants have a lower impact on machinability in particular circumstances.

Nonetheless, the environmental friendliness by cryo cooling, besides the benefits offered in regards to cutter life and surface quality preservation, demands the use of this excellent cooling technique [44]. MQL provides lubrication amid tool-work material and the cryogenic environment gives a chilling effect [45]. Therefore, cryogenic+MQL (hybrid method) combination was employed to curtail the friction by increasing the lube effect and boosting the cooling performance throughout the cutting process [46]. Hybrid environment enhances the productivity, machinability and end part quality in the cutting of NIA. Varied C/L strategies were explored, and finally proposed a new combined approach of C/L with an altered stream to progress the efficacy of machining [47]. Pereira et al. [48] examined external MQL and CO_2 as an internal coolant in the cutting of NIA. The grades display that internal Cryo+MQL enhances the cutter life by 57% with flood condition. It was concluded single C/L was incompetent before the hybrid method.

For various machining settings, literature contributed reports on the use of conventional, MQL and cryo lubrication. Manufacturing industries are persuaded that using alternative cooling methods will advance the economy, decrease environmental consequences, and improve part quality. A new method was employed to distribute lubrication (flank) and cooling (rake) on the faces of the insert. Based on a literature review, limited studies of Nimonic 80A milling with a hybrid environment can be observed. This holistic investigation is to evaluate the outcomes of various C/L techniques during Nimonic 80A cutting. Until now, no comparison study on machining outputs mentioned below was reported concerning MQL, CO_2 and hybrid environments. The present study is intended to fill the gap. Therefore, the effects of distinct green C/L approaches on milling temperature, power consumption, specific cutting energy, burr formation, XRD and grain growth are studied in milling of Nimonic 80A at varied speed-feed combo.

Table 1
Chemical elements.

Alloying element	Ni	Cr	Fe	Ti	Al	Others
Wt%	73.21	19.35	2.5	2.49	1.55	Bal.

2. Materials and methods

2.1. Machine, work material, and cutting tool

Nimonic 80A was employed as a work material in this work. It has remarkable thermo-mechanical attributes, specially designed for highly specific application areas in the automotive and aerospace industries [49]. The work material key characteristics are reliability at elevated heat, resistance towards corrosion and less thermal expansion. The work material having dimensions 150 × 100 × 10 mm^3 was utilized during the trials. The chemical elements present in the work material are presented in Table 1. As this material is operated in specialized applications that need a high level of surface smoothness thus, the end milling

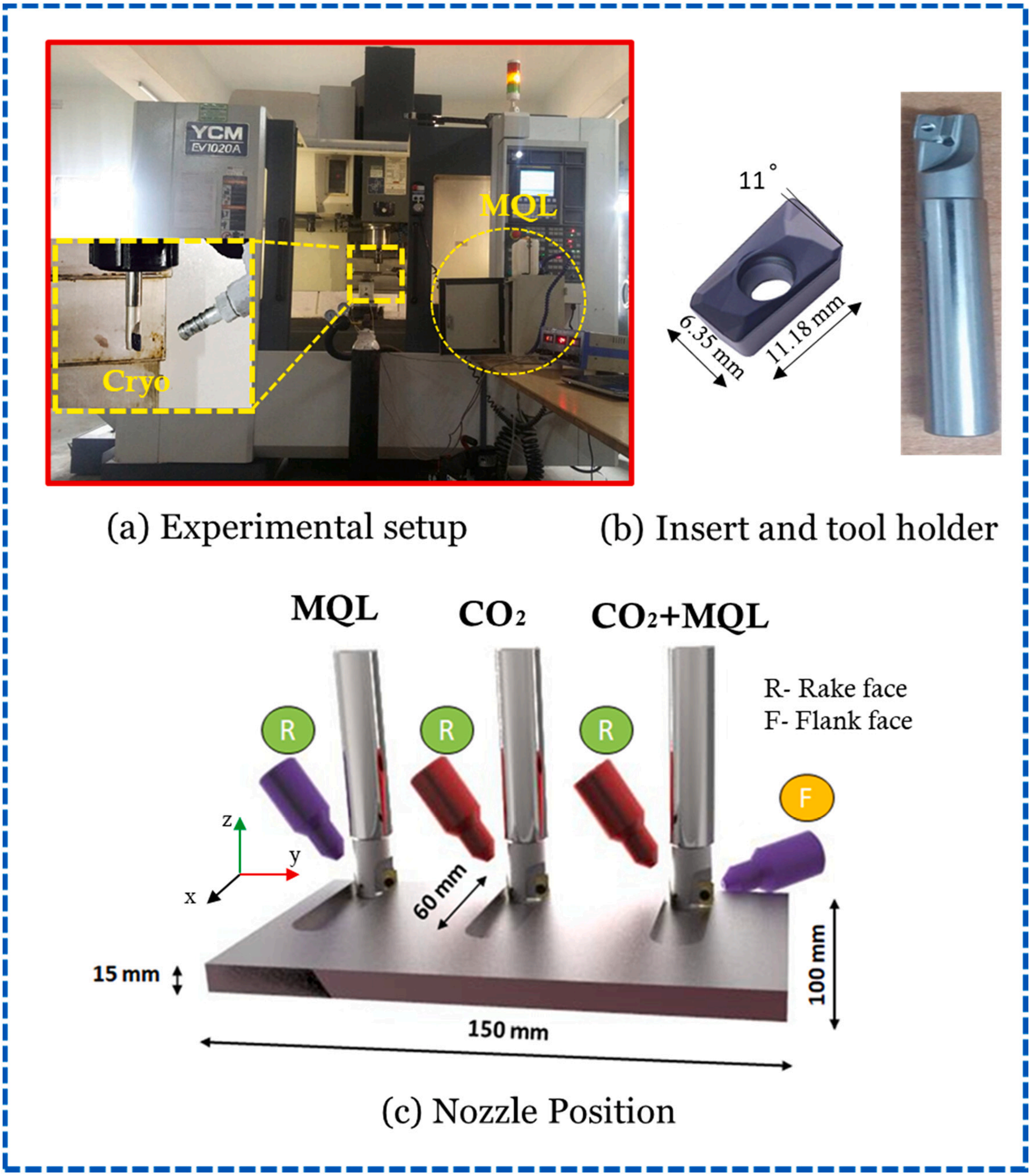

Fig. 1. Experimental methodology (a) Experimental Setup, (b) Insert and holder (c) Nozzle positions for MQL and Cryogenic system.

