An Experimental Investigation Into The Applicability Of Boric Acid As Solid Lubricant In Turning AISI 4340 Steel

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Abstract

The intense heat generation during the turning process is critical to the workpiece quality. Coolant and lubrication therefore play decisive roles in turning. The conventional cutting fluids employed in machining have certain limitations with regard to their use for ecological and economic reasons. Development of lubricants that are eco-friendly is acquiring importance. In this context, application of solid lubricants has proved to be a feasible alternative to the conventional cutting fluids. Solid lubricant, if employed properly, could control the machining zone temperature effectively by intensive removal of heat from the machining zone. Therefore, the aim of present study is to investigate the effect of boric acid as solid lubricant in the zone of machining. Experiments were carried out to investigate the role of solid lubricant such as boric acid on the surface finish of the product in machining AISI 4340 steel by TiAlN coated tungsten carbide inserts of different tool geometry under different cutting conditions. Results indicate that there is considerable reduction in the cutting forces, average tool flank wear, and the surface roughness of the machined surface with boric acid assisted machining compared to dry and wet machining. Chip thickness ratio is also evaluated to study the lubricating action of selected solid lubricant during turning.

1. Introduction

The study of various methods of machining has become a keen topic of research in recent times since it has acquired a prominent role as one of the primary processes in manufacturing industry. Turning is one such machining process which is most commonly used in industry because of its ability to have faster metal removal giving reasonably good surface quality. Surface roughness is one of the important factors for evaluating workpiece quality of machined components because the surface roughness influences the functional characteristic of the workpiece such as compatibility, fatigue resistance and surface friction. It is also one of the criteria in assessing the machinability of the materials. Hence the surface quality can become a significant performance measure.

Although a high surface quality had been achieved in earlier investigations (Konig et al. 1993, Tonshoff et al. 1995), widespread industrial applications of turning technology necessitated a better understanding of the effects of process parameters on surface quality. The surface quality of machined parts is affected by many factors, such as tool geometry and cutting conditions. It is generally considered that the heat produced during the turning process is critical in terms of workpiece quality. Coolant and lubrication therefore play decisive roles in machining. Cutting fluids have been the conventional choice to deal with this problem. It will help reduce friction and wear, thus improving the tool life and surface finish. These are also used to reduce the forces and energy consumption, to cool/lubricate the cutting zone, wash away the chips, and to protect the machined surfaces from environmental corrosion. The stiff air boundary layer which may form around the wheel periphery due to high wheel speed may restrict the accessibility of coolants to the grinding zone (Diniz et al. (2003), Avila and Abrao (2001), Klocke and Eisenblätter (1997), Varadarajan et al. (2002)). Minimization or possible elimination of cutting fluids by substituting their functions by some other means is of current research interest. Use of biodegradable coolants, the concept of minimum-quantity lubrication and use of a refrigerated jet of gas are some of the attempts in this direction (Sreejith, P.S. and Ngoi, B.K.A. (2000), Gaur, A.P.S. and Agarwal, S. (2010), Agarwal, S. and Rao, P.V. (2007)). In an effort to find out alternative approaches for replacing fluid coolants, an attempt to reduce the heat at its generation stage in the process would be ideal, rather than removing the heat after its generation. The advancement in modern tribology has identified many solid lubricants that can sustain and provide lubricity over a wider range of temperatures. If solid lubricant can be successfully applied to the grinding zone in a proper way as a means to reduce the heat generated due to friction, it should
yield better process results (Singh and Rao (2008), Brinksmeier et al. (1999)).

