Influence of cutting speed on coated TiCN cutting tool during turning of AISI 316L stainless steel in dry turning process

A M Zaharudin¹, S Budin¹

¹Faculty of Mechanical Engineering, Universiti Teknologi MARA Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia

Email: aznifa@ppinang.uitm.edu.my

Abstract. Coated Titanium Carbon-Nitride (TiCN) cutting tools are widely used in the industry to improve the surface quality, tool life and wear resistance because of its high hardness, superior chemical properties and thermal stability. In this work, coated TiCN was used for turning of AISI 316L stainless steel. The rotating cutting speeds selected in the experiments were 185, 415 and 660 rpm. It is observed that the surface roughness of the workpiece decrease while the wear rate increases of the cutting tool with the increasing of rotational cutting speed. TiCN coating not only ensure the cutting tools is wear resistance, but also ensure that the surface quality is maintained during cutting process.

1. Introduction

The selection of cutting tool materials is the most important factor in the machining operations. A cutting tool must possess certain characteristics such as the ability to withstand high temperatures, high contact stresses as well as rubbing along the tool-chip interface and machine surface in order to produce good quality result. The first characteristic is hot hardness where the cutting tool should maintain its hardness, strength and wear resistance at a high temperature in the machining operations. This property ensures that the cutting tool does not experience any plastic deformation, hence maintains its shape and wear resistance. Furthermore, the cutting tools should resist the impact of forces due to vibration and chatter without chipping or fracture. The thermal shock resistance also needed to overcome the rapid temperature cycling encountered during cutting process.

Tungsten carbide has been well famous cutting tool for the best performance, high hardness, and strength and wears resistance. Tungsten carbide (WC) typically consists of tungsten-carbide particles bonded together in a cobalt matrix. The amount of cobalt acts as improver toughness so the brittle fracture can be avoided. Tungsten carbide particles combine with the cobalt, resulting in a composite material with a cobalt matrix surrounding the carbide particles. The toughness of WC increases as the high toughness of cobalt while the wear resistance WC decreases as the carbon content increases [1].

Stainless steel is a material which has rapidly become widespread in industry nowadays. The demand in stainless steel components mainly in machining parts are increasing due to it wide application of uses. This material is used in a variety of applications as it resists corrosion excellently, can be used from low to high temperatures environment, is easy to deform and has a pleasant aesthetic appearance. The major factors that affect the machinability of stainless steel are its low thermal conductivity and the presence of strengthening elements such as chrome, nickel and molybdenum in its chemical composition. Among the austenitic stainless steel, AISI 316L has good mechanical properties because it contains low carbon and has a very high immunity from grain boundary carbide precipitation. The industry predominantly uses 316L stainless steels in the oil and gas and chemical industries. AISI 316L
stainless steel used as the workpiece material are generally more challenging to machine than standard carbon steel and a general rule is that the higher a steel’s alloying content, the more difficult it is to machine. When machining stainless steels, it is important to use the suitable tools that are designed for stainless steel. Commonly cutting tools used for machining stainless steels is either high speed steel (HSS) (wrought or sintered) or cemented carbide tools [2].

TiCN display an exceptional combination of high temperature hardness, strength, wear resistance, chemical stability, thermal conductivity and also this material commonly used for semi finishing and finishing operations on steel and cast iron [3, 4]. Commonly problems faced for high hardness cutting tools are poor surface finish and high tool wear [5]. Controlling the process parameter in machining especially in turning process is being a main issue in obtaining high surface quality. The fabrication of stainless steel components using machining process is still beyond satisfaction due to high material properties such as, high ductility and non-corroded steel which related to low machinability. This situation creates a demand in investigation of cutting tool with improved strength and hardness materials. Therefore, this study compare the machinability between uncoated tungsten carbide - cobalt (WC-Co) and coated titanium carbon nitride (TiCN) cutting tool to machine AISI 316L stainless steel components.

2. Methodology
The machined material were cylindrical billets of a AISI 316L stainless steel, approximately 200 mm long and 50 mm in diameter. Uncoated WC-Co and coated TiCN (TNMG 160408 designation) cutting tool inserts was clamped in the tool shank of GH-1860ZX geared head precision lathe. A range of cutting parameters were selected, rotational speed, \(N = 185, 415\) and 660 rev/min, feed rate, \(f = 0.2\) mm/rev, depth of cut, \(a_p = 0.5\) mm. The machining process was operated for 30 cycle times of turning on lathe machine. The experiments were carried out under dry cutting condition.

