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TECHNICAL PAPER

Enhancing the tribological aspects of machining operation by hybrid lubrication-assisted side-flank-face laser-textured milling insert

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Abstract

The objective of this study was to find ways of improving the machining performance of steel considering sustainable development by limiting the application of hazardous lubricant. The textures having the most advantageous shape were employed with hybrid lubrication consisting of graphite powder in combination with the MQL having best suited tribo-rheological properties. The genetic algorithm code generated for optimization of the machining parameters was one of its kinds that could consider categorical factors along with the continuous factors for optimization. It was found that the optimum machining condition was the low depth of cut, textured flank face impregnated with graphite powder and boric acid-dissolved MQL. Waviness in shape and the rougher inner surfaces of the textures produced through laser beam machining were found to allow the insert to act as a self-lubricating insert satisfactorily throughout the machining operation. Reduction in surface roughness of 64.4% was observed with the proposed technique. Providing an extremely minimal amount of lubrication to the textured tool using the developed technique led to the improved machining performance through cleaner production aiming at omitting waste.

Keywords Side flank face texture · Milling insert · MQL · Sustainable manufacturing · Hybrid lubrication · Flat-end milling

1 Introduction

Development and the use of a textured cutting tool is one of the state-of-the-art techniques to enhance cutting tool performance. When a minimal amount of cutting fluid is introduced to the textured tool, the textures act as tiny reservoirs of the lubricant. The textured insert impregnated with solid lubricant also acts as a self-lubricating tool and performs better during machining by providing the lubricant exactly at the machining zone. Most of the problems associated with the conventional metal cutting operation can be reduced/eliminated by providing proper lubrication to the machining zone during the machining process [1]. Moreover, improvement in the machining performance through texture generation on the cutting tools, impregnation of the textures with solid lubricant powders and use of minimum quantity lubrication (MQL) technique are the attempts to show the way to green manufacturing by limiting the lubricant usage.

Most of the research works reported in the literature were based solely on the textures made on the rake face [2–10]. Filling the textures with solid lubricant was also found beneficial [2–4, 8, 11]. It was well recognized that the rake face textures provided better machining performance in all machining conditions regardless of the fact whether a lubricant was used or not [2, 4, 12–14].

Results on rake face textured tools are well established in the literature [12], but flank face textured tools are lagging behind it. Plowing force is mainly associated with the flank face. Moreover, the flank face is encountered with the flank wear, which is set as a tool life criterion in many cases. It determines the stability and reliability of machining and dimensional accuracy. Flank wear rate can be retarded by engraving appropriate textures on the flank face [15]. Some researchers considered flank face texturing aiming to reduce flank wear but applied it to turning operation [16–18]. Fatima and Mativenga [12] produced textures on both rake

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and flank faces and found improvement in the machining performance as compared to the regular one. Their work did not show the effect of flank face separately. A very few attempts have been made for the flank face textures produced on milling tool. According to Sugihara and Enomoto [15], flank wear resistance was improved when micro-stripe grooves were developed on the flank face during face milling experiments performed at dry and flooded lubricating conditions. They neither impregnated the textures with solid lubricant powder nor applied MQL.

The viscosity of a metal working fluid plays crucial role in machining processes when applied through MQL. According to Einstein [19], viscosity of suspension can be defined by the following equation:

$$\eta = \eta_{\mathrm{o}}(1 + Qc)$$

where η is the viscosity of the suspension, η_{o} is the viscosity of the pure liquid, c is the concentration by volume and Q is the shape factor. Very low values of η_{o} and Q make the boric acid-dissolved water-based emulsion very low viscous in nature, allowing the fluid to provide better machining performance by penetrating the contacting surfaces easily when applied through MQL. Rheological characterization of the fluid confirmed the low viscosity of the fluid. The tribological properties of the graphite powders can be utilized by impregnating the textured insert with the powder. The fluid provides good cooling effects of the heated cutting zone, and the graphite powder provides good lubrication when the two lubricants were applied by the proposed method. When boric acid-dissolved and graphite powder-suspended water-based emulsion was applied through MQL technique, the surface roughness value obtained was 717 nm [20]. However, the reduction in surface roughness of 64.4% was observed with the technique proposed in the present article.

Flat-end milling operation is widely employed for machining of steels in the manufacturing industry. High heat generation occurs due to severe plastic deformation of steels during machining. Burr formation is a side effect of this deformation, especially in the slot milling operation where side flank face of the milling tool remains in contact with the workpiece material at the nascent sides of the slots.

As evident from the literature survey, the application of side flank face textures on the milling tools was not addressed properly. Moreover, no previous study has examined the ability of a self-lubricating textured insert to provide lubrication throughout the machining process. As a contrast to other studies, a combination of state-of-the-art methods was also utilized in this work. This paper significantly advanced the fundamentals in the field of improvement in cutting tool performance. Special attention was drawn toward the self-lubricating ability of the side-flank-face textured milling insert during hybrid lubrication that consisted of a combination of solid lubricant impregnation and MQL application. In this study, micro-textures were developed on the side flank face of a flat-end milling insert. These textures were impregnated with graphite powder. Boric acid-dissolved emulsion of a cutting oil ServoCut S was applied as MQL to the graphite powder-filled self-lubricating insert during finish milling of steel. The surface roughness of the workpiece and geometrical condition of the inserts after the machining were studied. Burr formation and chip morphology were analyzed qualitatively as well as quantitatively. Side flank face textures with the most advantageous shape impregnated with graphite powder were combinedly employed with the MQL having best suited tribo-rheological properties. Mathematical modeling was also performed to predict surface roughness of the finished surface of the workpiece. Finally, the continuous and categorical parameters were optimized through genetic algorithm. Special intelligent formulation was generated to incorporate both types of variables for GA. The code thus generated for GA was successfully utilized to optimize the problem.

