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Comparison of Tool Wear, Surface Morphology, Specific Cutting Energy and Cutting Temperature in Machining of Titanium Alloys Under Hybrid and Green Cooling Strategies

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Abstract
Cutting energy must be reduced in order to make machining processes more eco-friendly. More energy was expended for the same amount of material removed, hence a higher specific cutting energy (SCE) implies inefficient material removal. Usually, the type of coolants or lubricants affects the SCE, or the amount of energy needed to cut a given volume of material. Therefore, the present work deals with a study of SCE in the turning of Ti–3Al–2.5V alloy under green cooling strategies. In spite of this, the research effort is also focused on the mechanism of tool wear, surface roughness, and cutting temperature under hybrid cooling, i.e., minimum quantity lubrication (MQL) and cryogenic. The tool wear rate, were explored with tool mapping analysis, and the results were compared with dry, MQL, and liquid nitrogen (LN$_2$) conditions. The tool wear rate analysis claims that the dry condition causes more built up edge (BUE) formation. In addition, the hybrid cooling conditions are helpful in reducing the SCE while machining titanium alloys.

Keywords Green cooling · Hybrid cooling · Sustainable manufacturing · Titanium alloys · SCE

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1 Introduction

Because of their mechanical and bio-functional qualities, titanium and its alloys are widely used in fields like medicine, aviation, and aerospace [1]. A number of specifications namely extreme strength and high resistance to corrosion and oxidation make this material group a strong candidate for leading engineering products [2]. But, combination of some features such as low thermal conduction ability, convenience for chemical interaction with surrounding materials and low elasticity reduce the machinability of such materials [3]. In addition, the high strength of this special alloy is responsible for the excessive cutting forces which rises the chatter tendency during machining operations [4]. Mechanical, thermal and chemical load factors lead to various single or multiple wear mechanisms specially in the machining of titanium and its alloys inevitably in the natural flow of metal cutting. As a result, a number of wear types located on the clearance and chip faces decreases the life of cutting tool. The high friction coefficient and high heat production is the another issue observed while machining titanium and its alloys [5]. Furthermore, an insufficiently high elastic modulus creates an excessive amount of deflection which pulls

the titanium workpiece away from the cutting tool during machining. The workpiece has a natural propensity to spring back as the cutting edge advances. The result is a deflection, vibration, and a clattering sound from the object [6]. The machining performance of titanium and its alloys are improved with the following methods:

- integrating laser, vibration and hybrid devices [7],
- finding optimum parameter combinations [8],
- improving cutting tool properties via coatings and textures [9],
- using advanced lubrication and cooling systems [10].

The use of modern lubrication and cooling systems (such as MQL, cryogenic, high-pressure cooling (HPC), etc.) are efficient to improve the machining performance. Airo et al. [11] applied the cryogenic and MQL facilities to compare them with traditional dry and wet machining for improving machinability of titanium alloy. The authors indicated that combination of cryogenic nitrogen promotes better machinability to reach low SCE and roughness along with longer tool life. Hong and Ding [12] worked on the impact of cryogenic cooling considering different applications such as precooling of workpiece, cooling different surfaces of cutting tool etc. As a result, the authors indicated that simultaneous cooling of rake and flank faces is the best option for lowering the cutting temperatures. Hong et al. [13] researched the performance of cryogens while machining of titanium based materials. Accordingly, remaining useful life was improved for five times when comparing with traditional methods. Machining performance of titanium alloys was studied by Silva et al. [14] at various cooling conditions. Their reports showed that enhanced pressure improves tool life eliminating the governing wear mechanisms. Lu et al. [15] defined the optimum cutting parameters for machining of titanium alloy under high pressure cooling. The results demonstrated that tool wear can be tolerated more than seven times while comparing with traditional approach. Yi et al. [16] made a comparison for base fluids and nano particle added fluid in machining of titanium alloy. Changing concentration of nanofluid was huge impact on machinability improvement in terms of wear situation, force components and oscillations. Shokrani et al. [17] used hybrid cryoMQL approach for a comparative analysis between single methods in milling of titanium alloy. They found that tool life was improved as 30 times while comparing with flood machining. In another work [18] the authors concentrated on the enhancement of efficiency of titanium machining. Their findings showed that low cost and better machinability indices are possible with cryogenic method when comparing with near-dry and drought environments. Ezugwu et al. [19]compared flood cooling and high pressure cooling environments for better machining of titanium alloy. Under determined cutting conditions, high pressure cooling increased tool life as two times according to author's findings. Sartori et al. [20] evaluated the efficiency in eliminating of wear development of uncoated and coated inserts under cryogenic media. Accordingly, cooled nitrogen was found as the best choice for lowering and erading of tool wear. Revuru et al. [21] optimized the cutting parameters under five different lubri-cooling environments. However, the impact of such facilities need to be tested in order to understand their impact level on machinability index [22]. Despite the fact that modern lubricating and cooling strategies have made a game changer effect on the machining characteristics, it is still questionable for the heat resistant alloys [23].

As a new material in this field, grade 9 titanium has been selected very rarely as the workpiece material for machining operations to this date. When it comes to making a choice between chemically similar materials on the market, it is critical to understand the priorities and weaknesses of each. Grade-9 titanium is a trade product that has better ductility, higher strength, and better corrosion resistance compared with other titanium-based alloys, which makes it a strict competitor in the aerospace and medical sectors. Therefore, this paper focuses on the quality level of machinability indicators of this alloy for the first time, considering cutting tool, machined part, and machine tool specifications. The major topic in the section is about measuring the ability of various cooling and lubricating modes to improve these machining characteristics, as shown in Fig. 1.

Such an approach provides a new point of view for the pioneers who favour Ti-alloys as the main materials. Thus, the capability of single and hybrid lubrication/cooling
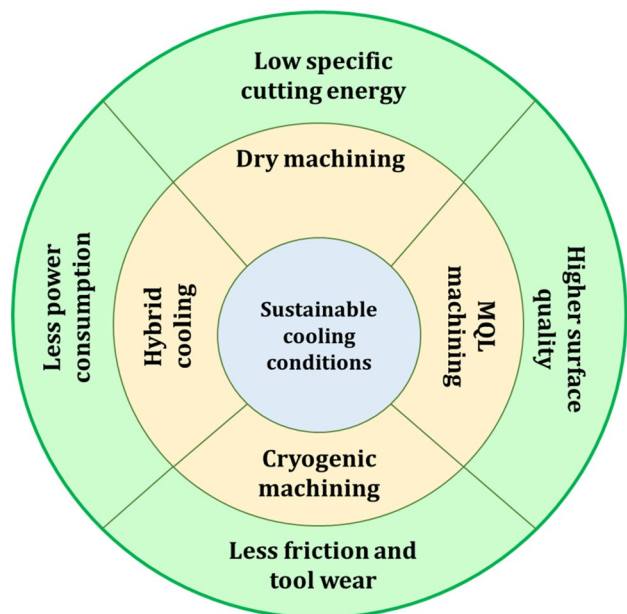

Fig. 1 Benefits of sustinable cooling conditions

strategies such as MQL, cryogenic, and cryo + MQL over dry medium on important machining outcomes is observed. Then, the tool wear rate is evaluated by considering cutting length along with wear profiles compared to actual cutting tool edges. In addition, the surface roughness, cutting temperature, SCE and surface morphology is examined from the perspective of cooling mediums. Finally, SCE calculated in various environments is analyzed by focusing on the length of cutting.

