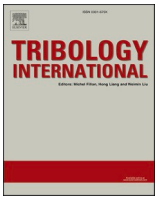
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Potential use of cryogenic cooling for improving the tribological and tool wear characteristics while machining aluminum alloys

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ABSTRACT

Understanding the process of tool wear in the initial and steady wear stages is crucial for ensuring the dimensional accuracy and surface quality of the workpiece, especially during the finishing step. In order to improve the tribological and tool life behaviors when machining the AA2024-T351 alloy, the current paper focuses on the potential use of cryogenic cooling conditions. Here, the experiments were performed under dry, minimal quantity lubrication (MQL), liquid nitrogen (LN_2), carbon dioxide (CO_2), conditions. The critical tool wear factors in terms of geometrical aspects and physical phenomena were investigated under sustainable cooling environments. The results prove that cryogenic cooling is helpful in improving tool life with good tribological characteristics.

1. Introduction

Aluminum alloys and composites have increased rapidly in recent years and become one of the most useful engineering materials with a unique combination of properties [1,2]. Aluminum is light, and many of its alloys have very good strength and electrical and thermal conductivity, which have increased its importance in the computer, aviation, and vehicle fields. Furthermore, the alloy's resistance to corrosion makes it useful in the biomedical sector. It is known that the machinability of aluminum is changed by the processing conditions and the metallurgical structure of the material. The main machinability problem of aluminum is the generation of continuous and quite chips. In addition, the ductility of aluminum alloy is also responsible for the stickiness of material to the tool surface and creates another machining problems like high tool wear values, breaking of tool etc. The high cutting temperatures also occur and cause poor tool life, surface related properties such as integrity, roughness, hardness etc. [3,4]. Due to abovementioned issues, it is of the utmost importance to control the flow of chips [5] and the development of heat at the machining area while cutting ductile materials like aluminum alloy [6].

The utilization of cooling and lubricating fluid is important for controlling the heat generation [7] and reducing friction at the interfaces of tool-work and tool chip [8]. Besides, the chips flow smoothly with the existence of such fluids without effecting the cutting performance of cutting tool and provides longer useful life and part quality [9]. In addition, the application of lubricants contributes positively to the cutting ability of the tool due to their oiling, refrigerating and chip removal properties [10,11]. However, the use of conventional cutting fluids cause negative effects in the manufacturing process in addition to the mentioned advantages [12,13]. When waste management is not done well, cutting fluid with chemical content mixes with the soil and harms the nature [14]. It is a fact that these chemical liquids, which come into contact with the skin of the employees on the production line, also harm human health. Controlling the lubricants used in machining not only in terms of chemical content but also in terms of quantity is important because of its impact on nature, human health, and production costs. Therefore, reducing the amount of cutting fluid used arises as a need for the aforementioned issues. Another important point here is

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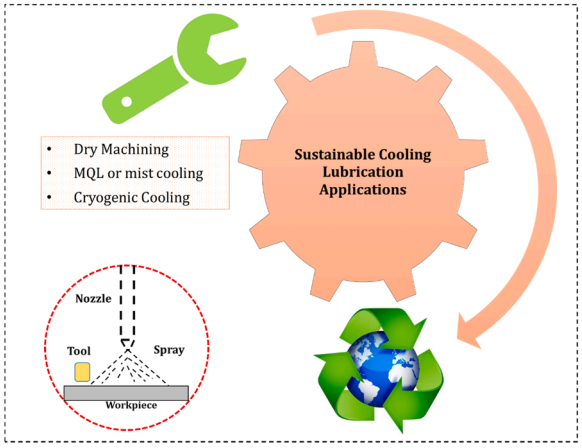


Fig. 1. Well-known sustainable machining methods.

that while reducing the amount of cutting fluid used, it does not adversely affect the product quality and cutting tool life. Some techniques are used to restrict the consumption of lubricants in machining operations. These are cutting without using cutting fluid (dry cutting), cutting with compressed air, vortex tube cooling (air cooling), cryogenic cooling and MQL techniques [15,16]. The framework of sustainable cooling conditions is depicted in Fig. 1.

In addition to making a significant contribution to employee health because cutting fluid is not used, the absence of cutting fluid to be disposed of after processing is one of the reasons for choosing dry machining [17]. In machining with MQL, it is preferred because there is no lubricant to be eliminated like dry machining [18]. In the cryogenic cooling process, various cryogenic gases (CO_2, LN_2) are targeted in the cutting zone [19]. Wakabayashi et al. [20] carried out a MQL machining study by placing multiple different nozzles from the surfaces where nose and crater wear of the cutting tool were analyzed. Compared to dry turning, tool wear has been reported to be similar or less when MQL and coolant are used. Chinchanikar and Choudhury [21] studied the impact of tool coatings on wear behavior when utilizing tungsten carbide tools with three different PVD coating materials during dry and MQL machining. Using MQL in all cutting conditions, decreased nose wear was observed in the machining of all three tools. Wang et al. [22] focused on the evaluation of impacts of conventional coolant and cryogenic cooling method for wear types and roughness in the turning of tantalum with high corrosion resistance, and finally determined that the cryogenic method elevated the remaining life of cutting tool up to 300% by decreasing the interface temperature between cutting tool and material. In addition, the authors determined that surface roughness decreased about 200% and the cutting forces about 60%. Inconel 718 super alloy was processed by Wang et al. [23], via combining the cryogenic cooling method and plasma-based machining with conventional turning. The authors indicated that the roughness decreases approximately 250%, the force values are lowered approximately 30–50% and the life of the cutting tool increases up to 170% compared to traditional machining. Dhar et al. [24] performed turning tests with conventional coolant and cryogenic cooling method. They examined the impacts of cooling environment on wear progression, dimensional accuracy, finishing surface of C60 material applying speed and feed ranges used in industrial applications. Cryogenic cooling creates less tool wear and enhances the characteristics of both the tool and the workpiece.

There is some evidence in the literature that cooling conditions can significantly improve the machining properties of many materials. Cutting tool wear progressions has not been reported, even though machining studies were considered. AA2024-T351 alloy machining has not been studied in detail. As a result, this study first examines the tribological and tool wear behavior while machining AA2024-T351 alloy under different cooling conditions. The following factors are considered in details during the current investigations:

- Nose wear,
- Crater Wear,
- Flank Wear
- Promoting Mechanism.

2. Materials and methods

2.1. Machine tools, workpiece and cutting tool details

Aluminum alloy AA2024-T351 with a diameter of 30 mm and a length of 100 mm was used for the testing on CNC machine. Because of the L/D ratio and to reduce chattering, this size was selected [25]. The coated cutting tools with ISO designations of CNMG 120408 and AA2024-T351 alloy were also utilized.

2.2. Cooling modes and experimental design

The cutting tests were performed under dry, MQL, LN_2 and CO_2 conditions. In MQL, vegetable oil is delivered to the rake and clearance surfaces of the tool via two specialized nozzles with 45 mm distance from cutting zone. The flow rate is 50 milliliters per minute at a pressure of 6 bar was kept fixed in all experiments. Similarly, a flow rate of 0.35 l/s and a pressure of 4 bar were used to supply the LN_2 and CO_2 coolants. The machining was performed at 150 m/min cutting speed, 0.2 mm/rev feed rate, 0.5 mm depth of cut, respectively.

2.3. Tool wear measurement details

The cutting tool's nose wear, crater wear, flank wear, and promoting mechanism were examined in this study. Sensofar Confocal Microscope was utilized to analyze the wear patterns on the nose, crater, and flank surfaces of the cutting tools. Additional analysis was carried out using the Jade and Mountains map program. Final analysis of wear under various cooling settings were examined with high resolution scanning electron microscope (SEM) supported with EDX (Oxford instruments). Fig. 2 depicts the entire tool wear measurement process used in this study and Fig. 3 shows the ISO standard used to measure the tool wear, respectively.

