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Tribological behavior of the boric acid and titanium dioxide based nanofluid in machining of EN24 steel

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ABSTRACT

Turning operation is a widely recognized metal removal process in the industry. If the machining were not run efficiently, it may affect the performance of the tool and the work piece by generating higher cutting forces and the temperature as in hard steel. To minimize these effects, lubrication has to be effective in reducing these forces and lowering the tool temperature. In the present study, machining experiments were conducted on EN24 steel with the application of nano sized boric acid (50 nm) as the solid lubricant that is mixed with titanium dioxide (100 μm) in SAE 40 oil. Turning tests are conducted using tungsten carbide tool inserts under dry, wet and MQL conditions to measure and compare the cutting forces, tool temperatures and roughness of the work piece. Results indicate that boric acid enables significant reduction in the cutting forces which in combination with the titanium dioxide helps to improve the heat dissipation; an advantage that makes such lubricants an effective cutting fluid. H_3BO_3 and TiO_2 based nanofluid resulted in reducing the surface roughness of up to 2.7 μm that is a re-duction by ~15%.

Keywords: Turning; EN24 steel; Solid lubricants; Nanofluid; Minimum quantity lubrication.

1. Introduction

Cutting fluids plays a key role in machining processes by improving the productivity, tool life [1-2]. The cutting fluid primarily functions as a coolant in regulating the temperature at the tool tip and lubrication to reduce the tip-workpiece friction. However, due to their damaging effect on the environment, their use in the industrial processing of materials has been restricted [3-4]. Novel design of cutting fluids in machining processes are been developed to help improve the environment safety.

Minimum Quantity Lubrication (MQL) makes use of a precision dispenser to draw a very small amount of the cutting fluid and apply to the tool-workpiece interface (typically at flow rates of 50 – 500ml/hour) [5]. This amount is at least three to four orders of magnitude lower than the amount of liquid used in the conventional wet cutting that discharges the fluid to a rate of 60 l/h [6]. The commonly used lubricants with MQL machining include – mineral oil, emulsions that are of soluble or synthetic type, synthetic oils, esters, neat oil, and vegetable oil [7-10]. Among the list of lubrication, the vegetable oil is found to be more favorable in machining conditions that allow for reduction in tool wear, cutting force, and surface roughness [11-13]. The strategy of using small amounts of fluids to performing the machining effectively while ensure safe operation and long life span of the tool has made the MQL a more popular technique.

The present work aims to investigate the effect of boric acid particle on its lubricating be-haviour. Machining experiments are conducted on EN24 steel with the application of boric acid and titanium dioxide as an additive in the SAE 40 oil. Boric acid powder with and without titanium dioxide as solid additive in SAE 40 oil, were used for the study to investigate as to how the titanium dioxide influences the tribological properties of the nanofluid.

2. Materials and methods

A special type of liquid particulate dispensing system is developed and used along with MQL system for maintaining the proper at tool-chip interface. Boric acid particles were mixed with SAE40 oil and titanium dioxide was applied during the turning experiments. The complete methodology is illustrated in Figure 1.

The experiments were performed on EN24 steel with the application of boric acid and tita-nium dioxide as an additive in the SAE 40 oil. We have used various experimental conditions such as dry cutting, SAE40 oil, mixture of SAE40 with boric acid or titanium dioxide (solid lubricant), and composite lubricant (SAE40 + Boric acid + TiO2). Following machining parameters i.e., speed, feed rate, depths of cut were considered by varying one parameter at a time; the full factorial experimental design matrix is pro-