2 Materials and Methods

2.1 CNC Turning Center, Workpiece and Cutting Tool Details

Computer numeric control (CNC) machine was employed to conduct the turning experiments on Ti–3Al–2.5V alloy. This titanium grade is alternate of titanium grade 5 alloy and it is mostly used in aerospace as well as biomedical sector. This alloy consists of major elements like Al 3.2%, V 2.5%, Fe 0.25%, Ti, etc. The diameter of this alloy was 35 mm with 200 mm length and the final experiments were performed with CNMG 120408 uncoated carbide inserts.

2.2 Cooling Conditions

The present study contends with the application of dry, MQL, LN_2 and hybrid MQL + LN_2 while machining titanium alloys. In MQL system, the vegetable oil-based biodegradable cutting fluids were employed with the compressed air having 6 bar pressure. Two nozzles were used at the cutting zone having 45° position with flow rate of 50 ml/h. In LN_2 spraying, the 99.1% pure nitrogen gas was supplied at the cutting region with single nozzle. The flow rate of 0.35 L/min having self-pressure of 4 bar was used during the supply of LN_2. Similarly, in hybrid cooling system, one nozzle of MQL and the other nozzle of LN_2 was used at the cutting zone with same parameters. The complete cooling mechanisms and systems are shown in Fig. 2.

2.3 Measurement of Responses

The cutting experiments were performed at 150 m/min of cutting speed, 0.20 mm/rev of feed rate and 0.5 mm of depth of cut. The tool wear was noted with the Sensofar Confocal Microscope with ISO 3685 standard (1993). Then, the tool wear rate (R) is calculated with Eqs. 1, 2 [24]:

$$R = log \frac{VBmax}{ls} = log \frac{VBmax}{1000 * t * Vc} \tag{1}$$

$$t = \frac{\pi * D * l}{1000 * f * Vc} \tag{2}$$

Fig. 2 Cooling systems adopted in current work
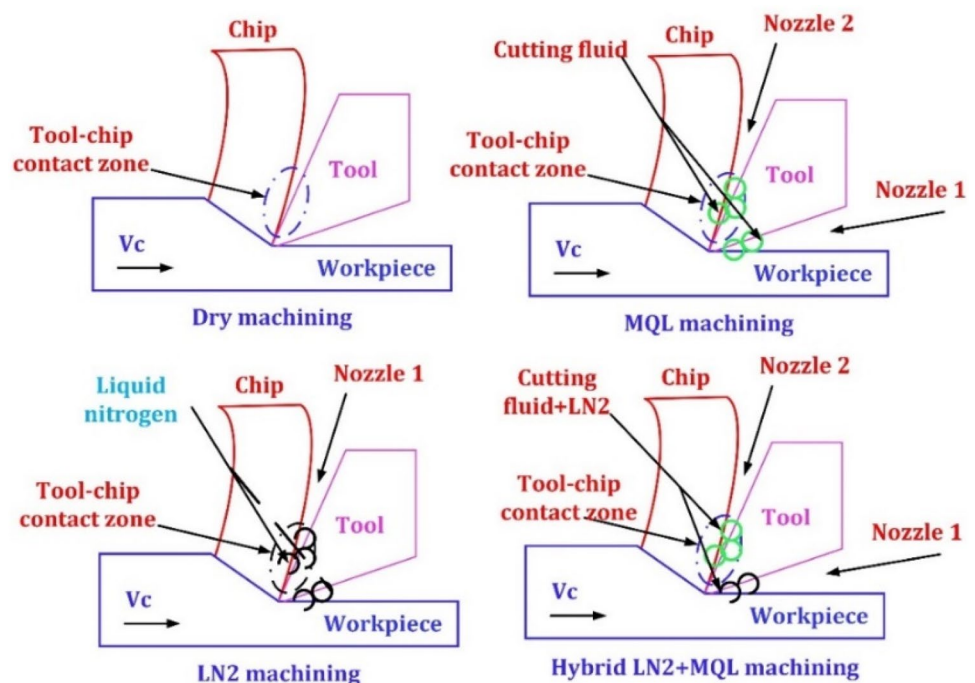
where *VBmax* is flank wear in mm, *ls* is spiral length of cut in mm, machining time is *t* in min, cutting speed is *Vc in m/min, f* is termed as feed rate in mm/rev, workpiece diameter, i.e., $\underline{D}$ is used in mm and linear length of cut is *I in mm.* The values of Ra, i.e., the arithmetic surface roughness was measured with Mitutoyo roughness tester at five separate places and then the mean value is taken. For temperature measurements, a thermal camera was utilized. Then, the SCE, J/mm^2 was calculated with the help of Eq. 3 [24]:

$$SCE = \frac{Power\ consumption}{MRR}. \tag{3}$$

$$MRR = Vc * f * d$$

where *MRR* is material removal rate; depth of cut is *d* in mm. The power consumption is calculated from the total power of the 3 phases given by the KAEL network analyzer. The power consumption of the CNC device in Watts was measured separately by the three phases, and then all of the power was collected and recorded from the analyzer. Figure 3 shows the machining schematic used in current work.