3. Mechanism of different cooling conditions

3.1. Dry cooling

The harmful effect of cutting and metal working fluids are eliminated in the case of dry machining because the machining operation is performed without the application of cutting fluids [27]. Dry machining is beneficial because: (1) it does not expose workers and the environment to dangerous cutting fluids; (2) it reduces the cost of machining by eliminating the expenses of disposal, filtration, and cleaning; and (3) it creates a cleaner work environment. While dry machining is effective in eliminating cutting fluids' unsustainable properties, it also generates greater heat because of the increased friction and adhesion between the cutting tool and the workpiece, as shown in Fig. 4. As a direct result of the shorter tool life, more frequent tool replacement is required [28].

3.2. MQL

Dry machining refers to a technique in which cutting fluids are not used and near-dry machining (NDM) refers to a process in which lubricants are used, but only a very tiny amount (often between 10 and 150 ml/h) is delivered to the cutting zone as a mist, as shown in Fig. 4. As a result, utilizing NDM (also known as MQL) can significantly reduce the overall cost of the operation. Avoiding the use of cutting fluid and switching to dry machining, in conjunction with newly developed high-

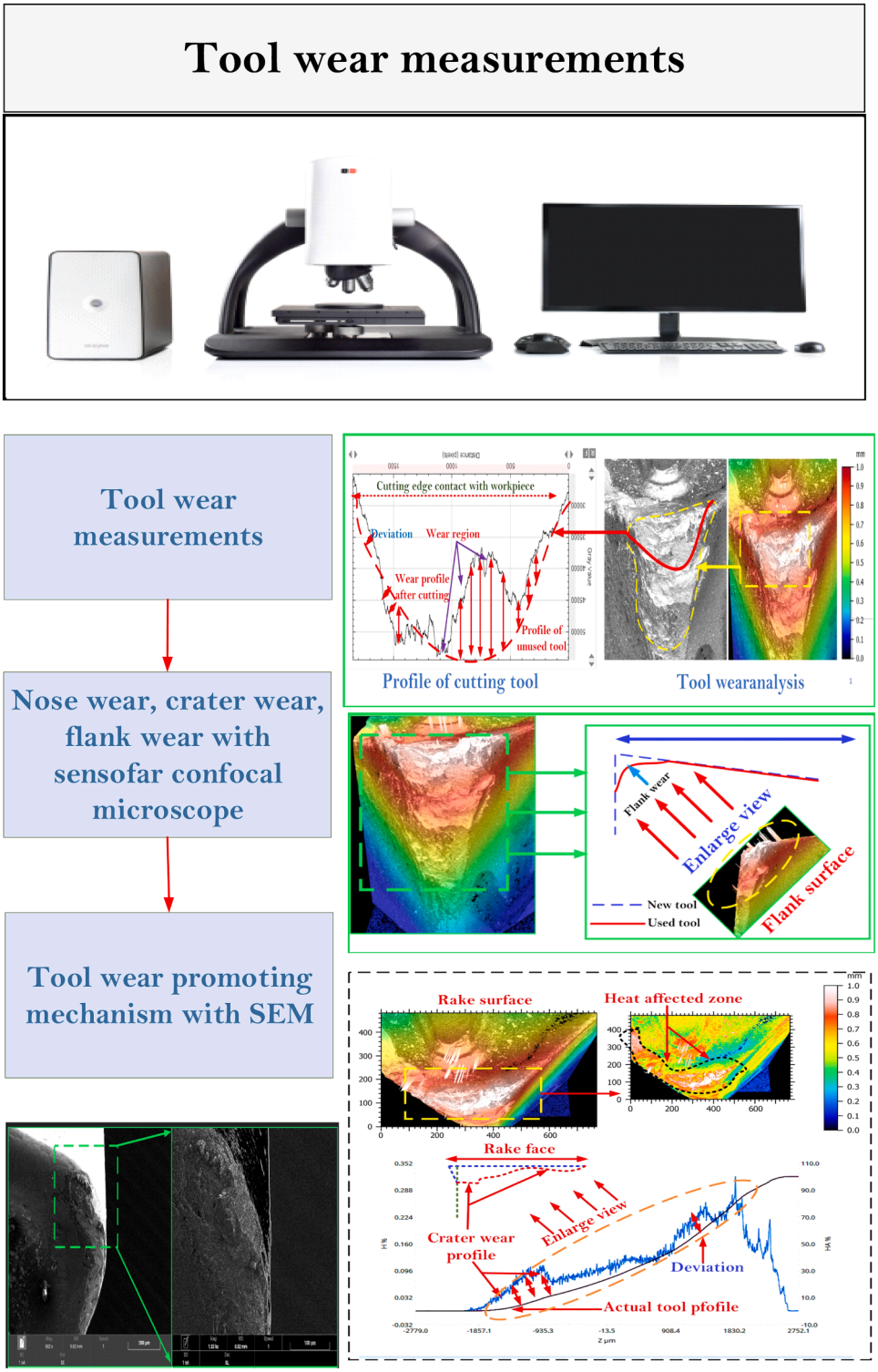


Fig. 2. Tool wear measurement procedure followed in current work.

performance coated cutting tools, would pave the way for significant developments in environmentally friendly technology. The following tribological effects may also be observed during MQL machining:

- By chilling the underside of the chip, MQL machining reduces the chip's curling radius to a minimum. The droplets reduce the amount of drag between the chip and the tool by forming a thin fluid layer there [29,30].
- Additionally, it reduces the amount of force applied by the chip to the tool. MQL machining, thanks to the lubricating effect it produces, increases chip flow rate [31].
- Compared to traditional cooling methods, the rate of heat transmission is increased due to evaporation [32,33].

3.3. Cryogenic cooling

Rapid cooling of the cutting zone can be achieved with the

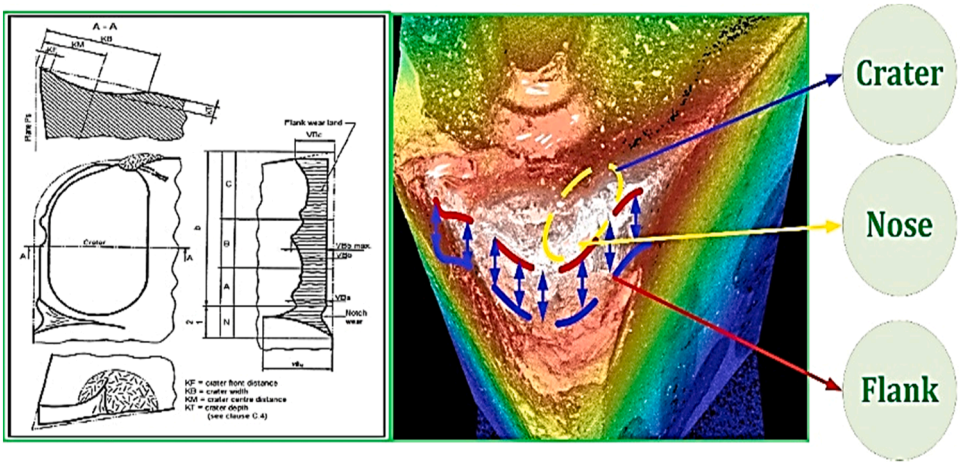


Fig. 3. ISO 3685 standard (1993) for tool wear [26].

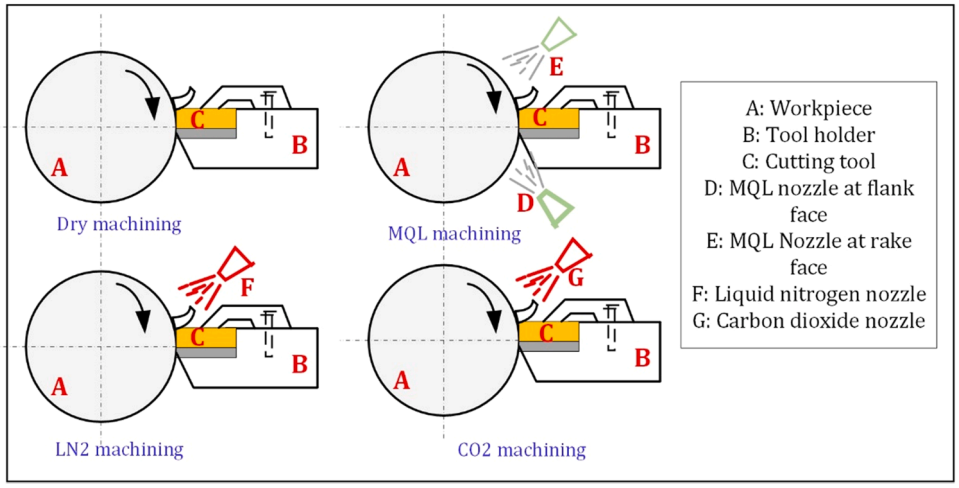


Fig. 4. Representation of dry, MQL, LN_2 and CO_2 cooling.

application of LN_2 and CO_2 during machining operations [34]. It is remarkable not only for its superior cooling effectiveness, but also for its eco-friendliness and tidier machining environment (no oil or liquid is left behind) [35]. By using this state-of-the-art cooling system the durability of cutting edges during the machining process is increased [36,37]. Nonetheless, cryogenic coolants are inefficient as lubricants because they evaporate the moment they leave the nozzle [38,39]. The complete schematic of cryogenic cooling is also shown in Fig. 4.