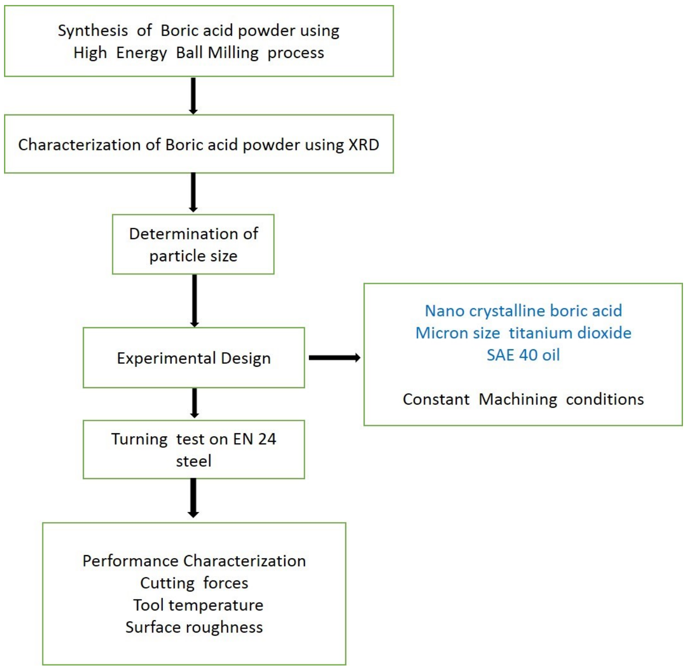

Fig. 1 Steps involved in the particle characterization and machining studies.

vided in Table 1. Turning experiments have been conducted using tungsten carbide tools. Cutting forces (strain gauge dynamometer), tool temperatures (thermocouple) were measured on-line and roughness (Talysurf) were measured off-line during machining. The various sizes of boric acid that have been considered for experimentation are 50nm, 60nm, 80nm, 538nm. The different weight percentages of titanium dioxide considered for the experimentation are 1%, 3%, 5%, and 7%. Boric acid particle of size varied from 538nm to 50nm were used in suspension in SAE40 oil in proportions of 0.75% by weight.

Table 1: Full factorial experimental design matrix

Type of coolant	Speed, rpm	Feed, mm/rev	Depth of cut, mm
1. Dry 2. Wet (SAE40 oil) 3. TiO_2 + SAE40 oil	95	0.15	0.4
			0.5
			0.6
4. Boric acid + SAE40 oil 5. Boric acid + TiO_2 + SAE40 oil (H_3BO_3: 538, 80. 60, 50, TiO_2: 1, 3, 5, 7)	220	0.1136	0.4
			0.5
			0.6

3. Results

The experiments were analyzed for various lubrication methods that can be broadly groups into five, 1) Dry cutting, 2) Wet cutting, 3) MQL using H_3BO_3 in SAE 40 oil, 4) MQL using TiO_2 in SAE 40 oil, and, 5) MQL using H_3BO_3 and TiO_2 in SAE 40 oil.

Effects of boric acid and titanium dioxide mixture studies were performed by varying the composition for various cutting condition. The turning process of the EN24 steel were per-formed for a lubrication flow at a rate of 10 ml/min for the following cutting conditions – cut-ting speed of 100 m/min., depth of cut of 1.0 mm, and feed rate of 0.1 mm/rev.

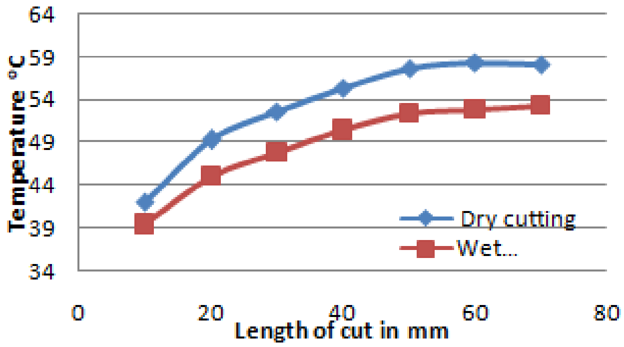

Fig. 2 Effect of dry vs wet cutting on the tool temperature for varied length of cut for the following cutting conditions: Speed=95RPM, Feed=0.15mm/rev, Depth of cut=0.4mm

