Abstract

Turning is one of the most fundamental and indispensable processes of metal removal in industry. Increasing pollution-preventing initiatives globally and consumer focus on environmentally conscious products has put increased pressure on industries to minimize or eliminate the use of cutting fluids. The use of solid lubricant in machining operation is one of the most effective strategies in this direction to achieve sustainable machining system. In the present research work, the feasibility of a novel approach for developing a new generation of machining technique namely High Pressure Minimum Quantity Solid Lubricant experimental set-up has been envisaged with an aim to improve process performance and to eliminate the use of cutting fluids in machining operation. A detailed comparison has been made with wet, dry, and MQL machining operation to assess the process performance on the basis of tool wear and surface finish. The results indicate that HP-MQSL mixture at a small and constant flow allows better penetration of the mixture into the tool-work and tool-chip interface, thus providing reduction on the tool wear and surface roughness more effectively than a wet, dry, and MQL machining at high speed conditions, thereby to achieve sustainable machining system.

1. Introduction

In machining industries, high production machining with high material removal rate inherently produces high cutting temperature in the machining zone which leads to tool failure and low quality machining [1]. There is tradeoff between using either dry machining and flood cooling mechanism. Using large quantity of cutting fluids leads to pose difficulties in procurement, disposal, storage and maintenance [2]. Increasing pollution-preventing initiatives globally and consumer focus on environmentally conscious products has put increased pressure on industries to minimize or eliminate the use of cutting fluids. All the costs involved with cutting fluids (purchasing, recycling, chip drying, etc.) represent 7.5-17% of the manufacturing costs of a part, which in many cases even higher than tool cost [3, 4]. In other words, apart from cost, using flood cooling of cutting fluids in the machining operation is not environmentally acceptable [5]. As a result unconventional cooling/lubricant methods such as minimum quantity lubricant (MQL), cryogenic, solid lubricants etc., have been introduced as an alternative method to reduce or possible elimination of the use of high rate cutting fluids, whilst increasing machinability as compared to dry cutting conditions. Dry machining leads to poor outcome with rough finish and less accuracy while flood cooling mechanism faces environmental issues and price increases significantly [6]. However, researchers started minimizing or eliminating the use of cutting fluids in the recent past.

Being intermediate between dry machining and flood cooled machining; MQL is prefect alternative to majority of machining processes. While flood cooling machining uses excess of lubricant to achieve cooling by heat absorption, MQL uses limited quantity of lubricant which targets on reducing friction between tool and workpiece to obtain cooling [7]. But in MQL there is a sudden vaporization of the water upon reaching the machining zone decreasing the cooling and lubrication aspects thereby affecting the tribological properties [6]. Hence, minimum quantity...
lubrication may be considered as an economical and environmentally and compatible lubrication technique for limited applications at low speed, feed, and depth of cut machining condition [8]. Control of machining zone temperature is achieved by providing effective cooling and lubrication. But, machining without the use of any cutting fluid (dry or green machining or sustainable machining) is becoming increasingly more popular due to concern regarding the safety of the environment [9].

Machining without the use of environmentally effective cutting fluid (dry cutting/near dry cutting) is an important objective in the industry to reduce environmental and production costs [8]. The advantages of dry/Near dry cutting include free from pollution of the atmosphere or water which will be reflected in reduced disposal and cleaning costs; no danger to health, being non-injurious to skin and allergy free. Dry cutting is becoming more and more prevalent around the world [11]. But, in dry cutting, there will be more friction and adhesion between the chip-tool and work-tool interface. This will result in increased tool wear and hence reduction in tool life [7, 11]. So, in reality, sometimes they are less effective when higher machining efficiency, better surface finish quality and severe cutting conditions are required [1]. Therefore, increasing the productivity in the machining industry through cost reduction by abandonment of the cutting fluid, saving the environment and at the same time improving machining properties is the main concern [9]. So, there is a need for concentrated efforts in this direction to overcome the above stated drawbacks and to look into new machining methods to achieve sustainable machining system. The use of solid lubricant in machining is one of the most effective strategies in this direction [12].

