Reliability of coated carbide tool during turning hardened steel

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Abstract. Reliability of a cutting tool in terms of tool wear is of foremost importance in metal cutting owing to its direct impact on the surface quality of the machined surface, and its dimensional accuracy, and consequently, on the economics of machining operations. With this view, in the present work, reliability of single layer PVD-coated TiAlN carbide tool is assessed during turning of hardened AISI 4340 steel (35 HRC) at various cutting conditions. Dry cutting tests were carried out with cutting speeds of 142, 265, 345 and 487 m/min and feed and depth of cut values of 0.125 mm/rev and 0.8 mm, respectively. Flank wear and its growth was monitored at regular intervals of length of cut using a digital microscope with a maximum magnification of 230X. Reliability of cutting tool obtained at different cutting conditions is compared with a view to understand the progression of tool wear and wear mechanisms at different stages of tool life. Environmental scanning electron microscope (ESEM) with energy dispersive X-ray spectroscopy (EDAX) system was used to understand tool wear and wear mechanisms. It has been observed that a better reliability of a PVD-coated tool could be obtained by limiting the cutting speed 200-250 m/min as at higher cutting speeds lower cutting tool reliability resulted due to the weakening of the cutting edge by an accelerated crater wear rate.

1. Introduction

Cutting tool reliability in terms of tool wear, especially the flank wear, is extremely important and needs to be given highest priority during machining as tool wear has directly influences product quality and dimensional accuracy. Several researchers have been made significant efforts in understanding the cutting tool reliability by developing predictive models for obtaining reliability of a cutting tool. Several studies have been performed on soft (≤ 45 HRC) and hard (≥ 45 HRC) machining using coated and uncoated carbide tools.

The machined surface characteristic properties and quality are prominently influenced by the shape and form of the cutting tools. In practice, tools are often reinstated during machining well before the end of tool life as tool fracture or catastrophic failure of the cutting tool can lead to discarding the machined part and halt stoppage of the entire production line [1]. The cutting tool wear is considerably
more critical while hard machining as higher wear rates and often catastrophic failures of cutting tool are observed during machining of these hard materials [2-6].

A group of researchers established predictive tool wear models to know the progress of wear during machining. Luo et al. [7] predicted rate of flank wear using combination of an empirical model and cutting mechanics simulation. The simulation results and machining data in together were used by them to obtain model wear constants. Huang and Liang [8] predicted flank wear rate considering material properties of tool and workpiece, process arrangement and cutting parameters in turning. Dawson and Kurfess [9] investigated flank wear progression for coated and uncoated tools. The researchers have been made several attempts for understanding the tool wear-cutting force interrelationship and modelling the flank wear considering effect of cutting force on tool wear [10-12]. Dureja [13] developed flank and crater wear statistical models for TiN coated CBN tool considering the input parameters such as work hardness and cutting parameters during hard turning. Several researchers have developed models to evaluate the cutting tool reliability under various cutting conditions. Carlson and Strand [14] developed a model to obtain tool life considering the expanded Taylor’s tool life equation. Klim et al. [15] developed model to predict reliability using the cutting tool face and flank wear. A proportional hazards model was also used by the researchers to obtain the cutting tool reliability [16]. Wang et al. [17] built up a reliability subordinate disappointment rate to evaluate the cutting tool reliability.

Although, efforts have been made to evaluate the cutting tool reliability and modelling tool wear, very few of them have assessed the reliability and modelled the tool wear while hard machining with coated carbide tools. In the context of green manufacturing, assessment of reliability of cutting tools and progression of tool wear will have prime importance as the surface finish and machining and dimensional accuracy will greatly affected using a severely worn tool. Hence, cutting tool replacement well before its end of tool life will have higher impact on machining economy.

In the present work, reliability of PVD-coated carbide tool is assessed in turning of AISI 4340 steel at various cutting conditions. Cutting tool reliability is evaluated at different cutting conditions to understand the behaviour of cutting tool reliability and wear mechanisms at different levels of tool wear. Dry cutting tests were performed at different cutting speeds (142, 265, 345 and 487 m/min) and using feed value of 0.125 mm/rev and depth of cut of 0.8 mm. Growth of flank wear was monitored using a digital microscope after regular interval of length of machining. Scanning electron microscope with EDAX system was used to understand cutting tool reliability and wear mechanisms.

2. Tool Wear and Cutting Tool Reliability

Tool wear and hence, cutting tool reliability is a critical issue in machining as the machined surface quality and dimensional accuracy has direct impact on the machining economy. Failures in cutting tools generally take place in following three different ways [18]:

- Mechanical breakage due to higher magnitude of cutting forces and vibrations.
- Cutting edge plastic deformation which causes quick dulling due to excessive temperature and stresses.
- Gradual cutting tool wear.