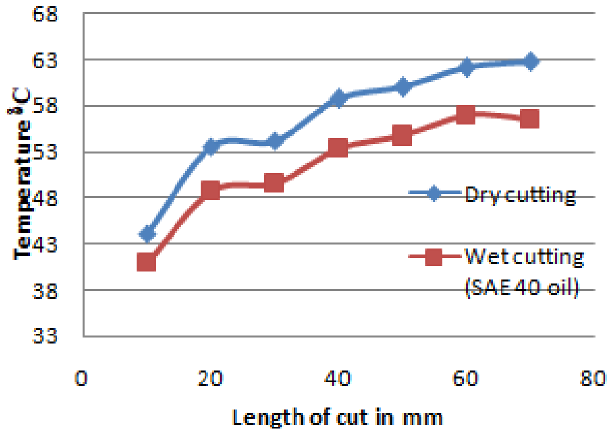

Fig. 3 Effect of dry vs wet cutting on the tool temperature for varied length of cut for the following cutting conditions: Speed=95RPM, Feed=0.15mm/rev, Depth of cut=0.5mm

3.1 Dry and wet cutting

With increasing length of cut the tool temperature tend to increase both for the dry and wet cutting (Fig. 2). The reduction in temperature is about 5 degree Celsius. With increase in the length of cut the temperature also reaches a saturation level where the difference in temperature levels for dry vs wet cutting appear to be unchangeable. For 0.5 mm depth of cut, the change in temperature is not different from the 0.4 mm depth of cut (Fig. 3).

3.2 Effect boric acid and titanium dioxide

To study the performance of boric acid or/and titanium dioxide as a solid lubricant in SAE 40 oil as a base material, tests were performed for a combination of the particle (100 µm TiO_2 at 7 wt. %, 50nm H_3BO_3). Machining is performed for 6 minutes for each of the test cases by keeping the flow rate of the lubricant at 10 ml/min. for a L/D ratio (length to diameter) of the work piece in between 7-8.

MQL machining was also investigated to study the effect of high feed and low feed rate. The details of the process parameters used for the study were,

- Cutting speed =95,220 RPM
- Feed rate =0.15, 0.1136 mm/rev
- Depth of cut =0.4, 0.5, 0.6 mm

Fig. 4 Effect of low speed (LS) at high feed rate vs high speed (HS) at low feed rate on the cutting force (kgf) for different lubrication methods at 0.4 depth of cut.

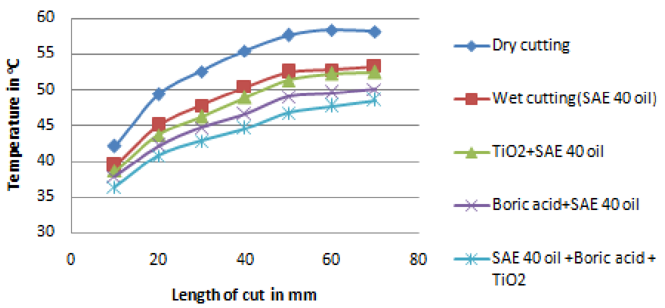

Fig. 5 Effect of lubrication on the cutting temperature for varied length of cut for the following cutting conditions: Speed=95 RPM, Feed=0.15mm/rev, Depth of cut=0.4mm.

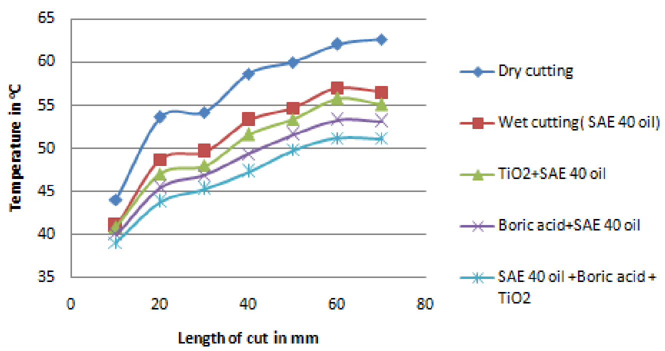

Fig. 6 Effect of lubrication on the cutting temperature for varied length of cut for the following cutting conditions: Speed=95 RPM, Feed=0.15mm/rev, Depth of cut=0.5mm.

