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REGULAR PAPER

Small Quantity Lubrication Assisted End Milling of Aluminium Using Sunflower Oil

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Abstract
The current study evidentially brings out an interesting finding that the chemically inert microcrystalline diamond (MCD) coating having sp^3 hybridized C–C network could produce no better result than an uncoated carbide tool in machining aluminium when the latter was provided with the assistance of small quantity lubrication (SQL) technology in an intermittent machining operation like end milling using sunflower oil as cutting fluid. Such an outstanding performance of uncoated tools under SQL condition is thus found to be a potential green solution for milling of aluminium and its alloys where only built-up-edge formation is the primary challenge. Investigation was done on pure aluminium, considering that aluminium alone or Al-rich solid solution phase of any Al-alloy causes the chip to adhere to tool. The SQL, at a flow rate of mere 10 ml/h, when adopted to assist an uncoated carbide tool resulted in superior surface finish (about 75%), compared to that produced by a MCD coated tool under dry environment. An oil film containing long chained molecules of fatty acid got developed at the interface of chip and uncoated tool, enabling an adequate hydrodynamic lift to ensure the arrest of aluminium diffusion in Co-matrix. On the contrary, the rough diamond coating morphology, having projected hard and sharp crystallites of MCD with average height of 1.6 µm resulted in unfavorable deeper groves on finished surface. In addition, the edge radius on the tool, which is otherwise for an effective coating deposition, impaired the smooth shearing action during machining. Interestingly, the same rough morphology of MCD coating served as micro reservoirs of cutting fluid, during SQL application, resulting in a substantial improvement of surface finish, but yet poorer than that obtained under SQL-uncoated tool combination. Two important characteristics of sunflower oil, i.e., its lubrication and wetting ability were investigated and compared with those of a commercially "green" cutting oil before selecting the former as an eligible alternative.

Keywords Aluminium · BUE/BUL formation · SQL · End milling · Uncoated carbide · MCD · Surface finish

1 Introduction

Green machining is the latest trend in manufacturing to produce machined components without polluting the environment. This can be best achieved without using any coolant, i.e., by adopting dry machining [1]. Although aluminium is soft and ductile, its high chemical affinity makes it very difficult to be machined under dry condition [2]. Uncoated carbide tools receive severe BUE (built up edge) formation. Presence of cobalt (Co) in the cemented carbide tool promotes the chip adhesion by diffusion process [3]. However, it is feasible to machine aluminium and its alloys dry, with CVD (chemical vapour deposition) diamond coated tools when all other coated tools do not serve the purpose effectively [4]. Diamond's unique properties like chemical inertness towards aluminium and its alloys, high hardness at elevated temperature and thermal conductivity are the primary factors, which lead to such outstanding capability of this class of tool materials [5]. Interestingly, the growth of CVD diamond requires rounded cutting edges, which affects its sharpness [6] causing difficulty in aluminium machining. The round edged tools are more prone to form BUE than sharp tools. The cutting force is less and more stable in the case of sharp tools than round edged tool [7]. The diamond crystals grown by CVD route is also not very fine, which unfavourably leads to irregular surface of diamond coating [8]. Due to rough texture of such micro crystalline diamond (MCD) coating, movement of flowing chip of softer work material like aluminium and its alloys receives mechanical

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restrain [9]. The sharp diamond particles grown on the cutting edge further scratch on finished surface of workpiece, resulting in high surface roughness on the machined surface [10]. Polishing of diamond coating is sometimes helpful to reduce the surface roughness [11]. Improvement in surface quality and decrease in cutting force, tool wear and tendency to form BUE in turning of A390 alloy have been reported. On the other hand, uncoated carbide tools, although prone to BUE formation, have smooth surface and sharp cutting edges, which are favourable for aluminium machining but subject to the arrest of chip adherence. With suitable cooling/lubrication arrangement, uncoated tools can significantly escape from BUE/BUL (built up layer) formation. Consequently, surface roughness of the workpiece gets improved. In this regard, flood cooling with conventional cutting fluids has been found to reduce [12] the severity of chip adhesion on the cutting tool to some extent due to additional cooling and lubrication. The cutting fluid penetration is the most challenging factor in flood cooling environment. The effective penetration depends on the pressure of the jet, tool geometry and cutting parameters. The low velocity emulsion based cutting fluids were reportedly unsuccessful for rotating cutting tools like end mills due to poor penetration. The air-wall generated surrounding the rotary cutting tool, blocks the way of the coolant towards the tool center in end milling of AA5083-H112 [13]. However, the effectiveness is significantly improved if the same is applied in the mist form. This observation led to the emergence of minimum quantity lubrication (MQL), which is other way known as small quantity lubrication technology (SQL). It is not only a near-dry, economic approach but is energy efficient, too. It was observed that BUE formation could be substantially arrested [14] on HSS tools with MQL approach. Most of the research papers related to MQL machining used paraffin oil as an MQL medium [15], however, the use of such oil is not recommended for green machining.

