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Role of dual textured tools in MQL turning operation

N. Bhaskar[1,2]✉, Manjunath K.[1], B. Venkata Narayana[1] & P. Sivaiah[3]

The present research focuses on machinability assessment of AISI 304 material under the integrated effect of MQL and hybrid texture tools in turning operation. AISI 304 poses significant machining challenges because of poor heat transfer and more strength. To enhance tool performance, novel dual micro-texture tools integrated of continuous wavy and circular dimple textures were developed and the developed tool performance was evaluated under conditions. The results revealed that the synergistic impact of MQL with textured tools outperformed both wet and dry environments by significantly reducing cutting temperature (T), flank wear (T_f) and rake wear (T_r), while also improving surface finish (R_a). The textures acted as micro-reservoirs for lubricant retention and promoted better chip flow at the cutting zone, contributing to improved tribological performance at the tool–chip interface. It was observed that the MQL condition reduced the 'T', 'Ra','Tf' and 'Tr' to 18%, 25%, 31% and 42% respectively when compared to dry cutting environment. Whereas it was 14%, 13%, 15% and 25% when compared to wet condition. The synergistic benefits of MQL and hybrid textured tools meets the functional improvement with eco-friendliness requirement while cutting AISI 304.

AISI 304 steel material has major applications in the fields of aerospace, marine, food processing, and biomedical industries due to its exceptional properties in terms of high hardness, more corrosive resistance, and low thermal conductivity[1]. The peculiar properties make the machining of this material difficult[2]. Conventional cooling methods fail to meet the high performance with eco-friendly requirements[3]. The recent emerging machining techniques, such as MQL and textured tool offers eco-friendliness along with improved process performance. However, the effectiveness of MQL largely depends on how efficiently the facility is created to store the mist at the cutting zone. In this connection, surface textured tools help to retain more coolant in grooves. Recently, studies have reported on this concept.

For instance, Şencan et al.[4] performed turning experiments with conventional tools on AISI 304 under dry, MQL and nano MQL conditions. The MQL base oil used in the work was sunflower oil and SiO_2 as nanoparticles with different percentages. It was observed that the 0.5% Nano-MQL method substantially improved R_a, T, T_r and T_f due to effective lubrication over other cooling methods. Manikanta et al.[5] turning operation performed on AISI 304 with developed trihybrid nanofluid and observed paramount performance in terms of R_a, and T_f due to low 'T'. Sen et al.[6] better viscosity provided by the nano-MQL in turning of Hastelloy contributed to positive results than other conditions. Similarly, with nanofluid machining, a significant rise in the turning process performance was noticed in the cutting of different materials[7–10]. Saraf et al.[11] observed high chip curl in micro-pillar textured tools owing to more heat removal from the cutting zone in turning of titanium alloy. Sathiya Narayanan et al.[12] noticed chip entrapment in the texture tools under nano-solid lubrication resulting in low 'F_c' and friction while turning SS304 material. Sivaiah et al.[13] investigated the machinability study on AISI 304 material with a hybrid texture tools in turning operation under different conditions. Wet conditions provided best lubrication at the cutting zone and contributed to low 'Ra', T', and 'V_b' than dry conditions. Further, observed few surface defects and low adhesion in wet cooling. In other work, it was concluded that texture design perpendicular to cutting edge tool with MQL showed improved results due to low cutting temperature over other tools[14]. Furthermore, identified optimum conditions for turning operation while cutting AISI304 material with single pattern textured tool[15]. Reddy et al.[16] machinability indices were examined under the combined impact of MQL and single pattern textured tools while cutting AISI 304 material. They reported that positive results were found in textured tools owing to the superior lubrication effect over untextured tools. Zhou et al.[17] This study explores how combining micro-textures and AlCrN coating specifically applying textures before coating enhances tool performance during dry cutting of AISI 304. The textured and coated tool (TCT) showed improved adhesion strength and reduced tool-chip contact (T), leading to less chip adhesion and wear. Cutting tests revealed that TCT reduced cutting and radial forces by up to 27% and 38%, respectively,

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at high speeds. These findings suggest the method effectively improves tool durability and performance under rough cutting conditions. Other than machining, researchers work on AISI304 material in different operations. Machining experiments were performed on AISI304 material with cryogenic treatment technique and suggested cutting conditions to get the martensitic transformation[18,19]. Machinability investigation carried out on AISI 304 material in drilling operation[20].

Roushan and Chetan[21] performed turning experiments on PH 13 – 8 Mo with developed single and hybrid pattern textured tools and evaluated its performance in turning PH 13 – 8 Mo steel material. They found better results with dual textured tools and concluded that texture geometry was significantly affected by the derivative cutting mechanism. França et al.[22] fabricated internally cooled tools (ICT) and examined their performance while machining AISI304 material. Results indicate that there is a significant reduction of temperature in ICT with MQL over other conventional tools with dry and MQL conditions. Bharath and Venkatesan[23] this study evaluate the machinability of Inconel 713 C during dry turning using cutting tools with different surface textures dimple (T1), honeycomb (T2), and broken-parallel (T3) with and without a graphene solid lubricant. Honeycomb-textured tools, especially when combined with graphene solid lubricant, are the most effective for dry machining of Inconel 713 C due to increased shear angle and decreased chip curl diameter. Broken-parallel textures also performed better than dimple textures. Further, they found that dry-textured tools showed higher adhesion and abrasion effects, whereas graphene-lubricated honeycomb tools had less severe wear and better overall durability. George et al.[24] explored the impact of single pattern textured tools under WS_2 nanoparticles and dielectric fluid condition in turning of Ti6Al4V material. It was reported that friction (μ) reduction at the cutting zone with impact of the synergy of textured tools and WS_2 nanoparticles substantially reduced the 'L' to a maximum of 19% over untextured tools. Tiwari and Amarnath[25] found improved turning performance in machining of AISI-1040 steel owing to friction reduction in MQL with coconut oil to other conditions. Zou et al.[26] investigated how the location of surface textures on cutting tools affects friction and cutting performance, especially in the sticking and sliding friction regions. They observed low thermal load in the tool with textures near the cutting edge while turning AISI304 material. Palanivel et al.[27] examined the machinability indices in dry turning of Ti-6Al-4 V and found low 'L' and more shear angle in diagonal pattern (DP) tools over other tools. Khani[28] explored the machinability indices in the turning operation of Aluminum 7075 material in combined conditions of nanofluids with different single pattern textured. They noticed that low 'T' in textured tools contributed to less adhesion wear than conventional tools. Li et al.[29] observed improved turning performance by integration of the single pattern textured tools with MQL over other conditions. They observed that low BUE contributed to positive results in textured tools in turning of titanium material. Ranjan and Hiremath[30] observed effective entrapment of wear debris in crescent structure tools over conventional structure tools. Rajurkar and Chinchanikar[31] performed dry turning experiments on Inconel-718 with various textured tools. They compared two homothetic textures (dimples and channels) and six hybrid textures with various orientation angles (0°, 45°, 90°) and geometric combinations (triangle, square, dimple). 90°oriented dimple and channel textures on the rake face delivered the best performance. Optimally oriented micro-textures, particularly dimples and channels at 90°, significantly enhance cutting tool performance in machining Inconel-718 by improving durability and chip control. In recent times, extensive work has been reported in single and dual textured tools performance in turning of different materials[32–38].

