Gouging-Abrasive Wear Conditions in Turning Operations

Titus Bitek Watmon*, Fredrick Joseph Otim, Peter Okello-Obeli

Department of Mechanical & Production Engineering, Faculty of Engineering, Kyambogo University, Kampala, Uganda

Abstract This paper presents results of a long study for different types of tool materials ranging from TiN coated tungsten carbides, uncoated tungsten carbides, plain ceramic carbides and high speed steel. These tool inserts were used to cutmild steel grade EN1-A. Cutting speed of 300m/min was used and the cutting lasted for 15 minutes for each tip with sufficient mist coolant supply to the tool-work and chip-tool interface. Mild steel is sometimes referred to as carbon steel or plain steel. Typically, it is stiff and strong. This type of mild steel does not rust easily and they can be easily painted or primed. Wear on rake face takes place in the form of a crater away from the cutting edge in a zone where the temperature is highest. Primary wear mechanism is by way of abrasion caused by the chip rubbing against the tool surface. Results show that at the speed investigated, the coated tungsten carbide inserts have a much higher resistance to wear. All the inserts failed by abrasion action as result of friction at the tool-work interface except for plain ceramics carbides which failed catastrophically by chipping. The criterion used for failurewere both work surfaceroughness criterion and tool flank wear measurement criterion.

Keywords Tool, Chipping, Materials, Abrasive, Crater, Flank, Wear, Carbide, Mild-Steel, TiN

Nomenclature

BS EN ISO 8503-2:2012(E) (*surface roughness characteristics of blast-cleaned substrates*

KB	=	distance of outer crater from the main (primary) cutting edge
KF	=	distance of inner crater from the primary cutting edge
KI	=	Crater index
KL	=	width of crater
KM	=	distance of crater mid-point from the primary cutting edge
VB	=	average flank wear width
VB_{max}	=	maximumflank wear width
VN	=	width of primary groove
VC	=	width of secondary groove (wear notch)
Vc	=	Cutting Velocity/speed
HSS	=	High speed steel

Introduction

Abrasive wear is the removal of material by a hard asperity (two-body wear) or a particle interposed between the two surfaces (three-body wear) [1]. Abrasion wear occurs at points of contacts where one of the surfaces is considerably harder than the other, or where hard particles are introduced into the contact zone.This type of wear takes place when hard particles on the underside of the chip pass over the tool face and remove total material by mechanical action. When harder surface asperities are pressed into the softer surface it results into

plastic flow of the softer material around the hard one. In other situations the harder surface moves tangentially, ploughing and removing the softer material resulting in grooves or scratches on the surface. The mechanisms of abrasive wear have been studied extensively by several authors [2-5]. There are several types of abrasive wear but three main dominant types are;

- Gouging abrasion (impact)
- High stress abrasion (crushing), and
- Low stress abrasion (sliding)

This study looked at abrasive wear by gouging because of the three forms of abrasion mentioned and gouging is associated with turning operation using single point cutting tool on the lathe machine. This type of wear occurs when coarse material tears off sizeable particles from the wearing surface. This situation normally involves high imposed stresses. It is usually encountered when handling large lumps of chips/debris especially in a turning operation on the lathe. The authors recognise that the most conventional forms of wear often used are flank wear popularly known as wear-land and crater wear which occur on the tool rake face.

Abrasion wear creates other tool failure mechanisms like chipping, thermal cracking, plastic deformation which result in;

- Outer chip notch on the rake face formation. This occurs when chips or swarfs moving at high velocity rubs against the tool rake face and cause a groove
- Inner chip notch on the rake face
- Secondary groove (oxidation wear) on the end flank containing the secondary cutting edge,
- Primary groove (outer diameter groove) on the flank this occurs when the tool flank rubs the newly machined work surface and the tool flank develops wear-land