3 Results and Discussion

3.1 Development Procedure of Wear Maps

The tool wear rate (R) was calculated for each cutting condition using Eq. (1). The cutting parameters are not varied during the experiments and the wear map is drawn by following
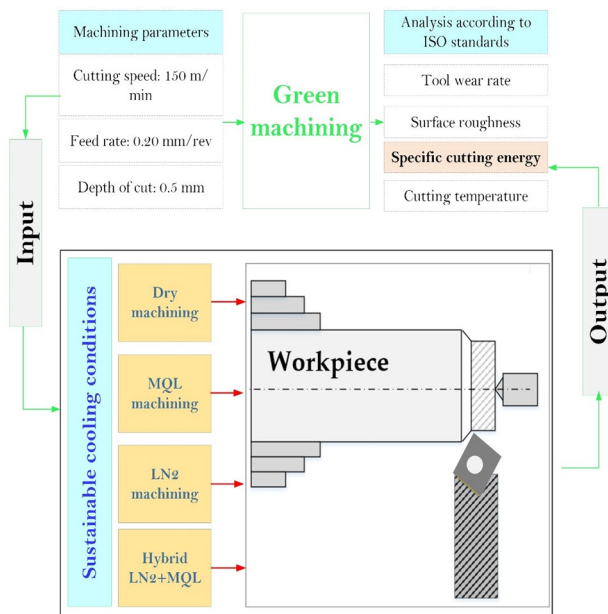

Fig. 3 Machining schematic adopted in current work

the cutting length and different cooling conditions, and this is the major novelty of the work. The three major findings of the current work are depicted in Fig. 4a–c, namely (a) tool wear rate (b) wear map showing different zones (c) wear promotion mechanism under different cooling conditions. The change in cutting length is considered at X-axis and the tool wear rate values are shown at Y-axis with respect to dry, MQL, LN2, and MQL+LN2 cooling conditions. Further, the map developed in Fig. 4b is divided into three different categories, i.e., low wear zone, medium wear zone, and high wear zone. These zones are considered based on the tool wear values and the mechanism generated during the machining operation. The complete mechanism of tool wear i.e., tool wear progressions, different mode of wear, abrasion, formation of built up edge etc. is provided in Sect. 3.2 with all its details.

3.2 Tool Wear Rate Analysis

When determining tool life, which is the most significant factor for cost and workpiece quality in machining, traditionally flank wear or crater wear is measured and decided. However, flank wear is often taken into account as it is more practical to measure and affects the accuracy, surface finish and integrity of parts [25]. It is possible to make a comparison with the machinability of the material at different cutting speeds by calculating the time in minutes required to reach a wear criterion (such as VB = 0.3 mm) in flank wear. However, this comparison has shortcomings in terms of standardization or normalization as it does not take into account the amount of material removed. An attempt (e.g., tool wear rate, R) to normalize the effect is to take a ratio of side wear and then divide this by the actual cut length for the material being machined. The wear map is a practical and useful tool for manufacturing engineers and machinists to show the relative wear status of the cutting tool [24]. This wear map serves as an essential guide for identifying areas characterized by several wear volumes and specific wear mechanisms. After determining the flank wear values for all cutting conditions by means of a microscope, the tool wear rate, R was calculated using Eq. 1, the details of which are already given in Sect. 2. The wear map given in Fig. 4a indicates the changes in the wear rates against cutting length under various lubri-cooling regimes. Since the value of the linear cutting length will always be greater than the tool wear, the wear rate is negative under all machining conditions. Therefore, the higher absolute of the wear rate demonstrates lower tool wear and therefore higher tool life. The wear map may also be described as a contour map which is frequently utilized by tribology and manufacturing studies to examine features such as tool condition, wear mode, surface roughness, and so on [26]. This produced map may be categorized into several regions defined by low, medium,
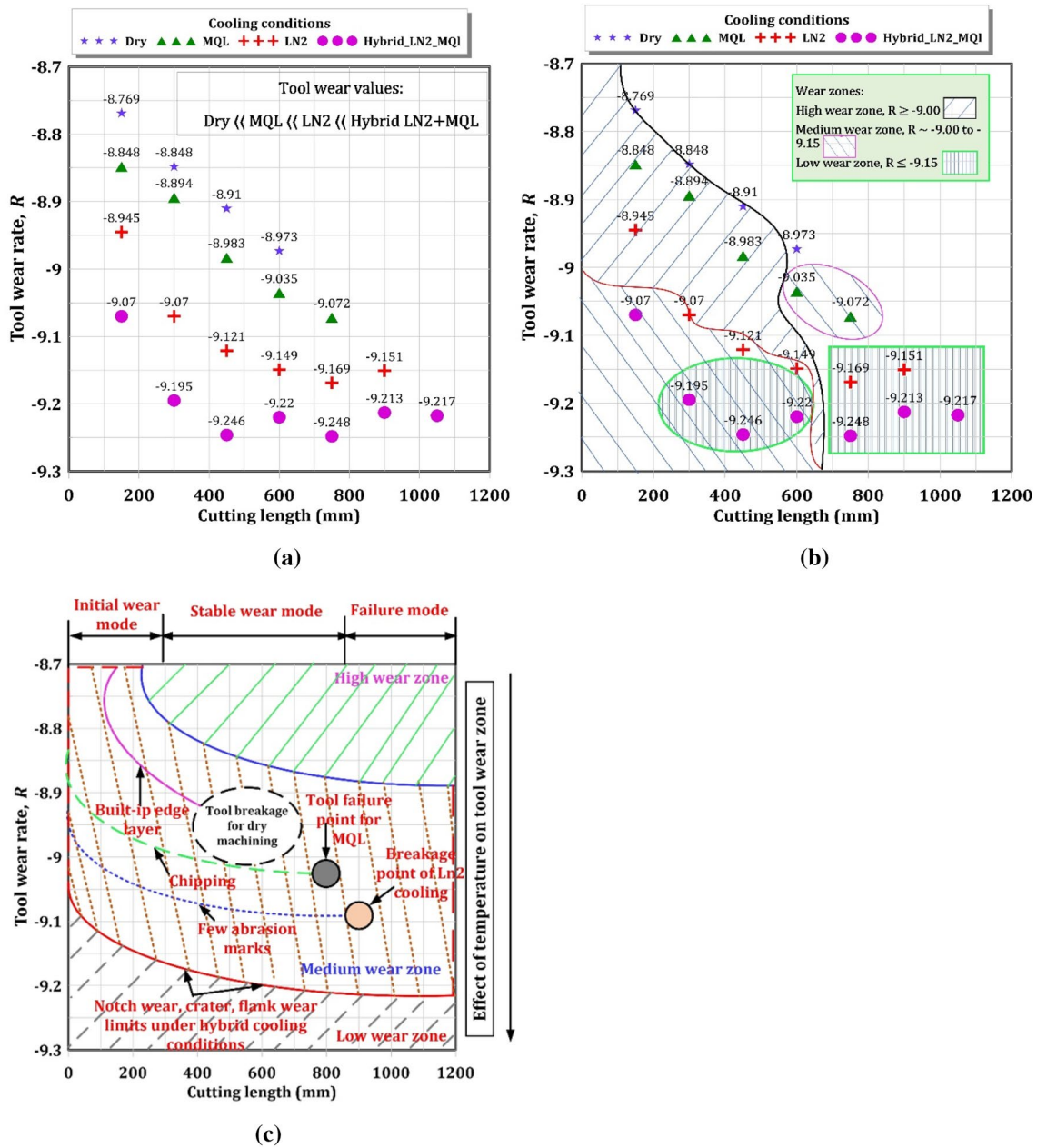
Fig. 4 **a** Tool wear rate, **b** wear map showing different zones, **c** wear promoting mechanism under different cooling conditions