Table 2
Peaks Intensity and FWHM (111) values at Vc = 90 m/min, f = 0.08 mm/rev.

Material condition	2 θ	Intensity	FWHM
As received	44.15	14,863.6	0.72648
MQL	44.07	12,000.2	0.78309
CO_2	44.00	11,500.5	0.82478
CO_2 + MQL	43.05	9200.3	0.86301

process was engaged to study the surface attributes. Milling studies were steered on a YCM EV20 Machining Center with a 10,000 rpm (range) spindle speed and a power of 20 kVA (Fig. 1(a)). Further, parallelogram-shaped cutters (inserts) were engaged to mill the work material. End milling was done using a PVD-TiAlN coated insert (APMT 1135 PDTR, DARMET) held in a tool holder (BAP-07H), both displayed in Fig. 1(b). The process parameters were chosen based on previous researches and industrial practices: Vc, f, and cooling conditions (Environment). All of these have a significant impact on surface features. The experimental details and cutting parameters are presented in Table 2.

2.2. Machining conditions

The MQL system was used to spray VO into the cutting region, which was accompanied by air in a mist form. The oil from the sump is pumped into the mixing chamber, where it passes through the flow control valve. From the compressor, another hose joins the mixing chamber. The increased reach of oil to the cutting area is aided by the controlled air pressure. The wettability at the shearing area was good due to the nozzle exit (2 mm) and distance from the cutting place-nozzle. The position of the nozzle is displayed in Fig. 1(c). With a flow rate of 60 ml/h and a pressure of 2 bar, a mist of olive oil+air was sprayed. The fatty acid components of olive oil are responsible for a significant reduction in

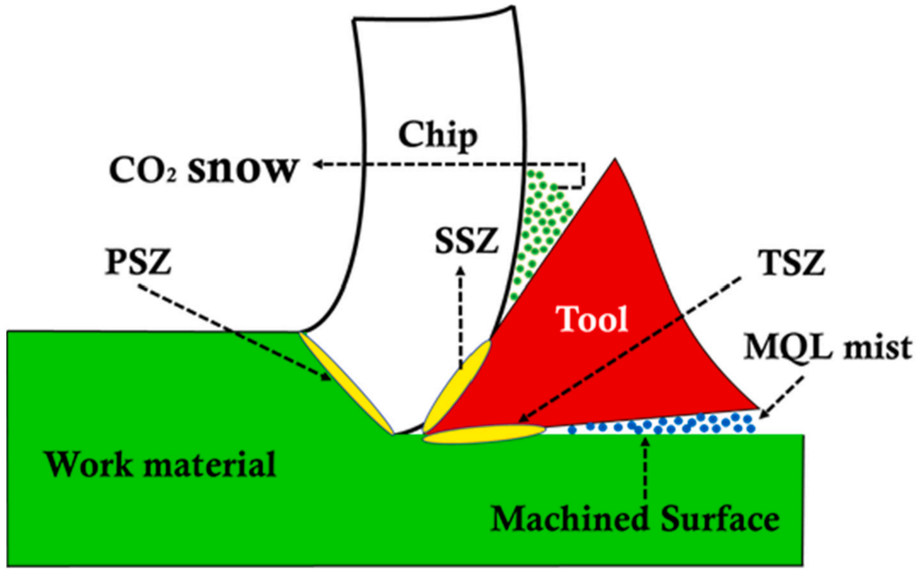

Fig. 2. Effect of shear zones under hybrid metal cutting.

friction. The chemical elements of olive oil comprise of two main compounds: 85% unsaturated fatty acids and 15% saturated fatty acids. The inclusion of a significant number of unsaturated fatty acids helped to keep olive oil stable during oxidation, and this stability made olive oil a good lubricant. Olive oil's superior low-temperature qualities also made it excellent for lubrication. For example, it has been claimed that the iodine number of CF must be less than “95” for excellent lubricating conditions, yet olive oil has an iodine number of “89” [50].

The cryo environment controls the heat developed at the cutting surface instantly and dissipates into the surroundings without leaving any deposit. It satisfies three major criteria of sustainable practices: economic, socio, and ecologic. The pressure regulator is fitted to the hose to regulate the quantity of the fluid. With 2.5 bar pressure, cryo CO_2 was made to flow via the nozzle exit.