2 Materials and methods

Several experiments were performed to understand the combined effect of unique textures produced on side flank face of end-milling insert on chip morphology, flank face topography, burrs formation and workpiece surface roughness. Further, the same effects were studied with graphite powder impregnation of the textures and boric acid-dissolved emulsion-based MQL application during finish milling operation of steel. A schematic diagram of slot milling of the workpiece by using the textured insert is shown in Fig. 1.

Machine tool used in these experiments was a five-axis CNC milling machine (EMCO Concept Mill 250) with the power of 7000 W in the main motor and tool rotation speed of up to 10,000 rpm. The MQL setup attached to the milling

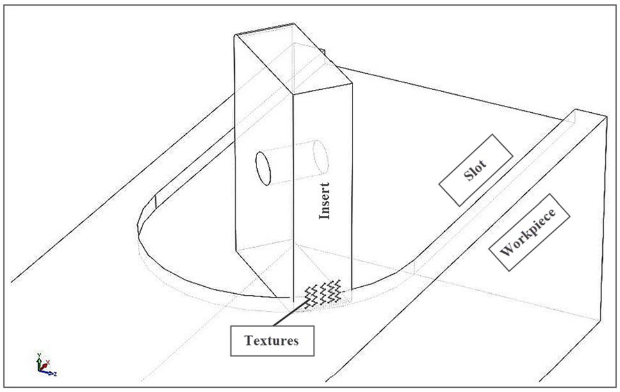

Fig. 1 Schematic diagram representing the position of textures along with the slot

machine is shown in Fig. 2. The MQL nozzle of the setup was provided, in a controlled way, by compressed air from the compressor and cutting fluid from the oil chamber. An air drier supplied dry air to the compressor that allowed the air to enter the nozzle at a pressure of 5 MPa from one end. 10 wt% boric acid dissolved in the emulsion of a water-based cutting fluid ServoCut S diluted in water at oil–water ratio of 1:20 entered the nozzle from another side at a flow rate of 150 ml/h. The two fluids were controlled by the regulators connected to the flow lines. The mist thus generated was then impinged on the cutting zone from the nozzle fixed in front of the cutting tool making an angle of 10° with respect to the surface of the machine bed in front of the cutting tool. Based on the literature survey, the metal working fluid selected for MQL application was the boric acid-dissolved water-based emulsion of ServoCut S because of its low viscosity and high thermal conductivity. As described by Muaz and Choudhury [20], viscosity of metal working fluid played an important role in providing proper lubrication as far as MQL technique was concerned. The low viscosity of the fluid was responsible for ease of penetration of the tiny droplets coming out from the MQL nozzle to the machining zone. Low-viscosity fluids were best suited for MQL as a contrast to the flooded lubrication where high-viscosity fluids performed better due to the formation of a stable and thick lubricating film. Characterization of the fluid developed for this study was done to understand its rheological behavior. Anton Paar Rheometer (Physica MCR 301) was used to determine its viscosity (at room temperature, 25 °C). The boric acid powder was dissolved into the emulsion of cutting oil, ServoCut S, produced by Indian Oil Corporation Limited, India. The emulsion was prepared by mixing oil and water in the ratio of 1:20. As a performance standard, ServoCut S meets IS: 1115–1986 (Reaffirmed 1996). The cutting fluid was selected from the authors' previous work on experimental investigations and multi-objective optimization of MQL-assisted milling process for finishing of AISI 4340 steel. The average viscosity of the cutting fluid developed for this study was 2.387cP [20]. The three lubricating conditions used in this study are as follows.

T: No lubricant was applied to the textured tool. TG: Textures on the tool insert were impregnated with graphite particles. TGM: Textured tools were impregnated with graphite powder particles, and water-based emulsion of cutting oil mixed with boric acid powder was applied through MQL technique.

Cutting speed and feed rate were kept constant throughout the experiments at 7500 rpm and 500 mm/min, respectively. The selected values were the optimum ones as described by Muaz and Choudhury in their work in which they performed the optimization of the flat-end milling process through TGRA method [20]. The depth of cut was varied at two levels as 0.5 mm and 1.0 mm. During the slot cutting operations, a mist came out from the MQL nozzle as shown in Fig. 2. It impinged over the workpiece and the textured insert mounted on the CNC milling machine (Fig. 2).

The material of the workpiece used in this work was AISI 4340 steel having hardness of 15 HRc and dimensions of 250 mm × 100 mm × 15 mm. A Rockwell-type Macromet I hardness tester (Make: Buehler Ltd. USA) was used to verify hardness of the workpiece. A 16 mm tool with indexable insert was used for slot milling operation with full immersion. Designations for tool holder and insert used in this study were F4042.W16.016.Z02.08 and ADMT 080304 R-D56, respectively (Make: Walter tools Ltd.).

A zigzag pattern was generated on the side flank face of the insert by using Epilog laser. Actual textures developed on the side flank face of the insert are shown in Fig. 3a while the dimensions of the textures are shown in Fig. 3b.

