Investigations on the Machining Performance using Solid Lubricant Mixed with Varying Proportions in Vegetable Oil during Hard Turning

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Abstract: The solid lubricant assisted machining is gaining more attention from last decade as use of cutting fluids becoming more and more prevalent around the world due to health and environmental concern. However, very few studies reported on use of solid lubricants during machining. With this view, in the present work, hard turning experiments with boric powder as a solid lubricant mixed with varying proportions in vegetable oil (refined sunflower oil) were performed using coated carbide tool. Machining performance in terms of surface roughness and cutting forces (tangential, feed and radial components of force) were investigated at different cutting conditions under dry and with three varying proportions of boric powder namely, 1%, 5% and 10% mixed with vegetable oil. It has been observed lower values of surface roughness and cutting forces when using solid lubricant assisted hard turning (SLHT) as compared to dry hard turning. Lowest values of surface roughness were observed when using 10% proportion of boric powder mixed with vegetable oil. However, cutting forces although observed to decrease with increasing percentage of proportion of boric powder in lubricating oil, no significant reduction; especially in tangential and feed components of forces, were observed when using 5% and 10% proportion of boric powder mixed with refined sunflower oil. SLHT experiments were also performed under mist lubrication (Mist-SLHT) with a view to assess the feasibility of variants of solid lubrication system in hard turning.

Keywords: hard turning, surface roughness, cutting forces, solid lubricant, vegetable oil, MQL

1. Introduction
In high precision works dimensional accuracy and geometrical tolerances are of prime importance. However, accuracy and properties of the machined component significantly get affected due to higher temperatures generated during machining. Frictional behaviour at the flank and face of the tool mainly determines the amount of heat generated during machining. Moreover, amount of heat generated in turn frictional behaviour by the tool depends on the cutting conditions used during machining. Cutting conditions includes cutting parameters namely cutting speed, feed, depth of cut, work and tool material properties and cooling medium used and it’s type of application (flood cooling, minimum quantity of lubrication, cryogenic cooling etc.). High heat generated at the interface due to friction between the tool and the work-piece leads to poor machined surface quality and significantly affects the tool wear.
It is reported that approximately 320,000 tons of lubricant (neat oil, water-soluble fluids, and gases) were used per year in the European Union which clearly indicate importance of lubricant in machining. Water-soluble fluid is most commonly used in machining. However, this typically mineral-based oils known to be harmful to the worker and to the environment as they exhibits toxic product when degraded in soil. Moreover, with becoming environment consciousness enhanced laws and regulations green cutting will become important tendency of machining. Dry machining can eliminate the use of lubricant and consequently exterminate the bad effect of using mineral-based lubricant. However, dry machining limits the cutting parameters to be used during machining due to high amount of heat generated which significantly affects the quality of surface finish especially when machining at higher cutting speed and feed rate [1]. Therefore, attempts have been made by the researchers to use vegetable oil which is nontoxic and biodegradable as against the mineral oil. Most of the vegetable oil has triglycerides in its composition which enhances lubricity of oil. Moreover, viscosity of vegetable oil remains stable at high temperature due to their high viscosity index [2].

Hard turning is mostly sighted in the literature under dry condition as high temperature involved in the process makes chip deformation and shearing of the material easier. Moreover, at higher cutting speed heat is carried away by the fast flowing chip makes the use of cutting fluid redundant. However, dry cutting creates problems of chip transportation and significantly affects tool life due to increase in chip-tool and work piece-tool friction [3-5]. On the other hand, machining under wet condition (use of abundant cutting fluid) facilitates chip transportation, lowers friction and cools the work piece. However, it increases the cost of cutting and in hard turning it does not allow the work piece to soften, which is good for the process. Therefore, most of researchers performed machining with Minimum Quantity Lubrication (MQL) which represents a compromise between the advantages and disadvantages of completely dry cutting and cutting with abundant soluble oil [6-7]. Attempts have been also made by researchers using vegetable oil, solid lubricants and solid lubricants mixed in varying proportion with mineral-based oil and vegetable oils during machining. Lawal et al. [8] evaluated the performance of vegetable oil as against mineral oil during turning and observed that the vegetable oil surpasses conventional oil-in-water performance within the domain of the parameters selected in their study. Babur et al. [9] experimental investigation concluded that vegetable oil is effective in producing better surface quality and less tool wear in comparison to synthetic cutting fluids during turning. It is reported that performance of vegetable oil can be improved by utilizing powder particles such as MoS2, graphite, boric acid etc. Sodavadia and Makwana [10] observed better performance in terms of surface finish, coefficient of friction, wear and cutting force using powder particle aided lubricant during machining. It is reported that better machining performance observed when using solid lubricants is because of lattice layered structure of powder particle, their relatively high load carrying capacity and having low steady state coefficient of friction [11].