Literature review above suggests that the application of solid lubricant in machining has proved to be a feasible alternative to fluid coolants, if it can be applied properly. If friction at the tool and workpiece interaction can be minimized by providing effective lubrication, the heat generated can be reduced to some extent. Therefore, the aim of present study is to investigate the effect of boric acid as solid lubricant in the zone of machining. In the first stage of this work, experiments were carried out to investigate the role of solid lubricant such as boric acid on surface finish of the product, tool life and chip thickness ratio in machining AISI 4340 steel by TiAlN coated tungsten carbide inserts of different tool geometry (approach angle and rake angle) under different cutting speeds and feeds. An experimental setup was envisaged and built. In the second stage, a comparative performance analysis of boric acid assisted machining with dry and wet lubrication, the heat generated can be reduced to some extent. Therefore, the aim of present study is to investigate the effect of boric acid as solid lubricant in the zone of machining. In the first stage of this work, experiments were carried out to investigate the role of solid lubricant such as boric acid on surface finish of the product, tool life and chip thickness ratio in machining AISI 4340 steel by TiAlN coated tungsten carbide inserts of different tool geometry (approach angle and rake angle) under different cutting speeds and feeds. An experimental setup was envisaged and built. In the second stage, a comparative performance analysis of boric acid assisted machining with dry and wet machining was conducted.

2. Experimentation

The experimental study was conducted using HMT make lathe machine. A new experimental set-up was designed and developed for the supply of fine graphite powder at the desired flow rate (Fig. 1).

![Fig.1 Photograph of the experimental setup](image)

The primary objective of the solid lubricant powder feeder setup is to maintain constant flow rate of powder to the machining zone in order to attain optimum results in machining. The solid lubricant is supplied into the machining zone as the feeder moves along the length of the shaft, which is being turned. The solid lubricant feeder together with the motor is mounted on the carriage, in order to facilitate the movement of feeder system with tool during machining operation.

As far as the working of solid lubricant feeder is concerned, initially the fine solid lubricant powder, with 2 µm average particle size, was loaded into the upper conical part (hopper) of the feeder. The powder falls into the cylindrical portion of the feeder due to gravity. The opening at the end of the lower conical portion is selected in such a way that it is just sufficient for the powder to flow continuously onto the workpiece. Further, the cutting action of the tool and workpiece will drag the powder to the machining zone. After ensuring the setup for proper lubrication, the experiments were carried out. The entire machining operation, while using solid lubricant, was carried out in a closed chamber. Thus, powder is not allowed to mix freely in air. Trial experiments were carried out to see the influence of increasing flow rate of solid lubricant powder from 1 gm/s to 12 gm/s on the friction coefficient. It could be seen from the experimental results that the saturation of powder flow rate was observed at 5 gm/s, hence, all the experiments in boric acid assisted machining were carried out at 5 gm/s flow rate.

In the present investigation, the most influential factors affecting the surface finish were studied by conducting a set of experiments. The factors considered for the experimentation were cutting speed, feed, approach angle and rake angle. The experimental conditions are shown in Table 1. The experiments were planned using a CCD technique and the test conditions are shown in Table 2. The experiments were conducted under dry, wet and solid lubricant assisted machining conditions. The cutting fluid used in the experimentation was soluble oil (Emulsion strength 5–10%) with water in the ratio of 1:20. The cutting tests have been carried out on a lathe machine. The work material was a through hardenable steel (AISI 4340) which was hardened to 45 HRC by heat treatment and then tempered at 200°C to remove residual stresses and to obtain a homogeneous structure. It is general-purpose steel having a wide range of application in automobile and allied industries by virtue of its good hardenability. Bars of 70 mm diameter and 350 mm length were used in the present investigation. The chemical composition of the specimens is shown in Table 3. Surface finish of the machined part was measured by using Taylor Hobson Talysurf equipment.

3. Results and discussion

Effective control of heat generated at machining zone is essential to ensure workpiece quality in turning because of high friction between the tool and workpiece interface zone. Conventional cutting fluids have been the traditional choice to deal with this problem. However, these fluids have a direct influence on, both to human health and environment and therefore, being questioned in the light of economic and ecological manufacture. The need to use less cutting fluid and to limit its disposal and the operator’s contact are all very important in order to minimize the ill effects of the cutting fluid usage. Machining with boric acid as solid lubricant is a possible environmentally friendly alternative for effective control of heat generated at the
machining zone. Hence in the present work, boric acid has been used as solid lubricant to reduce the friction between tool and workpiece and thereby reduce heat generation at tool and workpiece interface.