2.3. Measurement of responses

For the assessment of generated heat at the cutting area, an infrared thermometer (HTC brand) with a range of −50–1650 °C (±1) was used. To obtain absolutely close readings, the thermometer's emissivity was adjusted to 0.95–0.97. The thermometer was positioned at a 45° angle and 70 mm away from the cutting region. To evaluate the cutting forces, a three-component piezoelectric Kistler model (9257B) dynamometer was utilized and then specific cutting energy was calculated. The details are given in further sections of the result and discussion. A video measurement system (2010 F) was used to assess the burr formation. An X-ray diffractometer was used to specify the d spacing and 2Θ. An optical microscope with a magnification of 100× was used to examine the microstructure of the sliced surfaces. The ASTM E112-13 standard was

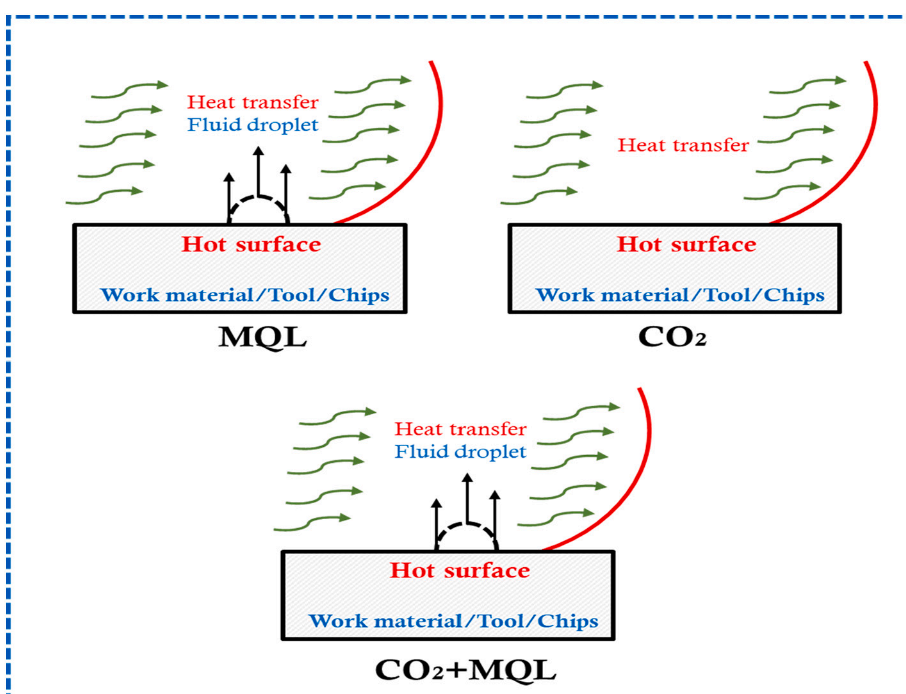

Fig. 3. Distinct cutting environments in milling of Nimonic 80A.

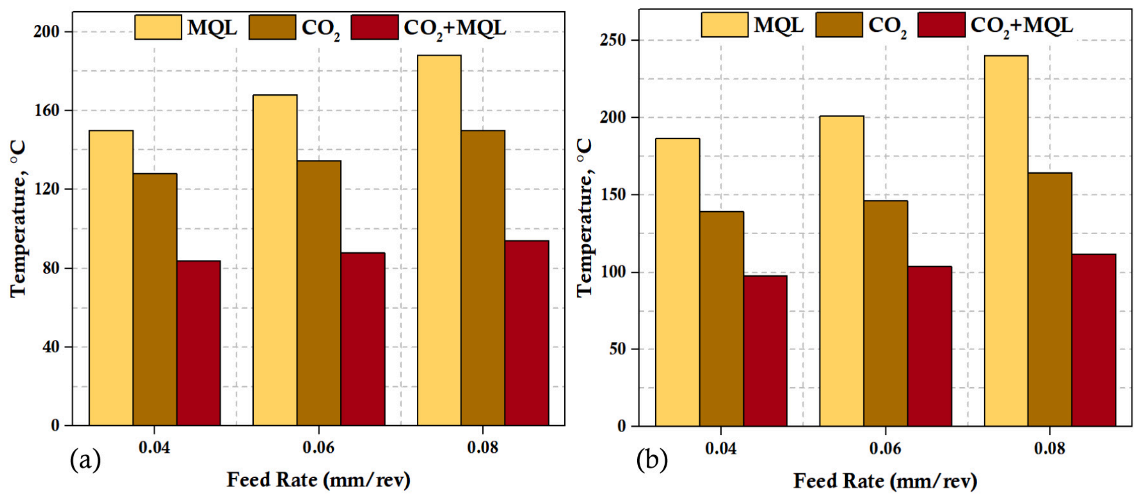

Fig. 4. Impact of distinct environments and speed-feed combo on average surface roughness at a Vc of (a) 75 m/min (b) 90 m/min.

employed to determine the average grain size.

3. Cutting mechanism

During removal of material, rigorous deformation happens in 3 diverse areas adjacent to the work material-tool juncture. (i) Primary shear zone (PSZ), established by forming of chip from the material; (ii) Secondary shear zone (SSZ), development through friction in the contact area (rake face) of the tool-chip; (iii) Tertiary shear zone (TSZ), where plastic deformation arises due to work material interference with a tool flank surface. Heat transfer is an integration of conduction, convection and radiation [22].

Through solid materials, e.g., cutter, work material, tool holder and chips, the heat generated at the cutting zone will be carried out. The schematic representation of mechanical phenomenon evolving at the hybrid cutting environment is displayed in Fig.2. The MQL mist, supply lubrication effect to the flank surface which reduces the friction, the balance heat transferred to the flank face, which was removed with the help of cryo environment. The heat transfer mechanism of distinct environmental conditions is displayed in Fig.3.

Under MQL, CO_2 and hybrid cutting environments, forced convection is involved to keep the heated areas cool (refer to Eq. (1)).

$$Qcv = hA\Delta T \tag{1}$$

Here, Qcv – convection heat transfer, h – heat transfer coefficient $\frac{W}{m^2K}$, A – area (m^2), ΔT is – initial temperature and final temperature variation.