Literature indicated that dual textured tools have shown potential to further improve performance compared to single-textured tools. Further, it has been found from literature that textured tool performance is significantly affected by geometry and type of pattern of the texture. Therefore, the study goal is to develop a novel dual micro-texture tools integrated of continuous wavy and circular dimple textures and understand the synergistic effects of dual tool texturing and lubrication strategies on turning operation performance in terms of 'R_a', 'T', and 'V_b'.

Experimental procedure

Machining environments considered are dry, wet, MQL and SMARTURN make SINUMERIK 828D BASIC model NC lathe was used to machine AISI 304 material (ø30mmx150mm) with developed dual surface textured tools. Using a nozzle, MQL mist was externally supplied to the cutting zone using a MQL setup. Coconut oil with a flow rate of 150 ml/hr was used in the MQL setup to supply the coolant at cutting zone. Castor Emulsion based coolant was used in wet cooling. A Fibre laser was used to develop surface texture designs on a conventional cutting insert. Dual surface texture design is a combination of zig-zag grooves, linear grooves and circular dimple holes as depicted in Fig. 1. The main aim of the selected textured design is to store and supply the coolant to the cutting zone effectively. Figure 2 illustrates the methodology followed in the work. The three machining environments are shown in Fig. 3. On the basis of the Taguchi L9 orthogonal array design, experiments were carried out to reduce the experimental cost for analysis. Fresh edges of tungsten carbide inserts designated SNMA 120,408 K68 were used for each experiment. The processs parameter range was selected based on the preliminary tests and tool manufacturer recommendation. Each experiment was conducted with a machining length of 400 mm. The cutting temperatures in the machining zone were recorded using a Fluke make thermal imaging camera with Model TiS55+. Surface roughness readings were obtained using a SJ-310 model Taly surf tester of make and Mitutoyo. Tool wear was measured using a Zeiss make metallurgical optical microscope with model BX-53 M. Wedia make PSBNR K12 tool holder was used to fix the cutting inserts.

Results and discussion

Impact of integrating effect of dual textured tool and MQL on temperature

The turning process variables impact on cutting temperature with textured tools is depicted in Fig. 4. It is understood from Fig. 4 that cutting temperature rises as 'v', 'f' and 'a_p' rise. It is noted 34% reduction in 'T' at 'v' of