3.1 Surface finish

A comparative performance analysis of the solid lubricant application with dry and wet machining is done. Figure 2 shows the variation of surface roughness different machining environments. In all the cases under study, surface roughness first decreased then increased with the increase in approach angle. This is due to the fact that at low approach angle, the effective cutting edge is increased. As a result, the chip thickness becomes smaller and favors low surface roughness. With further increase in approach angle, the cutting forces are distributed over a shorter section of the cutting edge since the main cutting edge enters and leaves the cutting zone suddenly at 85 deg approach angle, thus subjecting the workpiece to maximum loading and unloading condition. It has been observed from the results that the minimum surface roughness was observed at 75 deg approach angle in boric acid assisted machining and 65 deg approach angle in dry and wet machining. It has also been observed from the Fig. 3 that the surface roughness decreases with increase in cutting speed. This could be due to the reduction in the cutting forces at high speeds. Similarly it can also be observed from the Fig. 2 that when feed rate was increased, the roughness was found to increase. This is due the fact that more material has to removed per revolution, for which more energy is required, which ultimately increases the cutting forces and temperatures leading to high wear of the cutting tool, which might have resulted in the increase of surface roughness. However, surface roughness produced by the solid lubricant is again lower than that of dry and wet machining. The lubricant effectiveness in minimizing the frictional effects at the tool and workpiece interface in the case of solid lubricant assisted machining is evident from the reduced surface roughness compared to that of dry and wet machining. Boric acid is known to be good solid lubricant because of the low friction at the interface, which could have contributed to the reduction of surface roughness. The key to this performance of boric acid lies in its layer-lattice structure. The atomic structure consists of layers of atoms or molecules, and the structure is called “layer-lattice” structure. The substantial reduction of surface roughness by boric acid assisted machining can be attributed to the formation of the thin film of lubrication, reducing the shear stress in
the contact zone between tool and work piece and between tool and chip, which makes machining easier. It can also be observed from the boric acid experimental results that the surface roughness was minimum at 200 m/min speed, 0.11 mm/rev feed rate and 75 deg approach angle. From the above-mentioned results, it can be inferred that surface quality is better controlled by the solid lubricant in addition to the cutting conditions and the tool geometry parameters during machining.

3.2 Cutting forces

The comparative performance of dry boric acid assisted machining with the dry and wet machining could also be seen from Fig. 3. The lubricant effectiveness in minimizing the frictional effects at the tool and workpiece interface in the case of solid lubricant assisted machining is evident from the reduced cutting force compared to that of dry and cutting fluid assisted machining. Dry boric acid is known to be good solid lubricant because of the low friction at the interface, which could have contributed to the reduction of cutting force. The key to this performance of dry boric acid lies in its layer-lattice structure. The atomic structure consists of layers of atoms or molecules, and the structure is called “layer-lattice” structure. The substantial reduction of cutting force by dry boric acid assisted machining can be attributed to the formation of the thin film of lubrication, reducing the shear stress in the contact zone between tool and workpiece and between tool and chip, which makes machining easier. It is important that the solid lubricant should adhere strongly to the metal surface; otherwise it should be easily rubbed away and gives very short service life as well as lubricating properties also.

3.3 Tool life

Tool-life is one of the most important economic considerations in the metal cutting. Tool-wear/tool-life not only effects other machining performance measures, but it is very essential to predict tool-life to insure timely tool changes for uninterrupted machining and to avoid loss of production due to tool breakage. The life of a cutting tool was terminated by tool wear or tool failure. Fig. 4(a) shows a comparison of the variation of surface roughness as a function of time. It is observed that a surface roughness within $R_a=1.1\mu m$ could be maintained for 360 s during solid lubricant assisted machining.
Fig. 4 (a), (b) Variation of surface roughness and average flank wear with time of cut during dry, wet and solid lubricant assisted machining. Fig. 4 (c) Variation of average tool flank wear with cutting speed during dry, wet and solid lubricant assisted machining ($S=150 \text{ m/min}, f=0.26 \text{ mm/rev, } \kappa =65^\circ, \gamma =8^\circ$) machining where as it is 150 s in dry turning and 210 s in wet turning. Fig. 4(b) represents the comparison of average flank wear with time. It is observed that during dry turning the average flank wear was 0.3 mm after 150 s when the surface roughness became $R_a=1.1 \mu m$. The micrographs of flank wear after a cutting time of 130 s during dry turning wet turning and solid lubricant assisted machining are shown in Fig. 5. Flank wear is minimum during solid lubricant machining, compared to dry and wet conditions with respect to cutting time.