In the current study, green machining is prioritized due to strict environmental regulations. Vegetable oils are highly attractive substitutes for petroleum-based oils because they are environmentally friendly, renewable, less toxic and readily biodegradable [16, 17]. Vegetable oils consist of triglycerides, which are glycerol molecules with three long chain fatty acids attached at the hydroxyl groups via ester linkages. The fatty acids in vegetable oil triglycerides are all of similar length, i.e., between 14 and 22 carbons long. The triglyceride structure of vegetable oils provides desirable properties of lubricant [18]. Long, polar fatty acid chains provide high strength lubricant films which interact strongly with metallic surfaces and reduce both friction and wear [19].

Available literatures on SQL machining of commercially pure and silicon free aluminium alloys are very few [20, 21]. Since BUE/BUL (built up layer) formation is a predominant problem in machining these materials, application of SQL with uncoated tools is a potential alternative to dry machining with expensive MCD coated tools. It is noted that among different vegetable oils, sunflower oil showed its superior performance in reducing tool wear and surface roughness in machining steel [22]. Thus, it is suggestive that the application of SQL technology and the use of long chained fatty acid rich, slightly sticky vegetable oils like sunflower oil, if combined, it shows a good promise but on intermittent cutting where a cutting edge releases the chip once it detaches itself from the work. Subsequently it pulls in a new lubricant film, which sustains a hydrodynamic lift on sliding chip, separating the interfacial contact of chip and tool. It is apprehensible that Si-rich aluminium alloy or ceramic reinforced aluminium composites cannot be dealt with the uncoated carbide tools due to high abrasion wear resistance characteristics caused by the hard phases of the work material. However, machining of pure aluminium and its other alloys should be conveniently managed but with judicious combination of SQL and a suitable cutting fluid. It is worth mentioning that exploring the potential of such bio degradable vegetable oil, i.e., sunflower oil [23] and SQL technology as an alternative to the highly expensive application of MCD coating technology also ascertains the criteria of a green alternative to the existing challenge. The primary FCC aluminium phase causes the BUE/BUL formation. Commercially pure AA1050 was selected as work material because any arrangement which helps in improving BUE/BUL formation on cutting tool for this material would also succeed for other Al-alloys. The wettability and antifrictional characteristics of the vegetable oil were examined before machining test to understand its performance as SQL medium.

2 Experimental Methodology

Sunflower oil has been selected as the cutting fluid for SQL application. This vegetable oil contains long chained molecules of fatty acid, which make it easily adhere to any metallic surface and subsequently contributes to lubrication. Its tribological behaviour and wettability towards carbide surface have been first evaluated before being tested for its efficacy in SQL machining. The pin (carbide) on disc (aluminium) test on a tribometer was conducted at a sliding speed of 300 m/min, which was even higher than the selected cutting speeds and corresponding order of chip sliding speeds on tool rake during machining. Slot end milling (100 mm × 10 mm × 0.5 mm) operation was performed on a pure aluminium block under dry and SQL environments by two fluted uncoated and diamond coated carbide end mills (⌀10). The experimental conditions are detailed in Table 1. The SQL set up was indigenously built using a micro-dosing pump (Make: Acculube, USA). An internal mix nozzle