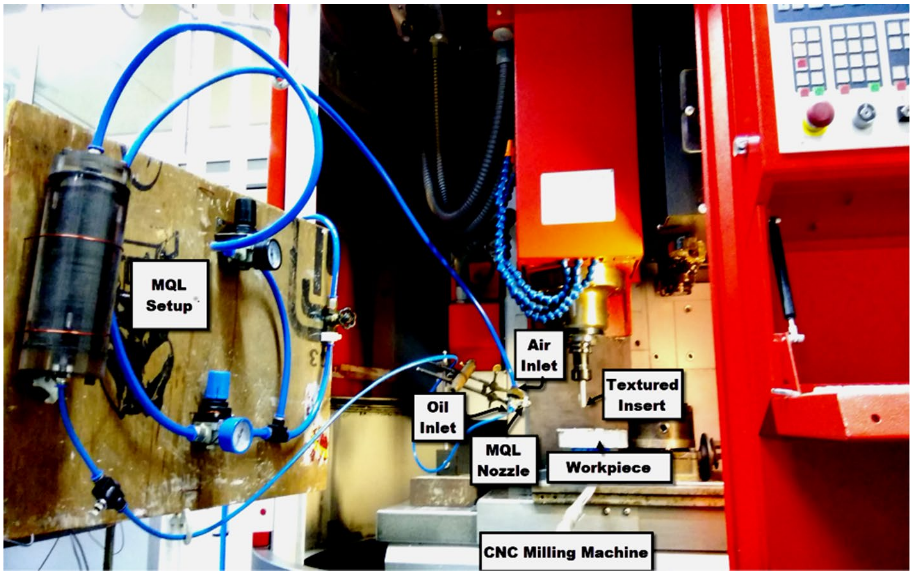

Fig. 2 Experimental setup showing MQL attachment on CNC milling machine

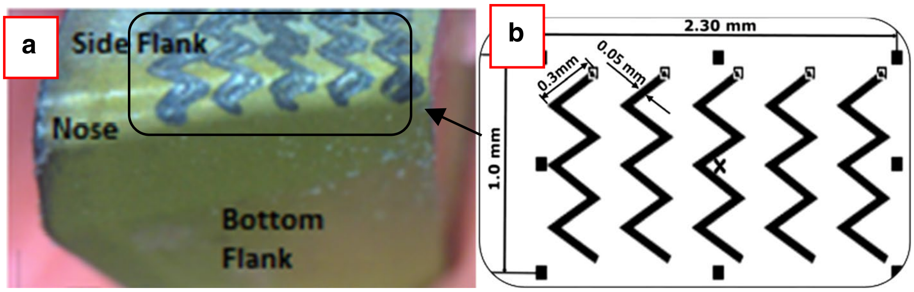

Fig. 3 **a** Textures on the milling insert, **b** textures' dimensions

The laser beam machine was a solid-state pulsed ytterbium fiber laser (air-cooled) with maximum engraving area of 812 × 508 mm, focal length (F-theta lens) of 127 mm and the maximum material thickness of 285 mm. Laser beam machining produced rough surfaces inside the valleys of the generated textures which were responsible for enhancing the sticking ability of the powder particles. The rationale for developing zigzag shape was also to enhance the capability of the textures to retain graphite powders during extreme cutting conditions. The textures were impregnated with graphite powder manually. The texture acted as a reservoir of the lubricant during cutting and supplied the lubricant slowly until the end of the operation. As the cutting inserts were highly wear-resistant, no significant wear was observed during the experiments even after observing under a USB digital microscope (Dino-lite Premium) at different magnifications.

The workpiece surface roughness (R_a) was measured in the feed direction by using SURFTEST SJ-210 (Make: Mitutoyo, USA). R_a was measured at five points. Burrs formed at the beginning of the cutting as well as at the end of the cutting were observed under a USB digital microscope (Dino-lite Premium) at a magnification of 50×. The same microscope was used to investigate the chip morphology and tool textures.

3 Results and discussion

The cutting fluid developed for MQL application contains an extremely low amount of mineral oil as it was diluted at very high water-to-oil ratio. Environment-friendly lubricant powders, namely boric acid and graphite, were also utilized simultaneously to limit the usage of the mineral oil. An extremely low volume of easily available mineral oil is sufficient to get acceptable performance if it is applied with the developed technique. Moreover, when the fluid was applied through MQL technique, most of the oil was evaporated [21] as it entered exactly the heated machining zone. Therefore, there was no need for disposing or recycling of the mineral oil.

3.1 Side flank morphology

Self-lubrication is one of the main advantages of the lubricant-assisted textured cutting tools. The textures must have the ability to provide the solid lubricant until the end of the machining. This ability could be enhanced by increasing the sticking capability of the inner surface of the texture and providing proper shape to the grooves. Otherwise, the lubricant would leave out the textures completely at the initial stages of the machining. The condition of the textures was examined to ensure the presence of solid lubricant inside the grooves after performing machining operation. Figure 4 depicts the condition of the textured flank face morphology after performing slot cutting operations. In the first experimental run, slot cutting was performed at a depth of cut (doc) of 0.5 mm using textured insert without impregnating graphite powder as shown in Fig. 4a1. The same experiment was performed at 1.0 mm doc as shown in Fig. 4a2. Then, the textures on the flank face of the insert were impregnated with graphite powder. Slot milling operations were performed again using the insert with graphite powder-impregnated textures on its flank face at the two levels of depth of cut. It is clearly seen from the pictures of the flank face of the insert having graphite powder-impregnated textures that the graphite powder still remained there even after being used for machining at both depths of cut as shown in Fig. 4b1, b2. However, the amount of graphite powder present in the textures is lesser after being used for higher depth of cut (Fig. 4b2) as compared to the lower depth of cut (Fig. 4b1). Waviness in shape and the rougher inner surface of the textures made it possible for the graphite powder to be retained there so that the insert acted as self-lubricating tool till the end of the machining. Finally, when MQL was applied to the insert containing graphite powder, almost all graphite powder was removed from the textures probably in the initial stages of machining due to the flushing action of the mist generated by the MQL technique. Graphite powder removed from the textures was, however, sprinkled over the finished surface and remained there until the end of the machining. Graphite powder is clearly visible on the finished surface in Fig. 4c1–c2 showing exit burrs for