The solid lubricant assisted machining is gaining more attention from last decade as powder particle such as boric acid, graphite, MoS2 are environmentally friendly and do not pose threat to operational workers. According to the Environmental Protection Agency, which is desirable in creating a greener lubrication in machining application [12].Toenshoff [13] investigated the tribological aspects of turning with ceramic tools. According to their study, cooling effect reduces the thermal load of the cutting edge, and thus increases tool life as compared to dry cutting. Further, their study reports that surface roughness of the work piece can be reduced either by chemical interaction between the work piece surface and extreme-pressure additive of the coolant or by mineral oil application. Avila and Abrao [14] investigated the effect of cutting fluid on the machining of hardened AISI 4340 steel. Their study investigated the performance of three type of cutting fluids and machining performance using cutting fluids was compared with dry machining when using mixed alumina inserts. Their experimental investigation showed that the application of a cutting fluid based on an emulsion without mineral oil resulted in longer tool life compared to dry cutting and the use of cutting fluid is responsible for reducing the scatter in the surface finish at high cutting speeds. However, Inspite of all beneficiaries these fluids produce harmful environmental results and to the human health issues. Varadarajan et al. [15] investigated the turning with minimal fluid application and its application with dry and wet turning. Results showed that overall
performance during minimum cutting fluid application is found to be superior to that dry turning and conventional wet turning on the basis of cutting force, tool life, surface finish, cutting ratio, cutting temperature, and tool-chip contact length.

Although, sufficient work have been reported on use of cutting fluids and their comparative evaluation when applied under wet, minimum quantity lubrication during machining, very few studies reported on use of solid lubricant mixed with varying proportions in vegetable oil during hard turning. Moreover, contradictory findings reported on use of cutting fluid during hard turning. With this view, in the present work solid lubricant assisted hard turning (hereafter referred as “SLHT”) experiments with solid lubricant mixed with varying proportions in vegetable oil were performed to find the feasibility of solid lubricant assisted hard turning. SLHT experiments were also performed under mist lubrication (hereafter referred as “Mist-SLHT”) with a view to assess the feasibility of variants of solid lubrication system in hard turning.

2. Experimentation

2.1 Experimental Set-up and Measuring Instruments

Hard turning (SLHT and Mist-SLHT) experiments were performed on hardened AISI 52100 steel (60-62 HRC) on a CNC lathe. Experiments were performed using PVD-coated nano-laminated Ti-Si-N, Ti-Al-N carbide inserts. All the inserts have identical geometry designated by ISO as CNMG 120408 with integral chip breaker geometry as MF2. A right hand side tool holder designated by ISO as PCLNR 2525M12 was used. A schematic of the experimental setup with actual photograph of the setup is shown in Figure 1. Machining experiments were performed at eight different combinations of cutting conditions with values of cutting speeds; \( V = 100, 150 \) and \( 200 \) m/min, feed \( f = 0.1 \) and \( 0.3 \) mm/rev and depth of cut \( d = 0.1 \) and \( 0.3 \) mm.

For the coolant injection along with compressed air a spray-painting gun was used. Nozzle was fixed by means of a magnetic stand in such a way that the cutting fluid or mist formed is injected at the interface of the tool and work material. Nozzle has two inlets, one for oil and other one for air. Air inlet of nozzle is connected to compressor via flexible pipe and oil inlet of nozzle is connected to the oil container. Air and oil are injected simultaneously and gets mixed just outside at the exit of the nozzle. Compressed air pressure was set at a pressure of 2 bar. Various instruments were used for measuring the responses. Surface roughness (Ra), often shortened to roughness, is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. Surftronic DUO surface roughness tester (Taylor and Hobson make) was used to measure the surface roughness. The surface
tester has error of 0.7μm. Cutting forces were measured by a strain gauge type lathe tool dynamometer. This strain gauge type dynamometer which was mounted on the cross slide of the CNC lathe along with cutting tool holder is used to measure the three components of a cutting force coming on the tool tip during turning. The sensor is designed in such a way that it can be rigidly mounted on the tool post, and the cutting tool can be fixed to the sensor directly. This feature will help to measure the forces accurately. The sensor is made of single element with three different wheatstones strain gauge bridge. Provision is made to fix 1/2” size tool bit at the front side of the sensor. Forces in X-Y-Z directions namely feed force \( F_f \), radial force \( F_r \) and tangential force \( F_t \) is seen individually and simultaneously in three digital Indicators.