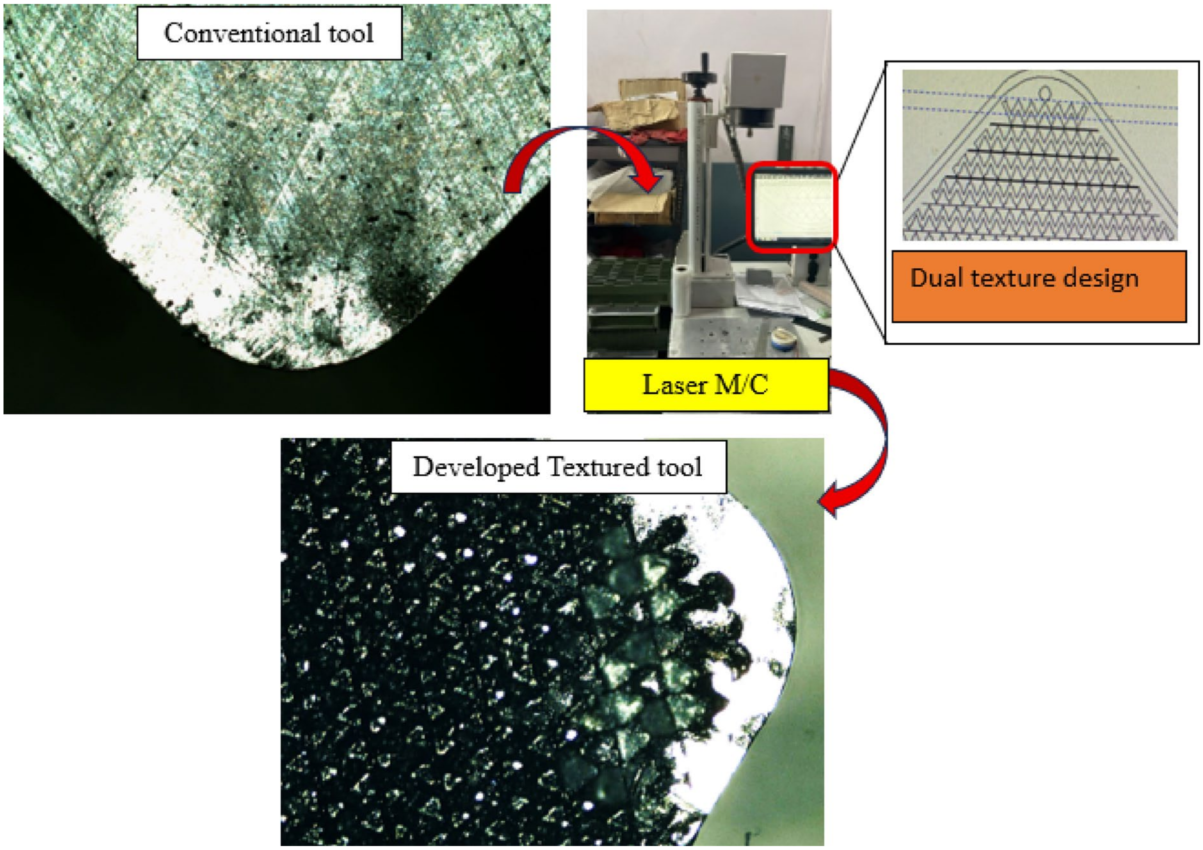

Fig. 1. Developed dual textured tool.

1000RPM when compared to 2000RPM. Similarly, at low 'f' and 'a_p' the drop noticed in 'T' was 16% and 6% than higher levels. This impact results from the upsurge of friction at the cutting zone at increased process parameter levels which cause an upsurge of cutting temperature. Additionally, Fig. 4 illustrates how the cutting environment affects the cutting temperature. Lower temperatures are found in MQL than other conditions. In MQL, cutting temperatures were lowered by 18% and 14%, respectively, under dry and wet cutting circumstances. Whereas, a 5% lower temperature was noticed in wet condition over dry cutting. In MQL, textured tools store the coolant in the microgrooves and cool the cutting zone by continuously supplying the coolant from microgrooves to the tool-workpiece interface, causes lower friction and hence low 'T' in MQL. On the other hand, high pressure MQL mist lifts the chip from the tool's rake face and enters the cutting zone, thereby lower 'L' leads to low 'T'. Figure 5 illustrates the image associated to cutting temperature recorded during cutting operation using a thermal image camera.

Impact of integrating effect of dual textured tool and MQL on 'R_a'

The load carrying capacity of any product substantially depends on the 'R_a' of the product. In the present work, how 'R_a' is affected by the turning process parameters are shown in Fig. 6. When cutting velocity escalated from 1000RPM to 2000RPM, the surface roughness followed decreasing trend. At a 'v' of 2000RPM, the 'R_a' reduction found was 50% over a cutting speed of 1000RPM. The reason is higher cutting speed offers lower 'L' which leads to positive cutting action, hence lower surface roughness values. Further, from Fig. 6, it is pragmatic that when 'f' and 'a_p' upsurge, the 'R_a' increases due to the rise of 'T'. The 'R_a' drop found in lower levels of 'f' and 'a_p' are 18% and 5% respective over higher levels of respective parameters. Surface roughness during cutting operations was significantly influenced by the cooling environment, as seen in Fig. 6. Especially, MQL significantly controlled the 'R_a' to 25% and 13% correspondingly in dry and wet conditions. Further, noticed 13% lower surface roughness with wet cooling over dry conditions due to the cooling effect. This is because the coolant storage sites available in the textured tools provide coolant to the cutting zone when MQL mist is sprayed at the machining zone. and helped for smooth cutting action, thereby lowering surface roughness in MQL environment.

Synergic impact of MQL and dual textured tool flank wear

Cutting tool life plays a significant role on total the manufacturing cost. Therefore, assessing tool wear is a crucial role and the present study has taken up this task. As illustrated in Fig. 7, the type of cooling method also has a significant impact on tool wear. Because of the low cutting temperatures and tool-chip contact length, the MQL cooling technology has greatly decreased tool flank wear. As depicted in Fig. 7, the flank wear drop in MQL was 31% and 15% than in dry and wet cooling conditions. Likewise, the noticed flank wear drop was 19% in wet