The heat transmission during the C/L of the cutting area is influenced by the machined face condition (smooth or uneven surface) and the fluid flow parameters (laminar or turbulent). Accelerating the Reynolds number due to fluid velocity promotes turbulent flow with greater heat transfer. When the surface temperature approaches the coolant's saturation point, film boiling and nucleate heat transfer occurs. Both were the major heat transmission mechanisms on the cutting tool at a temperature over 300 °C, according to earlier findings for dual-phase oil-compressed airflow. Cryo-CO_2 has less saturation temperature than oil, and film boiling can occur at temperatures far lesser than MQL. In film boiling, the development of a vapour layer can considerably limit the heat transmission from the cutting zone [46].

4. Results and discussion

4.1. Hybrid cooling on milling temperature

High heat and friction at the insert and work material juncture cause cutter wear, resulting in a lower level of accuracy at the machined face. The majority of the mechanical energy related to chip production is transferred to heat in traditional milling [51,52]. The insert and work material may be thermally damaged as a result of the increased heat. When milling, chips taken from the block spoils the insert as the cutter advances into the work material as a reason of low thermal conductivity. Metal cutting uses a lot of energy, which is mostly turned into heat [53]. The insert is introduced to periodic heating and cooling during the milling operation [20]. The choice of C/L media aids to lessen the heat at the cutting region. Fig. 4 displays the movement of M_T examined by IR gun at the Vc of 75 m/min and 90 m/min. The M_T values at a Vc of 90 m/min and a *f* of 0.08 mm/rev are 240 °C, 164 °C and 112 °C for MQL, CO_2 and CO_2 + MQL cutting strategies, respectively. The improvement of the hybrid condition seems to be 53% over MQL and 32% over cryo condition. The maximum M_T was created with MQL condition at the Vc of 90 m/min and lesser heat was found while using CO_2 + MQL, as an outcome of the effective C/L activity of hybrid condition into the cutting area. MQL condition produces higher M_T in the shear zones when compared to all other cutting environments. Higher Vc under MQL condition produces faster evaporation or burning of oil, reducing its lubricating properties, as compared to a lower Vc [54]. With the employment of cryo cooling, heat at the insert tip, work material contact and adjacent area were curtailed. When CO_2 was jetted to the tool-work material juncture, by swallowing the heat, the coolant evaporated, which reduced the heat. The concurrent application of CO_2 and MQL outpaced other cooling environments in terms of higher lubrication by MQL and elevated cooling effectiveness by cryogenics. Due to the joint effect of low cooling and high lubrication, frictional force at the tool-work material contact was found to be lower than stand-alone CO_2 and MQL.

4.2. Hybrid cooling on power consumption

Machining consumes a lot of energy and has a big impact on the environment. Machine tools produce waste and heat in addition when processing materials [55]. The energy usage might be measured, projected, and lowered if a proper classification was formed. Multiplying the main cutting force with the cutting speed yielded the power consumption values (Eq. (2)) [52]. The dynamometer was deployed to monitor the cutting force components (F_x, F_y and F_z) in the milling operation. The resultant cutting force (F_c) was later estimated by the formula $Fc = \sqrt{F_x^2 + F_y^2 + F_z^2}$.

$$P = Fc \times Vc/60 \tag{2}$$

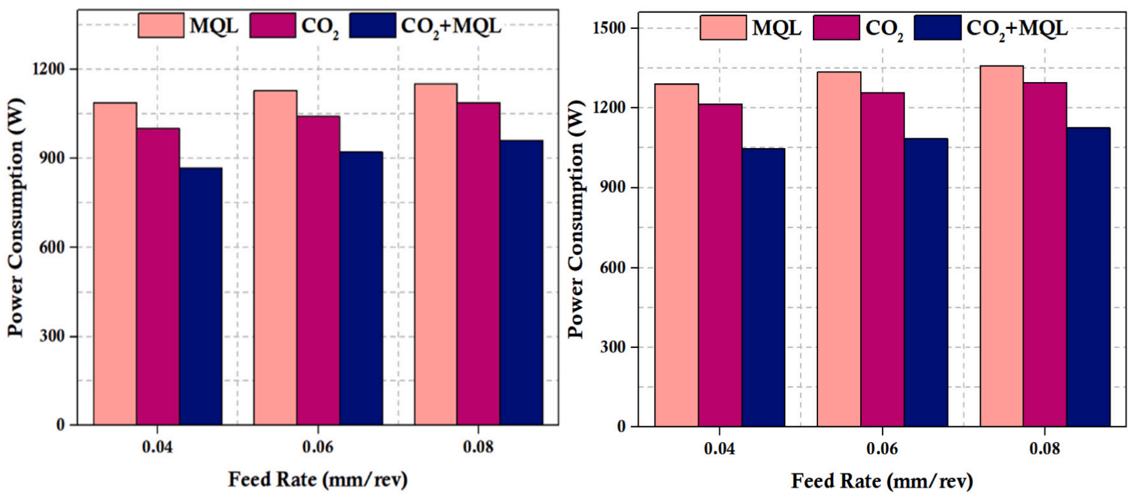

Fig. 5. Impact of distinct environments and speed-feed combo on power consumption at a Vc of (a) 75 m/min (b) 90 m/min.