Variation in the cutting force for various lubrication mediums and at high feed rate is com-pared with low feed rate at 0.4 depth of cut (Fig. 4). Decreasing the feed rate results in a sig-nificant reduction in the cutting force for all the lubricant formulations MQL, wet and dry cutting method used. Effect of changing the lubricant show a small reduction in the cutting force for high feed rate and negligible change at low feed rate. The H_3BO_3 + TiO_2 mixture-based lubricant have little significant in reducing the cutting force at lower feed rates in com-parison to dry cutting.

With increasing length of cut the tool temperature tend to increase both for the dry and wet cutting at low speed and high feed rate at 0.4 depth of cut (Fig. 5). MQL based formulation also tend to improve the regulation of the tool temperature. MQL with boric acid, MQL with titanium dioxide and MQL with H_3BO_3 + TiO_2 mixture tend to reduce the temperature further with the reduction being most significant with the H_3BO_3 + TiO_2 based formulation (reduces by 10 degree Celsius relative to dry cutting). At 0.5 mm depth of cut, increase in the length of cut increases the temperature linearly however do not attain a saturation level (Fig. 6). MQL using H_3BO_3 + TiO_2 based formulation is found to be effective in reducing the tool tempera-ture. MQL machining tend to show temperature saturation at 70 mm length of cut indicating a potential advantage in temperature relation and that the temperature may remain within the 52 degree Celsius for continuous operation.

The surface finish as obtained for low speed at high feed rate is compared with the high speed at low feed rate for various lubrications (Fig. 7 and Fig. 8). Regardless of the type of lubricant used, the surface roughness is found to increase with increase in the depth of cut.

4. Discussions

The tribological behaviour of the H_3BO_3 and TiO_2 in SAE 40 oil-based lubricant formulation is studied for the EN 24 steel machining. The initial experiments are performed under dry conditions and then by using the carrying medium (that is, SAE 40 oil) the cutting forces and temperature were determined and compared.

It is found that the forces and the temperature under dry conditions are higher than the wet cutting performed using SAE 40 oil. Use of titanium dioxide and boric acid show a remark-able reduction in the feed, cutting and thrust forces; caused lowering of the tool temperature. The reduction is highest when using H_3BO_3 at a size of 50nm together with 7 wt. % of TiO_2 in machining of the EN24 steel. Experimental values signify that such combination confers best tribological properties to the solid lubricant. There is a significant drop in tool temperature by about 10 degree Celsius in comparison to the dry cutting. A reduction in temperature of ~2-3 degree Celsius is observed when changing from MQL with TiO_2 alone to MQL using H_3BO_3 alone and MQL with H_3BO_3 + TiO_2 based lubricant formulation in SAE 40 oil.

Among the forces experienced by the tool tip, the cutting forces were found to be dominating the three components followed by the thrust and feed force. The depth of cut rather than the other controllable parameters considered for the experimentation influences the cutting force majorly. At higher depth of cuts, more amount of material comes in contact with the tool which requires more cutting force to remove the material. Earnest and Merchant [14] theory defines that the cutting force is directly proportional to the cross-sectional area of the uncut chip. The increase in the cutting force is also found to be affected by an increase in chip load [15] that increases the energy required to machine the surface.

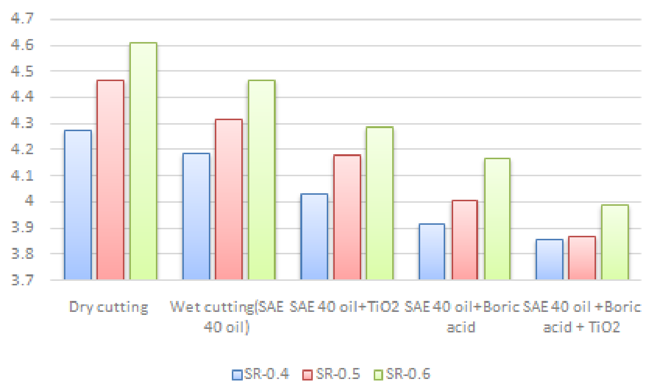

Fig. 7 Effect of depth of cut on the surface roughness for different lubrication methods at low speed and high feed rate.