4. Results and discussions

Cutting tool wear is a progressive failure mechanism, having dominant wear that depends on cutting circumstances, workpiece and tool material, and tooltip shape [40]. The evolution of tool wear for a determined material pair may be simply dependent on cutting circumstances, such as machining parameters. Nose, flank, and crater wear are the main types of tool wear that occur more frequently while turning with single-point cutting tools.

4.1. Analysis of nose wear

In this paper, the types of wear leading to failure have been extensively studied under each sub-section. In this sub-section, the nose wear of the tool while machining of the Al alloy in several cooling strategies has been investigated and findings are shown in Fig. 5. From Fig. 5(a), it is possible to see excessive damage in the nose region during the turning process under dry conditions. The abrasive wear mechanism on the primary edges of the cutting tool causes nose wear, or edge rounding, which results in a negative rake angle rise. Increasing the negative rake angle will result in increased cutting forces, more energy consumption, and poorer surface roughness [41]. Fig. 5 shows the profile line of a worn cutting tool, which shows that the tool nose wear under dry cutting has spread over a larger area, resulting in a much larger area of damage. The nose profile deteriorates as a result of the cutting edge's plastic deformation and thermal softening at high cutting speeds. Plastic or elastic deformation, as well as a close relationship to cutting conditions, can all contribute to this type of wear. Cutting tools frequently suffer from built-up edges (BUEs), a type of wear and tear that occurs when machining materials with low melting points (such as aluminum and its alloys) [42]. The use of cutting conditions and an appropriate lubricating environment when machining aluminum alloys will relatively reduce sticking and tool damage, otherwise the cutting process will result in a severely worn tool and catastrophic tool failure, as provided in Fig. 5(a). Thus, a little oil supplement to the cutting area will both reduce the friction on the contacting surfaces, break the effect of abrasive wear and help prevent or reduce adhesion. As a matter of fact, it is possible to see in Fig. 5(b) that the damage in the nose area in the turning process performed under MQL occurs in a narrower area than in dry cutting. However, it cannot be said here that the application of MQL perfectly reduces nose wear. MQL may offer good lubrication when the

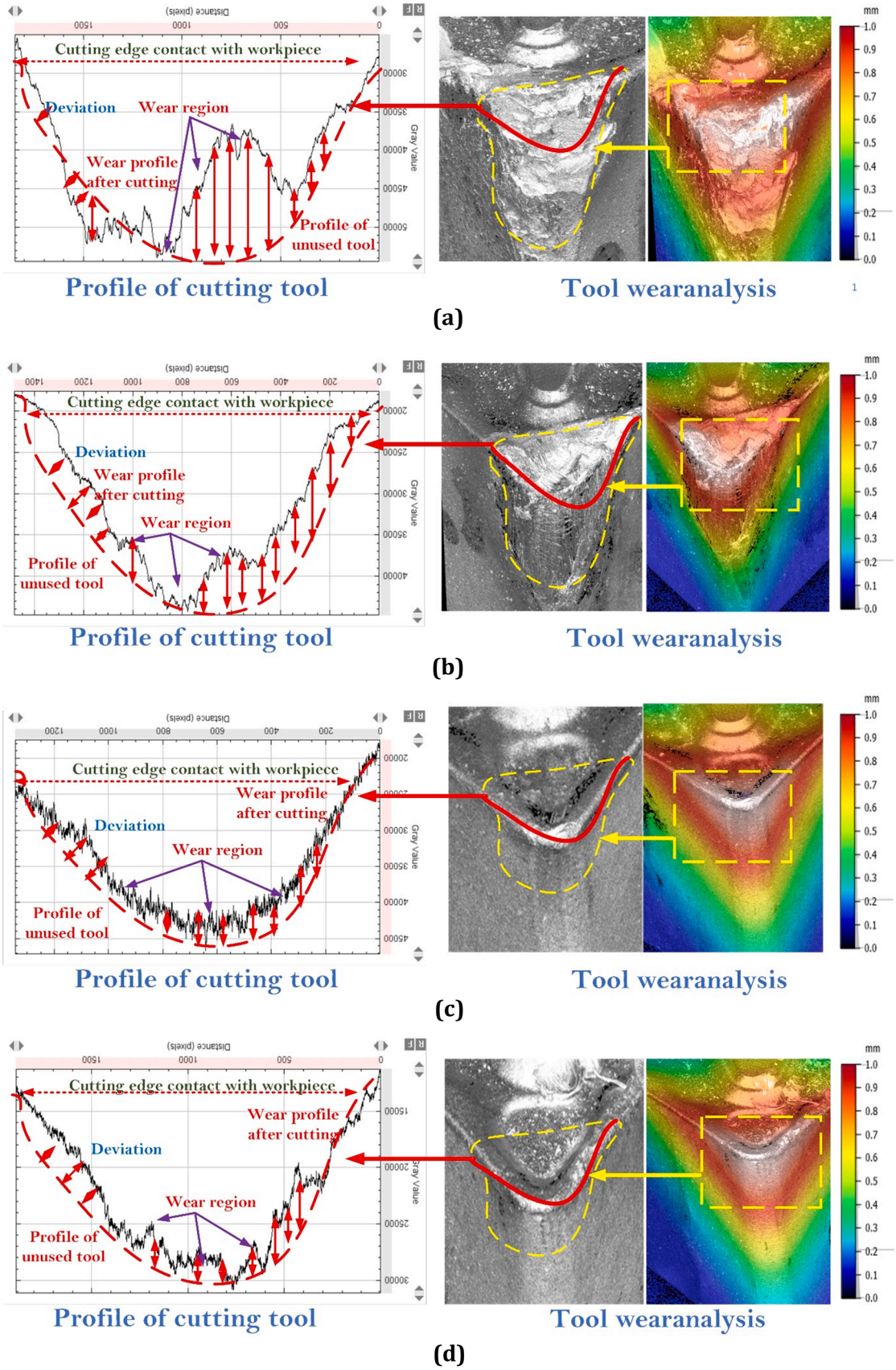


Fig. 5. NTool nose wear and its profile under a) Dry b) MQL c) LN_2 d) CO_2 conditions.

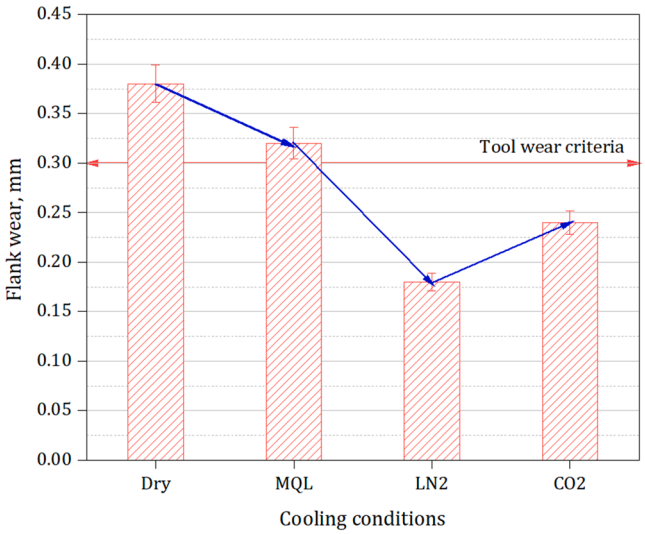


Fig. 6. Flank wear values under dry, MQL, LN_2 and CO_2 conditions.