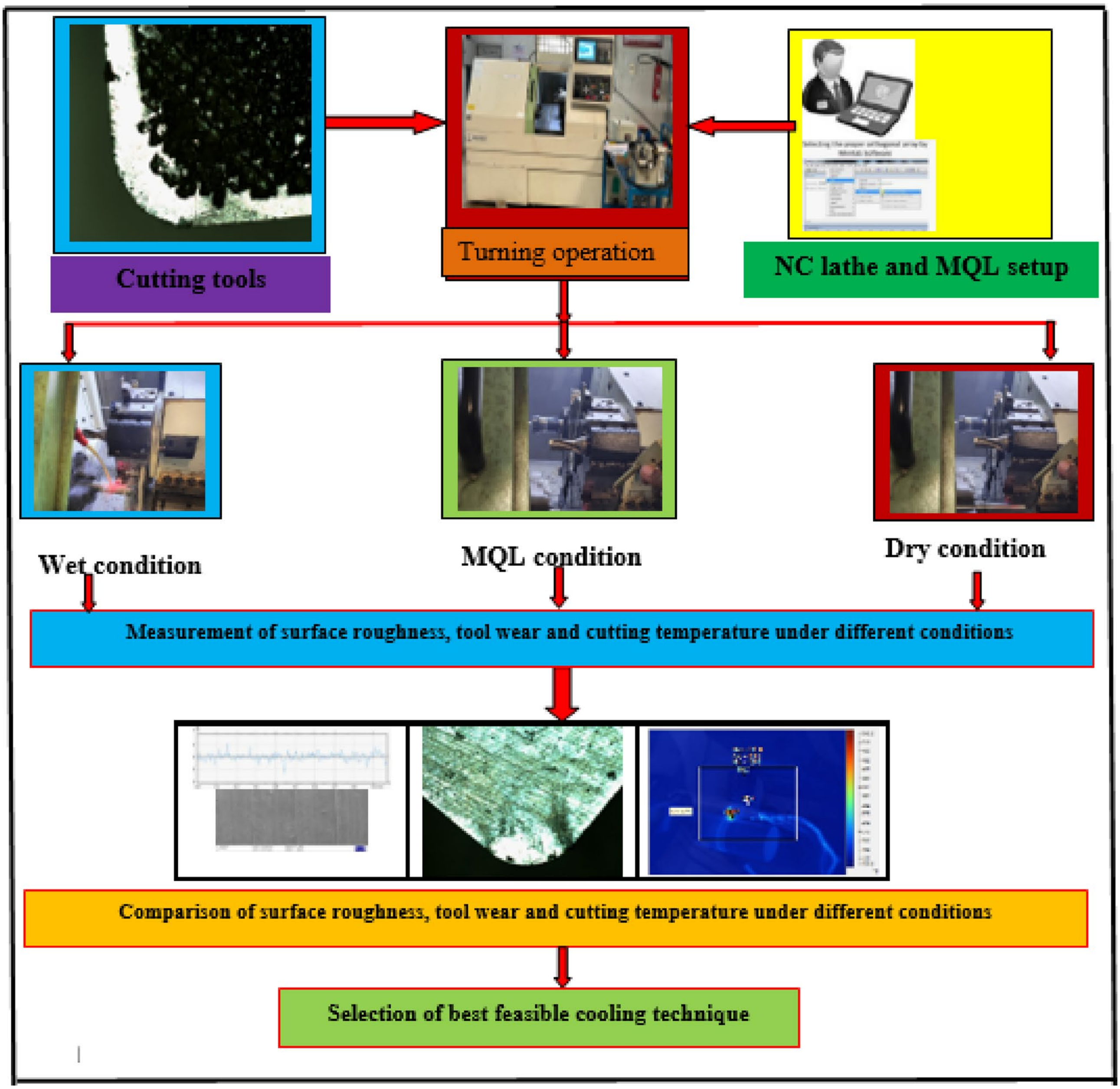

Fig. 2. Methodology.

cooling over dry condition. When cooled, textured tools served as coolant storage locations and improved cooling and lubrication at the cutting area. Figure 8 illustrated that adhesion and edge chipping were contributed to tool wear in dry condition, whereas few adhesions and edge retainment were found in MQL condition. Additionally, it is noted that when 'v', 'f' and 'a_p' rose respectively, tool flank wear increased as well. This is owing to the rise of 'T' at higher cutting levels which causes exposure of the cutting edge to higher temperatures, hence higher flank wear. It observed that flank wear is mainly influenced by the cooling environment and cutting speed.

Impact of integrating effect of MQL and dual textured tool on rake wear

The rake wear raised as the 'v', 'f' and 'a_p' rise from lower level to higher level range as depicted in Fig. 9. Rise of temperature at higher level contributed to this increasing trend of rake wear. Further, notice that at a cutting speed of 1000RPM, a 45% drop of 'T_r' when than a 'v' of 2000RPM. Similarly, 16% drop in rake wear was observed at a 'f' of 0.1 mm/rev over 'f' of 0.14 mm/rev. It has been observed that 'v' significantly affects the 'T_r' when compared to other parameters because of higher temperatures. Cooling environment also played a meaningful impact on rake wear as shown in Fig. 9. When compared to all the cutting conditions, it was found lower rake wear in MQL. When MQL mist is sprayed at high pressure on the textured tool, coolant accumulates in the microgrooves and the cutting edge is provided with a ceaseless supply of coolant with the assist of microgrooves which leads to chip lift off taking place from the tool face thereby lower 'L' hence lower rake wear. It is found that 42% and 25%