The above mentioned studies indicate the great potential of using solid lubricants for low cost and eco-friendly sustainable machining [14]. Solid lubricants assisted machining could be a viable alternative method to increase the life of the cutting tool. In addition, research studies highlighting that although the resulting lubrication is sufficient with solid lubricants, still there is a need to look into flushing action and tool cleaning methods to make the solid lubricant more attractive than conventional liquid lubricant in mixture form (MoS2 and SAE 40 oil) as a high velocity jet, at constant flow rate to the machining zone. In addition the present study aims to experimentally investigate the role of High Pressure Minimum Quantity Solid Lubricant jet assisted machining

2. Design and development of High Velocity Minimum Quantity Solid Lubricant for turning of Mold steel

The solid lubricant mixture needs to be supply at low flow rate and impinged at high speed through the nozzle towards to the cutting zone. Considering the cutting conditions required for the present research work and constant supply of solid lubricant mixture at a low flow rate over a reasonably long cut; an High Pressure Minimum Quantity Solid Lubricant (HP-MQSL) jet assisted machining system has been designed, fabricated and used. Fig. 1 shows the schematic diagram of the developed HP-MQSL jet assisted machining for turning process and its parts are enumerated in order to be easy understanding about description and functioning. As shown in Fig. 1 the HP-MQSL jet assisted machining system is comprised of four important components. Syringes pump unit, mixing chamber, nozzle, and nozzle fixture. The high velocity jet was projected along the cutting zone, so that the solid lubricant mixture reaches close to the chip-tool and work-tool interface as possible. The nozzle fixture is attached to the tool holder support such that solid lubricant mixture jet coming out of the nozzle reaches to the machining zone interface at a flow rate of 40 ml/hr for effective lubrication of critical area. The outer diameter of the nozzle is 0.2 mm. The nozzle was designed in such a way that
it provides a direction of flow and particle velocity sufficiently lubricant stream that will cover the intended tool target. It can be seen from Fig.1 that syringe pump system is used to supply the solid lubricant mixture to the nozzle. Experiments were performed on the developed experimental set-up to evaluate the performance of HP-MQSL and the results compared with wet, dry and MQL conditions.

3. Experimentation

Experiments were carried out on a high power rigid lathe HMT PVT 260 CNC turning machine at a selected cutting speed, feed and depth of cut under wet, dry, MQL and solid lubricant assisted machining conditions to study on the machinability characteristics of the STAVAX ESR work material mainly in respect of tool wear, and surface finish. The main input parameters (cutting speed, feed and depth of cut) were selected based on the preliminary testing. The cutting conditions selected after testing preliminary testing to the definitive tests were cutting speed 100m/min, feed rate is 0.1 mm/rev and depth of cut is 1mm. these parameters were chosen based on the current day industrial requirements and kept constant throughout the tests.

The performance parameters such as tool wear, and surface roughness were measured during wet, dry, MQL and solid lubricant assisted machining. A stylus type Mitutoyo SJ-400 Profilometer was used for measuring surface roughness, where the tracing velocity and the cut-off length were fixed at 18mm/min and 0.8 mm respectively. The flank wear were measured using an inverted metallurgical microscope (Olympus: model BX-51M) fitted with a micrometre. The deviation in the job diameter before and after cuts were measured by a precision dial gauge with a least count of 1μm which was travelled parallel to the axis of the job. Water-soluble cutting oil was used in the conventional cooling condition i.e., wet machining. In case of MQL, Unist mist oil 310 (Synthetic Ester, viscosity 20cSt at 40°C) was used as a lubricant and it was supplied at a pressure of 0.6 Mpa and coolant flow rate 43.2 ml/hr. based on the previous study, 20% MoS₂ solid lubricant particles of 20 μm size were manually mixed in SAE 40 oil to prepare a solid lubricant mixture. Within the practical range investigated a low delivery rate of 60 ml/hr of solid lubricant mixture was selected.