Table 1 Experimental conditions

Cutting tool and work material	Environment and operating parameters
Work materials: AA1050 Machine: Vertical Machining Center (Model: DTC-300, Make: Ace Micromatic) Tool type: End mill cutter Tool material: uncoated and MCD coated carbide Helix angle: 30° Diameter: 10 mm No of flutes: 2	Environment: SQL SQL Medium: Sunflower oil (Viscosity: 41.55 mPa s at 35 °C, Flash point: 322 °C) Cutting Speed, V_c (m/min): 60, 120, 180, 200, 300, 400 Feed rate, f (mm/min): 100, 200, 300, 400, 500 Axial depth of cut, a_a (mm): 0.5 Width of cut, a_p (mm): 10

with a flexible nozzle positioning fixture was employed for SQL application. Compressed air was supplied at 6 bar to the internal mix nozzle for the necessary atomisation. The consumption rate of sunflower oil was set at 10 ml/h. The effectiveness of the novel approach was assessed in terms of surface finish of the machined component and cutting force data. A perthometer (Make: Mahr GmBH, Germany, Model: M2) and a piezoelectric dynamometer (Make: Kistler Instrumente, Switzerland, Model: 9257B) were, respectively used for the aforesaid purpose. Microdetails of the machined surface was inspected under a scanning electron microscope and a 3D profilometer (Make: Bruker, model: Contour GT-K) to critically observe the cutting action of the tool and quality of the surface. Necessary EDS (energy dispersive spectrometry) analyses were carried out to trace any aluminium diffusion. Underside micromorphology of the chips was also given due importance to understand the interaction of tool and flowing chip. Surface roughness and the 3D texture of finished surface were also included in the primary focus of the current work.

3 Result and Discussion

3.1 Characterization of Wetting and Lubrication Properties

The wettability and lubricating ability of the vegetable oil were assessed in reference with a commercially available vegetable oil based cutting fluid. Figure 1 displays the images of wetting of both the oils on a carbide surface of roughness, $R_a = 0.12$ µm. It can be observed from the figure that wettability of sunflower oil was relatively poorer than that of the commercial oil. When the sunflower droplet produced a wetting angle of 38°, its counterpart produced 25° when a near equilibrium condition was achieved.

The combined effect of surface tension and viscosity (lower values) seemed to favour the performance of commercial synthetic oil. Both oils were further subjected to lubrication test. The formerly used SQL system was integrated with the tribometer for the set.

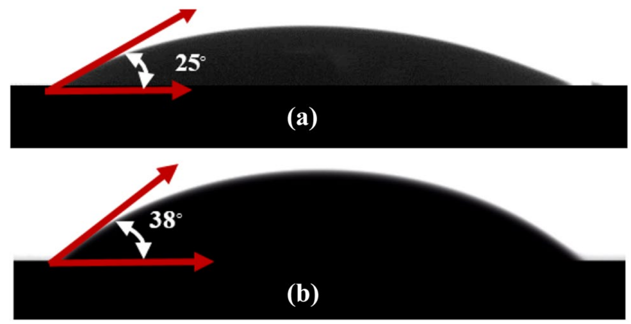


Fig. 1 Variation of wetting angle produced by **a** commercial cutting fluid and **b** sunflower oil on uncoated carbide substrate

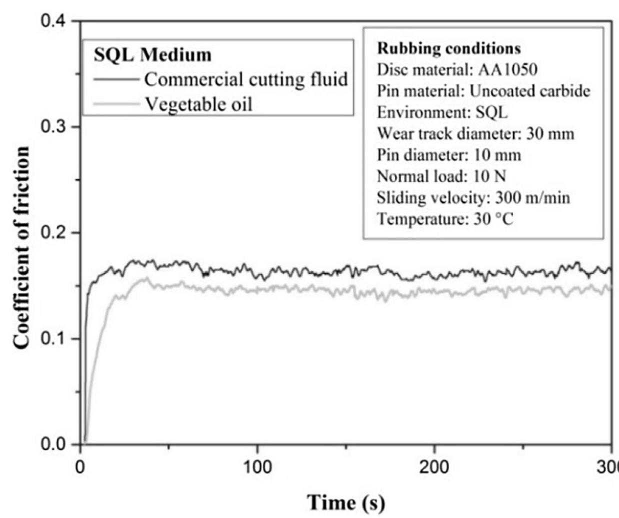


Fig. 2 Variation of coefficient of friction with time using commercial cutting fluid and sunflower oil (vegetable oil)

The experiment was conducted on a track diameter of 30 mm at a sliding velocity of 300 m/min. A carbide (WC-6Co) pin of 10 mm diameter was engaged to slide on pure aluminium (AA1050) disc with a normal load of 10 N. Figure 2 brings out the dynamic variation of coefficient of friction (COF) at pin-disc interface. It is evident that the sunflower oil outperformed the counterpart in terms of significantly lower and steady COF throughout test period.