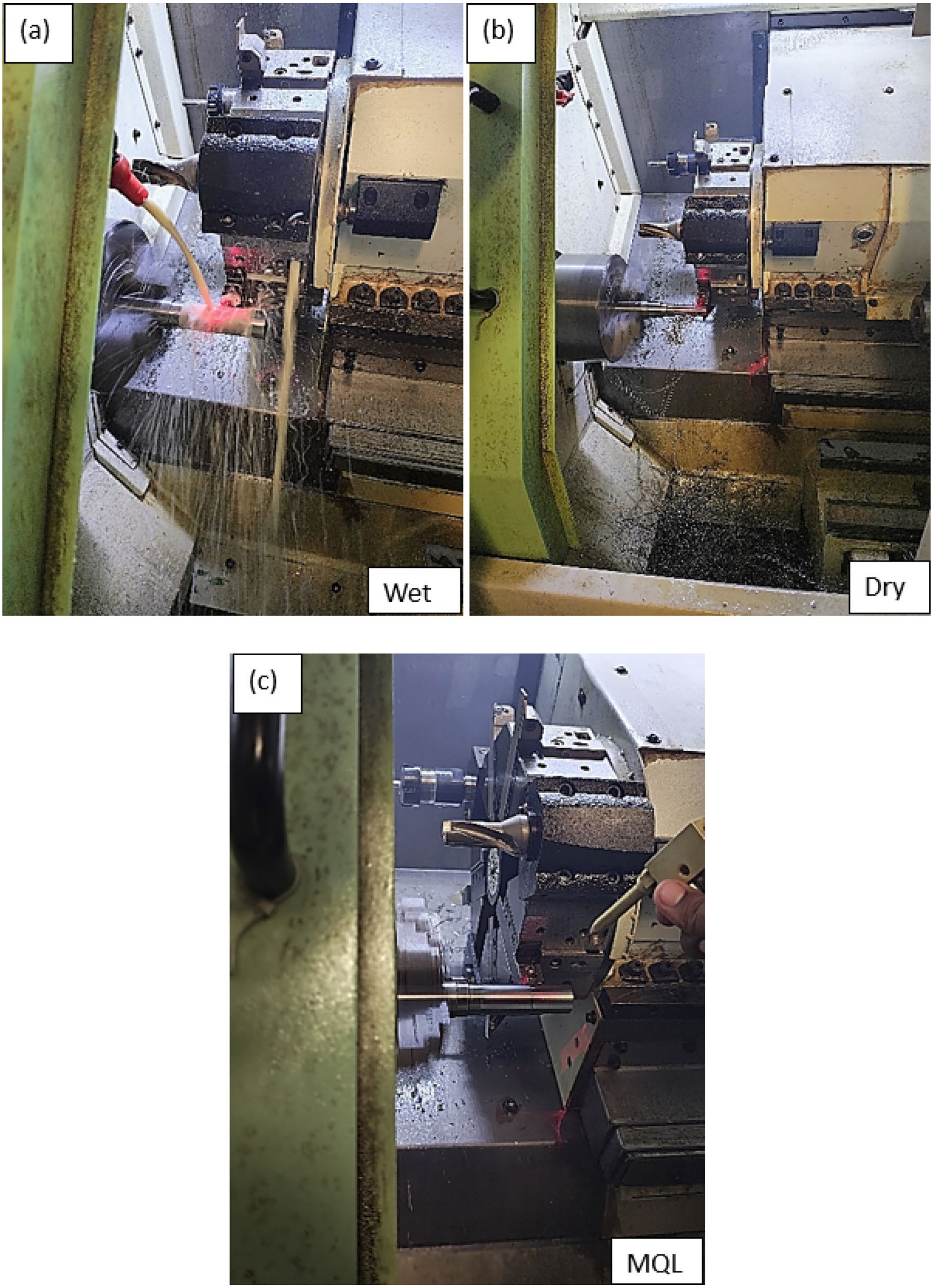

Fig. 3. Machining zone conditions (**a**)Wet (**b**) Dry (**c**) MQL.

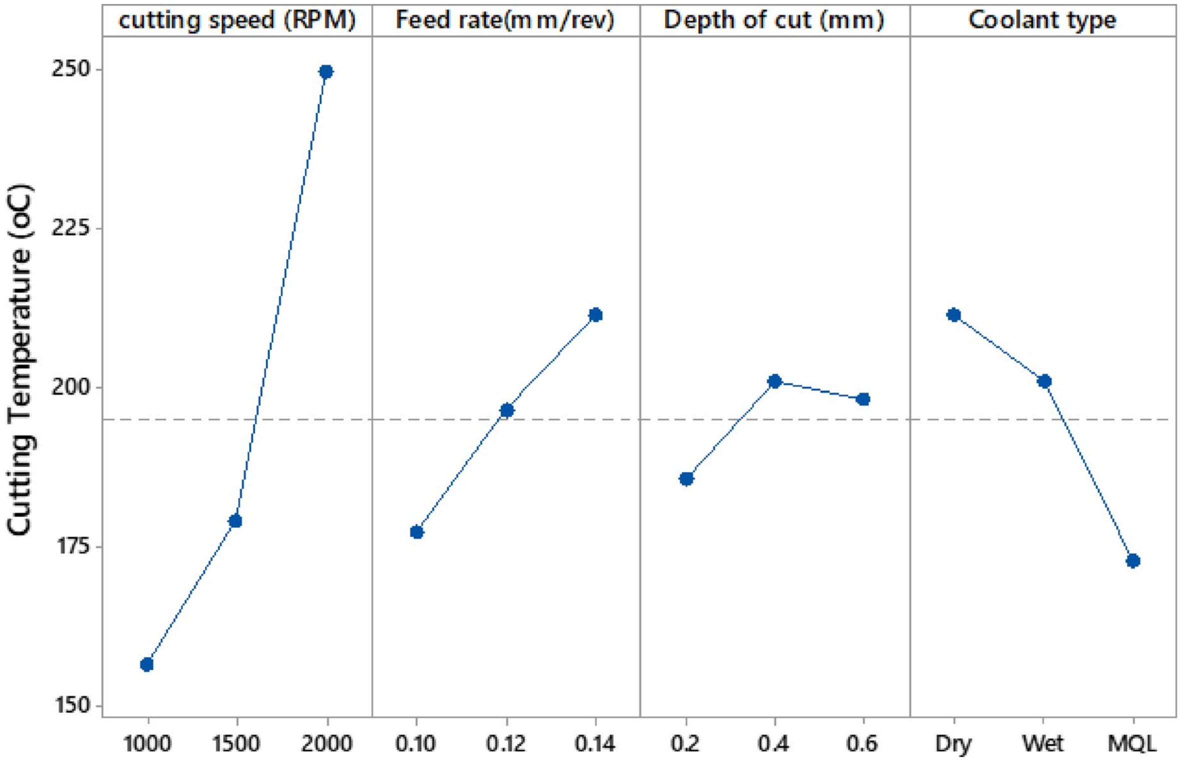

Fig. 4. Impact of integrating effect of dual textured tool and MQL on temperature.

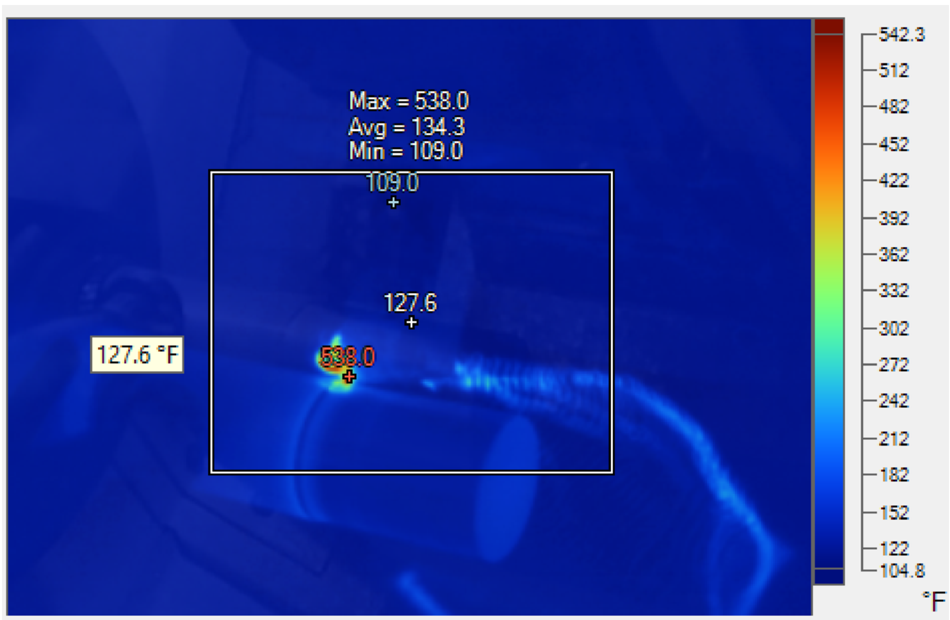

Fig. 5. Sample thermal image camera.