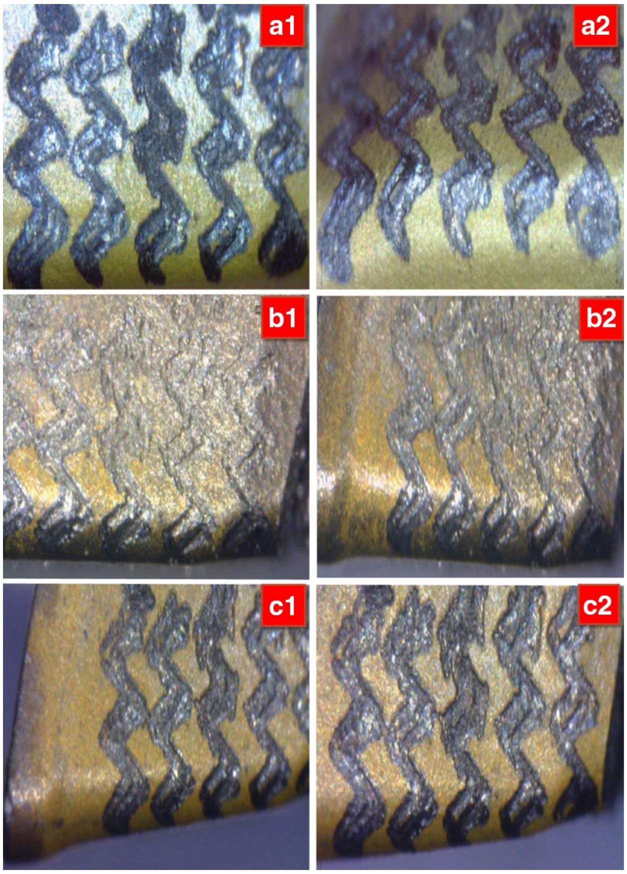

Fig. 4 Textures' morphology after machining (**a1**–**a2**) without any lubricant (**b1**–**b2**) with graphite powder impregnation (**c1**–**c2**) with MQL application for doc of 0.5 mm and 1 mm, respectively

TGM. This layer of graphite powder protected the finished surface and hence contributed to improved surface quality.

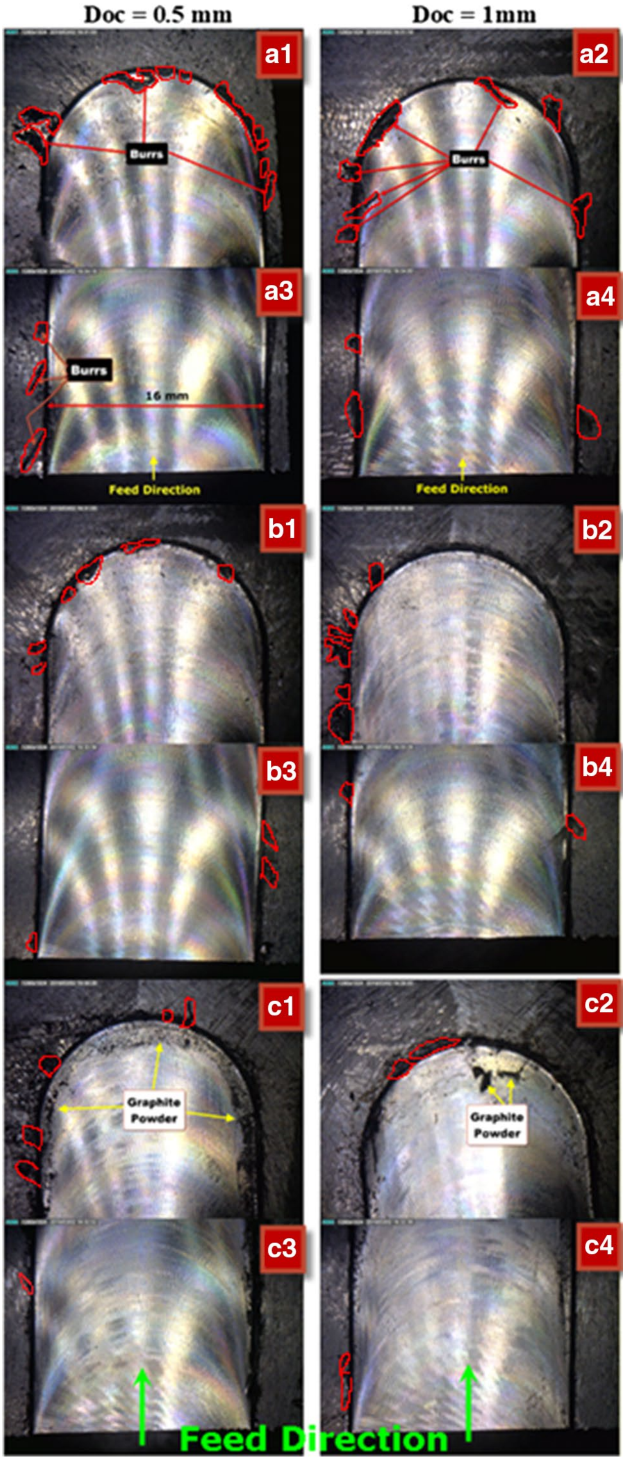

Fig. 5 Burrs at the start and at the end of the machining (**a1**–**a4**) without any lubricant (**b1**–**b4**) with graphite powder impregnation (**c1**–**c4**) with MQL application for doc of 0.5 mm and 1 mm, respectively

3.2 Burr formation

Burrs are not acceptable during finishing operations. They are responsible for producing poor surface integrity as well as for initiating cracks. Grzesik et al. [22] explained that during machining processes, plastic deformation of the workpiece material occurred. This deformation led to the production of burrs at the edge of the machined surface. Slot milling of steels is usually encountered with burrs generated at both sides of the slot. The side burrs formed at the end of the slot cutting are shown in Fig. 5a1, a2, b1, b2, c1, c2 while the side burrs formed at the beginning of the slot cutting are shown in Fig. 5a3, a4, b3, b4, c3, c4. Reduction in burr formation was quantified by measuring the total height of the burrs. Total burr height was measured for each case shown in Fig. 5 and plotted as bar graphs in Fig. 6. The total height of the burrs was evaluated as summation of the height of all burs in a particular case. The maximum height was observed when no lubrication was applied to the textured tool while the minimum total height was observed when MQL was applied on the graphite-filled textured inserts. Total burr