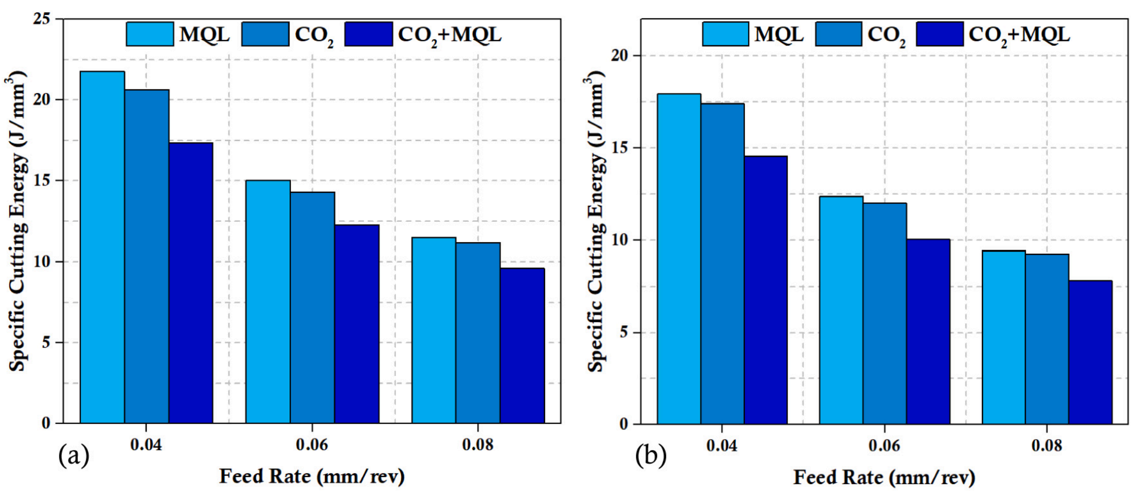

Fig. 6. Impact of distinct environments and speed-feed combo on Specific cutting energy at a Vc of (a) 75 m/min (b) 90 m/min.

where Fc represents the main cutting force which is in N and Vc denotes the cutting speed in m/min. Machining of Nimonic 80A with a coated insert in a 5.5 kW CNC lathe machine at 75 and 90 m/min, *f* of 0.04, 0.06, and 0.08 mm/rev, and a constant depth of cut of 1 mm was carried out in this work. Fig. 5 presented the differences in power consumption as an outcome of cutting parameters concerning disparate cutting strategies. It was discovered that increasing the *f* and Vc had an increasing effect on power usage. The estimated values were 1359 W for MQL, 1296 W for CO2, and 1125 W for CO2 + MQL strategy at a Vc of 90 m/min with f of 0.08 mm/rev. The reduction in power consumption when compared to CO2 + MQL, was determined to be 17–19% over MQL and 11–13% over CO2. The largest power consumption was found to be 1359 W at a *f* of 0.08 mm/rev under MQL condition and the lowest value was found to 868 W at a *f* of 0.04 mm/rev. The poor lubricity of MQL rises the contact amid work-tool material, which in turn increase the power required for milling under all MQL conditions that are displayed in Fig. 5. The cooling effect by cryogenic condition somehow managed to curtail the power consumption by reducing the tool wear. One of the reasons for power consumption is insert wear [56]. The cryogenic with MQL method applied to the flank side acts as a cushion and provides lubrication, which thereby reduces the friction. The reduction in friction limits the point of contact which decreases the power consumption. When evaluating the impact of power consumption, Bhushan [57] found that machining condition optimization is crucial for long-term sustainability.

4.3. Hybrid cooling on specific cutting energy

Energy usage during cutting accounts for a large amount of manufacturing costs. Manufacturing industries consume around 60% of all energy, according to the report [27]. Pump and compressor utilise the most energy during the applications under varied environments. The use of energy measured in this study is based on the working speed.

The obtained cutting force during machining is utilized in Eq. (3) to calculate the cutting energy [58] for each attempt.

$$SCE = Fc/(f \times a_p) \quad (3)$$

Fig. 6 illustrates how cutting energy varies depending on the speed-feed and environmental measures. It's fair to say that when Vc rises, cutting energy during milling decreases. Higher M_T and cutting forces were created at elevated speed-feed combinations, necessitating larger energy to execute the cutting operation [53]. More energy consumption was recorded with the MQL environment due to increased cutter wear and friction during the cutting of Nimonic 80A. Lower energy consumption was noted with the use of hybrid coolant, subsequently, its C/L efficiency reduces friction in the cutting region. The magnitude of cutting force is a direct indicator of the scale of energy spent by a machining process (Khalid et al. [59]), high levels of SCE is a result of high cutting