4. Results and discussion

Within the frame work of an optimization of the cutting process the knowledge of the tool wear is essential. Tool wear is an important factor that affects the productivity and manufacturing efficiency. For that reason, the key objective of cutting research is the assessment of tool life and prediction of tool wear. Cutting tools often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness [15]. Among different patterns of tool wear, the flank wear is the most significant because it governs the surface finish on the job as well as dimensional accuracy.

Irregular and high flank wear leads to dimensional accuracy and poor surface finish.

4.1 Flank wear

During the machining trails under wet, dry, MQL and solid lubricant assisted machining, mainly the growth of flank wear have been monitored. The tool wear of the inserts

![Dry](image)

![Wet](image)

![MQL](image)

![HP-MQSL](image)

Fig. 2 Flank wear of the tool being used for about 10 minutes of machining at different cutting environments
is observed under tool maker’s microscope to study the tool wear. It is important to note that the tool was completely worn out under dry condition after 13 minutes of machining with the considered cutting condition, where under wed, MQL, and solid lubricant assisted machining, it has been continued 27, 24, 34 minutes respectively. Fig. 2 shows microscopic observations of the flank wear of the tool after being used for about 11 minutes of machining and Fig. 3(a) compares the values of flank wear quantitatively under wet, dry MQL and solid lubricant assisted machining. The solid lubricant assisted machining product lower flank wear that did the wet, dry MQL machining, which is a positive aspect. During machining of difficult to cut materials, high rate of heat is generated at the primary deformation zone and secondary deformation zone and results in high cutting temperature. Under such high temperature, applying solid lubricants in the machining zone generate a thin lubricating film. The solid lubricant mixture flows at the interface can decrease the plastic contacts, leading to reduction of flank wear. Using machining experimental results empirical equations have been obtained to estimate tool wear with the significant parameters i.e., cutting speed, feed rate and depth of cut. The results of statistical analysis indicate that the main effects of cutting conditions are significant at 99% confidence level and that their interaction effects are significant.

4.2 Surface roughness

Finally, the lubricant ability of the MoS$_2$ mixture was also evaluated in terms of the final surface. The arithmetic average value of surface roughness ($R_a$) was measured for the considered cutting conditions and is presented in Fig. 4 (with an average error ±5μm for each condition). It appears from Fig. 3(b) that surface roughness was more under effective in reducing surface roughness. It could be due to the fact that, solid lubricant assisted machining improves surface finish mainly by controlling the machining zone temperature, which reduces deterioration of the cutting edge by abrasion, built up edge formation and chipping.

5. Conclusion

This research work contributes to a new insight of development of high velocity thin pulse jet solid lubricant assisted machining that helps to improve the performance of turning hard steel. The machining performance of high velocity solid lubricant jet assisted machining is better that of wet, dry and MQL machining because it provides benefits mainly by reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edge. Surface finish mainly improved due to reduction in wear and damage at the tool tip by the application of solid lubricant. Such reduction in tool wear would either improvement in tool life or enhancement of productivity allowing higher cutting velocity and feed. If the fluid are applied precisely to the machining zone, improved results can be expected. The methodology presented here clearly indicates that for an economical machining along with environmental aspects, high pressure solid lubricant jet assisted machining is one of the promising alternative. Academic research should focus on trying to increase the material removal rates with these environmentally conscious methods. The other improvement of HP-MQSL is chip breakability. As a result it is shown that with the selected machining parameters and cooling/lubricant conditions, chip breakability is improved.

In general, with the developed experimental set-up it has been shown that sustainable machining effectively provides virtually

- Improved environmental friendliness
- Less cost,
- Reduced wastes and more effective waste management,
- Greater operational safety

With the increasing worldwide trends in achieving sustainable machining, wet, dry, MQL and high pressure minimum quantity solid lubricant assisted machining options are emerging as viable and more sustainable alternatives to flood cooling in machining processes.

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References