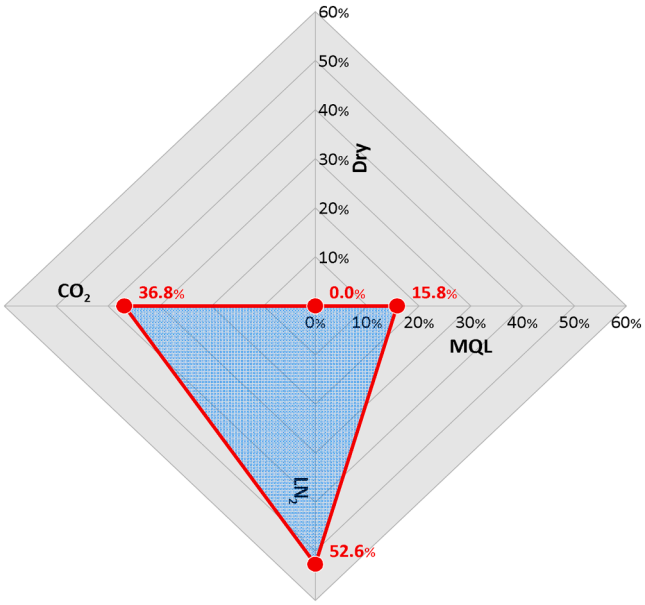


Fig. 7. Percentage reduction in wear with reference to dry cutting.

right lubricant is applied, according to Itoigawa et al., [43]; despite this, it is impossible to completely prevent causing tool damage or picking up material on the surface of the tool when cutting aluminum.

In addition to dry and MQL turning, the effect of cryogenic environment i.e., LN_2 and CO_2 on nose wear during machining of aluminum alloy is presented in Fig. 5(c) and (d). When these are examined, it is noticed that the worn nose profile parallels the original profile in both environments. In addition, the damage condition and the size of the wear areas were found to be more reasonable than in dry and MQL environments. The tremendous thermal energy at the cutting area is absorbed by cryogens placed around the contact surfaces. Because cryogenics have low boiling points, they absorb and evaporate the thermal energy transferred around the interfaces. As LN_2 and CO_2 collide in different forms between material and cutting tool, the friction contact surface, and temperature in the chip tool are reduced [44]. Thus, a more regular and reasonably worn cutting nose area is obtained.

4.2. Analysis of flank wear

Cutting tools utilized in metal cutting applications are sensitive to variations in geometry as well as changes in material characteristics. Frictional conditions induce tool wear during cutting on the chip and flank surfaces. Tribological events between the tool flank and the machined workpiece surface cause flank wear, which leads to the cutting edge to deteriorate. Eventually, dimensional accuracy, surface finish quality, chip formation, and cutting forces are all affected by flank wear [45]. In practice, flank wear is frequently utilized as a criterion for tool wear. That's why reducing flank wear is particularly crucial for tool life and other critical outputs. In this sub-section, tool flank wear's findings were presented and discussed.

From Fig. 6, the values of flank wear is seen in different environments. Accordingly, the maximum flank wear occurred in dry cutting, while the minimum flank wear value was reached under LN_2 cryogenic machining. The average flank wear (VB_{max}) for carbide tools should be less than 0.3 mm, according to ISO 3685:1993 as a criterion for determining effective tool life [26]. From this perspective, it has been determined that the cutting tools used under both cryogenic environments i.e., LN_2 and CO_2 maintain their effective life at the end of the same period. Flank wear arises when the freshly created surface rubs against the tool's clearance face, creating adhesive and/or abrasive wear that is aggravated by the increase in temperature while cutting. The frictional motion results in a decrease of relief angle on the tool's clearance face, resulting in wear [46]. The main way to reduce abrasion, adhesion, and high-temperature wear is to prevent them from exceeding critical values. This has been partially achieved by benefiting one or more of these factors, thanks to MQL and cryogenic environments. When compared to dry cutting, the tool flank wear reduction with MQL, CO_2, and LN_2 aided cutting was 15.8%, 36.8%, and 52.6% for the three methods correspondingly (Fig. 7). High-pressure LN_2 penetration of the contact zone results in reduced friction owing to the microscale hydrostatic resultant force, as reported by Hong [47]. Cutting using LN_2 reduces cutting temperatures, resulting in a reduced effective shear strength needed to remove the material. When a cutting tool is sprayed with LN_2, it soaks up the gas, enhancing the tool's hardness and reducing wear, as seen in Fig. 8, resulting in a better surface finish. Potta [48] also stated that the cutting tool edge had a reduced BUE because of the lower cutting zone temperatures given by LN_2.

4.3. Analysis of crater wear

One of the most important forms of wear is known as crater wear, which also refers to wear on the rake face. The intense friction that occurs between the chip and the rake face causes a scar to form on the rake face, and this scar is typically aligned in the same direction as the primary cutting edge. Despite the fact that crater wear might lessen the amount of cutting force required and increase the operating rake angle, the cutting edge is still degraded due to this wear [49]. Formed by diffusion and adhesion when the chip passes over the rake face, high temperatures at the chip–tool contact are often associated with the crater. When the chip and the rake face come into contact, the crater's depth reaches its maximum at the halfway point of the contact length. The cutting edge's form can be altered by excessive crater wear, reducing chip generation [50]. In this work, the detailed analysis of crater wear was performed under all cooling conditions. The crater wear profile is shown in two colors i.e., blue and red. The blue color profile of crater wear is observed after the machining and red color profile is before the machining operation. The difference between both lines are represented in terms of deviation. Fig. 9(a)-(d) shows that tool damage increases in direct proportion to the extent of the heat-affected zone on the rake face (i.e., crater wear). The crater wear is more important than the nose and flank wear in determining the tool's thermal balance. Raise faces, which are exposed to high temperatures and stress levels, create wear that can be assessed by depth of cut and cross-sectional area at a distance from the tool edge. Some of the factors that contribute to the formation of deep craters are adhesion, abrasion and diffusion [41].