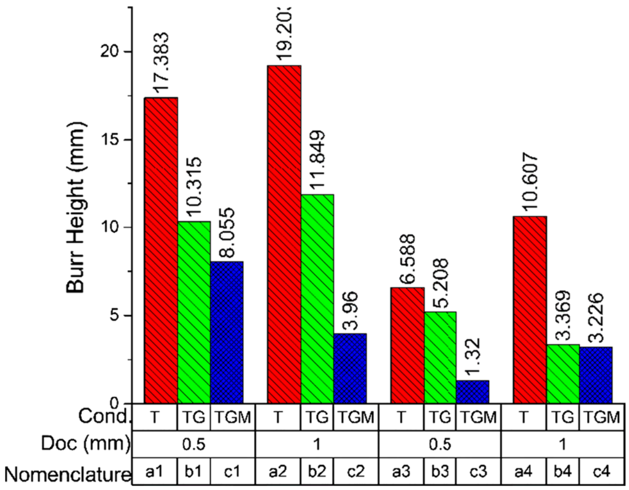

Fig. 6 Burr height (mm)

height was reduced up to 80% by using the proposed technique. This was attributed to the brittleness induced in the workpiece material due to the cooling and lubricating action of MQL. Most of the graphite powder was flushed out from the textures and sprinkled over the machined surface due to the application of MQL. As the lubricant used in the MQL was a water-based emulsion of cutting fluid, it has excellent heat-dissipating capability due to the presence of water as well as highly pressurized air. The low viscosity of the emulsion also played a crucial role in penetrating the tiny droplets of the mist into the mating surfaces of the machining zone. That phenomenon was responsible for the sudden cooling of the heated material leading to its quenching and hence local hardening. The induced hardness reduced the amount of plastic deformation of the material at the edges of the slot, and hence the formation of burrs was restricted. As far as graphite powder-impregnated textures without MQL assistance were concerned, burr formation was lesser than that of the textured inserts without having any lubricant. As the textures were produced at the side flank of the insert, the graphite powder was supplied by the insert from the textures mainly at the sides of the slots, which were the sites prone to burr formation. Therefore, these sites were properly lubricated by the graphite powder throughout the machining process and hence the burr formation was retarded.

3.3 Chip morphology

The chips were characterized by observing them under the microscope, Dino-lite Premium. Chip thickness coefficient was evaluated as the ratio of undeformed chip thickness to the deformed chip thickness. Feed per tooth was taken as undeformed chip thickness while the deformed chip thickness was measured on the microscopic images of the chips as shown in Fig. 7. As chip thickness coefficient is inversely proportional to the chip deformation, higher values of chip thickness coefficient are favorable. Effect of different conditions on the chip thickness coefficient is plotted in Fig. 8 at two different depths of cut. For both of the depths of cut, the coefficient was minimum for the condition where no lubricant was applied while it was maximum for the condition where MQL was applied to the textured tool. A maximum of 22.8% improvement in the chip thickness coefficient was observed by using the proposed technique. The typical chips formed during machining are shown in Fig. 9. Figure 9 illustrates that the surfaces of the chips became smoother when graphite powder was impregnated. Improvement in the chip thickness coefficient as well as in the smoothness of the chips was the clear evidence of the self-lubricating ability of the insert by providing proper lubricant from textures to the machining zone throughout the machining operation. Chips having smoother surfaces were formed when MQL

Fig. 7 Deformed chip thickness

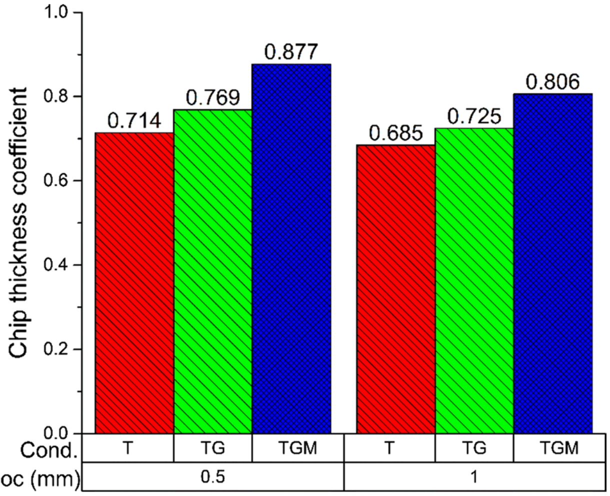

Fig. 8 Chip thickness coefficient

Fig. 9 Chip morphology when textured insert was applied at different depths of cut (**a1**–**a2**) without any lubricant (**b1**–**b2**) with graphite powder impregnation (**c1**–**c2**) with MQL application for doc of 0.5 mm and 1 mm, respectively

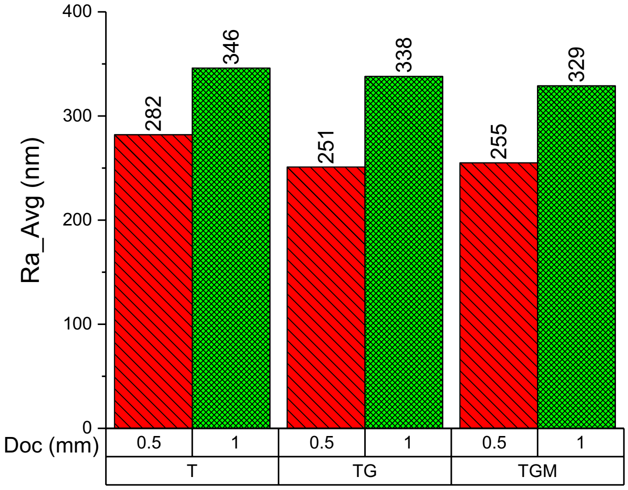

Fig. 10 Average surface roughness for different conditions

was applied too as compared to the textured insert without any type of additional lubrication. It was attributed to the lubricating ability of the mist generated by the MQL, which could easily penetrate the contacting surfaces due to the low viscosity of the water-based emulsion. Color of the chip was changed from blue to golden when MQL was applied. This was accredited to the hardening of the chips by quenching due to the sudden drop in the temperature. The very high temperature was reduced to very low temperature when chips came in contact with the pressurized mist coming from MQL setup. It also confirmed the very high heat-conducting ability of the cutting fluid used as MQL. Similarly, the blue color of the chips shown in Fig. 9b1–b2 for the case when MQL was not applied indicates that the temperature reduction was lesser as compared to the case when MQL was applied.