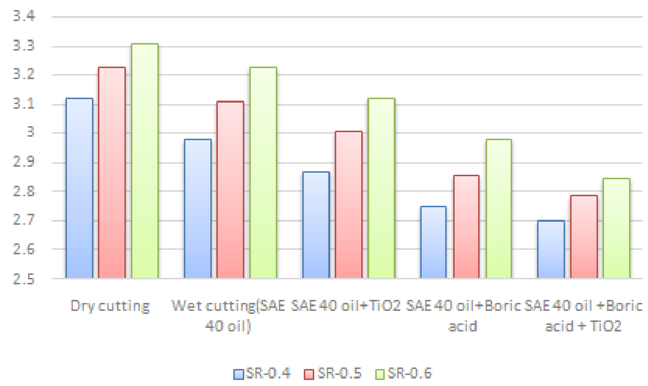

Fig. 8 Effect of depth of cut on the surface roughness for different lubrication methods at high speed and low feed rate.

Depth of cut also plays an important role in increasing the feed force and the thrust force. The increase in thrust force can be rationalized by the fact that at higher depth of cuts, more material is removed, thus requiring a higher force [16]. This is also attributed to the fact that with the increase in the depth of cut, the chip thickness becomes significant to cause the growth of volume of the material deformed and which requires enormous cutting force to cut the material [16]. Increase in the feed force is found to be affected by the cutting velocity. It is observed that there is a substantial effect on the feed force at higher cutting velocities. In general, increase in the cutting velocity can lead to the rise in temperature at the cutting zone [17-19] which makes the metal to behave more like a plastic material which in turn reduces the efforts necessary for machining.

Further, the rise in temperature at the vicinity of cutting zone can lead to a change in the viscous behaviour of the fluid in contact with the sliding surface. Studies indicate that an increase in the temperature at the cutting zone causes an increase in the viscosity of the carrying medium which in turn disturbs the formation of a layer of fluid film (formation of a thin film is required for smooth sliding of the surfaces) across the cutting surfaces; thus, increasing the power required to machine the surface [17, 19]. With the increase in the cutting velocity, more amount of material surface comes in contact with the tool as the built-up edges disappear [17]. With increase in the frictional force, it is be inferred that, either of the cutting force or thrust force increase or both of the force components increase collectively. The boric acid in the carrying medium SAE 40 demonstrates the lubrication performance whereby the surfaces are separated by a liquid lubricant film and protected by the powder which is also consistent with the study using graphite powder in the oil [20].

At higher cutting velocities, there is a drastic increase in the tool temperatures. The effect of cutting velocity on tool temperature is predominant in comparison depth of cut and feed rate. Surface quality is affected majorly by feed rate. Feed rate is a dominating factor when compared to other cutting parameters considered for the experimentation. Surface roughness is a function of feed and for a given nose radius, it changes with the square of the feed rate value [21-23]. At higher cutting velocities, the surface quality improves because the built-up edges disappear with the increase in the cutting velocity. Such a phenomenon can be observed during the machining process, where the surface quality improves with the increase in the cutting velocity. At higher cutting velocities, it is seen that the surface roughness values decreases. However, at lower cutting velocities, built up edges are formed which impairs the surface quality [23, 24]. The built-up edges disappear with the increase in the cutting velocity. This phenomenon is visible in the experimental values obtained during machining, where the surface quality improves with the increase in the cutting velocity. The phenomenon of de-creased surface quality in terms of particle size is proved in one of the works where solid particles of sizes ranging from micro to nano level were used during turning operations. The experimentations revealed that better surface finish is obtained when larger particle sizes in the nano regime are used [25].