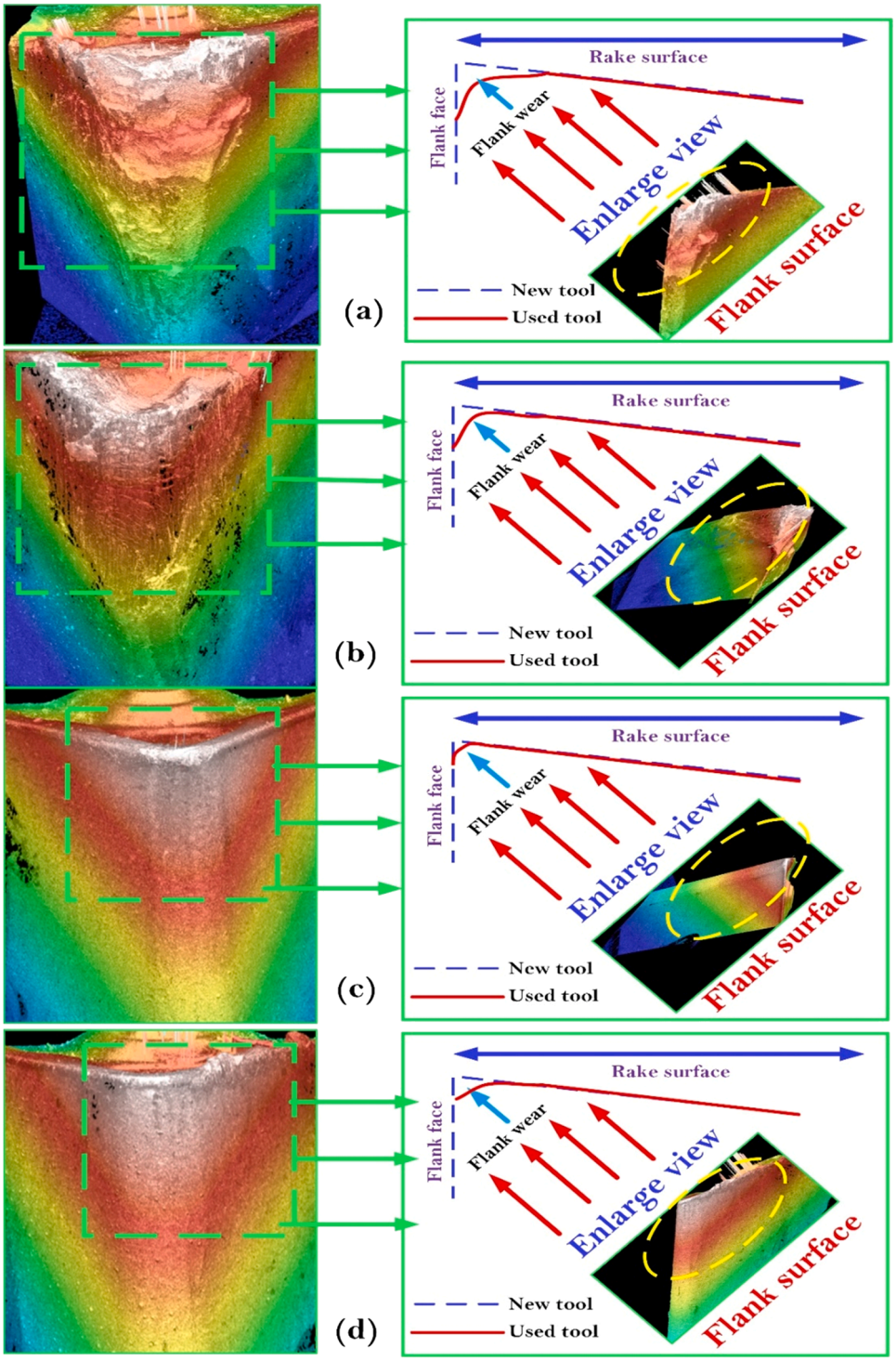
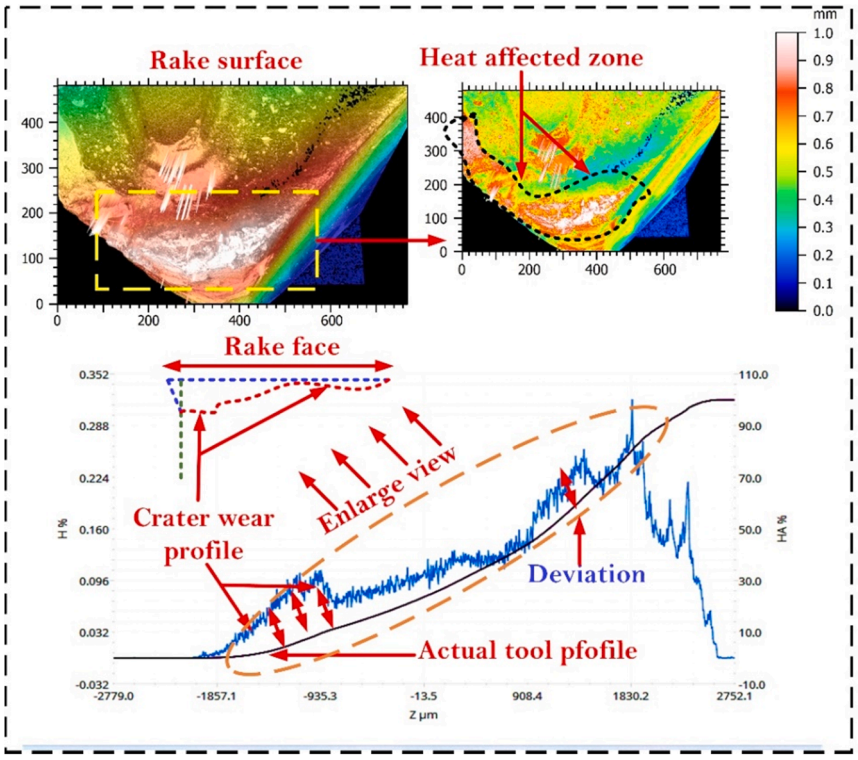


Fig. 8. Flank wear analysis under (a) Dry (b) MQL (c) LN_2 and (d) CO_2 conditions.

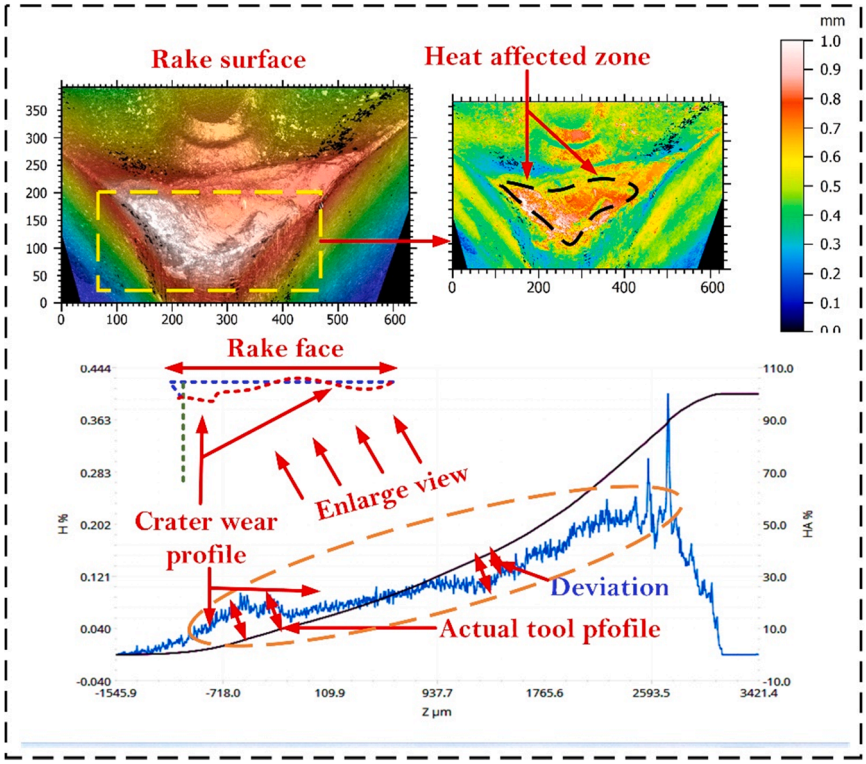
Larger tool failures can occur near the cut spot due to crater depth variations, as seen in Fig. 9(a)-(d). It is possible to discern a correlation between contact length and crater wear in Fig. 9(a)-(d), in addition to the area impacted by heat. The reduction in tool-chip contact length and cutting forces due to a change in tribological characteristics is hypothesized to occur when coolant and lubricant are applied to the tool-chip interface [51]. There is less friction between the rake face and the chip in the secondary deformation zone because the tool-chip contact length is shorter. This reduces BUE and adhesion wear. From this point, it can be said that cryogen provides superior coolant accessibility and lubricity than dry and oil-based cooling/lubrication environments, resulting in extended tool life [52]. Dinesh et al. [53] found that using LN_2 during machining decreases the cutting force significantly when comparing with dry environment. Furthermore, a small thin of LN_2 applied to the cutting area between work-tool and tool-chip lowers friction, resulting in less force than dry machining for a given cutting tool.