3.2 On Cutting Force

The performance of uncoated and MCD coated tools under both dry and SQL-sunflower oil environment are presented simultaneously in Fig. 3. Maximum value of the F_Y component (the direction is shown in the figure) of cutting force was considered for the comparison. This component was chosen mainly because when a cutting edge shears the workpiece with the maximum chip thickness, it is this component what is purely active. Four trials for each condition were carried out and the highest levels of F_Y component in the four trials are represented through the error graph along with its mean as the height of the column of the plot. Force results suggest that the performance of sunflower oil in SQL mode with uncoated carbide tool was outstanding. Cutting force got substantially reduced when uncoated carbide tools were used with SQL-sunflower in place of MCD coated carbide end mills under dry (which is a common practice in machining industries) environment.

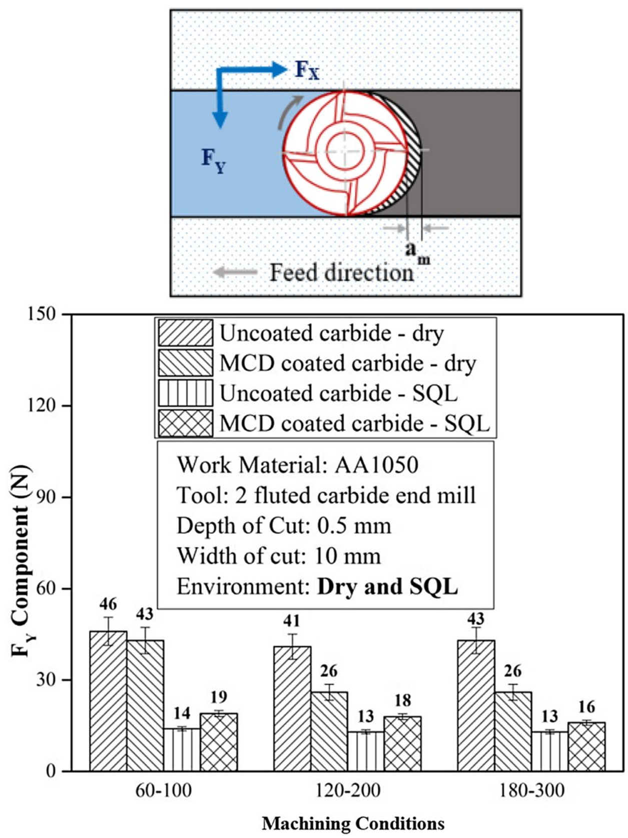


Fig. 3 Variation of F_Y force component with uncoated and MCD coated end mills under different environments (AA1050) [60–100: cutting velocity (V_c): 60 m/min; longitudinal feed rate (f): 100 mm/min]

The order of reduction was in the range of 50–67%, depending on the conditions. Use of sunflower oil in SQL along with MCD coated cutter could also reduce the force level by approximately 30–50% of the value obtained under dry environment. The diamond tools were provided with some corner radius. The edge radius on the MCD coated tool is not visualized. It is required for good quality deposition of diamond. After deposition, it was in the order of 3–4 µm in the used tools under current investigation. Both types of radius have negative impact on machinability and lead to escalation of specific force component, especially when feed per tooth of milling cutter was low. Difference in the geometry might have contributed to escalation of force level but the escalation seemed to receive a significant share from the resistance of chip flow on rake surface due to high roughness of diamond texture on MCD coated tool.

Figure 4 compares the performance of sunflower oil with that of the commercial cutting oil. It can be observed that the sunflower oil was marginally but consistently superior to its commercial counterpart at all sets of cutting speed-feed combinations. This could be attributed to the heavier molecules of sunflower oil making a more effective chip separating oil film and better lubrication. Although the wettability was poorer, it appeared to be adequate to fetch the beneficial effect in favour of sunflower oil. The effect pronounced significantly better in case of the diamond coated tools as it contain inter crystallite space to serve as oil reservoir.

