Comparative Evaluations of Tool Nose Wear Progression under Dry and Near-Dry Cutting Conditions during Hard Turning through Experimentation and Mathematical Modeling

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Abstract

In present work, attempts have been made to compare the tool nose wear progression under dry and near-dry (minimum quantity lubrication) cutting conditions through experimentation and mathematical modeling in view of disagreement of the researchers about the use of coolants in hard turning. Experiments on hardened AISI 4340 steel (55 HRC) were performed using PVD-applied TiAlSiN coated carbide inserts varying the cutting speed and feed in the wide range of cutting conditions and at constant depth of cut of 0.3 mm. Mathematical models which could be used to predict tool nose wear progressions with machining time under dry and near-dry cutting conditions were developed based on experimental data. Near-dry cutting experiments were performed using a mist formed by a very small quantity of oil (S40) of 60 ml/hr and compressed air at pressure of 5 bar. It has been observed that tool nose wear progressions are prominently affected with cutting speed in comparison to feed. However, this effect has been observed to be more prominent when machining under dry cutting conditions. Higher tool life obtained under near-dry cutting conditions can be attributed to lower cutting temperatures and better evacuation of chips during machining. However, at lower cutting speed, no significant difference in tool nose wear progression has been observed under dry and near-dry cutting conditions. Coefficient of correlations of developed mathematical models found close to 1, which shows that the models could be used to predict reliably tool nose wear progressions within domain of the cutting parameters selected under dry and near-dry cutting conditions using PVD-applied TiAlSiN coated carbide tool.

Keywords: Tool wear, Dry and Near-dry cutting, Mathematical modeling, Hard turning

1 Introduction

From last decade, green machining is getting more attention by the researchers as use of metal cutting fluids in manufacturing is becoming more and more prevalent around the world due to stringent environmental regulations rules (Diniz et al., 2003). With this view, a comparative evaluation of different cooling environments, namely, dry cutting, near-dry or minimum quantity lubrication (MQL), mist lubricating and cooling, compressed air cooling, liquid nitrogen cooling and use of gases during machining is comprehensively investigated and widely reported by the researchers in the literature (Kilickap, 2011; Khan and Dhar, 2006; Bruni et al., 2006; Shokrani et al., 2012; Machado and Wallbank, 1997).

Among users, machining of extremely tough and hard steels using coated carbide tools is continuously increasing (Avila et al., 2008; Noordin et al., 2007; Chinchanikar and Choudhury, 2013a; Chinchanikar et al., 2013). Machining performances, namely, cutting force/s, tool life, surface roughness during machining of hardened steels were mostly investigated by the researchers under dry cutting conditions as increase in temperature during the process makes chip deformation and shearing of the hardened material easier (Chinchanikar and Choudhury, 2013a; Chinchanikar et al., 2013). Although, there is disagreement between the researchers about the use of coolants during hard turning (Bruni et al., 2006), several studies concluded that the machining under near-dry or minimum quantity lubrication produce better performance in comparison to flood (Khan and Dhar, 2006) and compressed air cooling (Kilickap, 2011).

However, most of the studies made so far were concentrated on comparative evaluations of the surface roughness, cutting forces and tool life under different cooling environments (Kilickap, 2011; Khan and Dhar, 2006). On the other hand, comparative evaluation of progression of tool wear, which severely affects the
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dimensional accuracy and surface finish of the machined workpiece under dry and near-dry (minimum quantity lubrication) cutting conditions is rarely reported in the available open literature.

Tool wear is the most undesirable characteristic of machining processes as it affects the dimensional accuracy and surface finish of the machined workpiece. Several attempts have been made by the researchers to develop tool wear models. Dawson and Kurfess (2006) developed a tool wear model to predict the flank wear progression during hard turning of bearing steel using polycrystalline cubic boron nitride (PCBN) tools. Huang and Liang (2004) developed a flank wear rate model during finish hard turning of hardened steel. Singh et al. (2010) developed a model to predict flank wear of ceramic inserts during hard turning of bearing steel. Dureja (2012) developed flank and crater wear models during hard turning of AISI-H11 steel with TiN coated CBN tool. They observed cutting speed and feed as having prominent effect on flank wear.

During hard turning, tool wear takes place at the tool nose section (as depth of cut is less than tool nose radius) which adversely affects the dimensional accuracy and product quality. Almost no attempt has been made to compare the tool nose wear progression during hard turning under dry and near-dry cutting conditions. Moreover, tool wear models available during hard turning are applicable under dry cutting condition using CBN or ceramic tools. Therefore, comparative evaluation of the tool nose wear progression under dry and near-dry (minimum quantity lubrication) cutting conditions through mathematical modeling will be extremely valuable in view of disagreement of the researchers about the use of coolants in hard turning.

In present work, attempts have been made to compare the tool nose wear progression under dry and near-dry (minimum quantity lubrication) cutting conditions through experimentation and mathematical modeling. Hard turning experiments were performed on hardened AISI 4340 steel (55 HRC) using PVD-applied TiAlSiN coated carbide inserts varying the cutting speed and feed in the wide range of cutting conditions and at constant depth of cut of 0.3 mm. With the developed model the effect of cutting parameters and machining time on tool nose wear progression under dry and near-dry cutting conditions are investigated.