4.4. Mechanism promoting the tool wear

Considering that it is essential to ensure sustainable machining, the



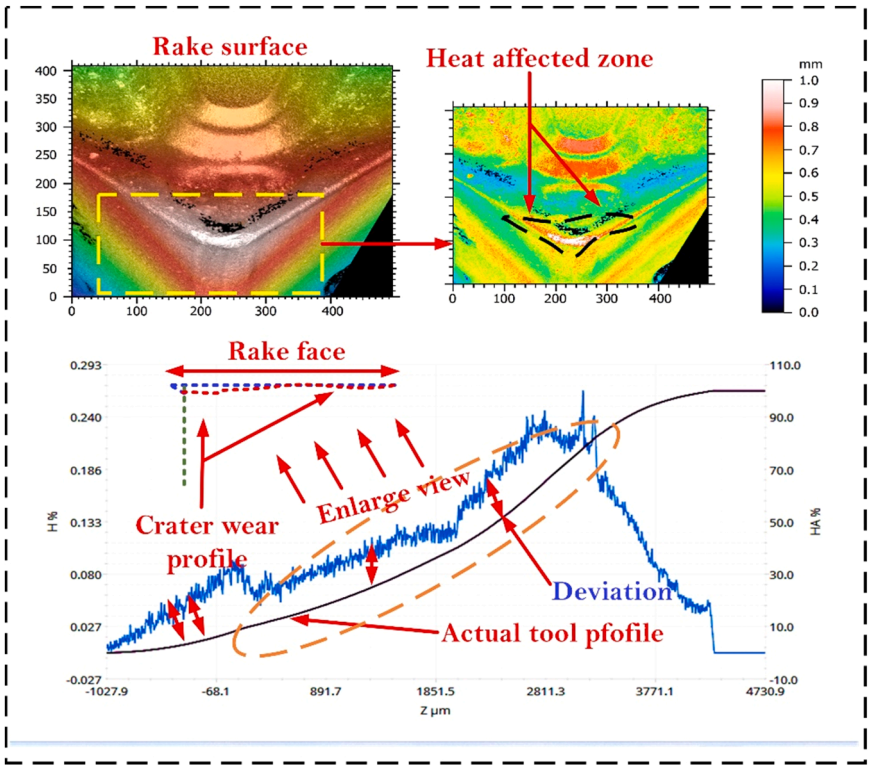
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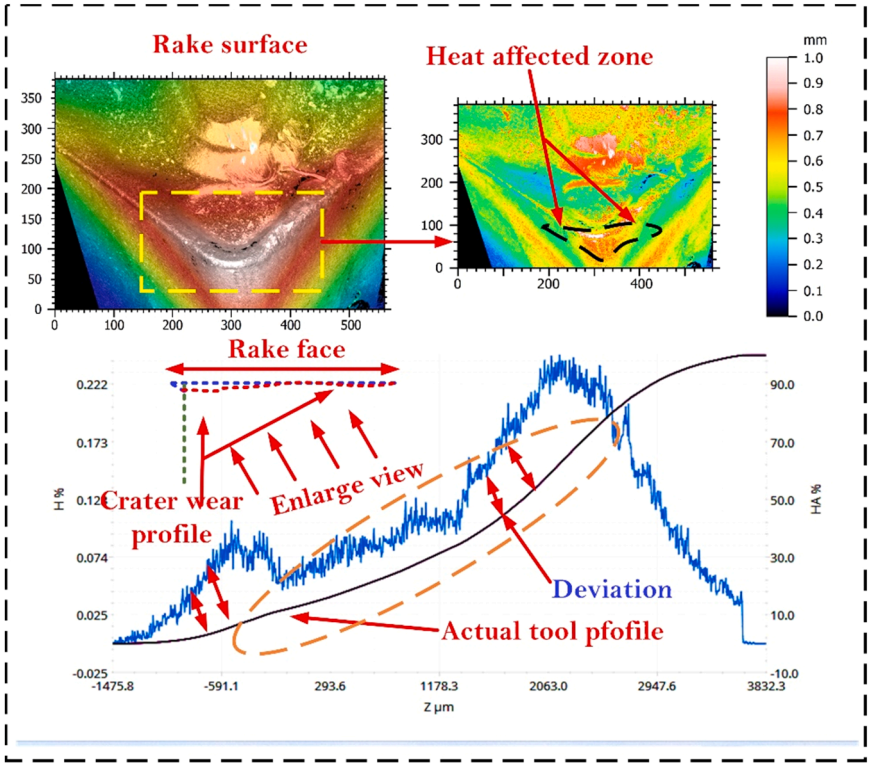
(b)

Fig. 9. The rake face analysis of tools after experiments under a) dry b) MQL c) LN_2 d) CO_2.

mechanisms leading to tool wear should be first determined to improve useful utilization tool. However, the combination of one or more mechanisms occurring on the tool during chip removal complicates the wear process. Although the abrasion wear mechanism is also observed in the turning of aluminum alloys, the dominant wear mechanism is undoubtedly adhesion [54]. In this paper, the final state of the tool, which



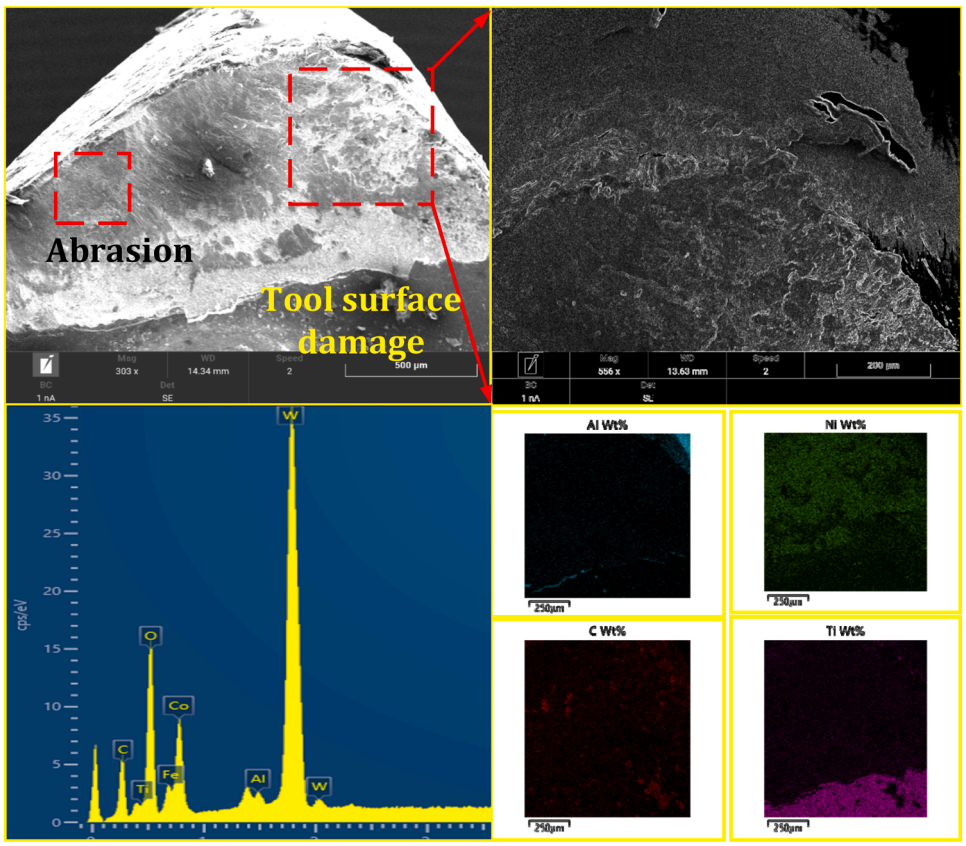
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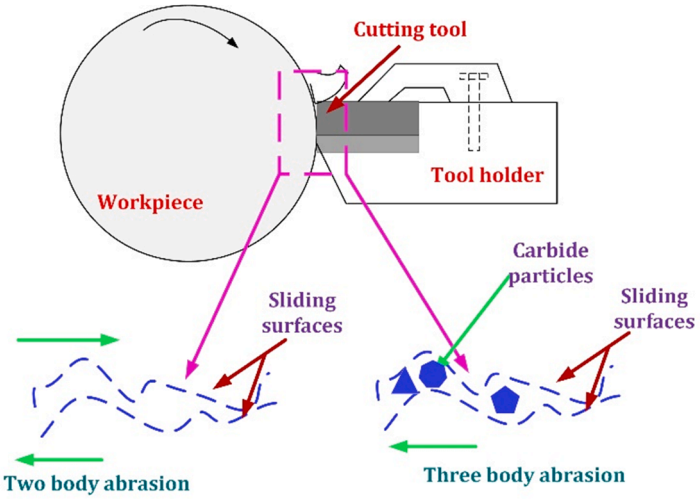
(d)

Fig. 9. (*continued*).

has been subjected to cutting under various environments were investigated. Fig. 10 (a) illustrates the SEM and EDX results of the worn tool formed under dry cutting. According to the image obtained in the SEM analysis, it is clearly seen that the coating on the rake face is separated. The distribution of elements (especially the presence of W, Co, and Al elements) on the rake face as a result of the EDX analysis confirms this.