3.3 Post Machining Observation of Tools

SEM images (Fig. 5) of the post machining conditions of tools bring out the necessary information on built-up edge, built-up layer or traces with high resolution and EDS analyses. The images and the EDS results are portrayed in the

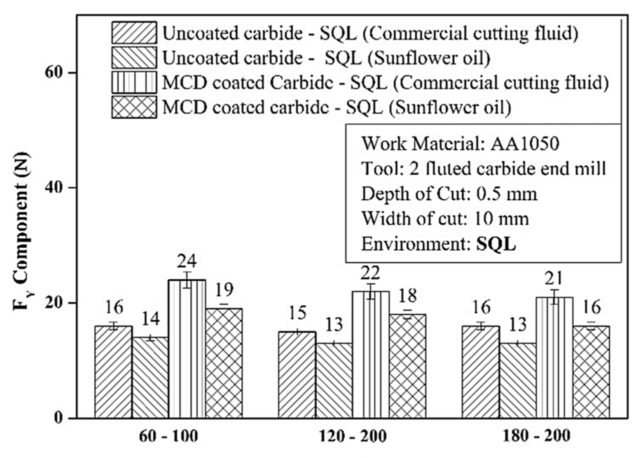


Fig. 4 F_Y force component under different SQL environments using sunflower oil and commercial cutting fluid

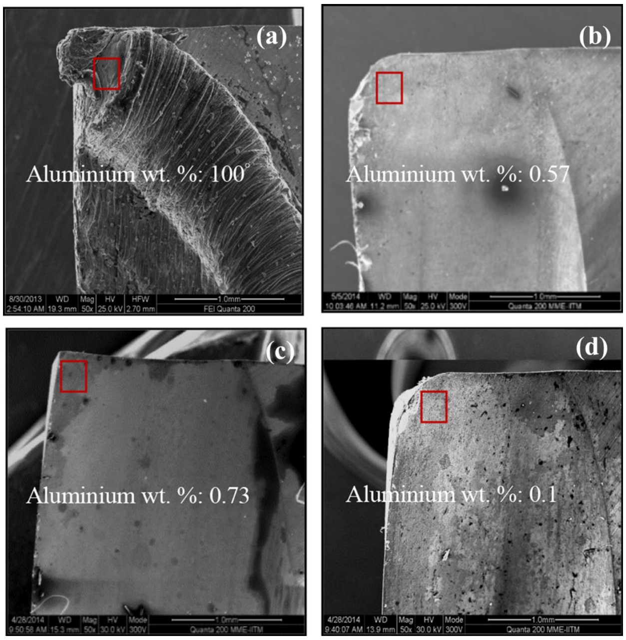


Fig. 5 SEM images of rake surface of end mills under dry and SQL environments after machining AA1050 at V_C: 120 m/min; f: 200 mm/min; a_a: 0.5 mm. **a** Uncoated carbide–Dry, **b** MCD–Dry, **c** Uncoated-SQL, **d** MCD–SQL under dry environment

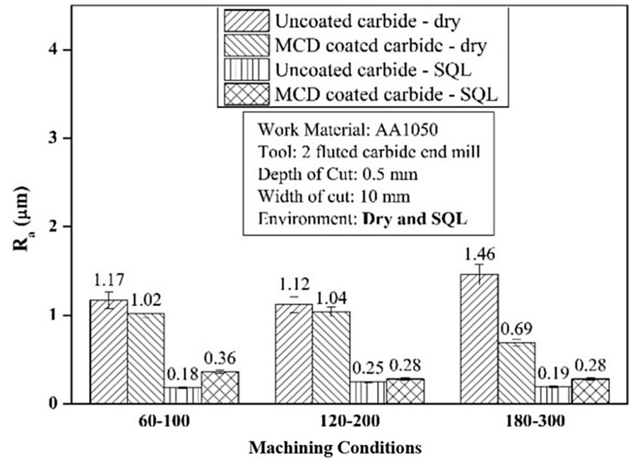


Fig. 6 Variation of surface finish with uncoated and MCD coated end mills under dry and SQL environments

figure for 120–200 condition. 120–200 condition refers to the combination of a cutting velocity of 120 m/min and a feed rate of 200 mm/min. It can be seen that a chip was severely adhered to an uncoated tool when used in dry condition. Microscopic inspection of tools suggested that uncoated tools received adhesion of work material. On the contrary, there was a negligible trace of aluminium of only 0.57 weight percentage (wt%) on diamond coated tools, used in dry condition. SQL environment on uncoated tools offered comparable results, thus justifying its efficacy in arresting aluminium diffusion on uncoated tool. MCD diamond tools appears to gain substantially additional favour from SQL application as the adherence was almost eliminated.