and high wear zones, as shown in Fig. 4b. A zone of severe tool wear is also apparent between the low and medium wear zones, as seen in Fig. 4b. In machining operations performed under hybrid cooling, tool wear remained in the low wear region according to the wear map. LN$_2$ has the most spots in the low wear zone following hybrid-assisted cutting. Generally, in the tests performed under LN$_2$, although the wear is located in the medium wear region, it was also observed in the high wear region. In the MQL-assisted cutting process, the tool wear distributions were shared as medium and high on the wear map. From this point, it is possible to say that

all wear rates under dry medium are in the high wear zone. This situation proves that the tool performs very poorly in the experiments with a dry cutting from the beginning of the cutting wear rate. In other words, even if the amount of flank wear, which is accepted as a standard for tool life, is not reached, the usability of the tool is very short in the chip removal process under dry cutting in terms of wear rate. Figure 4c presents wear stages and corresponding damage modes on the tool wear map. Also, Fig. 5 demonstrates microscopic images of cutting tools and wear profile comparisons under different cooling conditions. The limits of

Fig. 5 Microscopic images of cutting tools and wear profile comparison beneath various cooling media, **a** dry, **b** MQL, **c** LN_2 and **d** hybrid LN_2 + MQL
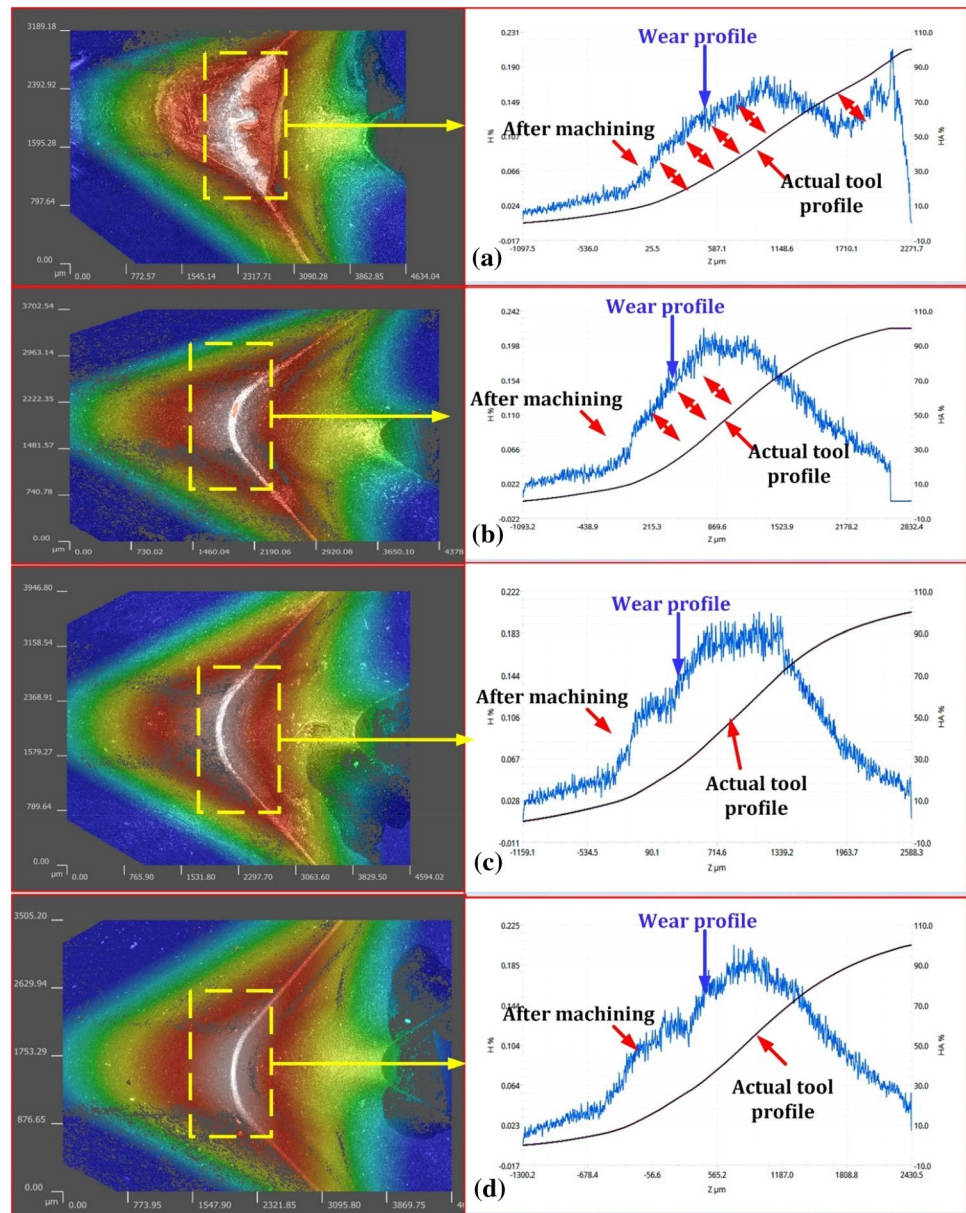
possible mechanisms that cause tool damage are visible on this map given in Fig. 4c. Accordingly, especially under dry cutting, the adhesion mechanism caused by higher temperatures and the BUE formation formed by its effect are seen as the main cause of the damage. Abrasive wear and chipping were considered as other important mechanisms leading to tool damage.