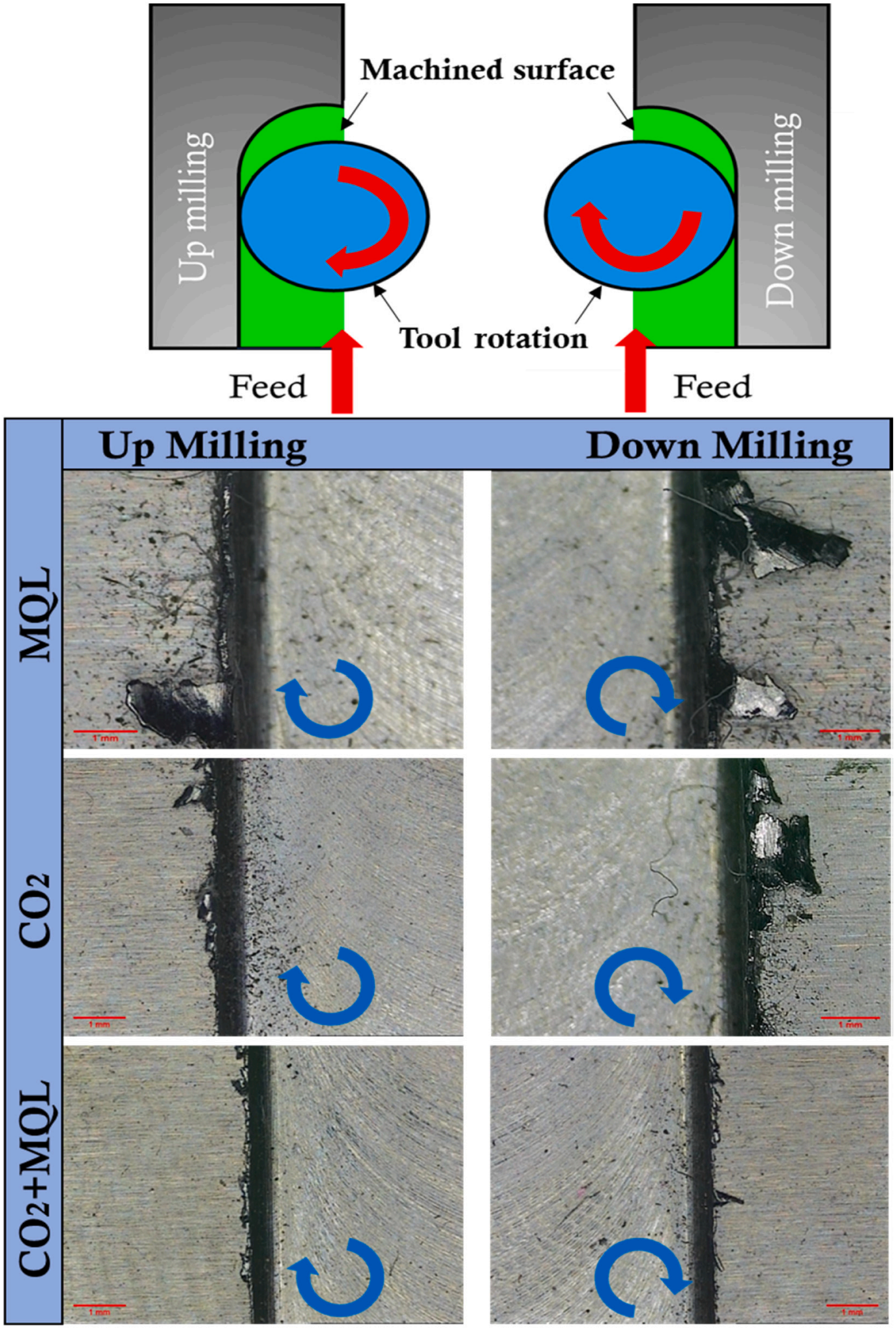

Fig. 7. Development of Burr under distinct environments at Vc = 90 m/min, f = 0.0.08 mm/rev.

force values. In comparison to the MQL environment, the hybrid medium diminishes energy usage by about 17–20%. Similarly, the use of MQL has resulted in a 14–16% reduction in energy usage when compared to CO_2 reduction.

4.4. Hybrid cooling on Burr development

It is usual to see side burrs throughout the orthogonal cutting process, and its height is determined by the temperature of the work material being cut [60]. Burrs can be extremely big, uneven, or smaller in size. A secondary procedure like deburring is both expensive and time-

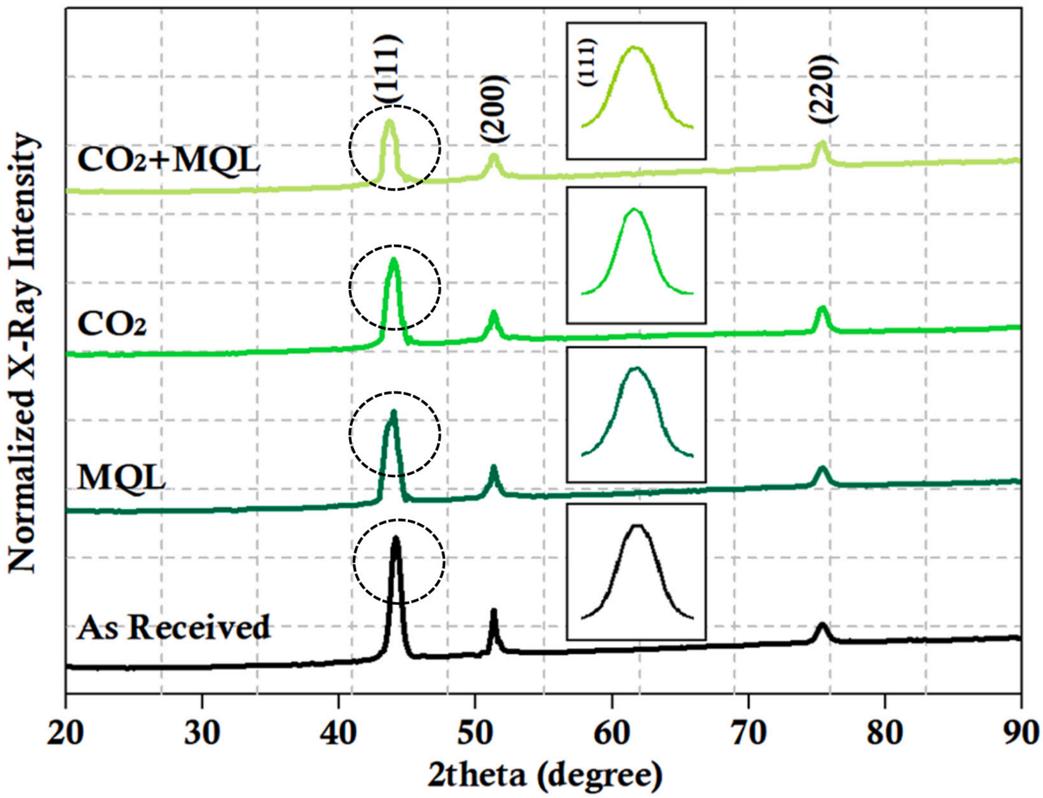

Fig. 8. X-ray diffraction of Nimonic-80A alloy under distinct environments at Vc = 90 m/min, f = 0.08 mm/rev.

consuming. Deburring costs and time are determined by the size and complexity of the job. Larger or harder burrs usually necessitate more time and a more effective deburring technique [61]. To reduce burr formation and perhaps increase the surface quality and cutter life, a thorough understanding of burr development mechanisms in the end milling process was examined with the help of up-milling and down-milling. The precise choice of cutting parameters is crucial in the evaluation of burr development. Burr formations for the varied strategies are given in Fig. 7. During the up-milling action, the cutter scoops the metal and works its way up. Particularly, the chip's width will begin at zero and gradually rises [62]. Under down-milling, the maximum chip thickness is reduced to minimum thickness with rotation of the cutter [63].