3.4 On Surface Roughness

R_a values in Fig. 6 depict that SQL-Sunflower oil condition could help uncoated tools in producing a significantly lower roughness than that produced by MCD coated tools under dry and SQL environment. Comparing the images of Fig. 5, it is therefore conclusive that the adopting SQL-sunflower combination for uncoated tool is very useful. For example, at 120–200 condition, R_a value was as low as 0.25 μm on the surface machined by uncoated tools under SQL-Sunflower oil environment.

This value was 76% less than that produced by MCD-dry and 12% lower than that obtained with MCD-SQL combination. Since there was no evidence of built up edges in either of the cases, the uncoated tool enjoyed an advantage of producing sharper cutting than the MCD coated tool, which had a significantly higher edge radius. Figure 7 presents the SEM images of the surfaces produced with uncoated-SQL and MCD-dry combinations. It clearly suggests that the cutting action of the diamond coated tool under dry was not as good as that of uncoated tool under SQL and induced ploughing impressions.

This also justifies the use of SQL application. Even the small volume consumption rate, as little as 10 ml/h at 4 bar could help in BUE free cutting in WC tools.

Hydrodynamic lift obtained by the chips in SQL application was adequate to arrest any chance of aluminium diffusion subsequently allowing the tool to cut without BUE/BUL formation. As uncoated tool cutting edge is sharper than that of diamond coated tool, the lay patterns are visible without any trace of ploughing/surface tearing. Ploughing marks are quite pronounced on the surface it machined under dry environment. While the SQL (with sunflower oil) environment was used for both uncoated and MCD, the latter

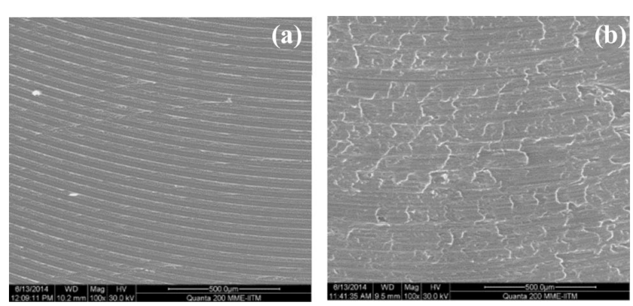


Fig. 7 Micro morphology of machined AA1050 surfaces produced by **a** uncoated tool under SQL and **b** MCD coated tool under dry environment

produced little higher surface roughness due to unfavourable radiusing of cutting edge and scratches produced on the finished surface by sharp crystals on cutting edges. Images of machined surfaces with colour mapping of Z-heights of each point are displayed in Fig. 8. Corresponding R_a values indicate that the presence of SQL environment could also make a notable difference in improvement of the performance of the MCD coated tool. Rough coating texture seemed to retain lubricant better and aerosol jet also helped in cleaning the loosely adhered ploughing debris from machining zone. For uncoated tool, role of SQL-sunflower application was substantially beneficial. Complete arrest of BUE formation was realized unlike that observed in dry cutting.

The beneficial effect of sunflower oil over the commercial oil was also realized in terms of improvement in machined surface finish (Fig. 9), as was observed in reduction of cutting force component F_Y. The relative effect was slightly better in case of MCD coated end mill due to rough textures of the coating. However, the surface finish achieved under SQL-sunflower combination with uncoated end mill was superior to that produced with MCD coated diamond tool under similar environment.