respective drop in rake wear in MQL than dry and wet conditions. Moreover, the 'T_r' drop observed with wet condition is 24% over dry condition. Figure 10 (c) evidence that MQL cooling retains the cutting-edge shape due to low 'L' and contributed to smooth cutting and low rake wear. Whereas, as depicted in Fig. 10(a)&10(b), high temperatures are the reason for severe cutting-edge damage and BUE in dry and wet condition. The MQL cooling technique provided better lubrication when compared to other cutting conditions.

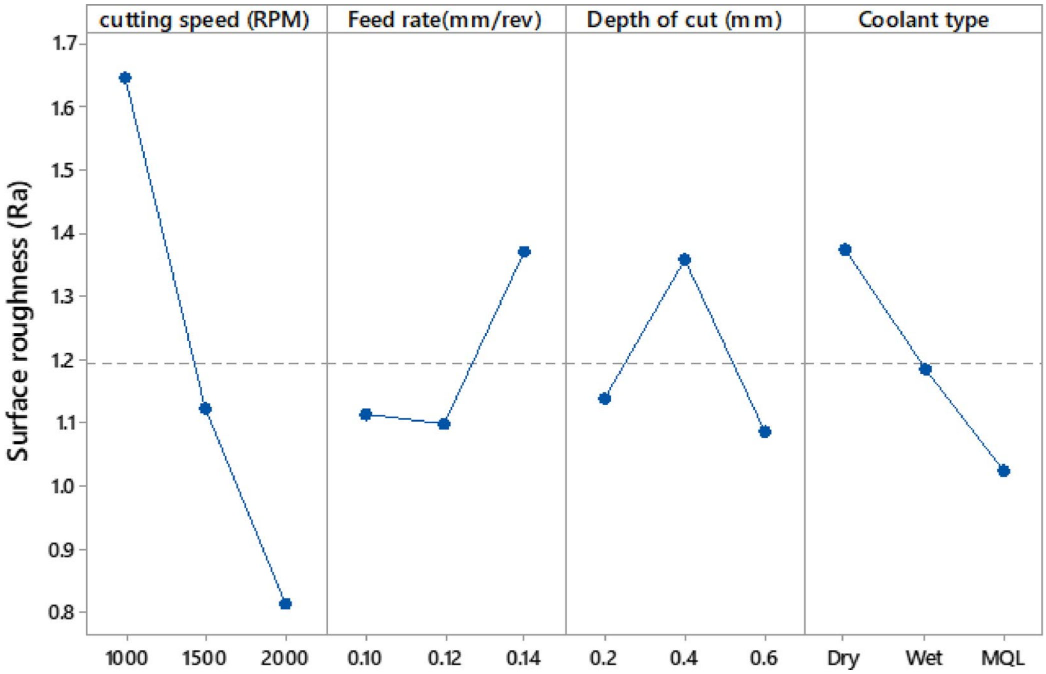

Fig. 6. Impact of integrating effect of dual textured tool and MQL on 'Ra'.

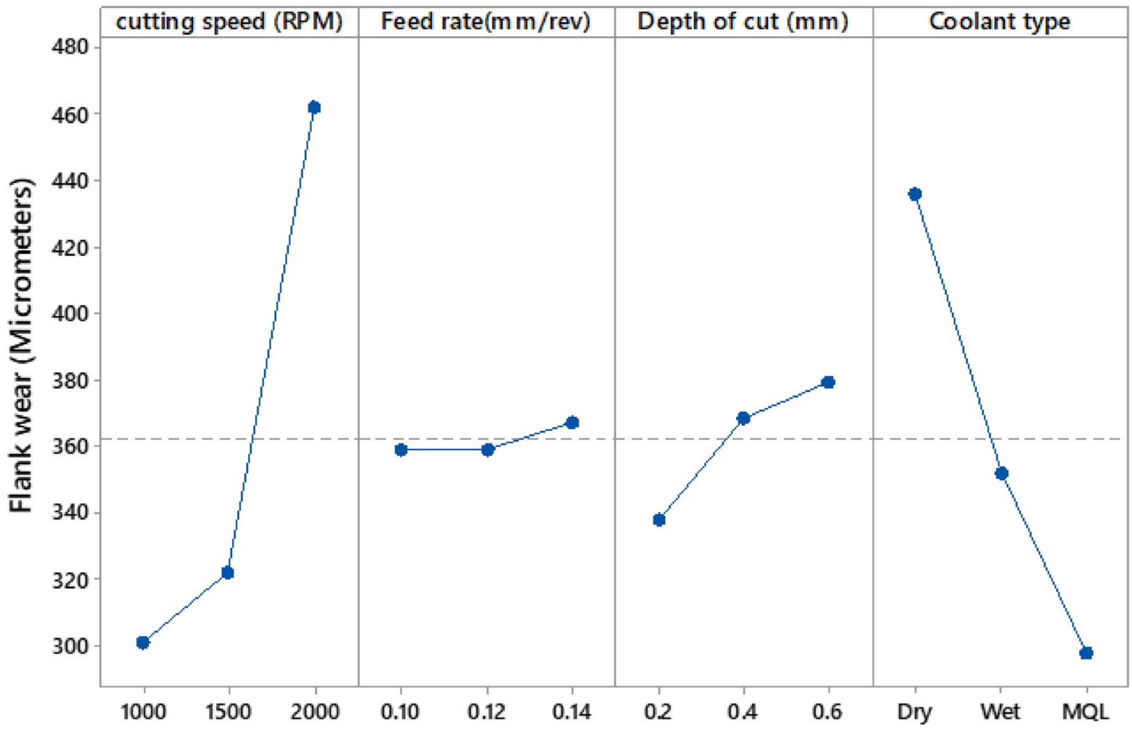

Fig. 7. Impact of integrating effect of dual textured tool and MQL on flank wear.