2 Experimental set-up and procedure

2.1 Experimental set-up

From last decade minimum quantity lubrication (MQL) technique in machining is getting more attention. The researchers have suggested different methods to obtain air and lubricant mixture. In this study, a simple near-dry cutting set-up was designed and fabricated which is shown in Figure 1. Nozzle used was designed and fabricated to direct the flow of mist at the tool/work interface as shown in Fig. 1. Nozzle has two inlets at 90° to each other, one for the air and the other for the cutting fluid. However, outlets of the fluid and the air are in the same direction which is directed at the tool/work interface. In this study, the flow of liquid to nozzle was made by gravity and to keep the flow to a very minimal value, a needle of a syringe was fixed at the outlet of nozzle. The nozzle was fixed in a particular position with the help of a nozzle holder which was designed in such a way that the distance between the tip of the nozzle and tool/work interface could be easily varied. The entire arrangement was made in such a way that the pressurized air with the cutting fluid falls vertically on the tool/work interface.

Figure 1 Near-dry machining set-up

2.2 Experimental procedure

Experiments were carried out using a very small quantity of fluid of 60 ml/hr which was controlled using a regulating knob of glucose bottles as shown in Figure 1. The ratio of oil (Servocut S, water-based cutting oil) to water was kept 1:20. The compressed air of 5 bar pressure was used and kept constant throughout the experiments. Experiments were performed on a HMT-make (Hindustan Machine Tools) centre lathe varying the cutting speeds at three different levels, namely, 100, 125 and 150 m/min and at constant values of feed and depth of cut, namely, 0.088 mm/rev and 0.3 mm, respectively. Experiments were performed using commercially available PVD-applied TiAlSiN coated carbide inserts having an ISO class of P-10 grade with an average coating thickness of 4 μm. The inserts used
have geometry designated by ISO as CNMG 120408 (80° diamond shape with 0.8 mm nose radius). For each experiment a fresh cutting insert was used. The insert was rigidly mounted on a right hand style tool holder designated by ISO as PCBNR 2020K12.

Before carrying out actual experiments, some rough turning passes were made in order to completely remove the surface irregularities and oxidized layer from the outer surface of the workpiece. Experiments were performed to validate and calibrate the developed model and to assess the accuracy of predicted results of tool nose wear progression with experimental results. During each experiment, the operation was interrupted at regular intervals of length cut and insert was checked using a Digital microscope (maximum magnification of 230X) to evaluate the tool nose wear. Models developed based on experimental observations were used to investigate the effect of cutting parameters, namely, cutting speed, feed, and depth of cut and machining time on the tool nose wear progression.

3 Results and discussion

3.1 Modeling of tool nose wear progression

It has been shown by many investigators that the wear under sliding conditions depends on the sliding velocity, the distance slid, the normal contact pressure between the sliding surfaces and the time and the magnitude of the wear land can be expressed in terms of the cutting conditions and time of cutting (Choudhury et al., 1999; Bhattacharya and Ham, 1969; Chinchanikar and Choudhury, 2013b). Therefore, magnitude of the wear land for a given tool-work interface under dry and near-dry cutting can be expressed in terms of the cutting parameters and time of cutting as shown in equation (1).

$$VB = KV^n f^b t^c$$

The unknown coefficients, exponents of $V$, $f$, and $t$ in equation (1) of tool nose wear when machining under dry and near-dry cutting were obtained by minimizing the least square error between experimental and predicted flank wear values corresponding to different time instants at various cutting conditions as described in Section 2.2. Total 72 experimental observations for dry cutting and 90 observations for near-dry cutting, obtained at various time instants, and cutting conditions, that were used to calibrate the models. Using ISO 3685-1977(E) as a tool wear criteria, experimental values of tool nose wear were measured up-to the maximum width of the flank wear land, $VB_{max} = 0.2$ mm or the occurrence of the catastrophic failure. The unknown coefficients were determined using DataFit software. Tool nose wear progression equations for dry and near-dry cutting are expressed as below:

For dry cutting:

$$VB = 5.9474 \times 10^{-4} V^{1.1494} f^{0.5138} t^{0.2925}$$

(2)

For near-dry cutting:

$$VB = 1.8196 \times 10^{-7} V^{0.818} f^{0.4228} t^{0.3568}$$

(3)

3.2 Model validation and discussions

The tool nose wear and its progress varying with machining time at different cutting conditions when machining under dry and near-dry cutting was predicted using equations (2) and (3), respectively. The plots between experimental and predicted tool nose wear values at various time instants and cutting conditions for dry and near-dry cutting are shown in Figures 2(a) and (b).
It can be seen that all the points nearly fall on a line of slope of $45^\circ$, with a correlation coefficient (The $R$-squared values) between the experimental and predicted values of 0.8812 and 0.8747 for dry (D) and near-dry (ND) cutting, respectively, indicating that the developed equations could be used to evaluate the tool nose wear progression of PVD-applied TiAlSiN coated carbide inserts during hard turning of hardened AISI 4340 steel (55 HRC) within the domain of the selected cutting parameters.