3.4 Workpiece surface roughness

The surface roughness of the workpiece was measured at five different positions in the direction of feed, and their average values are plotted in Fig. 10. The values obtained for R_a were less than 1 µm; therefore, the term nano-finishing was used. Highest R_a value was obtained when the tool with textures on its flank face was used without implementing any lubricant. Surface finish of the workpiece was improved significantly when solid lubricant was employed for the textured tool. Graphite powder being a good solid lubricant improved the cutting performance. The textures impregnated with graphite powder acted as the reservoirs for the solid lubricant and kept providing the lubricant indigenously during the machining process. Therefore, graphite powder entered the machining zone exactly at the mating surfaces of the side flank face of the insert with the workpiece material as well as at the interacting surfaces of the bottom flank face and the machined surface. Application of MQL to the textured insert impregnated with graphite powder resulted in the improvement in the surface finish as compared to the case where no lubricant was used with textured insert. At a low depth of cut, the R_a value was found to be a little larger but comparable to the TG case, at large depth of cut, it was lesser than TG case. When the mist impinged on the flank face, the graphite powder present in the textures was drained out to the finished surface as shown in Fig. 5. Then, the insert started acting as a textured insert with MQL. It proved that MQL applied to the textured tool also gave better surface finish than that of the case where the textured insert was used without any lubricant. At a larger value of the depth of cut, lowest R_a was obtained in TGM case as compared to the other cases. It was attributed to the chip flushing ability of the MQL. At larger depths of cut, proper flushing of the chips is a serious problem. If the chips were not removed easily, they might deteriorate the finished surface. The chips were flushed out by the mist applied through MQL technique along with providing proper lubrication. The water-based emulsion used as lubricant in the MQL had very low viscosity, which made it possible to penetrate the contacting surfaces easily and hence provide proper lubrication.

When boric acid-dissolved and graphite powder-suspended water-based emulsion was applied through MQL technique, the average surface roughness value obtained was 717 nm [20]. However, this value was only 255 nm when boric acid-dissolved MQL was applied to the textured tool impregnated with graphite powder. Therefore, the reduction in surface roughness of 64.4% was observed with the proposed technique.

3.5 Mathematical modeling

From the previous investigations, it was revealed that providing lubrication to the textured insert was a better alternative for improving the machining performance. Therefore, a regression model of surface roughness has been developed at 95% confidence level considering the depth of cut (*d*) as a continuous input parameter while the texturing and lubricating condition (Cond.) as categorical input parameters. Effect of the machining parameters like feed rate, nose radius, etc., was investigated, and the models were developed considering them by various researchers. However, for finish milling operation, depth of cut was found to have a significant effect on the variation in surface roughness of the workpiece. The contribution of the depth of cut (*d*) in the model, as shown in Table 1, is much higher than that of the texturing and lubricating conditions (Cond.). Regression analyses were performed by Minitab 18 software for producing different models to predict surface roughness. The categorical predictors were coded by 0 and 1 showing deactivation and activation of a particular predictor, respectively. For example, 0 for T and TG, while 1 for TGM suggested that the R_a value was to be determined when the graphite powder-impregnated textured tool was utilized along with MQL. Finally, the regression model that has highest *R*-sq value was selected for further analysis in this study. The predictive model is shown in Eq. 1 while the analysis of variance performed for the regression model is shown in Table 1. Very low *P* value and very high *F* value for the model also suggested that the developed model is very reliable. Very low *P* values and very high *F* values for both of the input parameters indicated that these parameters affected the surface roughness significantly. Therefore, the single model can be utilized to predict the surface roughness of the workpiece surface during finish milling operation under different lubricating and insert texturing conditions.

$$R_a = 201.70 + 150.0 * d + 0.0 * \text{Cond.}_T - 19.50 * \text{Cond.}_{TG} - 22.20 * \text{Cond.}_{TGM} \tag{1}$$

$$R^2 = 88.53\%, \quad R^2(\text{adj}) = 87.21\%$$

In the regression equation (Eq. 1), the value of depth of cut was to be entered in millimeters while the categorical parameters were to be supplied in 0 and 1 according to their presence and absence, respectively, and the R_a value was obtained in nanometers as output.

The residual plots attained normal probability distribution, and the fits were randomly distributed about the horizontal line passing through zero residual as shown in Fig. 11. These facts provided evidence for model adequacy. Moreover, the R^2 value of the model was large enough, and hence the model was able to provide a good fit.

The model predicted the R_a values to be very close to the observed values being maximum percentage difference restricted to only 2.47.

3.6 Optimization through genetic algorithm (GA)

The optimization problem for minimizing the surface roughness of the finished surface was addressed by GA. The regression model developed in this study was used as the objective function for GA optimization problem. It consisted of continuous as well as categorical variables. The GA optimization problem can be stated in mathematical terms as

$$\text{Minimize}\, f = 201.70 + 150.0 * x(1) + 0.0 * x(2) - 19.50 * x(3) - 22.20 * x(4) \tag{2}$$

where continuous independent input variable $x(1)$ is the depth of cut (mm), $0.5 \le x(1) \le 1$, while the categorical input variables $x(2)$, $x(3)$ and $x(4)$ are the conditions of T, TG and TGM. Equation (2) is similar to Eq. (1) except the changes in the nomenclature for the variables. Those changes were suitable for performing the optimization using genetic algorithm. The categorical variables could take only 0 or 1 indicating their absence or presence, respectively. In GA through MATLAB, the variables assume values in continuation from lower bound to the upper bound by default. In