Conclusions

The influence of cutting environment integrated with developed novel hybrid textured tools on turning operation machinability outputs were studied while machining AISI 304. The following observations were made after thorough study.

- The turning process outputs 'T', 'R_a', 'T_f' and 'T_r' found low with developed textured tools in MQL condition over dry and wet conditions respectively.

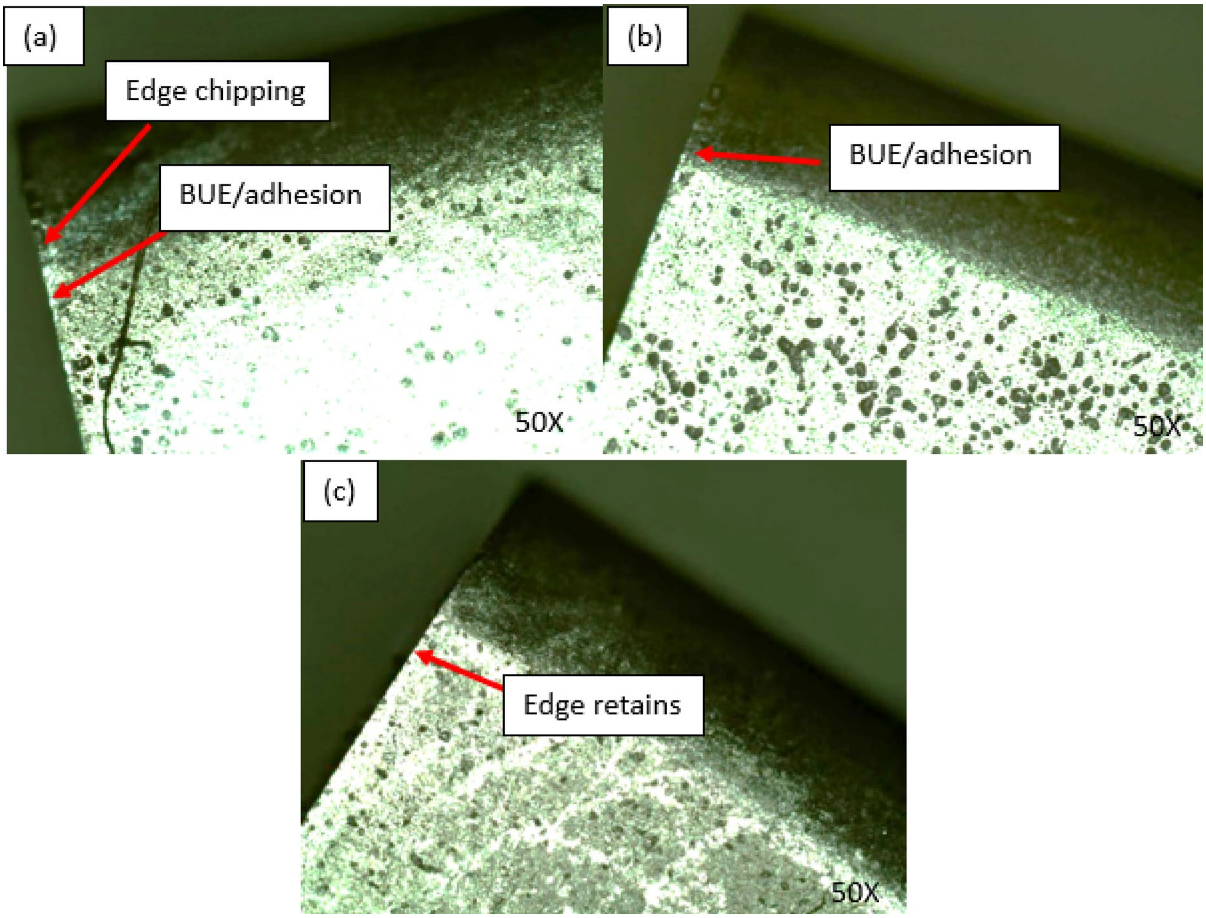

Fig. 8. (**a**) Dry (**b**) Wet (**c**) MQL condition.