3.3 Surface Roughness Analysis

The roughness of a surface is one of the most considerable contributors in detecting how a real component will interact with itself and/or its surroundings [27]. In tribology, rough surfaces generally wear faster on contact and have higher frictional coefficient than smooth surfaces [28]. Roughness is generally a key determinant of the performance of a mechanical component, as surface irregularities can create cracks or nucleation sites for corrosion [29]. On the other hand, roughness can also promote adhesion. In particular, rough surfaces that work with each other in a certain temperature range are more likely to stick [30]. As a result, it is known that the rough surfaces of engineering materials adversely affect part performance. While a high roughness value is generally undesirable, it can be hard and expensive to control in production. Reducing the roughness value often increases the cost of production. This often outcomes in a trade-off between a component's cost to manufacture and its performing in the application. Therefore, achieving good

surface quality at the end of a machining operation without the need for secondary surface treatment such as polishing, grinding, honing, etc., is very important in terms of time and cost, as well as part quality. As a result, manufacturers set an upper limit for roughness in production, taking into account the working location and performance of engineering surfaces. In this study, considering the roughness classes specified in the ISO 1302 standard [31], the surface quality was divided into three different regions as seen in Fig. 6. The lowest surface roughness region was reached under hybrid cooling only at the start of the operation. The extreme tool wear and the tool wear adhesion that affects the machined surface are assumed to be responsible for the poor surface quality of dry-machined parts [32]. While medium surface quality was achieved in LN_2 and MQL-assisted machined titanium workpieces, the results obtained in dry cutting were included in the poor surface roughness region. Here, besides the influence of refrigerating/oiling applications on roughness, it is also useful in preventing burnt surfaces seen in dry cutting. When the results of the current section are considered together with the results obtained in Sect. 3.1, it can be seen that tool wear behaviours have a key influence on the roughness of machined surfaces. That is, the appropriate cooling strategy can be said to be effective in limiting tool wear [33]. Therefore, it has been found that both cooling and lubrication are beneficial to improve the surface quality of the workpiece. This can also be confirmed by the fact that the quality of the surfaces obtained separately under MQL and LN_2 is poorer than that of hybrid cooling. Gajrani [34] et al. also claimed that the cutting oil that is applied using MQL is able to retain the tool's sharpness. Different cooling rates are shown in Fig. 7 together with their corresponding
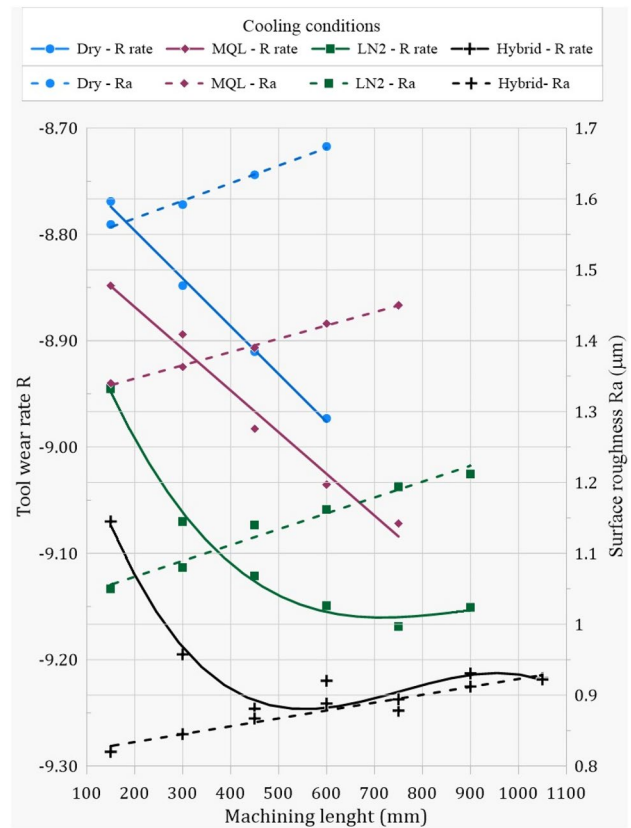

Fig. 7 Relationship between tool wear rate and surface roughness values according to various environments
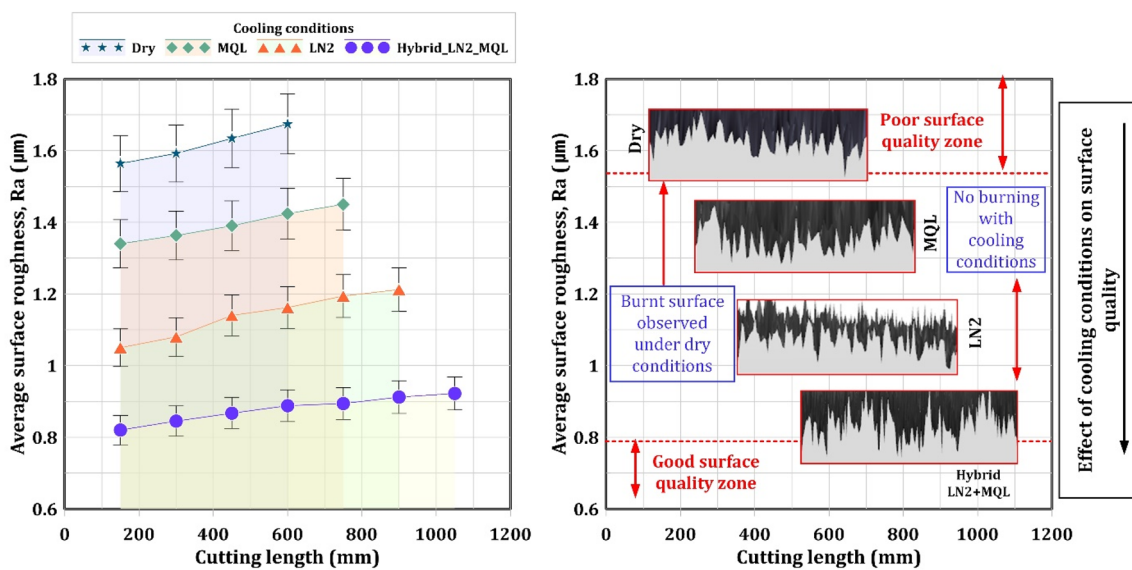

Fig. 6 Average surface roughness and mechanism promoting the poor roughness under different cooling conditions

effects on tool wear rates and surface roughness values. As a result, there is a robust inverse relationship between surface roughness and the values of tool wear rate. At different machining conditions, the trends in machined surface roughness alter as a function of the tool wear rate. These dissimilar trends can be attributed to the increased nose wear caused by the increased cutting length of some tools creating a wiper effect. It is thought that the peak curves of the roughness formed on the surface due to the wiper effect are reduced, as shown in Fig. 8 [35]. On the other hand, the smooth surface is observed under hybrid $LN_2 + MQL$ conditions and it is the combined effect of coolant and lubricant provides at the cutting zone.