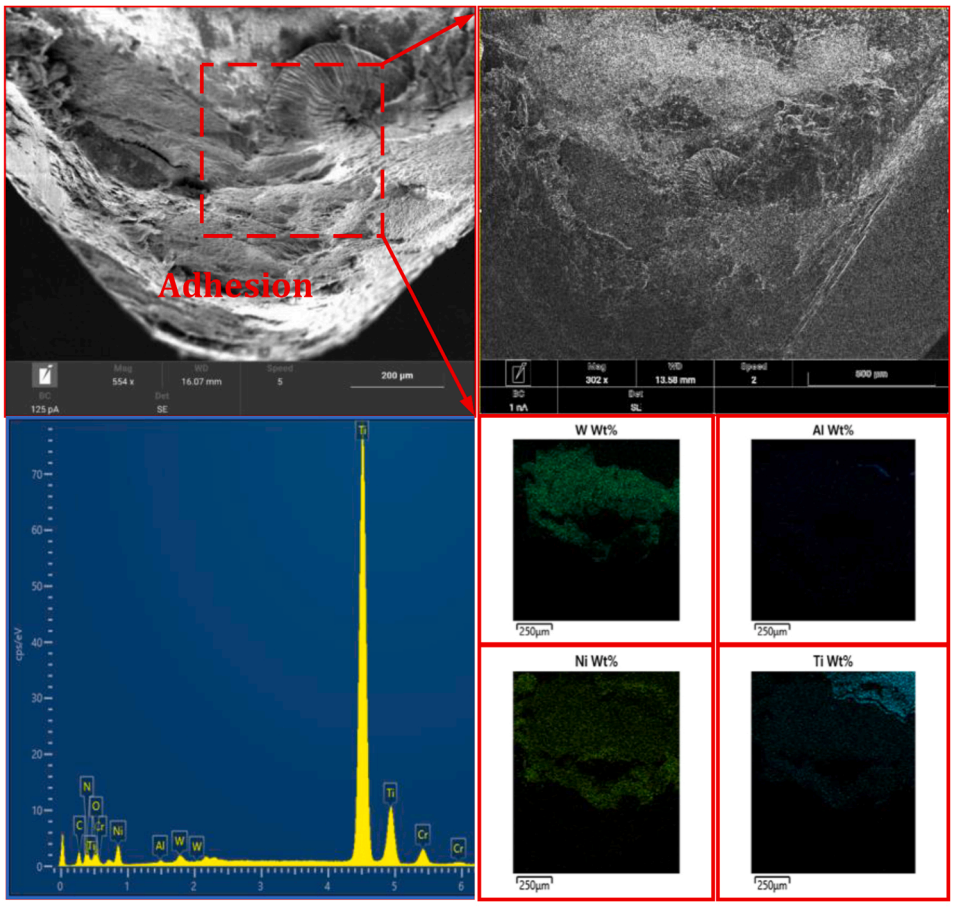
(a)



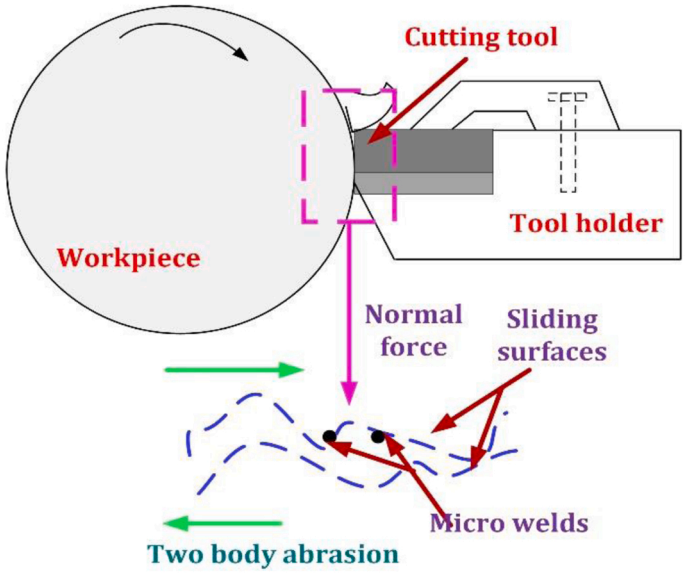
(b)

Fig. 10. (a) SEM and EDX analyses for worn tools under dry environment (b) Two and three body abrasion mechanisms observed during machining (Modified from [56] after copyright permission).

The reason is high temperatures and abrasion wear mechanism on the rake face. In general, the abrasion wear is generated when hard asperities, abrasives, roll, slide, or otherwise exert force on a surface. Depending on how the hard inclusions or particles that are present in the workpiece behave, this form of wear is sometimes characterized as either two-body abrasion or three-body abrasion. The phenomenon known as two-body abrasion has been seen when the abrasive particles are securely bonded inside the matrix of the workpiece. Nonetheless, if the particles are released during the cutting process and roll or slide over the contact surfaces, a phenomena known as three-body abrasion has



(a)



(b)

Fig. 11. (a) SEM and EDX analyses for worn tools under MQL environment (b) Two body mechanism observed during machining (Modified from [56] after copyright permission).

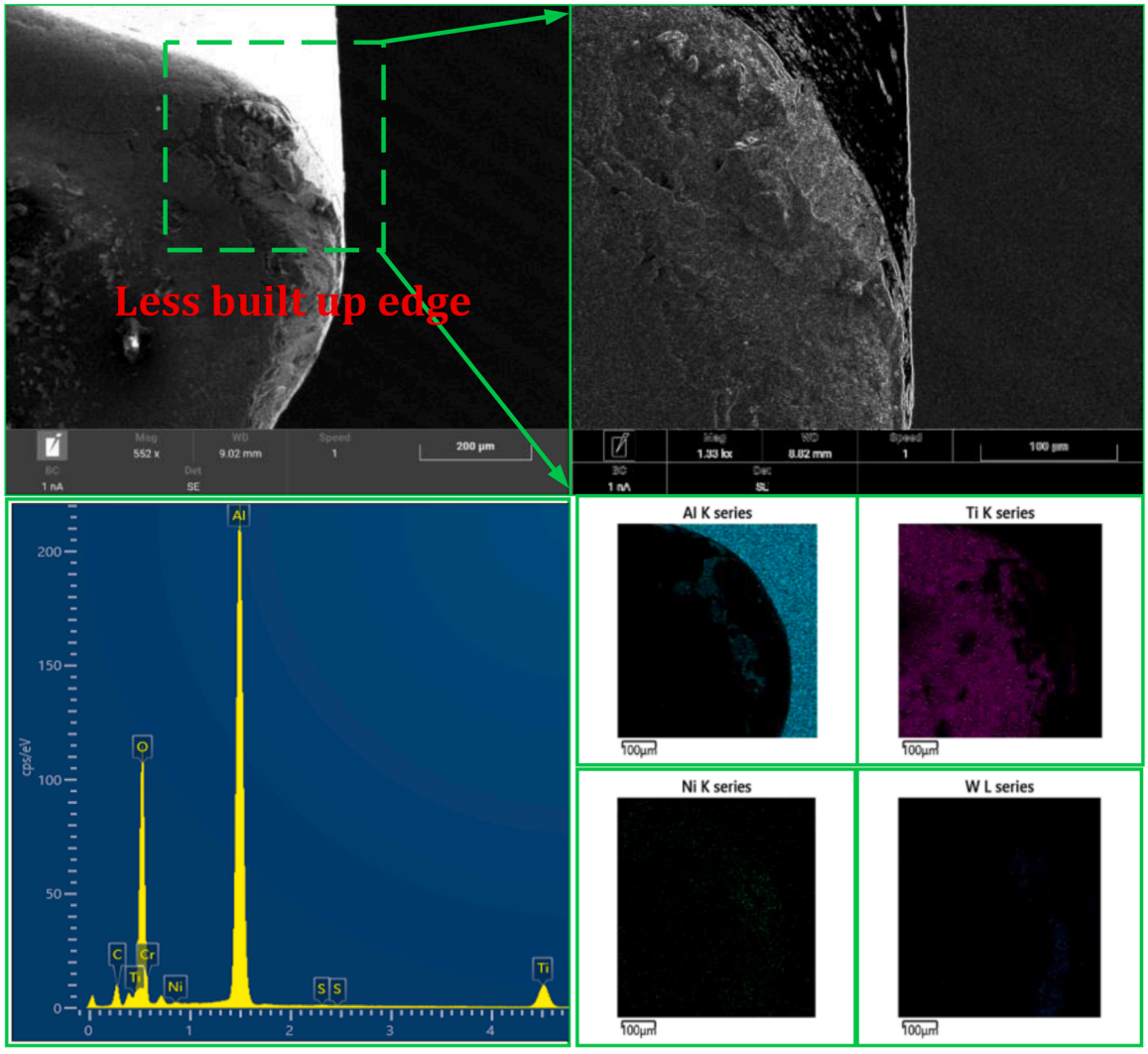


Fig. 12. SEM and EDX analyses for worn tools under LN_2 environment.