2.2 Materials
The physical properties of refined sunflower oil are shown in the Table 1. The Oil contains 59% polyunsaturated fat which is an advantageous because vegetable oil that are high in unsaturated fatty acid are susceptible to oxidation. Therefore, palm kernel oil that is high in saturated fatty acid are more stable in terms of oxidation. Although, the process of oxidation is influenced by many factors, nonetheless the fatty acid content can help to predict Sunflower oil oxidation stability.

| Properties                  | Refined Sunflower Oil |
|-----------------------------|-----------------------|
| Iodine Value                | 135                   |
| Dynamic Viscosity At 25°C   | 0.04914kg/(M*S)       |
| Density                     | 918.8Kg/M³            |
| Flash Point                 | 232°C                 |

The performance of lubricant is also highly influenced by the additional additives. Additives that are used in this formulation are emulsifier, anti-corrosion agent, antioxidant agent, biocide and boric acid powder. The physical properties of boric acid powder used for this investigation are shown from Table 2. The type of additives in this formulation is cautiously selected, and it is ensured that the materials are not hazardous to the operators and the environment.

| Properties:                  | Values                  |
|------------------------------|-------------------------|
| Density, G/Cm³              | 1.44                    |
| Molecular Mass, G/Mol        | 61.83                   |
| Melting Point, °C            | 160                     |
| Boiling Point, °C            | 300                     |
| Purity, %                   | 99.999                  |
| Particle Average Size, Mm    | < 8                     |
| Chemical Formula             | H₃BO₃                   |

3. Results and Discussion
With the view to assess feasibility of solid lubricant assisted hard turning (SLHT), hard turning experiments were performed at different cutting conditions using solid lubricant (SL) mixed in vegetable oil (VO) as a cooling medium. Boric acid was used as solid lubricant which was mixed in different proportions namely 1% by weight, 5% by weight and 10% by weight in refined sunflower oil (vegetable oil). Experiments were also performed using mist of sunflower oil and compressed air (Air; at a 2 bar pressure) and mist formed by sunflower oil carrying 5% by weight boric acid and compressed air (pressure 2 bar). A comparative evaluation of five different cooling mediums namely VO+1%SL,
VO+5%SL, VO+10%SL, VO+Air and VO+SL+Air was carried out in terms cutting forces and surface roughness at different cutting conditions. Surface roughness and three components of cutting force namely tangential force ($F_t$), feed force ($F_f$) and radial force ($F_r$) were measured at each cutting condition and under five different cooling mediums.

During the machining process, high temperature generated in the cutting zone is the cause for poor surface finish. Temperature can be minimized with the help of lubricant. Solid lubricant such as boric acid is one of the options to reduce the temperature at the interface between work piece and cutting tool as boric acid powder has high thermal conductivity and low coefficient of friction. Further, adding boric acid to oil lubricant might improve machining performance. High thermal conductivity of the boric acid powder mixed with lubricant oil might change heat transfer and thus aids in reducing temperature in the cutting zone. Experimental results obtained for three components of cutting force and surface roughness when using five different cooling mediums and at different cutting conditions are given below. It can be seen decrease in cutting forces with increase in cutting speed, feed and depth of cut values. Radial component of force can be seen as highest in magnitude followed by tangential force and feed force. Surface roughness also can be seen decreasing with increase in cutting speed and increased with higher values of feed and depth of cut. However, it can be seen that surface roughness gets affected significantly with feed followed by cutting speed and depth of cut. Further, it can be seen that lower values of cutting forces and surface roughness with increase in proportions of boric acid by weight in refined sunflower oil. However, significant improvement in surface roughness cannot be seen when proportion of boric acid by weight increased from 5% to 10% in refined sunflower oil. This can be justified as almost similar values of cutting forces or to some extent higher cutting forces were observed at 10% of boric acid proportion by weight as compared to 5% proportion of boric acid by weight with vegetable oil. This clearly shows that lower values of surface roughness and cutting forces could be obtained by having 5% of boric acid in proportion by weight in refined sunflower oil.