Objectives of the Study

The study aimed to investigate how abrasion by gouging affects tool performance and how it contributes to total tool failure. Tool failure is said to develop gradually [6] and premature failure can be caused by failure mechanisms such as chipping, breaking, plastic deformation, thermal softening and thermal cracking which are common in intermittent cutting. Tool-wear and its total failure is affected by a number of factors and these include the workpiece material, the tool material, tool geometry, type / amount of coolant used, machine tool characteristics and cutting parameters (machining variables). The cutting parameter involves the cutting speed (Vc), feedrate (f) and depth of cut (d). This experimental study comprehensively considered the performance of four different cutting tool materials mentioned in the abstract and compared their failure modes with the well-known tool wear criterion VB, KT and KI based on wear formations (ISO:3685). In order to validate our findings we also compared the work surface finishes. In finish turning, the tool replacement is defined by either the workpiece design specifications (dimensions) or surface measurement profile (roughness) and the tool wear. Generally, finish turning conditions are not aggressive enough to fracture the tool, thus it is important to monitor the surface roughness to establish the moment the tool needs to be changed. The reader should note that increase of tool wear results into increase in surface roughness [7]. In this study, we present results for the TiN coated Carbide tool insert and the plain ceramics carbides tool inserts and uncoated HSS. The uncoated tungsten carbides was excluded.

Equipment

The equipment used were;

a) CNC Hitachi Seiki Lathe Machine VC 500
b) Surface roughness measurement machine –Rank Taylor Hobson
c) Digital Blue QX5 Microscope
d) Tool inserts

The tool inserts had the following features which were standard pre-requisite for turning mild steel;

- Corner Radius (Rε) =0.8 mm
- Length (L) = 10 mm
- Rake Angle = 5^0

- Relief/ Flank Angle = 5^0

The coated TiN tungsten carbide inserts surfaces were prepared for coating in accordance with BS EN ISO 8503-2:2012(E) (*surface roughness characteristics of blast-cleaned substrates*). The tools were coated with TiN by the physical vapour deposition (PVD) process to a thickness of approximately 4 μm under vacuum at a workpiece temperature of about 480 ^{0}C

Procedure for Experiment

The tools were fixed rigidly in the tool holder and the work piece aligned and clamped appropriately to eliminate vibration as much as possible. Coolant supply was set at the appropriate pressure of 50 psi following advice from the machine operator/ technician. The Coolant spray nozzles were set in two locations (A and B) as illustrated in figure 1 below to help dissipate heat and wash away debris
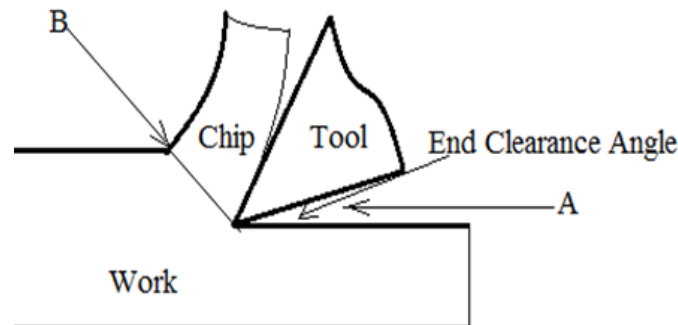

Figure 1: Location of Coolant Nozzles

In order to determine the tools wear patterns, the wear criteria ISO 3685: KB, KT, KI, KM, VC and VN were used. Typical wear patterns of metal machining using single point toolsare;Crater wear, flank wear, and depth-of-cut notch wear. Wear for High speed steels, carbide and ceramics tools, are standardized in ISO 3685 [23]. These wear patterns is illustrated in Fig. 2. The cutting tests were carried out on a Hitachi Sehiki CNC Lathe Machine with a constant surface speed programmed. The cutting parameters were:

- Cutting speed (Vc): 300 m/min
- Spindle speed: 1485 rpm
- Feed rate (f): 0.37 mm/rev
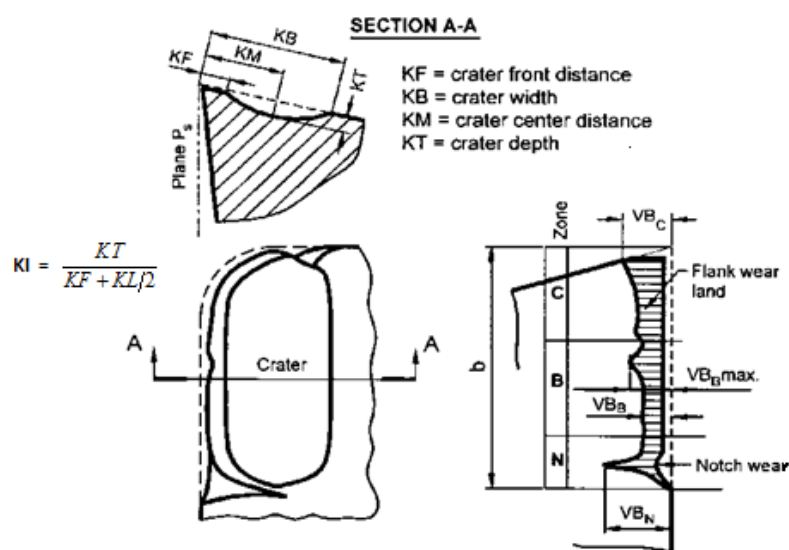- Length of cut: 200 mm
- Depth of cut (d): 1 mm