Table 1 Analysis of variance

Source	*df*	Seq SS	Contribution (%)	Adj SS	Adj MS	*F* value	*P* value	Remarks
Regression	3	45,122.1	88.53	45,122.1	15,040.7	66.91	0	Significant
d (mm)	1	42,187.5	82.78	42,187.5	42,187.5	187.69	0	Significant
Cond.	2	2934.6	5.76	2934.6	1467.3	6.53	0.005	Significant
Error	26	5844.2	11.47	5844.2	224.8			
Lack-of-fit	2	711.8	1.40	711.8	355.9	1.66	0.21	
Pure error	24	5132.4	10.07	5132.4	213.8			
Total	29	50,966.3	100.00					

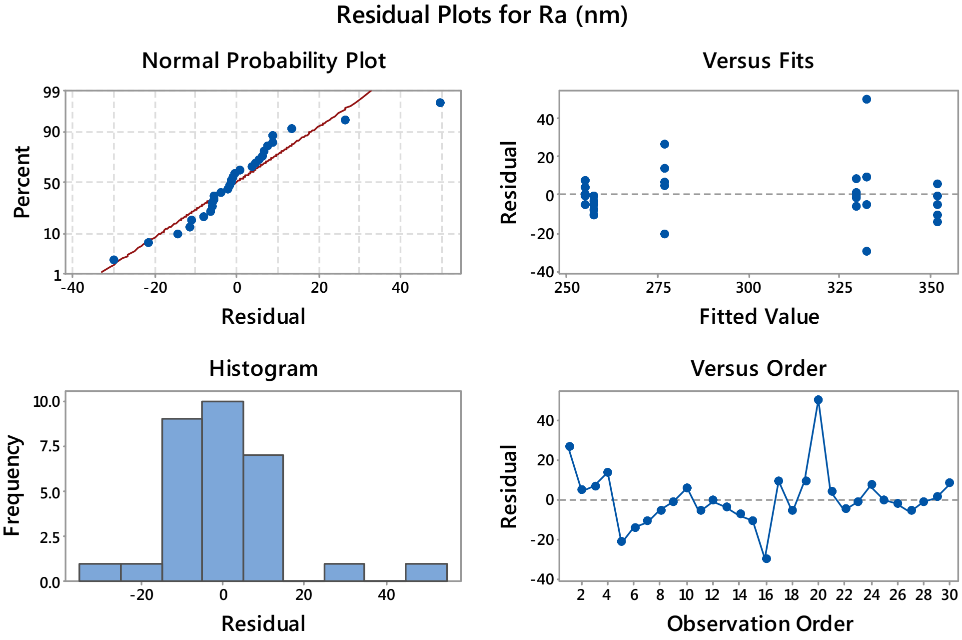

Fig. 11 Residual plots for work-piece surface roughness

order to provide only integer values as input variables to the conditions, 'IntCon' option was used for last three variables. This option allowed passing only integer values to the variables for which 'IntCon' was utilized. Then, lower and upper bounds were set for all three categorical factors as 0 and 1, respectively. As only one categorical variable should be activated at a time while others must be deactivated, a linear constraint was applied to these variables as shown in Eq. (3):

$$x(2) + x(3) + x(4) \leq \frac{3}{2} \tag{3}$$

The 'IntCon' option, in combination with the bounds and the constraint, passed only the required values to the categorical variables during the optimization process successfully. Moreover, the population type was taken as double vector and the population size was decided by max (min(10 * number of variables, 100), 40). Fitness scaling function was rank-based while the selection function was stochastic uniform. The elite count for reproduction was determined by max(min(10 * number of variables, 100), 40), and the crossover fraction was 0.8. The direction for migration was forward with a fraction of 0.2 and with an interval of 20. Initial penalty was 10 and the penalty factor was 100 for constraint parameters. Stopping criterion was based on the generations of 100 * number of variables. The fitness and constraint functions were allowed to be evaluated in series. The results of GA (Fig. 12) suggested that the optimum machining condition was a depth of cut of 0.5 mm and the MQL-assisted graphite powder-impregnated textured insert.

In other words, in order to get optimum machining performance, boric acid-dissolved MQL should be applied to the milling insert having zigzag-shaped textures on its side flank face and impregnated with graphite powder while the depth of cut should be kept at lowest possible value.

4 Conclusion

Lubricant-assisted tool flank face texturing for slot milling operation is a state-of-the-art technology that showed great potential for improvement in the metal cutting phenomenon. This research added a new significant scientific knowledge in this field. The present study was set out to determine the self-lubricating ability of the insert having textures produced on its side flank face through laser beam machining when graphite lubricant powder was impregnated and MQL was applied. Providing hybrid lubrication to the textured tool led to the improved machining performance by the usage of a very little amount of lubricant. Some noteworthy findings of this research are summarized as follows:

- Waviness in shape and the rougher inner surface of the textures produced through laser beam machining made it possible for the graphite powder to be retained there so that the insert acted as self-lubricating tool till the end of the machining.
- A maximum of 22.8% improvement in the chip thickness coefficient and 80% reduction in total burr height were observed when MQL was applied to the graphite powder-filled textured insert.
- In order to reduce the burr formation, the physical mechanisms responsible for the action of MQL and the graphite lubricant were found to be different. Minimum amount of burrs was generated when the insert having graphite