Table 3: SLHT: Cutting forces and surface roughness when used refined sunflower oil with varying % of boric acid

| $V$ (m/min) | $f$ (mm/rev) | $d$ (mm) | Refined sunflower oil with 1% by weight boric acid | Refined sunflower oil with 5% by weight boric acid | Refined sunflower oil with 10% by weight boric acid |
|------------|-------------|--------|----------------------------------|----------------------------------|-----------------------------------|
|            |             |        | $F_t$ | $F_f$ | $R_a$ | $F_t$ | $F_f$ | $F_r$ | $R_a$ | $F_t$ | $F_f$ | $F_r$ | $R_a$ |
| 100        | 0.1         | 0.1    | 120  | 88   | 161   | 0.41  | 80   | 64   | 129   | 0.31  | 70   | 52   | 132   | 0.3   |
| 100        | 0.3         | 0.1    | 140  | 97   | 212   | 0.62  | 130  | 81   | 206   | 0.56  | 117  | 71   | 192   | 0.5   |
| 150        | 0.1         | 0.3    | 123  | 87   | 172   | 0.54  | 88   | 73   | 145   | 0.46  | 85   | 81   | 167   | 0.6   |
| 150        | 0.3         | 0.3    | 170  | 108  | 224   | 0.91  | 130  | 55   | 191   | 0.69  | 110  | 64   | 177   | 0.7   |
| 150        | 0.1         | 0.1    | 90   | 71   | 145   | 0.33  | 65   | 59   | 117   | 0.28  | 60   | 55   | 128   | 0.3   |
| 150        | 0.3         | 0.1    | 123  | 88   | 173   | 0.56  | 98   | 68   | 161   | 0.48  | 87   | 56   | 174   | 0.5   |
| 200        | 0.1         | 0.1    | 70   | 61   | 133   | 0.81  | 60   | 55   | 109   | 0.58  | 55   | 53   | 119   | 0.6   |
| 200        | 0.3         | 0.1    | 98   | 82   | 197   | 0.72  | 78   | 64   | 182   | 0.62  | 70   | 61   | 203   | 0.7   |

$V$: Cutting speed, $f$: Feed, $d$: Depth of cut, $F_t$: Tangential force, $F_f$: Feed Force, $F_r$: Radial force and $R_a$: Surface roughness

Cutting force values shown are in Newton and surface roughness in $\mu$m
Table 4: Mist-SLHT: Cutting forces and surface roughness (refined sunflower oil with 5% of boric acid and compressed air)

| V (m/min) | f (mm/rev) | d (mm) | MQL (Mist of refined sunflower oil with air at 2 bar) | MQL (Mist of refined sunflower oil with 5% by weight boric acid with air at 2 bar) |
|-----------|------------|--------|-------------------------------------------------|--------------------------------------------------------------------------|
|           |            |        | $F_t$ | $F_f$ | $F_r$ | $R_a$ | $F_t$ | $F_f$ | $F_r$ | $R_a$ |
| 100       | 0.1        | 0.1    | 110   | 68    | 130   | 0.31  | 78    | 55    | 104   | 0.29  |
| 100       | 0.3        | 0.1    | 127   | 82    | 158   | 0.42  | 102   | 63    | 147   | 0.36  |
| 150       | 0.1        | 0.3    | 96    | 69    | 154   | 0.42  | 63    | 72    | 97    | 0.39  |
| 150       | 0.3        | 0.3    | 133   | 88    | 171   | 0.85  | 113   | 61    | 155   | 0.78  |
| 150       | 0.1        | 0.1    | 72    | 48    | 115   | 0.26  | 48    | 51    | 87    | 0.24  |
| 150       | 0.3        | 0.1    | 96    | 69    | 143   | 0.42  | 78    | 60    | 133   | 0.36  |
| 200       | 0.1        | 0.1    | 55    | 41    | 89    | 0.53  | 44    | 39    | 69    | 0.40  |
| 200       | 0.3        | 0.1    | 78    | 63    | 113   | 0.69  | 66    | 59    | 98    | 0.48  |

V: Cutting speed, f: Feed, d = Depth of cut, $F_t$: Tangential force, $F_f$: Feed Force, $F_r$: Radial force and $R_a$: Surface roughness.