Figure 2: Typical Wear Patterns as defined by ISO: 3685 [24]

Key:
  i.   *Region A* is the quarter of the worn cutting edge length *b* farthest away from the tool,
  ii.   *Region B* is the remaining straight part of the cutting edge in zone C,
  iii. *Region C* is the curved part of the cutting edge at the tool corner,
  iv.   *Region N* extends beyond the area of mutual contact between the tool and workpiece for approximately 1 – 2 mm along the major cutting edge. The wear is of notch type.

The wear was measured using a toolmaker's microscope (with video imaging systems) and a resolution of less than 0.001mm was set.

The workpiece material was mild steel EN-1A in the form of 75 mm diameter round bar billets. Fifteen minutes of cutting were carried out for each insert at the speeds investigated. Conventional tool inserts normally have a tool life of approximately 15 minutes of cutting. After every five cuts (passes) microscopic pictures of the tool wear profiles were examined under Digital Blue QX5 Microscope and the pictures were taken, in order to monitor the progressive wear on the rake face and on the flank of the insert. The power load was monitored for each cut taken using an on-board meter on the CNC machine to establish the amount of power needed for each stage of operation. The spindle drive for the machine is an 11 KW/hr motor. Concurrently, the work billet was removed from the machine and the surface roughness measured at 0.8 mm cut (λ_c) off length. The following conditions were set as standard;
  i.   Coolant pressure /supply was set at 50 psi and kept constant in the same way for all the cutting experiments.
  ii.   An angle was machined at the end of the cut length to facilitate easy ejection of the swarf.
  iii. Swarf was cleared after each cut/pass.
  iv.   Any built-up-edge on the insert was cleared prior to taking pictures.

The authors decided to use direct method of measuring the tool profile because of the limitations of available equipment. This direct measurement techniques managed to determine the tool condition by analysing the change in geometry of the cutting tool. Usually these techniques can be taken only between two sequential machining runs, because the major flank of the tool is not visible during actual machining operation. Otherwise, there are other indirect measuring techniques, whereby, tool wear is estimated using more measurable machining process variables such as cutting force, surface finish, acoustic emission, vibrations, energy consumption, and temperature [8]. A literature survey indicates that a variety of approaches have been applied to tool wear prediction [9-11]. All in all, the procedure was perfect and produced reliable results.

Observed Results
The results presented here are for the plain ceramics carbides inserts, HSS and the coated TiN coated tungsten carbide tool inserts. The uncoated tungsten carbide was excepted from the analysis because the authors did not see any remarkable different features to report about.

Results for Plain Ceramics Carbides
It is common knowledge that tool failure occur when the tool no longer produces components with the desired dimensions and surface finish. Our study, encountered a scenario where the tool cutting edge chipped. This happened with the plain ceramics carbides inserts as seen in figures 3(a & b) below.
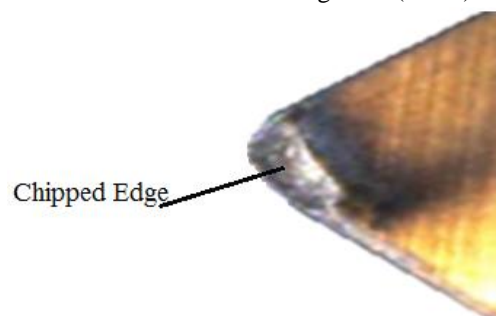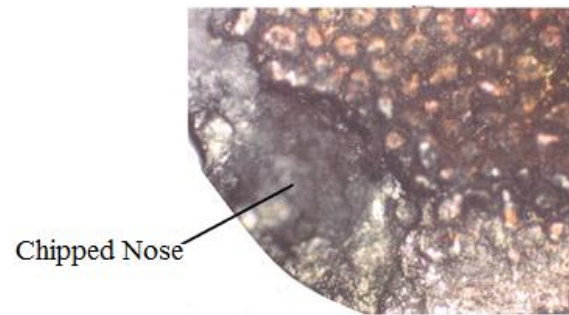