In comparison to other cutting strategies, burr formation under hybrid strategy was seems to be less intensive, which is more rigorous in MQL cutting and less with Cryo-cooling. The material's hardness contributes to burr creation during the metal cutting process [64]. As a result, in the cutting process of Nimonic 80A, burr creation can be seen more clearly. It is possible to say that there is no difference between no coolant cutting and MQL environment. In other words, MQL has no direct effect on the reduction in burr formation. The MQL method, on the other hand, may be an indirect supplier to the reduction in burr development because it minimises tool wear. Tool wear is another component that influences burr development during the cutting process explained by Maruda et al. As the tool wears, the radius of the tool's edge increases, and the tool's acuity reduces. Thus, the cutting procedure is challenging [65]. Burr formation increases as a result of this situation. In this case, cryogenic precooling applied locally to the workpiece surface produces a brittle structure on the surface. The literature suggests that cryogenic chilling raises the hardness of the material while decreasing the toughness of the material. Burr formation is greatly reduced following cryogenic pre-cooling. Hybrid cooling sustains the sharpness of the insert all over the cutting process, which in turn lessen the development of burr on the sides of the machined face.

4.5. *Crystallographic structures*

Patterns of X-Ray diffraction (XRD) of the machined face under disparate cutting environments are shown in Fig. 8, at a Vc of 90 m/min and a f of 0.08 mm/rev. To remove the influence of blade cutting, the samples were prepared for XRD examination using wire-cut machining. The initial finding of this study was that no phase transformation occurred under these circumstances. According to previous works, the melting temperature of this alloy is around 1320–1365 °C. Despite the fact that Vc was 90 m/min, the machined surface did not appear to be exposed to such high temperatures. However, after milling the Nimonic 80A alloy, noticeable modifications were discovered. Peak widening is often linked to increasing dislocation density and grain refinement, as well as a significant decrease in peak intensity [66]. The atomic radius and crystalline structure of several elements were obtained from international crystallographic tables. The diffraction angle 2θ, the intensity of the peaks are mentioned in Table 2. The lattice parameters 111, 200 and 220 were computed by using Bragg's Eqs. (4) and (5). There were minor variances in intensities and peaks are seen [5]. The received Nimonic 80A has the Full width half maximum (FWHM) value of 0.78648 and the hybrid condition produces the value of 0.86301 for the peak intensity of 111 at a Vc of 90 m/min and a f of 0.08 mm/rev. This FWHM shows peak widening under all cutting environments. The disparities occurred due to the deformation taken place in the lattice structures. The variances in the diffraction angle 2θ were also relatively similar in MQL and CO_2 environment when compared to the CO_2 + MQL condition.

$$2\lambda \text{ Sin } \theta = n\lambda \tag{4}$$

$$d_{(hkl)} = \frac{a_0}{\sqrt{h^2 + k^2 + l^2}} \tag{5}$$

The main findings from this section of the study include that employing CO_2 + MQL supply has impacts on the surface and depth