Cutting force values shown are in Newton and surface roughness in µm.

Further, hard turning experiments (mist-SLHT) were carried out using mist of refined sunflower oil with compressed air and mist obtained with sunflower oil carrying 5% in proportion by weight boric acid and compressed air at the same cutting conditions that were used in solid assisted hard turning as shown in Table 3. Experimental results for cutting forces and surface roughness obtained under mist lubrication are shown in Table 4. Referring to Table 3, 4 and from Fig. 2, it can be seen that the feed rate and cutting speed are the most significant factors on the surface roughness. The lowest surface roughness obtained at lower feed value can be justified as at higher feed rate, larger cross sectional area is being removed which consequently increases the friction at the chip-tool interface and hence, increase in cutting forces. It can be seen that mist lubrication obtained using sunflower oil carrying 5% in proportion by weight boric acid and compressed air produced lower values of surface roughness of 0.24 µm at cutting speed of 150 m/min and lower feed and depth of cut values of 0.1 mm/rev and 0.1 mm respectively. However, at the same cutting condition, surface roughness value produced can be seen as 0.28 µm when using 5% proportion of boric acid in refined sunflower oil under solid lubricant assisted hard turning. Although, significant improvement in lowering surface roughness is not observed by using mist lubrication with solid lubricant, but, encouraging reduction in cutting forces can be seen when using mist lubrication. In turn, saving in cutting power could be achieved due to reduction in specific cutting energy when using solid lubricant assisted vegetable oil mist lubrication.
Fig. 2 Cutting forces under Vegetable oil (VO) mixed with 1% by weight of boric acid, MQL (VO+Air) and MQL (VO mixed with 5% by weight boric acid +Air)

Improvement in machining performance with solid lubricant assisted vegetable oil mist lubrication can be justified as boric acid used as solid lubricant has high thermal conductivity and low coefficient of friction aids in reducing the temperature at the interface between work piece and cutting tool. Further, adding boric acid with vegetable oil alters heat transfer due to higher thermal conductivity of solid lubricant which helped in removing heat rapidly from the cutting zone. Moreover, the micro particle size of boric acid which has higher surface area increases the heat transfer rapidly from the cutting zone. In this investigation, it has been observed that use of boric acid in vegetable oil; to be specific 5% of boric acid by weight in refined sunflower oil and that too under mist condition, i.e. Solid lubricant assisted vegetable oil mist lubrication(mist-SLHT) is most applicable cooling medium during hard turning.

4. Conclusion

In the present work, solid lubricant assisted hard turning (SLHT) experiments were performed using boric acid mixed in varying proportions mixed with refined sunflower oil. SLHT experiments were also performed under mist lubrication (mist-SLHT) with a view to assess the feasibility of variants of solid lubrication system in hard turning. Experimental results obtained during SLHT showed lower values of cutting forces and surface roughness with increase in proportions of boric acid by weight in refined sunflower oil. However, significant improvement was not seen at 10% of boric acid as compared to 5% of boric acid mixed with vegetable oil. This study suggest to use 5% of boric acid in proportion by weight in refined sunflower oil during SLHT to obtain lower values of surface roughness and cutting forces. Further, hard turning experiments performed under mist-SLHT indicated that mist lubrication obtained using sunflower oil carrying 5% of boric acid and compressed air produced lower values of surface roughness of 0.24 µm at cutting speed of 150 m/min and at lower feed and depth of cut values of 0.1 mm/rev and 0.1 mm respectively. Significant improvement in lowering surface roughness was not seen when using mist-SLHT as compared to SLHT especially at higher cutting speed of 200 m/min. However, cutting forces were observed to be lower under mist-SLHT at all the cutting conditions used in the present study. Improvement in machining performance with SLHT and mist-SLHT is seen due to higher thermal conductivity and lower coefficient of friction of boric acid used as solid lubricant. In this investigation, it has been observed that use of boric acid (5% of boric acid by weight) mixed in refined sunflower oil under mist condition(mist-SLHT) is most feasible as a cooling medium in hard turning and saving in cutting power could be achieved due to reduction in specific cutting energy when using mist-SLHT.

5. References

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