Figure 3(a): Chipped Tip of Plain Carbide Too insert 80x

Figure 3(b): Chipped Tip of Ceramic Carbide Tool Insert 100x

Armarego and Brown (1965) defined total tool failure as the complete removal of the tool cutting edge, a condition that arises when catastrophic failure occurs [12]. Tool chipping in metal machining is undesirable as it can damage the work surface considerably rendering the component to be a reject or in a few cases requiring a re-work. In this case work surface measured was 3.5 µm which is really rough.

Results for Uncoated HSS

The test results of on HSS indicated three things; thermal softening of the tool, plastic flow and pronounce marks of gouging effects left by the swarfs on the tool rake face in the form of groove. The effect of the swarfs is shown in figure 4below.
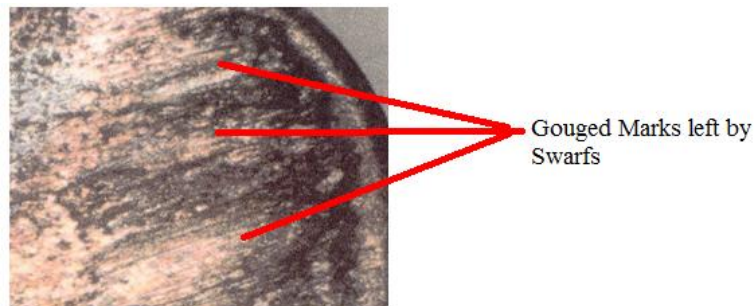

Figure 4: Gouging Effects left by the Swarfs

The tool-wear pattern on worn grooved tool insert is influenced by the three-dimensional chip-flow which confirms the complex chip-groove configurations studied by Ee, K.C.*et al,*(2003)in their work on tool failure criterion [13]. In fact, grooved tools demonstrate tool-failure as a result of concurrent multiple tool-wear parameters which is an indication that the tool-wear is affected by the combined effects of cutting conditions and the chip-groove configuration [14]. The work surface measurement readings was 3.9 µm which is rough an indication that the tool is not good.

For HSS, the room temperature hardness is strongly dependent on the heat treatment. However, for cutting tool applications, the hardness at elevated temperatures, i.e. hot hardness, is of greater significance [15]. It is worth noting that for HSS there is a continuous gradual decrease in hardness with increasing temperature up to the tempering temperature of approximately 600 ^{0}C [16]. Above this point, the decrease is relatively steep.

Results for TiN Coated Tungsten Carbide

Results for the TiN coated Tungsten Carbide inserts showed long tool life. As stated earlier in section 3.0 conventional tools have tool life of approximately 15 minutes of cutting at velocity of about 250 m/min. This study recorded tool life of 20 minutes for the TiN coated tungsten carbide inserts at cutting velocity (*Vc*) of 300 m/min which was the investigated speed. The work surface finish still remained good at 2.5 µm and the tool had just shown slight signs of wear. The small signs of groove beginning to develop can be clearly seen on the rake face of the tool in figure 5 below.
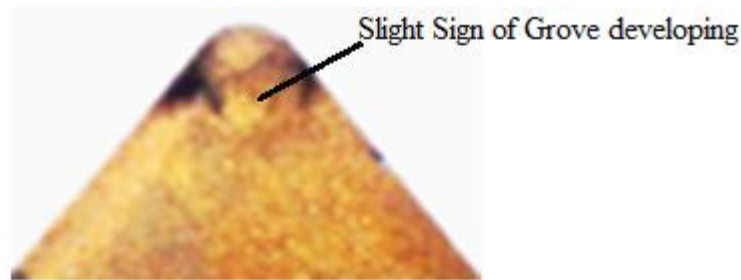
Figure 5: TiN Coated Tungsten Carbide insert after machining for 25 minutes

The additional feature identifiable is the dark burnishing marks left by heat generated between tool-work interfaces. The temperature at this point is very high but is kept controlled by the constant supply of coolant spray as discussed in section 3.0. The long life enjoyed by TiN coated inserts was based on the titanium nitride physical properties and chemical stability.