The mechanical breakage and quick dulling failure modes represent premature tool failure. These two tool failure modes are needs to be avoided during machining as these modes severely affect the machined workpiece surface quality and causes damages to the machine tool. However, for the given workpiece-cutting tool material pair mechanical breakage and quick dulling failures can be prohibited by selecting proper tool material, tool geometry and correct cutting conditions. On the other hand, rate of gradual flank wear can be slowed down by selecting proper cutting conditions to have higher tool life. The cutting tool has to be withdrawn immediately just before it completely fails to avoid machine tool damages and hence, to reduce downtime and scrapped components. The growing tool wear, especially the flank wear influences cutting forces, temperature rise, surface integrity and power consumption. Wear is loss of material from the surfaces due to the rolling and relative sliding[19]. In
the context of cutting tool wear, tool life is the useable cutting time of a tool and tool failure means end of tool life.

The wear formation and its location rely upon on cutting conditions for a given pair of tool-work material. In most of the machining cases gradual growth of tool wear is observed. However, other types of tool wear, such as chip hammering can be seen when machining stainless steel using ceramic tools. Thermal and mechanical cracking, subsequently leading to tool chipping or breakage, are mostly observed in interrupted cutting [20]. The Built-up edge creation is not a gradual tool wear. However, it promotes abrasive and adhesive wear mechanisms. Astakhov [21] considered cutting edge plastic deformation as a gradual tool wear, which changes the shape of a tool and eventually leads to tool failure. On the other hand, gross fracture is random and catastrophic in nature which occurs either at the start of the machining or after a little gradual tool wear.

The cutting tool progressive wear appears in two distinct ways. It first occurs on the flank or clearance faces of the tool as a result of abrasion by the hard constituents of the workpiece material and rubbing against the newly machined surface. Wear occurring on the tool rake face as a result of fast flowing chips resulting in the formation of a crater wear. It appears due to chemical interaction between the hot chip and tool rake face.

Tool life is treated to be over when the gradual growth of wear exceeds a predetermined limit. For flat faced-tools, ISO recommendations for tool life are established. However, it has been observed that groove tools fail quite often at earlier stage of predefined failure criterion [22]. Literature review revealed that the cutting tool reliability depends on tool and workpiece material (workpiece and tool hardness, chemical composition, etc.), tool geometry, and cutting parameters. With this view, in the present study, reliability of PVD-coated TiAlN carbide tool is assessed at different cutting conditions in turning hardened AISI 4340 steel.

3. Experiment Particulars
Experiments were performed on AISI 4340 steel (35 HRC) which is more commonly used in aircraft and heavy vehicle connecting rods and crank shafts, etc. The workpiece used has 90 mm in diameter and 400 mm in length. Dry machining experiments were carried out using PVD-coated TiAlN carbide tool at different cutting speeds (487, 345, 265 and 142 m/min) and feed of 0.125 mm/rev and depth of cut of 0.8 mm. In this study, straight cutting operations were performed to assess the reliability of cutting tool in terms of tool wear until flank wear had accumulated more than 0.2 mm, which is considered as a critical flank wear value in the present study. Flank wear and its growth was observed after regular interval of length of machining using a digital microscope. Scanning electron microscope with EDAX system was used to understand tool wear and wear mechanisms.

4. Result and Discussion
In this section, assessment of reliability of cutting tool and flank wear progression at cutting speeds of 487, 365, 245 and 142 m/min designated hereafter as R1, R2, R3 and R4 respectively, is discussed. Cutting test was carried out using constant feed and depth of cut values of 0.125 mm/rev and 0.8 mm respectively. Assessment of cutting tool reliability considering the progression of tool wear is summarized and wear mechanisms are discussed on the basis of SEM images and elemental analysis. The tool life was considered at an end when the maximum flank wear reached 0.2 mm or the occasion of the catastrophic failure (VBcritical = 0.2 mm). Reliability of a cutting tool is obtained by obtaining the values of limiting state function (denoted as G) for actual flank wear values varying with time of cutting. At the start of the experiment, the cutting tool insert is new and flank wear is considered as zero (no wear when the insert is new). However, the tool wears out with the progress in cutting time during machining.