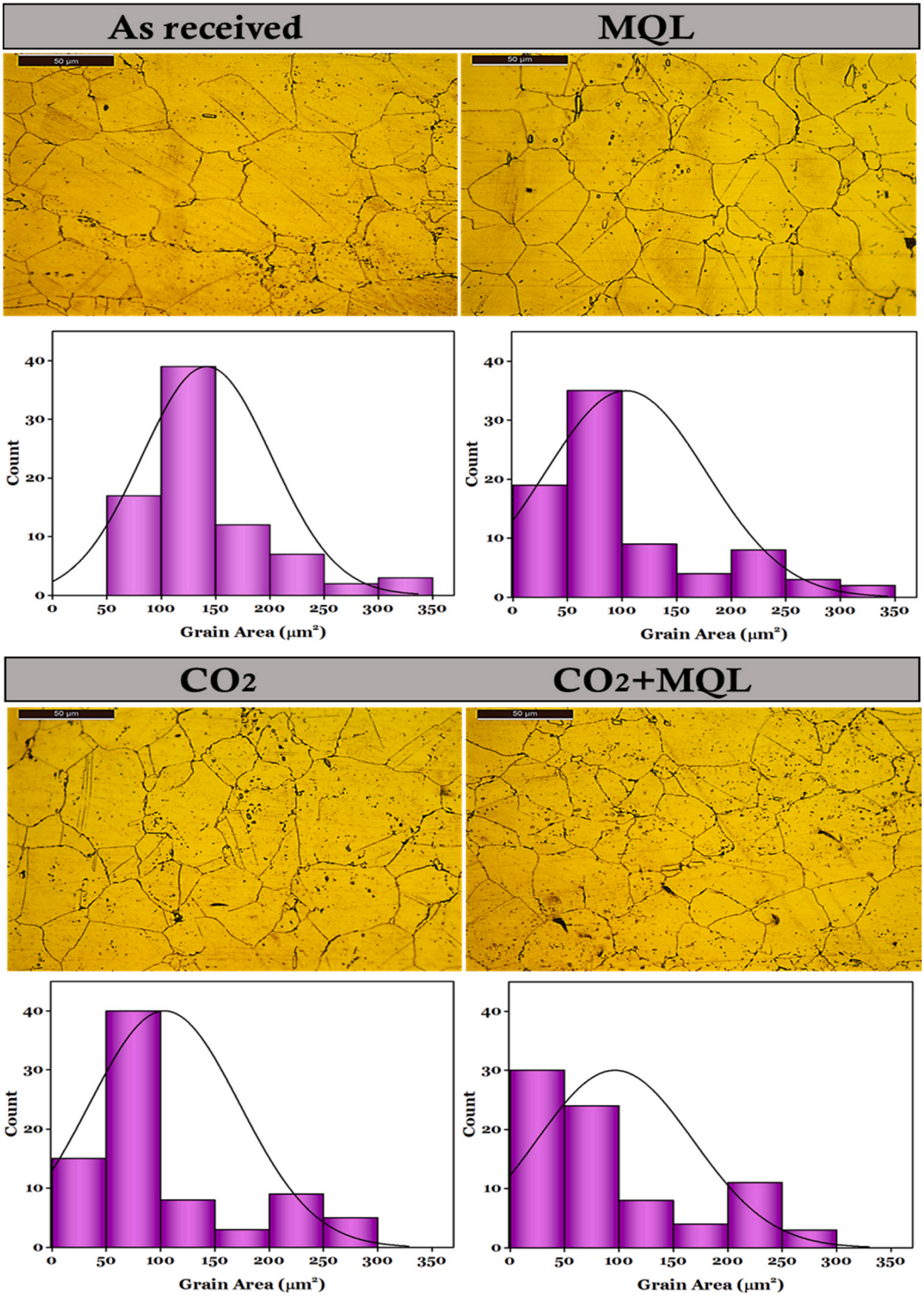

Fig. 9. Histogram of grain size distribution under distinct environments at Vc = 90 m/min and f = 0.08 mm/rev.

beneath machined components, although there is no evident phase change. Furthermore, cutting environments like MQL and CO_2 cause a comparable effect on the surface and depth beneath machined components. Increasing the Vc does not result in any further modifications to the surface or surface below the machined components.

4.6. Hybrid cooling on grain refinement

The microstructure formation of the material throughout the cutting process consequences in bigger grain sizes on the machined surface that are undesired [66]. Factors that impact the grain size are machine tool configuration, cutter and work material properties. Grain refinement is found to be a foremost aspect while cutting; fine grains (FG) are necessary for the best part [67]. The production of FGs is mostly ascribed to the dynamic recrystallization process caused by extreme plastic deformation [68]. It is reported from other studies, precisely, FGs can strengthen the mechanical assets of the material. The size of the grain is predicted using the well-known Zener-Hollomon equation (refer eq. 6) [69].

$$\frac{d_{rec}}{d_i} = 10^3\left[\dot{\varepsilon}\mathrm{expexp}\left(\frac{Q}{RT}\right)\right]^{-1/3} \tag{6}$$

where d_i = initial grain size of the material, d_{rec} = machined grain size a, $\dot{\varepsilon}$ = strain-rate, and Q = activation energy, R = gas constant and T = temperature. Many researchers utilized experimental work to detect and control the grain growth on the machined faces [70,71]. Fig. 9 compares the area of refined grain layer produced after machining with MQL, CO_2 and hybrid cutting conditions. At a Vc of 90 m/min, the grain area produced with CO_2 + MQL was relatively very low in comparison to MQL and CO_2. From the graph (Fig. 9), it is understood that the grain area fluctuates from 0 to 350 μm^2 for the unmachined Nimonic 80A sample. However, significant differences have been observed with MQL (0–320 μm^2), CO_2 (0–290 μm^2) and CO_2 + MQL (0–285 μm^2) environments. During milling, a part of the heat will be carried into the milled surface. In the current work, the hybrid environment rejected the heat created at the machined face by reducing the friction by the MQL system, and the surface is being quickly cooled by the CO_2. The speedy heating-cooling cycle with cryo lessens the size of the grain area. In other cutting environments, the cooling rate is lower. The grains near the surface will suffer rapid cooling and maintain a small and refined microstructure [72]. When milling heat is transported to the subsurface, it causes localised thermal softening, which helps the plastic deformation. The reduced cooling rate and less reduction in friction with MQL and CO_2 cutting environment permit the heat to be absorbed deeper and decrease the grain size.

5. Conclusions

This research examines the effect of process parameters on cutting temperature, power consumption, specific cutting energy, burr formation, XRD patterns, and grain growth in milling of Nimonic-80A with MQL, CO_2 and CO_2 + MQL. The remarks attained are

- In comparison to other cutting procedures, hybrid cooling lessens the heat of the cutting area to the greatest range possible. As an outcome of lower temperature, the surface trait improves and wear on the flanks is reduced.
- When associated with MQL and CO_2-assisted machining, the suggested hybrid technique used less cutting power as an outcome of its lower cutter-work material point of contact. MQL uses more power at the elevated cutting speed, as a reason for poor lubrication.
- The hybrid condition had the lowest specific cutting energy, followed by CO_2 and MQL conditions. The acuity of the cutting-edge warrants exhibiting a lesser quantity of power and cutting force during work-material cutting. As a result, under the CO_2 + MQL condition, lower specific cutting values were found.
- In the hybrid C/L situation, the burr formation was less in contrast with other cooling strategies. The sharpness of the insert tip maintained under the hybrid condition is the reason for the reduction in burr development.
- Even at high speed, machining-induced phase transformation does not occur. As a result, post-machining treatment is not required. Under all cutting environments, there was a small change in FWHM values.
- A decrease in grain size increases the fatigue strength of the product. Hybrid condition lowers the size of the grains by decreasing the friction at the cutting place and provide chilling effect when milling.

Future recommendations

The hybrid cooling methods are very helpful in improving surface integrity characteristics of super alloys. However, the simulation and analytical models are still not available that considers the application of hybrid cooling conditions. Therefore, the development of prediction models are recommended as a future work that enables the application of hybrid cooling conditions in various sectors.

Declaration of competing interest

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We also confirm that there is no conflict of interest between authors.

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