3.5 On Chip Study

Figure 10 brings out sample chips produced with uncoated-dry and uncoated-SQL (sunflower oil) combinations. The first one (Fig. 10a) visualizes a pair of jointed chips indicating chip adhering tendencies under dry environment. On the contrary, the single chip with smooth underside (Fig. 10b) under uncoated-SQL condition carries the evidence of diffusion-less free flow of chip on uncoated tool under SQL environment. Thus it is demonstrated that the film (of viscous sunflower oil) lubrication through SQL, which prevailed at aluminium chip-carbide tool interface, was so effective in reducing the interfacial friction and arresting aluminium diffusion in uncoated cutting tool material that no visible trace of aluminium adhesion could be imaged. Overall, the chips shapes were erratic under dry condition when produced by uncoated end mill due to the tendency of the chips to adhere to the rake surface and to be occasionally jointed. However, when the cutting was BUE free under SQL-uncoated and dry-MCD combinations, chips were of very much regular and of similar type under any set of operating parameters. Across different sets of operating parameters, the axial feed was kept unchanged and hence it led to form chips of similar width. However, greater chip curling was predominant under conditions with higher velocities under any specific environment.

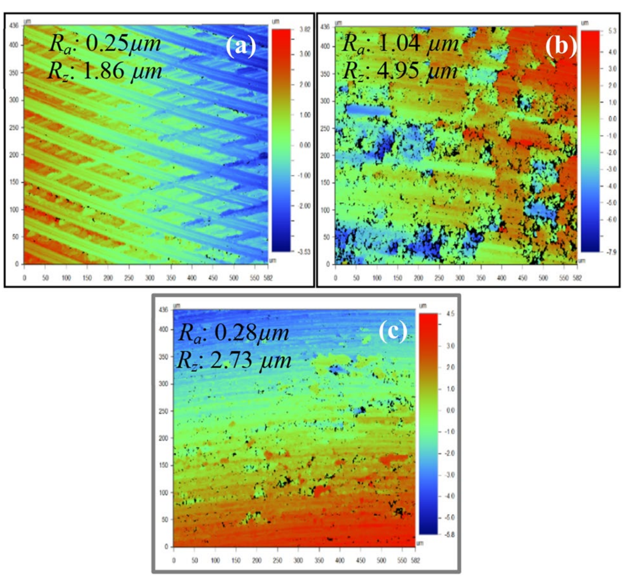


Fig. 8 Color mapped image of surface machined by **a** Uncoated carbide tool under SQL environment, **b** MCD coated carbide tool under dry environment, **c** MCD coated carbide tool under SQL environment (V_C: 120 m/min; f: 200 mm/min; a_a: 0.5 mm)

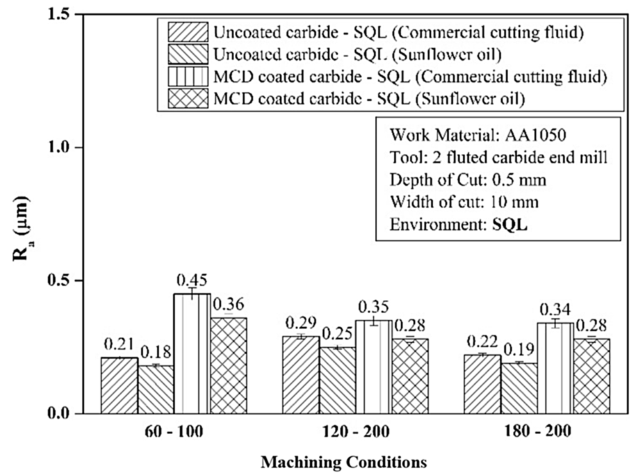


Fig. 9 Comparison of surface roughness (R_a) produced by two green bio-oils of SQL