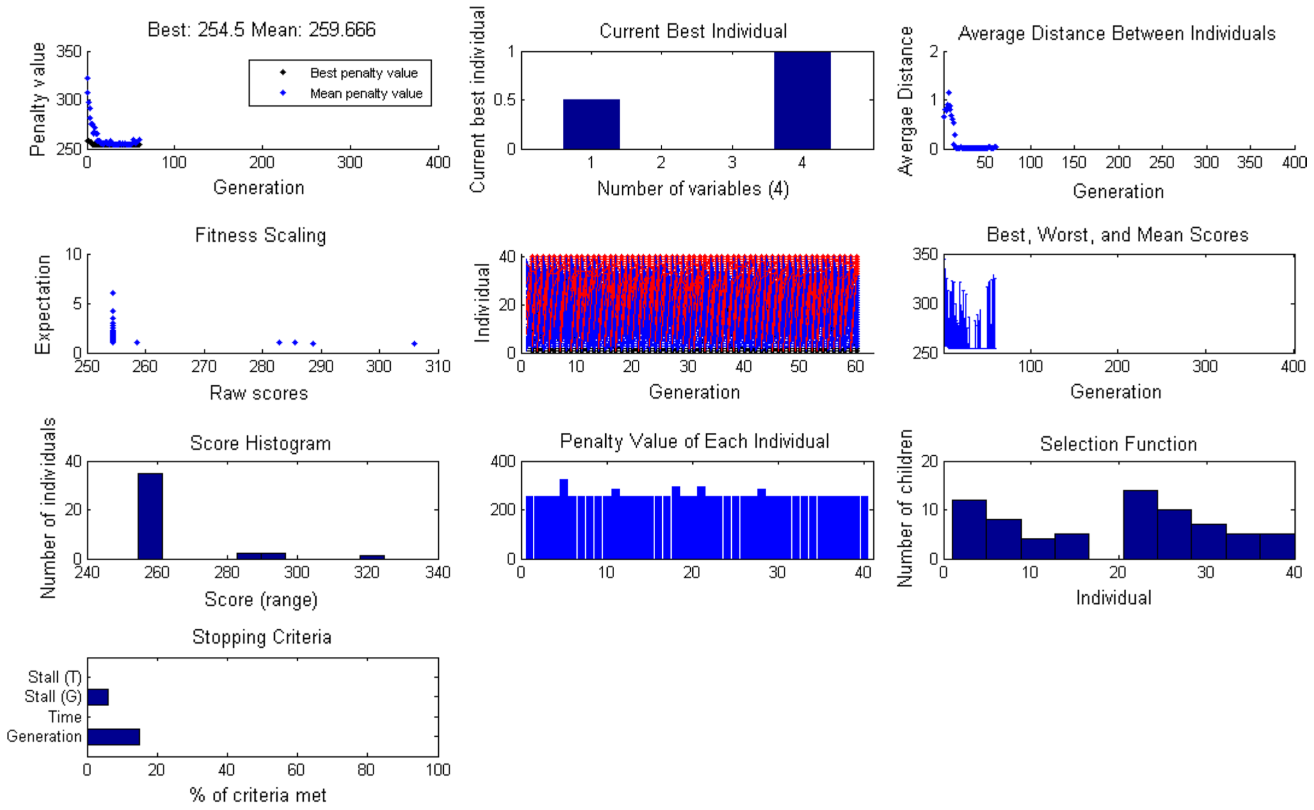

Fig. 12 Results of GA

powder-impregnated textures along with MQL was used. That was because of the brittleness induced in the workpiece material due to the cooling and lubricating action of MQL. The lubricant used in the MQL was a water-based emulsion of cutting fluid. Therefore, it has excellent heat-dissipating capability due to the presence of water as well as highly pressurized air. Low viscosity of the emulsion also played a crucial role in penetrating the tiny droplets of the mist into the mating surfaces of the machining zone. That phenomenon was responsible for the sudden cooling of the heated material leading to its quenching and hence local hardening. The induced hardness reduced the amount of plastic deformation of the material at the edges of the slot. Hence, the formation of burrs was restricted. As far as graphite powder-impregnated textures without MQL assistance were concerned, burr formation was lesser than that of the textured inserts without having any lubricant. As the textures were produced at the side flank of the insert, the graphite powder was supplied by the insert from the textures mainly at the sides of the slots. These sides were prone to burr formation. Therefore, these were properly lubricated by the graphite powder throughout the machining process and hence the burr formation was retarded.

- Chips that are more acceptable were formed when the textures were impregnated with graphite powder. The surfaces of the chips became smoother when graphite powder was impregnated. That was a clear evidence of the self-lubricating ability of the insert by providing graphite powder from textures to the machining zone throughout the machining operation.
- Chips having smoother surfaces were formed when MQL was applied too as compared to the textured insert without any additional lubrication. It was attributed to the lubricating ability of the mist generated by the MQL. The mist could easily penetrate the contacting surfaces due to the low viscosity of the water-based emulsion used for MQL.
- Surface finish of the workpiece was improved significantly when solid lubricant was employed to the textured tool. The textures impregnated with graphite powder kept providing the lubricant indigenously during the machining process. Therefore, graphite powder entered the machining zone exactly at the mating surfaces of the side flank face of the insert with the workpiece material as well as at the interacting surfaces of the bottom flank face and the machined surface.
- Introducing low-viscosity MQL at solid lubricant-impregnated textured insert copes with the chip removal

problem successfully, especially at higher depth of cut. When MQL was applied to the insert containing graphite powder, almost all graphite powder was removed from the textures probably in the initial stages of machining due to the flushing action of the mist generated by the MQL technique. Graphite powder removed from the textures was, however, sprinkled over the finished surface and remained there until the end of the machining. Therefore, the chip removal action along with the presence of the graphite layer sprinkled over the finished surface enhances the surface finish. The surface roughness was reduced by 64.4% when the two lubricants are applied on the textured tool by the proposed technique as compared to the one where the two lubricant powders were mixed with the emulsion and applied on the untextured tool.

- The optimization problem for minimizing the surface roughness of the finished surface was addressed by GA. The code generated for GA was one of its kinds that could consider categorical factors along with the continuous factors for optimization. It was found that the optimum machining condition was low depth of cut, textured flank face impregnated with graphite powder and boric acid-dissolved MQL. Therefore, surface finish can be improved by impregnating the textures with solid lubricant and by applying MQL to the textured tool.
- An extremely low volume of an easily available mineral oil is sufficient to get acceptable performance if it is applied with the developed technique. Moreover, the oil is evaporated completely as it enters exactly the heated machining zone during MQL. Therefore, the developed technique provided a feasible solution to the problems of disposing, recycling and environmental pollution.

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Compliance with ethical standards

Conflict of interest The authors have no conflict of interest.

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