TiN Physical Properties

In most literature, 'TiN is often considered to play the role of a thermal barrier, protecting the heat-sensitive tool substrate from thermal softening' [17-19].Table 1gives the thermal conductivity of TiN and for HSS. A simple temperature distribution analysis was performed by Hedenqvist, Olsson and Söderberg (1988) [20] by applying FEA for a tool surface temperature of 600 ^{0}C using the parameters as given in the Table. Their results showed that the maximum equilibrium temperature of the substrate was reduced by less than 5 ^{0}C by the addition of a TiN coating of 5μm thickness. This clearly demonstrates that TiN acts as a thermal barrier.

Table 1: Physical Properties of TiN and HSS

Parameters	TiN	High Speed Steel (HSS)
Density (g cm^{-3})	5.2–5.44	8.16–8.26
Melting temperature (^{0}C)	2948 ± 50	1450–1500
Thermal Conductivity	24 (400 K)	16.8–23.9 (300 K)
(W m^{-1} K^{-1})	67.8 (1773 K)	25.1–28.5 (773 K)

Source: Hedenqvist*et al,* (1988) [18]

(Paper: How TiN coatings improve the performance of HSS cutting tools, International Journal of Surface and Coating Technology. 41 (1990) pp.243-256)

TiN Chemical Stability

Tool life tests by other scholars revealed that TiN coated inserts exhibit longer life even when the coating has been partially removed, e.g. by edge wear or by regrinding, a prolonged tool life is still obtained [20-21]. To explain this fact Kassman*et al.* (1989) tried to prove the presence of a 'smearing mechanism' through an atomistic wear process, TiN material was assumed to be continuously transferred from the coated region of the edge on to the uncoated, thereby modifying the contact conditions and reducing the wear rate [22].

Comparison of TiN and HSS Mechanical Properties

The mechanical properties of TiN and HSS are given in Table 2. As can be seen the available data indicates that the Young's modulus of TiN is higher than that of HSS, indicating a stiffer behaviour. As for most ceramics, the Young's modulus of TiN is expected to decrease with increasing temperature. The mismatch in thermal expansion between TiN and HSS is of importance since it will cause thermal stresses, which may influence the performance of the coating.

Table 2: Mechanical properties of TiN and HSS at room temperature

Parameters	TiN	HSS
Young's Modulus (GPa)	251 – 616	229 – 237
Thermal expansion (K^{-1})	8 x 10^{-6}	8.4 – 10.7 x 10^{-6}
Hardness (HV)	2,000 – 2,500	700 – 1,000

Source: Hedenqvist*et al.* (1988) [18]

(Paper: How TiN coatings improve the performance of HSS cutting tools, International Journal of Surface and Coating Technology. 41 (1990) pp.243-256)

Conclusions

The overall performance of plain ceramics carbides and the HSS inserts is on the whole poor. It was evident that after only 10 minutes of cutting which equates to 25 cuts/ passes (note that the machine would be stopped for clearing swarfs from the work and tool), a substantial wear land becomes visible on the rake face and the flank of both the plain ceramics carbides and HSS specimens. It is to be noted that this observation was consistent for all two types of specimens tested. The plain ceramics carbides then chipped after 12 minutes of machining. The surface finish on the workpiece was consistently bad for both types of inserts. It was clear that the wear on workpiece machined by the plain ceramics carbide specimen was marginally higher which can be attributed to the higher friction which caused the fracture/chipping.

Oxides within the work material and other intermetallic compounds can be as hard as the constituents of the deforming or cutting tool. This means the abrasive wear by gouging becomes a competition between tool and workpiece whenever the lubricant fails to ensure complete separation of the interface [1]. According to Schey particles embedded in the workpiece material become particularly damaging when they receive strong support from a matrix that is almost as hard as the particle itself thus gouging ensues.

The TiN coating on the Tungsten carbide surfaces is visibly held for a much longer duration of cutting and that protected the substrate from frictional heat and made the tool to last longer. Results obtained confirmed the advantages of cutting at all speeds investigated using TiN coated inserts, in terms of reduced tool wear and low power loads. It is presumed therefore that the TiN coating protected the substrates from gouging effects. Thus abrasive wear could be avoided by coating cutting tools.

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