3.4 Cutting Temperature Analysis

Heat generation is a normal occurrence in machining operations especially between tool and work piece. The friction between chips, tools, and workpiece are responsible for the heat generation at the main cutting zone [36]. Heat generated during titanium machining is less efficiently evacuated by chips than in steel alloys due to their low thermal conductivity and high strain rate [37]. As a result, the cutting tool and machined surfaces suffer thermally-induced damage due to the creation of high temperatures. Titanium alloys retain their mechanical properties up to approximately 400 °C,

but after this level, a more challenging step is taken for the mechanical and microstructural properties of the alloy [37]. Moreover, excessive increase in temperatures leads to the creation of favorable conditions for diffusion [37]. The efficiency of machining can be increased by decreasing the cutting temperature and friction. For this reason, coolants with excellent cooling and lubrication properties, metalworking fluids, or new-generation sustainable cooling/lubrication methods should be used [38, 39]. Based on this knowledge, alternative (sustainable) cooling and lubrication strategies have been used to reduce the frication and temperature while machining titanium alloys. As presented in Fig. 9, in the dry and MQL turning processes, the cutting temperature increased above 400 °C, which is considered the critical-threshold value for the titanium alloy [26]. On the other hand, thanks to the employment of cryogenic LN_2 in the cutting zone, a lower cutting temperature (between 250 and 300 °C) than MQL is offered. It was indicated before that MQL is weaker than LN_2 in terms of cooling performance when machining superalloys under heavy cutting conditions [37]. The reason for this situation is attributed to the evaporation of the cutting fluid with the high temperature occurring in the cutting zone in the machining of superalloys.

In machining processes, the Newton's law of cooling is used to estimate the heat transfers between the cooling/lubrication method and the cutting zone [37]:
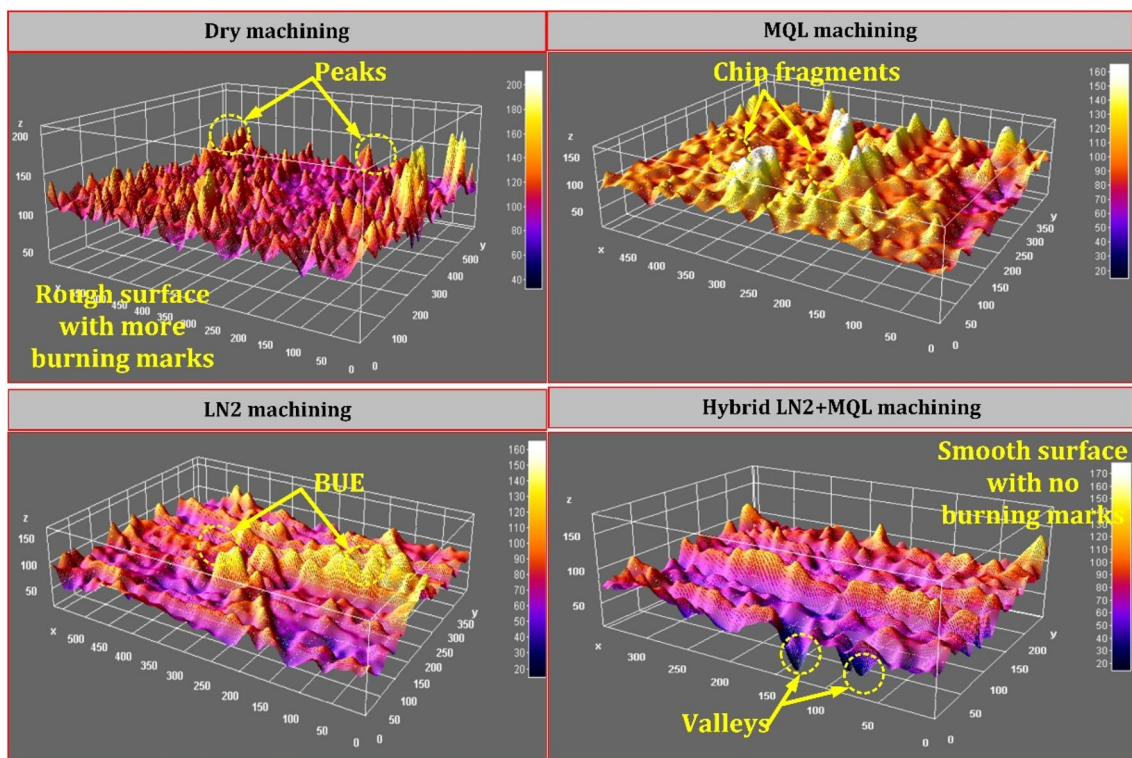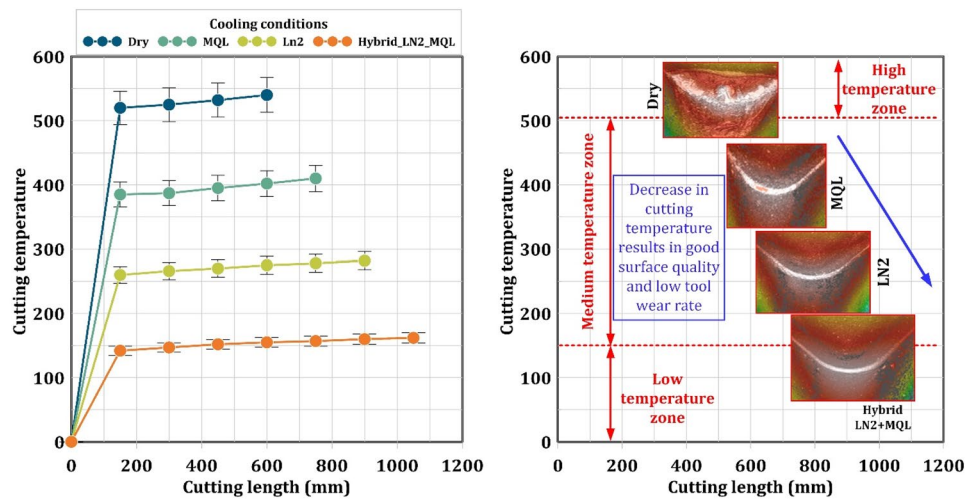

Fig. 8 Machined surface analysis according to various environments

Fig. 9 Cutting temperature and different temperature zones under different cooling conditions

$$\dot{Q}_{conv} = h \times A \times (T_s - T_f) \qquad (4)$$

where heat transfer (W) is represented by $\dot{Q}$, heat transfer coefficient (W/m²K) is h, surface area (m²) A, and T_s and T_f are surface temperature and fluid temperature, respectively.