In the present study, flank wear is measured after regular interval of length of machining till flank wear arrived at 0.2 mm or the incident of catastrophic failure. And, for all the time instants and corresponding actual flank wear, a limiting state function ‘G’ values are calculated. Flank wear progression at cutting speed of 487 m/min and at feed of 0.125 mm/rev and depth of cut of 0.8 mm
and corresponding values of limit state function and cutting tool reliability varying with time of cutting is given in Table 1.

| Cutting time (min) | Flank wear (mm) | Limit state function, G = (V_{critical} – V_{actual}) | Reliability, R = (G / V_{critical}) |
|--------------------|-----------------|------------------------------------------------------|----------------------------------|
| 0                  | 0               | 0.2                                                  | 1                                |
| 0.36               | 0.0697          | 0.1303                                               | 0.6515                           |
| 0.72               | 0.088           | 0.112                                                | 0.56                             |
| 1.22               | 0.099           | 0.101                                                | 0.505                            |
| 1.66               | 0.1063          | 0.0937                                               | 0.4685                           |
| 2.10               | 0.121           | 0.079                                                | 0.395                            |
| 2.44               | 0.1576          | 0.0424                                               | 0.212                            |
| 3.66               | 0.28            | 0                                                    | 0                                |

Flank wear progressions and calculated values of reliability of cutting tool at cutting speeds of 487, 345, 265 and 142 m/min, designated hereafter as C1, C2, C3 and C4 conditions and at feed of 0.125 mm/rev and depth of cut of mm are presented in Fig. 1 and 2. Reliabilities at these cutting conditions are termed as R1, R2, R3 and R4 respectively. Plots reveal that the flank wear increases and cutting tool reliability decreases with machining time. Flank wear for the fresh insert at the start of cutting is zero and cutting tool reliability (for fresh insert at the start of cutting) is one. However, as the cutting progresses, the tool wears out and cutting tool reliability decreases with machining time and can be seen from the plots at various cutting conditions. Plots demonstrates that flank wear progression normally enclosed three apparent regions; primary failure, constant wear rate and expeditious cutting edge failure and the same can be revealed from the reliability plots wherein slope at the start of cutting and end of cutting is steeper in comparison to region of uniform wear. The tool images shown (at the end of machining; Fig. 3) depicts flank wear, crater wear and catastrophic failure as presiding tool failure modes.

Figure 1. Flank wear progression with cutting time
From the plots, it can be seen that cutting tool performed better at lower cutting speed of 142 m/min as sizeable tool life of 48 min is obtained. However, at all other cutting conditions, it can be seen that cutting tool reliability is very low and reduces drastically especially at higher cutting speeds of 487 m/min and 265 m/min. Lower reliability of cutting tool at higher cutting speeds is resulted due to sudden fracture of the tool owing to the weakening of the cutting edge by increase in crater wear rate.

**Figure 2.** Reliability of cutting tool varying with cutting time at various cutting conditions

**Figure 3.** Tool condition at the end of cutting
From the above discussion, it can be seen that better cutting tool reliability and hence the tool life is obtained at cutting speed of 142 m/min and at low feed and low depth of cut. It is reported that when using this TiAlN-coated carbide tool cutting speed is to be restricted to 250 m/min and the same can be from the plots shown in Fig. 1 and 2 [23]. Tool wear basically occurs due to combination and simultaneous action of various wear mechanisms like abrasion, adhesion, plastic deformation of the edge, diffusion, chemical action, fatigue and catastrophic failure etc. [24]. In the present work, TiAlN coating due to its higher hot hardness value protects the cutting tool from higher cutting temperature generated during machining of hardened steel. Also, aluminum in the coating material when reacted with atmospheric oxygen formed an Al2O3 oxide layer which resulting in protection of cutting edge from heat protection. However, when this thin coating layer wears out during machining by adhesion and abrasion wear, the fast wearing of the substrate and sometimes catastrophic failures at higher cutting speeds resulted due to dominance of the oxidation-dominated diffusion wear.

From the above discussion, it can be seen that by knowing cutting tool reliability and its behavior, a suitable cutting condition can be selected with a view to assure the machined surface quality balancing with the overall machining economics. It can be seen that the reliability varying with machining time normally enclosed three apparent regions; primary failure, constant wear rate and expeditious cutting edge failure as like the flank wear progression with machining time.

5. Conclusion
In the present work, reliability of PVD-coated carbide tool is assessed in turning of AISI 4340 steel (35 HRC) at various cutting conditions with a view to understand the progression of tool wear and hence, cutting tool reliability at distinct stages of tool life. Flank wear and its growth was observed after regular interval of machining length using a digital microscope. Scanning electron microscope with EDAX system was used to understand tool wear and wear mechanisms. It has been perceived that a better reliability of a PVD-coated tool could be obtained by restricting the cutting speed 200-250 m/min as at higher cutting speeds lower cutting tool reliability resulted owing to the weakening of the cutting edge by increase in crater wear rate. It has been observed that the reliability varying with machining time is normally enclosed three apparent regions; primary failure, constant wear rate and expeditious cutting edge failure as like the flank wear progression with machining time. On the other hand, tool failed catastrophically at higher cutting speeds. Present study concludes that by knowing reliability of a cutting tool and its behavior, a suitable cutting condition could be selected with a view to assure the machined surface quality balancing with the overall machining economics.

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