been seen. The complete mechanism of two and three body abrasion wear mechanism is shown in Fig. 10(b). In the present aluminum alloy, no metal carbides were noticed and hence, two body abrasion mechanism phenomena is observed during dry machining. From Fig. 11 (a), SEM and EDX analysis of the worn tool formed under the MQL environment can be seen. The images obtained from SEM and EDX analyses and the distribution of elements show that the adhesion wear mechanism is active under MQL. The adhesive wear of the cutting tool is caused by the shearing that occurs at the interface of the tool-workpiece tribopair as a result of the constant relative motion of the two surfaces. In addition, this adhesion mechanism is occurring when two surfaces are in contact with each other, and stress and heat can cause asperities to form the contact area between them, resulting in microscopic welds. Indeed, the asperities that sustain it will also undergo a greater degree of distortion with the increase in normal load. Fig. 11(b) shows the adhesion wear mechanism under MQL conditions. Fig. 12 illustrates the SEM and EDX analysis of the worn tool formed under the cryogenic-LN_2 environment. Accordingly, the presence of BUE is seen near the cutting edge on the rake face. The Al element observed from EDX analyzes supports this formation. It is known that the formation cycle of the BUE on the cutting tool continues and a certain maturity is reached, so it is separated into the tool material together [55]. This precipitation-separation cycle is thought to be the cause of the micro-crater observed on the rake face. Lastly, from Fig. 13, SEM and EDX analysis of the worn tool formed under the cryogenic-CO_2 environment can be seen. Here, a smoother tool is seen at the end of the cutting process compared to other tools used in dry and MQL. The reasons for the positive effects of the cryogenic environment on the cutting process have been explained in the previous sections. The residue and workpiece material particles located on the tool can be observed. It can be said that these are relatively loosely attached to the cutting tool. Elements C and O seen from the EDX analysis were considered residues from cryogenic CO_2 cooling. In addition, the presence of Al is proof that adhesion continues in this cutting environment as the primary mechanism.

5. Conclusions

Following conclusions are drawn:

- Nose wear analysis illustrated that dry environment is open for excessive damage as a result of abrasive and adhesive wear mechanisms primarily due to the absence of lubri-cooling effect while turning of Al alloy. Therefore, the cutting tool becomes useless after

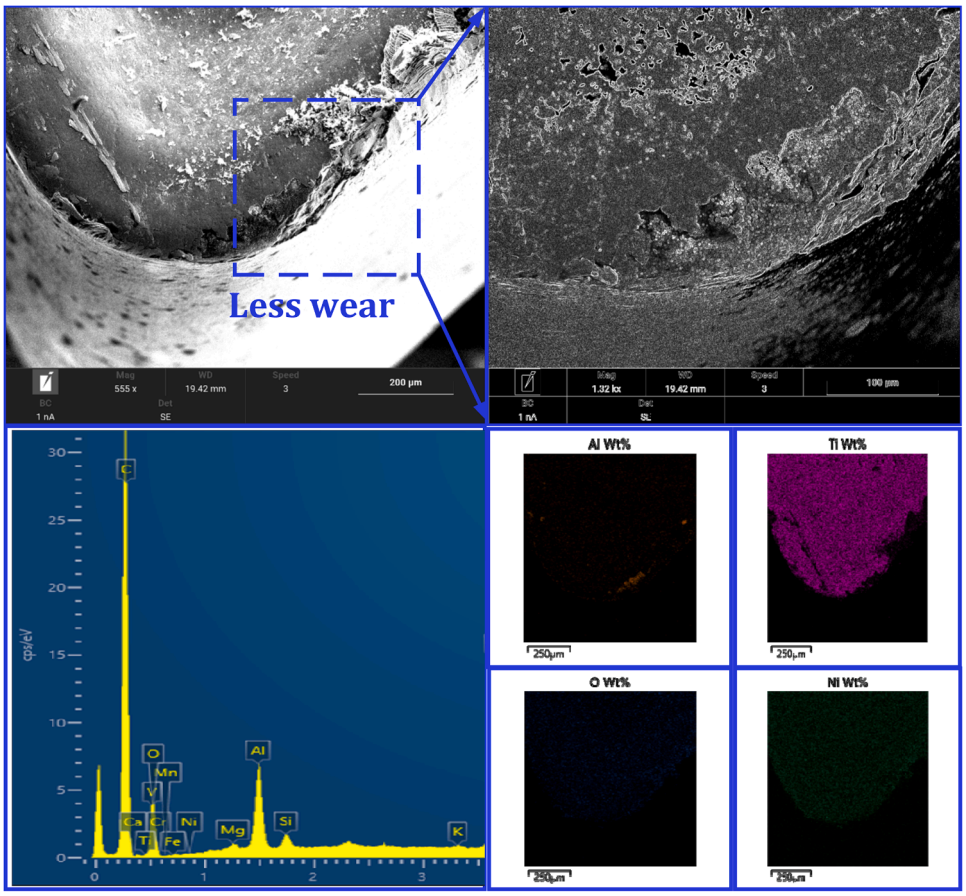


Fig. 13. SEM and EDX analyses for worn tools under CO_2 environment.

catastrophic failure. Application of pure-MQL significantly protects the tool profile with the abilities of lubricating and friction-reduction, however it was still found as insufficient compared to cryogenic assisted strategies.

- According to flank wear evaluation, the results are parallel to the nose wear findings and showed the superiority of cryogenic environment (especially when applying liquid nitrogen) over MQL and dry turning. On the other hand, a dramatic effect was observed when using lubricant or coolant at the cutting zone. Consequently, significant improvement was reached up to 15.8%, 36.8%, and 52.6% compared to dry turning while using MQL, CO_2 and LN_2 assistant machining respectively.
- Criticism of rake face of the cutting tool demonstrated the correlation between tool-chip contact length and crater wear. Accordingly, as per their functions cooling and lubricating mist particles infiltrate into the interfaces between tool-work and tool-chip activating the tribological mechanism. Thus, short contact length at these environments were obtained compared to dry cutting that provides low friction, thermal balance and low cutting forces eventually.
- Tool wear mechanism analysis shows that adhesion is the governing mechanism type without looking to the cutting conditions. But the cooling and lubricating facilities have clear impact to reduce it under determined level. Dry turning produces the worst cutting tool that loses the coating totally. Despite MQL strategy is successful in a certain level, still allowing a little crater wear land at the same time. It can be mentioned about a consensus in here including the previous wear results, cryogenic coolants are the best choice for turning of Al alloy.
- It is worthy to mention that the liquid nitrogen can be prioritized before carbon dioxide due to the better findings on rake and clearance faces that allows for longer utilization of cutting tool.

6. Future recommendations

In the present work, the detailed examinations of tool wear were performed under different cooling conditions. The recommendations for future studies are given below:

- Some analytical model could be developed to estimate the tool wear values especially under different cooling conditions.
- Thermal effect of cooling conditions with respect to the machining characteristics could be studied in the future.
- Tool wear results will be analyzed with the effect of different type of cutting fluids like nano-fluids, coconut oils etc. in the future investigations.

Statement of originality

As the corresponding author, I, M. Jamil, hereby confirm on behalf of all authors that:

1) The paper has not been published previously, that it is not under consideration for publication elsewhere, and that if accepted it will not be published elsewhere in the same form, in English or in any other language, without the written consent of the publisher.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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