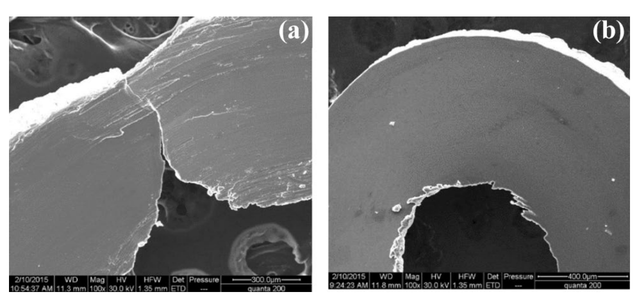
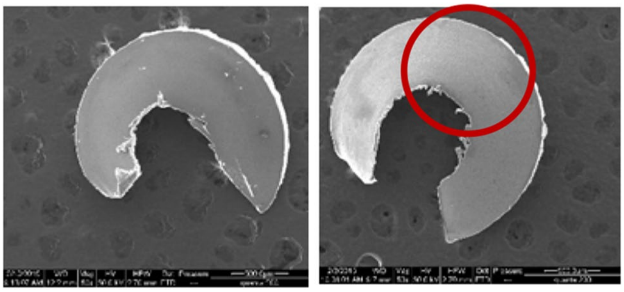
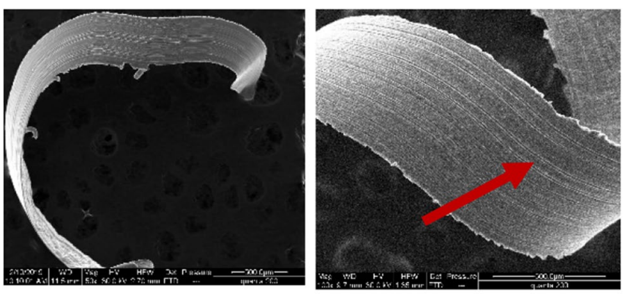


Fig. 10 SEM images of chips produced by uncoated carbide end mills under **a** Dry **b** SQL environment (V_C: 120 m/min; f: 200 mm/min; a_a: 0.5 mm)



(a) 60-200 condition (b) 200-500 condition

Fig. 11 Chips obtained with uncoated end mill under SQL environment at two different cutting velocities [60–200: cutting velocity (V_c): 60 m/min; longitudinal feed rate (f): 200 mm/min]



(a) 60-200 condition (b) 200-500 condition

Fig. 12 Chips obtained with MCD coated end mill under dry environment at two different cutting velocities

Figure 11 compares two such chips obtained with uncoated tool-SQL combination. The width of the chips are theoretically identical due to same axial depth of cut. Maximum thickness of chips could not be captured in a precise way. The chip curling phenomenon was also evident at higher cutting velocity in case of diamond coated end mill (Fig. 12). Although it was free from traces of chip-adherence, the underside of these chips revealed the impression of micro scratches developed by diamond crystallites of the coating. It also hints to the contribution of the rough texture coating in increasing the roughness of machine surface.

The evidences, presented so far, do suggest the effectiveness of SQL environment which utilized sunflower oil as liquid medium, rendering remarkable outperformance of uncoated carbide tool over the diamond coated tools under dry or even SQL environment. An uncoated carbide tool assisted by SQL with veg oil like sunflower oil is thus proven to be an effective green alternative of expensive diamond coated tool, although the former fails measurably under dry environment. Any other coated tool except diamond coated tool is known [2] to be susceptible to BUE/BUL formation in machining of pure aluminium or aluminium alloys under dry condition. The SQL with sunflower oil is expected to improve their performance, like it does for uncoated tool. However, considering the extent of benefit obtained with uncoated tool, use of other coated tools is not required as it saves the cost. In case, an aluminium alloy with considerably high strength and abrasion characteristic is chosen, the coated tools may offer better results with SQL assistance.

4 Conclusions

- Sunflower oil is recognized as a potential small quantity lubrication medium due to its good wettability and lubrication characteristics. The dynamic spreading of this bio-oil was found to form an instantaneous convex meniscus with an appreciable wetting angle of 38° on carbide substrate.
- The coefficient of friction at aluminium-carbide interface was reduced from 0.5 to 0.1 with application of SQL using sunflower oil. It was comparably lower than that found at diamond-aluminium interface.
- The performance of uncoated carbide end mill cutters in SQL environment was found to be outstandingly superior to that of diamond coated tools under both dry and SQL environment. BUE/BUL formation was completely avoided even on uncoated tools when SQL was employed. Presence of long chained fatty acid molecules in the oil was beneficial for BUE-free intermittent machining due to its sustained adherence at chip-tool interface as a lubrication film.
- The machined surface produced by the MCD coated tool was significantly rougher than the rest. Since these tools exhibited no sign of notable aluminium adherence, rougher texture of MCD coating and the presence of radius on cutting edge were held responsible for the rise of surface roughness. Underside morphology of the chips also revealed the impression of deeper scratches, which also justified the argument on the role of textural roughness of the coating on roughness of the machined surface.

Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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