In order to have a clear understanding of the effect of a given input parameter on the tool nose wear when hard turning under dry and near-dry cutting, predicted results were obtained by varying one of the input parameters by keeping the other parameters constant. Tool nose wear was calculated over a range of input parameters by reducing the developed equations (2) and (3) to two parameter levels. Graphs are plotted between the calculated tool nose wear values and the corresponding input parameter. The effect of cutting speed and feed on the tool nose wear at different values of machining time when hard turning under dry and near-dry cutting is shown in Figures 3(a) and (b), respectively.

From the plots shown in Figures 3(a) and (b), it can be seen that while turning under dry cutting condition cutting speed and feed are having more prominent effect on tool nose wear as compared to turning under near-dry cutting conditions. This can be also confirmed from the higher values of exponents for cutting speed and feed from equation (2) when turning under dry cutting condition in comparison to values of exponents for cutting speed and feed from equation (3) when turning under near-dry cutting condition. However, from the exponent of machining time from equations (2) and (3), it can be seen that machining time is having more significant effect on tool nose wear while hard turning under near-dry cutting condition.

Prominent effect of cutting parameters, especially cutting speed on tool nose wear can be attributed to higher cutting temperature employed during turning under dry cutting in comparison to near-dry cutting. In another study, the present Authors observed that cutting temperature get affected mostly by cutting speed followed by feed (Chinchankar et al., 2013). Higher cutting temperature generated at higher cutting speeds during hard turning, especially under dry cutting have influenced the flank wear rate more as compared to while hard turning under near-dry cutting condition.

Further, to have a better understanding of the tool nose wear progression under dry and near-dry cutting during hard turning, predicted values of flank wear varying with machining time at different values of cutting speed and feed are plotted as shown in Figures 4(a) and (b). Tool nose wear progression curve shown in Figure 4(a) is plotted at cutting speeds of 100, 125 and 150 m/min using constant feed and depth of cut values of 0.113 mm/rev and 0.3 mm, respectively. Although, near-dry cutting improved the tool life, almost no significant improvement in lowering the tool nose wear and hence in nose wear progression can be seen when hard turning under near-dry cutting at lower cutting speeds. Similarly, hard turning under near-dry cutting not significantly reduced the tool nose wear at lower values of feed which can be seen from Figure 4(b). However, significant differences in tool nose wear...
progression and hence, in tool life can be seen by employing near-dry cutting at higher values of cutting speed and feed as shown in Figures 4(a) and (b).

![Figure 4 Plots showing tool nose wear progression varying with machining time when hard turning under dry and near-dry cutting at different values of (a) Cutting speed and (b) Feed](image)

From the experimental investigations and developed mathematical models, it has been understood that while hard turning under near-dry cutting condition or minimum quantity lubrication (MQL) produce better tool life in certain range of cutting parameters selected for the given workpiece-cutting tool combination. In the present work, no significant benefit in tool nose wear progression and hence, tool life has been observed while hard turning at lower values of cutting speed and feed. However, a significant benefit in tool life has been observed at higher values of cutting speed and feed while hard turning under near-dry cutting condition. Further, cutting speed has been observed as having more prominent effect on tool nose wear progression as compared to feed, especially under dry cutting condition.

Mathematical models developed in this study based on experimental observations showed R-Squared values close to one indicate that these models could be used to predict tool nose wear progressions during hard turning of AISI 4340 steel (55 HRC) under dry and near-dry cutting conditions using PVD-applied TiAlSiN coated carbide tool within domain of the cutting parameters selected.

4 Conclusions

In present work, attempts have been made to compare the tool nose wear progression under dry and near-dry (minimum quantity lubrication) cutting conditions through experimentation and mathematical modeling in view of disagreement of the researchers about the use of coolants in hard turning. Experiments on hardened AISI 4340 steel (55 HRC) were performed using PVD-applied TiAlSiN coated carbide inserts varying the cutting speed and feed and in the wide range of cutting conditions and at constant depth of cut of 0.3 mm. Tool nose wear progressions with machining time were measured using digital microscope having magnification maximum up-to 230X. Experiments were planned using central rotatable composite design test matrix. Values of unknown exponents of cutting speed, feed and constants of mathematical models were determined by minimizing the least squares error between the experimental and predicted values of tool nose wear progressions at different time instants.

It has been observed that tool nose wear progressions are prominently gets affected with cutting speed in comparison to feed. However, this effect has been observed more prominent when machining under dry cutting conditions. Higher tool life obtained under near-dry cutting conditions can be attributed to lower cutting temperatures and better evacuation of chips during machining. However, no significant difference in tool nose wear progression and hence tool life has been observed under dry and near-dry cutting conditions when turning at lower cutting speed. Coefficient of correlations of developed mathematical models found close to 1, which shows that the models could be used to predict reliably tool nose wear progressions within domain of the cutting parameters selected under dry
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near-dry cutting conditions using PVD-applied TiAlSiN coated carbide tool.

References