Equation (4) indicates that the heat transfer from the shear zone is proportional to the temperature difference between the surface and the cooling medium. In other words, a significant amount of heat transfer is realized from the cutting zone since the large cooling effect will increase the temperature difference. The boiling point of LN_2 used in cryogenic cooling is approximately − 196 °C. When this cryogenic liquid is sprayed on the cutting zone, a significant temperature difference occurs between the surface and itself, and thus more heat transfer from the environment occurs [37]. As can be seen from Fig. 9, only hybrid

$LN_2 + MQL$ was established within the lowest temperature region (approximately between 100 and 200 °C). This can be explained by the elimination of the evaporation of very little oil delivered to the cutting zone by the MQL method at high temperatures. Preventing evaporation by cooling the cutting oil delivered with MQL employing LN_2 plays a key role in protecting the lubricating film at the interfaces. Thus, on the one hand, effective cooling is achieved with LN_2, and on the other hand, friction, which causes more heat generation, is reduced with MQL[40]. In addition, the cutting fluid may be evaporated in the cutting of titanium alloys, which may result in the generation of dry friction at cutting zone. However, this phenomenon is avoided with the use of cryogenic coolants, and the low temperature of cryogenic cooling maintains the thin film of lubrication for a longer time (refer Fig. 10a). Cryogenic cooling also reduces the effect of
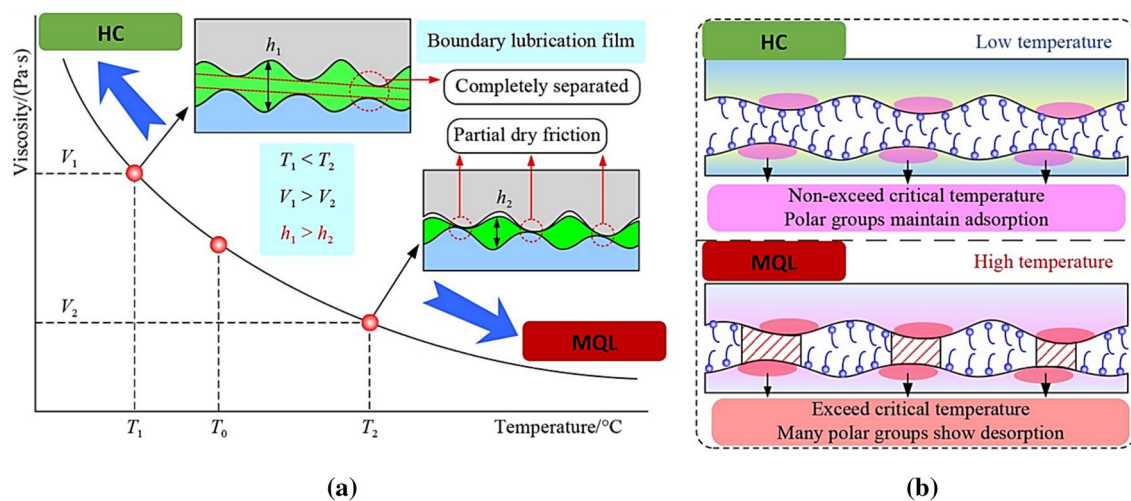

Fig. 10 A representation of the effect of hybrid cryogenic + LN_2 on the cutting zone, **a** the effect on viscosity, **b** the effect on the working of oil film [41]

oxidation and provides a good lubrication effect during the machining operations, as shown in Fig. 10b [41].

3.5 Specific Cutting Energy (SCE) Analysis

Every year, the world's demand for energy increases. The manufacturing industry consumes around 20% of the total yearly energy utilized worldwide. As a result, this industry accounts for a considerable portion of worldwide carbon dioxide (CO_2) emissions. A substantial amount of power is used up during the machining process carried out by the machine tool in the manufacturing process. The levels of operating parameters can be changed to reduce energy consumption. However, more caution should be exercised as this change may affect the cost and production capacity. Therefore, taking into account the SCE in the energy consumption analysis allows for more precise evaluations. In metal cutting, the energy (J) needed to remove a unit volume (mm^3) of the workpiece material is known as the SCE (J/mm^3). Therefore, SCE has a direct relationship with both energy usage and metal removal rate. Generally, it is desirable to cut a unit volume of material with less energy consumption.

SCE can be lowered by either increasing the amount of material cut while using the same amount of energy or by decreasing the amount of material cut while using the same amount of energy during machining. Reducing SCE will not only improve energy efficiency but also contribute to reducing carbon emissions. It is possible to adjust the SCE by changing the cutting parameters. Besides cutting parameters in the machining process, the cooling/lubrication strategies are also effective on SCE. The point to be considered here is that the cutting fluid to be used is a sustainable method that does not adversely affect the operator's health and the natural environment. In this study, the parameters are fixed, and then, only the effect of cooling/lubrication strategies on SCE was studied. The main contributing factors associated with SCE are shown in Fig. 11. Figure 12 shows the SCE results according to the machining length for each cooling medium. Accordingly, it is clearly seen that there are differences in each cutting environment for SCE. The lowest SCE was obtained in hybrid $LN_2 + MQL$, followed by LN_2, MQL, and dry cutting environments, respectively. The SCE is closely related to the plastic deformation energy (SCE_{PdE}) that is generated during cutting, the frictional energy at the tool/material contact (SCE_{FricE}), and the energy required for
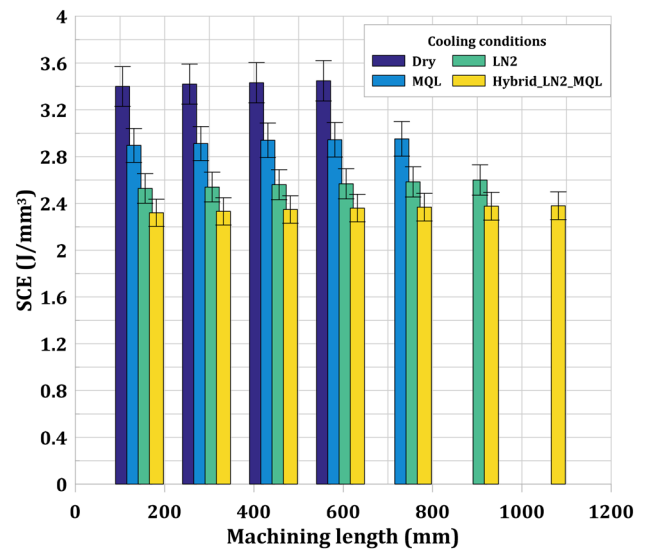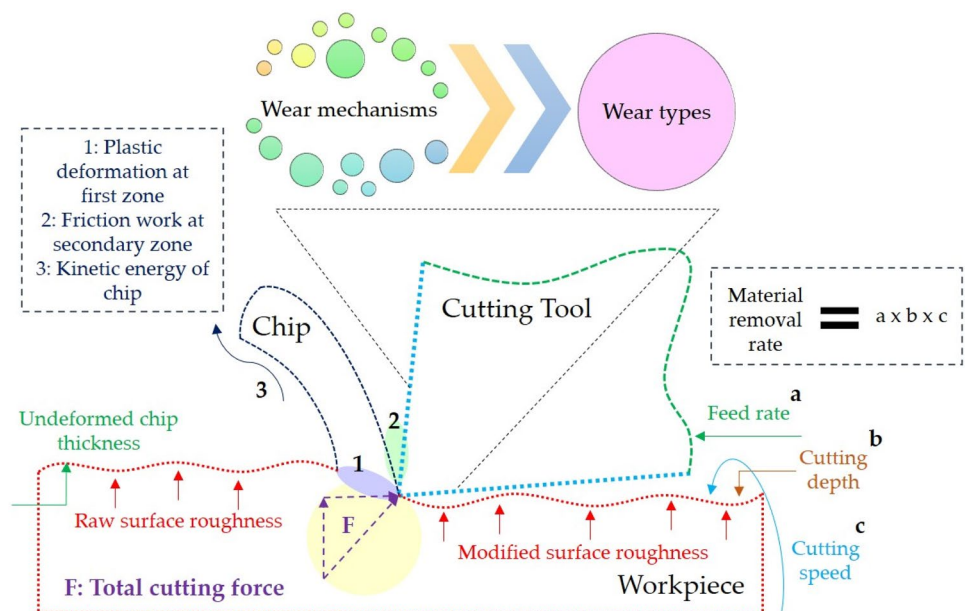