3.5 Chip thickness ratio

Chip thickness in metal cutting is not only governed by the geometry of the cutting tool and undeformed chip thickness, but also affected by the frictional conditions existing at the chip–tool interface. Friction between the chip–tool interface depends on the lubricating action of the applied lubricant. Hence, lubricant effectiveness in metal cutting may be

Fig. 5 Photographs showing flank wear during dry, wet and solid lubricant assisted machining. ($S=150 \text{ m/min}, f=0.26 \text{ mm/rev, } \kappa =65^\circ, \gamma =8^\circ$).

(Fig.4(b)). Similarly the flank-wear increases with increase in cutting speed. However, flank wear is minimum during solid lubricant machining, compared to dry and wet conditions at all cutting speeds (Fig. 4(c)). This may be attributed to the layer lattice structure of solid lubricants and the reduced frictional effects at the tool and workpiece interaction. Lattice layer structure helps to form an effective lubricant film.

Fig. 6 Variation of chip thickness ratio with different levels of cutting speed, feed rate, approach angle, and rake angle under dry, wet and boracic acid assisted machining characterized by chip thickness ratio. A lower chip thickness ratio implies better lubrication at the tool-chip interface and formation of chips of thinner sections; i.e. if the chip thickness ratio decreases, the process efficiency goes up. The chips were collected at the end of each experiment and the chip thickness was measured using Tool Maker’s microscope. The chip thickness ratio values, obtained during dry, wet and boracic acid assisted machining for a particular condition, were shown in Fig. 6. It was found that the chip thickness was less in boracic acid assisted machining as compared to that of dry and wet machining at all the levels of the
considered process parameters (cutting speed, feed rate, approach angle and rake angle). This substantiates the results obtained during experimentation involving surface roughness measurement. Hence, it can be concluded that boric acid assisted machining seems to be the better choice among the variants considered in this work.

The use of solid lubricant has been successful in reducing surface roughness and chip thickness while machining AISI 4340 steel with TiAlN coated tungsten carbide inserts. This may be attributed to the layer lattice structure of solid lubricants and the reduced frictional effects at the tool and workpiece interaction. Lattice layer structure helps to form an effective lubricant film. The results also indicate that the reduction in friction generated between tool and workpiece is more in boric acid assisted machining as compared with dry and wet machining. Hence, it can be concluded that boric acid is the better alternative for machining AISI 4340 steel and also to eliminate the use of cutting fluids making the machining pollution free. Although the lubricating action has been successfully taken care of in the proposed method, an effective means for substituting flushing action and tool cleaning, have yet to be identified in order to make solid lubricant assisted machining as viable alternative to conventional machining with cutting fluids.

4. Conclusion

In order to obtain better surface quality, investigations are carried out by introducing boric acid as solid lubricant in the machining process with a newly designed experimental setup. The use of solid lubricant has been successful in reducing the surface roughness, tool wear, and chip thickness ratio. The surface finish had improved by 8% to 35% during solid lubricant assisted machining. Similarly the tool life is improved in solid lubricant assisted machining as compared to that obtained with dry and wet machining, due to reduced flank wear in solid lubricant assisted machining. This was also confirmed by SEM micrographs. This study also indicates that higher value of optimum rake angle was observed with solid lubricant compared to dry and wet machining. Therefore, the tool appears to be sharper in the presence of solid lubricant and thus improving the machinability of AISI 4340 steel. The improved machinability, in solid lubricant assisted machining, results in better material removal rates without affecting the quality of surface produced. In addition, the use of boric acid as solid lubricant appears to offer considerable benefits in terms of improved environmental pollution point of view over the dry and wet machining. This work also emphasizes that solid lubricant assisted machining is essential for making it an interesting alternative to dry and wet machining.

References