The tribological properties of the nanoparticle-based lubricant can be understood in the following way. Addition of the nano particles enhances the heat transfer rate by increasing the thermal conductivity of the fluid [26-28]. Such increased heat dissipation ability is attributed to the Brownian motion of the nano particles whereby the particles move randomly through liquid enabling direct solid-to-solid transport of heat [26]. The irregular and random movement of the nanoparticles allows for an increase in the energy exchange rates in the fluid. As a result of this, thermal dispersion takes place which flattens the temperature distribution thereby increasing heat transfer rate between the fluid and the wall [27, 28]. The increase in thermal conductivity depends on various factors such as the shape of particles, the dimensions of particles, the volume fractions of particles in the suspensions, and the thermal properties of particle materials [29]. However, this theory appears in contrast to the one where the particles of millimetre or micrometer magnitudes are used where they tend to settle rapidly. Since the nano size particles have the tendency to agglomerate and stick to the surfaces, there can be a problem of the heat dissipation at the irregular surface of the tool. Embedment of the particles into the irregularities on the tool face increases at the nanoscale dimension of the particle, which forms sticky layer and due to this, there is a heat retention taking place. The heat retention phenomenon leads to higher temperatures at the tool chip interface. To counter such effects the weight percentage of the solid lubricant in the carrying medium should be as less as possible. In the present study, use of 7% of titanium dioxide has not yet resulted in the rise of temperature; suggesting that there is still scope for further increase in the weight percentage. At 7% of TiO2 the temperature was found to decrease significantly.

As per the expert reports, use of boric acid is considered safe as long as the user follows the safety rules and procedures to prevent prolonged exposure and avoids ingestion [30-32]. The Environmental Protection Agency clarifies that the dermal toxicity to boric acid is low supported by the animal studies to boric acid exposure and do not result in dermal irritation. Boric acid also shows low for ocular toxicity. Particulate exposure of boric acid, at concentrations of <10 mg particles/m^3 is found to cause respiratory and nasal irritation. While the laboratory experiments on animal showed no carcinogenicity, however, boric acid is classified as a group E carcinogen by the Environmental Protection Agency. Further they are environment safe and according to the Clean Water Act, it is not considered as a pollutant. On the other hand, titanium dioxide is bio-inert for the particle size of >100 nm, whereas for small sized particles, it has been reported to have low toxicity due to oxidative stress [33, 34]. Due to wide applications in cosmetics and pharmaceutical products, dermal exposure to nanofluid containing TiO_2 for limited time duration may not lead to any problem. Prolonged dermal exposure of TiO_2 as in sunscreens was found to be associated with skin cancer among Caucasian population in Europe. The toxic nature of the nanoparticle is effective only when it is in direct contact with the cells through skin penetration, oral and nasal route. According to the International Agency for Research on Cancer, TiO_2 is classified as a group 2B carcinogen [35].

5. Conclusion

The effect of TiO_2 and H_3BO_3 based lubricant formulations were studied and tested for their lubrication abilities in machining of EN24 steel and compared with the conventional lubrication. The combination of nanosized boric acid with microsized titanium dioxide is found to be very effective in reducing the cutting force in comparison to dry, wet cutting and MQL using TiO_2 or H_3BO_3 alone in SAE 40 oil; also corroborates with a previous study [36]. The tool temperature was found to be regulated with MQL based machining and improved the quality of the machined surface in comparison to dry or wet cutting. Combination of H_3BO_3 and TiO_2 was able to reduce significantly the working temperature by few degrees in comparison to the SAE 40 oil with H_3BO_3 or TiO_2 alone. Effect of low speed (LS) at high feed rate versus high speed (HS) at low feed rate on the feed force for different lubrication methods at various depths of cuts indicated drop in the cutting force. The forces were found to be highly influenced by the feed rate rather than the speed. Results indicated that the forces tend to reduce when machining was performed at lower feed rate of 0.1136mm/rev. in comparison to 0.15mm/rev. At lower depth of cut, effect of changing the lubricant shows a small reduction in the cutting force for high feed rate and negligible change at low feed rate. The mixture of H_3BO_3 and TiO_2 based lubricant has little significant in reducing the cutting force at lower feed rates in comparison to dry cutting. The surface finish of using such nanofluid formulation shows better finish than using either of the particles alone.

6. References

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