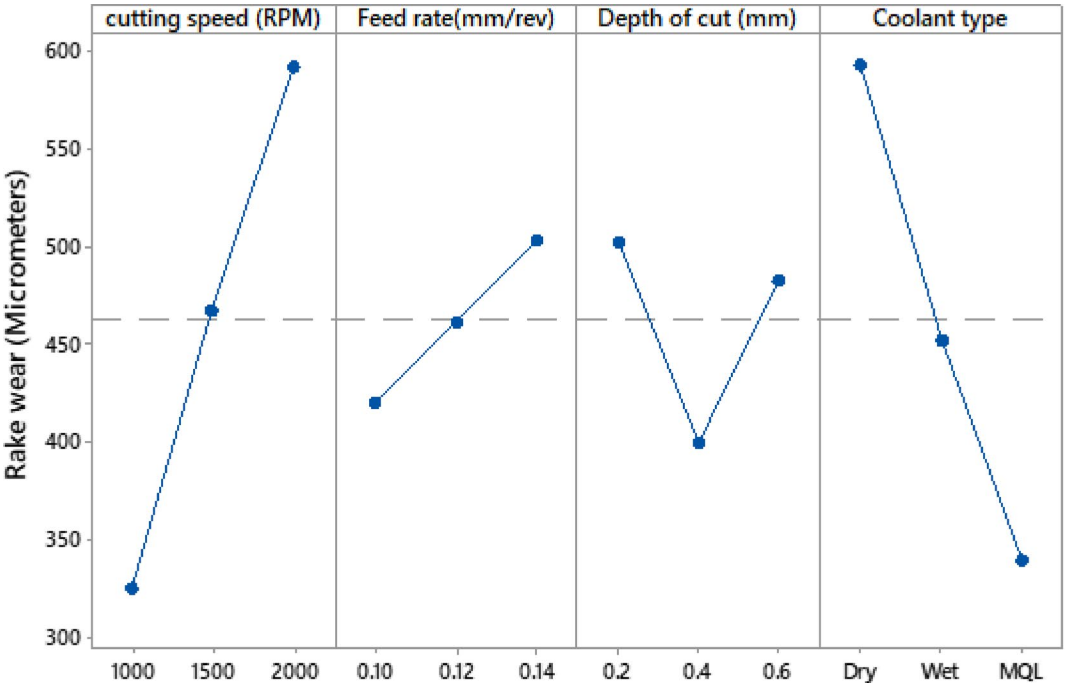

Fig. 9. Influence of cooling condition on rake wear.

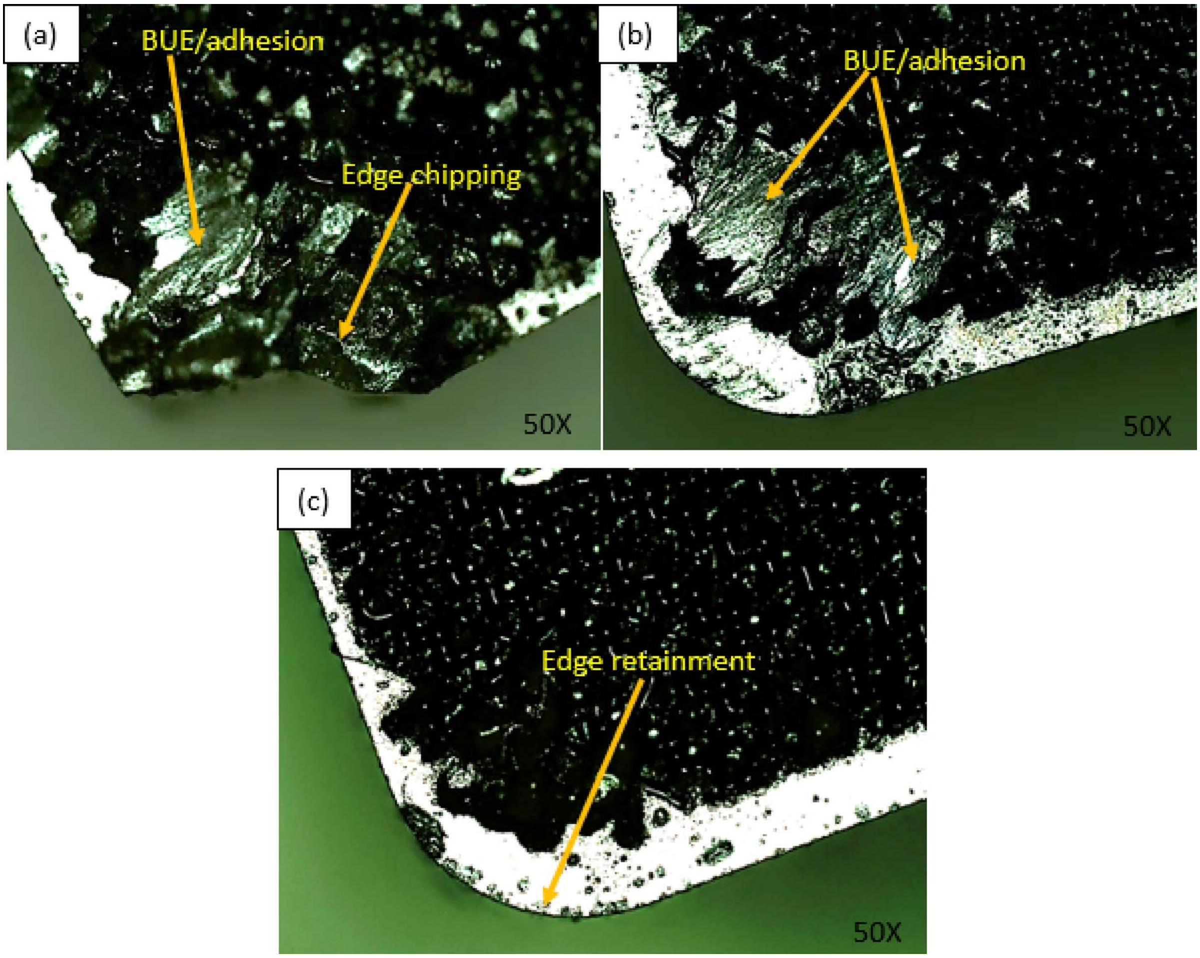

Fig. 10. (**a**) Dry (**b**) Wet (**c**) MQL condition.

- At MQL cutting zone, texture present in the tool served as a coolant storage site and provided better lubrication over conventional cooling.
- Among all the process controllable variables, cutting speed was found to as the most significant variable followed by the type of cooling condition on 'T', 'R_a', 'T_f' and 'T_r'.
- MQL condition reduced the 'T', 'R_a','T_f' and 'T_r' to 18%, 25%, 31% and 42% respectively when compared to a dry cutting environment. Whereas it was 14%, 13%, 15% and 25% when compared to wet condition.
- Overall, integration of dual texture design with advanced lubrication techniques like MQL presents a promising approach for achieving high-performance, eco-friendly machining.
- Compared to wet cooling, the MQL approach used less coolant and needed no coolant maintenance.
- Edge chipping and BUE are the main causes of tool rake wear in dry conditions.
- MQL found with low BUE over dry and wet conditions.

Data availability
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

N. Bhaskar: Conceptualization, Methodology, Data curation, Experimentation, Investigation, Writing-original draft. Manjunath. K: Supervision, Writing-review & editing. B. Venkata Narayana: Supervision, Data curation, Methodology, writing—review & editing. P. Sivaiah: Resources, Experimentation, writing-review & editing.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
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