Fig. 12 SCE obtained under different cooling conditions

Fig. 11 Contributive factors on SCE

the formation of the new surface and the movement of the chips (SCE_{FormE}). The total SCE can be expressed as:

$$SCE = SCE_{PdE} + SCE_{FricE} + SCE_{FormE} \qquad (5)$$

Therefore, each phase of energy consumption should be considered when analyzing the impact of cutting strategies on SCE. The absence of any cooling/lubrication in dry cutting paves the way for higher temperatures in the cutting zone. This event causes the material to soften and requires less energy for its plastic deformation. However, due to the high temperature, dry friction surfaces, and rapid tool wear, more energy is required for friction and the formation of new surfaces. Although it is known that the oil film formed on the tool-chip interface with MQL reduces the friction force [42], it is concluded that tool wear has a more negative effect on the cutting energy. SCE results in parallel with tool wear results also support this assumption. LN_2 cryogenic cooling is also thought to help maintain tool geometry by controlling temperature-related tool failures. Thus, cryogenic cooling also helped to keep SCE at a certain level. Moreover, the reduction in SCE with the use of hybrid $LN_2 + MQL$ was associated with reduced friction, accelerated heat transfer due to both cryogenic coolant and cutting oil in MQL, and improved tool life.

4 Conclusions

This study examines the impact of different cooling regimes on titanium alloy machining in terms of tool wear, surface morphology, specific cutting energy, and cutting temperature. Based on experimental results, the following conclusions are drawn:

- The application of hybrid $LN_2 + MQL$ significantly improves the tool life and surface quality. The primary reason is that the combined effect of coolant and lubrication is helpful in reducing the friction and cutting temperature at cutting zone and hence, a lower tool wear rate values were observed.
- The dry machining is more subjected to build up edge formation and low tool life as compared with other cooing conditions. The generation of high temperature is responsible for this phenomenon and this is clearly observed in the microscopic analysis of cutting tools.
- The hybrid $LN_2 + MQl$ produces the smoother surface with no burning marks. On the other hand, the more burning marks were seen under dry mediums. MQL and LN_2 conditions are also helpful in producing the smooth surface but the hybrid $LN_2 + MQL$ conditions provides the more cushioning effect during machining and less

vibrations produces smooth surface while machining sticky materials like titanium alloys.
- The effect of cooling conditions on cutting temperature was noticed and the maximum temperature was noticed during dry machining. This temperature is the result of more friction generation at cutting zone and as a consequence, the tool life and surface roughness were reduced under dry conditions.
- SCE is the function of power consumption and MRR during machining of titanium alloys. The low power is required to remove the material from resistant body under hybrid $LN_2 + MQL$ conditions. As a result, low values of SCE were observed under hybrid $LN_2 + MQL$ conditions.

5 Limitations and Future Works

Limitations of the study and suggested future studies are presented below.

- In the present work, the parameters used to perform the cutting experiments are kept fixed, and the comparison of results is only performed under various cooling conditions, such as dry, MQL, LN_2, and hybrid $LN_2 + MQL$. For instance, the cutting speed of 150 m/min, the 0.20 mm/rev feed rate, and the 0.5 mm depth of cut have been used under all cooling conditions.
- The flow rate of LN_2 and MQL is different from each other. Also, in hybrid cooling, LN_2 may have adversely affected the viscosity of the oil from MQL.
- The chips that come out during cutting and the oil mist formed in the MQL environment affect the measurement accuracy of the thermal camera.
- The energy consumption of external sources (compressor, MQL device, etc.) used in the calculation of total energy consumption and specific cutting energy are not taken into account.

Some recommendations for the scope of future work are listed below:

- The numerical elaboration of the results of the experiments by proposing adequate numerical models may facilitate the understanding of the process and improve the readability of the data.
- In future works, the mechanical and thermal effects of the hybrid cutting environment on the workpiece can be investigated.
- In the machining of such superalloys produced by additive manufacturing, the effects of cooling/lubrication methods on surface integrity and tool wear can be studied.

- Tribological tests of the cooling/lubricating conditions can be done.
- Sustainability analysis of the cutting process can be performed by considering all inputs.

Data availability Data is made available on request.

Declarations

Conflict of intertest The author declares that they have no competing interest.

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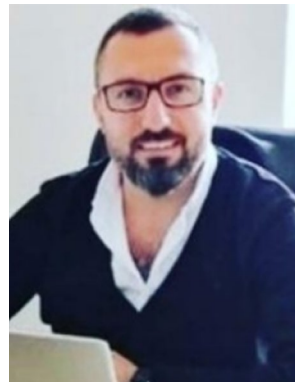
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