Portable surface roughness SJ-210 Surftest was used to measure the surface roughness, \(R_a\) of the workpiece. The wear rate, \(WR\) of the cutting tool is computed as follows:

\[
WR = \frac{mfN}{L\rho}
\]  

(1)

where \(m\) is the mass (g), \(\rho\) is the density which is in g/cm³ of the cutting tool insert, \(L\) is the length of the workpiece material (mm), while \(f\) is the feed rate (mm/rev) used and \(N\) is the rotational speed (rev/min). The tool life of the insert is described as the life span of cutting tool insert needs to be perfectly machining the workpiece. In this work, the adjustable tool life determined by using the equation 2.

\[
Adjustable\ tool\ life\ (min) = \frac{0.3}{V_B}t
\]  

(2)

0.3 mm is the basic or recommended criteria used for the average width of the flank wear to determine the tool life of the insert in turning operation. \(V_B\) is the flank wear value of the insert and \(t\) is the machining time. \(V_B\) was measured using the Scanning Electron Microscope (SEM).

3. Results and discussion
Surface quality is one of the most important customer requirements in machining of parts. The major indication of surface quality on the machined parts is the surface roughness value. Figure 1 shows the experimental results of the surface roughness of the workpiece. Uncoated WC-Co cutting tool was observed to have a lower value of surface roughness compare to coated Titanium Carbon Nitride (TiCN) cutting tool. Generally, it was observed that increasing of the rotational cutting speed will decrease the surface roughness values or improved the surface finish quality of the workpiece in turning operation. The surface roughness of the workpiece decrease gradually between 185 and 415 rev/min, from 6.37 to 2.85 µm while between 415 and 660 rev/min showed slightly decreased from 2.85 to 1.79 µm for coated Titanium Carbon Nitride (TiCN) cutting tool. The surface roughness of the stainless steel is become smoother when the rotational cutting speed is increased while the feed rate and the depth of cut remains...
constant. The results show that rougher surface obtained during low cutting speed and the smoother surface were achieved at high cutting speed. As the cutting speed increased to 600 rpm, the high repetition movement between the nose radius and workpiece material, generated more sliding contact and frictions, apparently generated high cutting temperature. During machining, graphite flake being pulled out by the shearing force from the cutting tool and formed small fragmented particle debris. This fragmented debris trapped between the cutting tool insert and workpiece and formed a thin film when reacted with high temperature [6]. Such film layer react as a lubricant to protect the machined surface from thermal effect and frictions. This resulting better surface finish under parameters investigated. The finding is consistent with findings of past studies [7][8]. Ibrahim Ciftci [7] in his research stated that for the austenitic stainless steels (AISI 304 and AISI 316) using chemical vapor deposition (CVD) multilayer coated carbide tools, the surface finish values decrease until a minimum value with the increasing of cutting speed. This trend are usually related to the built-up-edge (BUE) where the formation of a BUE is favoured in a certain range of cutting speed. BUE will be eliminated and the surface finish will improve as a result of increasing cutting speed beyond this region [9].

Figure 2 compares the wear rate of uncoated and coated cutting tool insert with increasing of rotational cutting speed. The wear rate for the coated TiCN shows lower value compared to uncoated cutting tool. For uncoated cutting tool, slightly increased of wear rate was observed between 185 and 415 rev/min, from 0.56 to 0.83 mm³/Nm. However, the wear rate increased dramatically about 138.55% between 415 and 660 rev/min. The wear rate become the highest value 1.98 mm³/Nm at 660 rev/min compared to the other variation of the cutting speed. When machining at low cutting speed, tool wear rate increased moderately due to less rubbing action between cutting edge and workpiece. The more contact stress of cutting tool can contribute to the developing of heat on the material workpiece. As cutting speed increased the wear rate increase drastically due to more heat generated between the cutting tool edge and workpiece. The coated TiCN shows only slightly increased in the wear rate from 185 to 660 rev/min. The trend is consistent with the study reported by Amin et al. [10] and Gu et al. [11]. Amin et al. [10] found that the increased of temperature in the cutting zone promotes the wear rate of the cutting tool insert. In addition, according to Gu et al. [11] the heat are generated as the byproduct of frictional force created between the surface of the cutting tool and workpiece. This influence the removal of certain volume from the cutting tool as the temperature reduces the hardness of the cutting tool insert by altering the hardness matrix of the cutting tool itself. This accelerates the abrasion capability of removing material from cutting tool. The effects of heat towards the cutting tool are rapid tool wear, BUE and plastic deformation. The result relates to the findings by Arsecularatne et al. [12] where the tool wear is found to be significantly influenced by the increased in temperature. More heat is generated between the edge and machined surface with increased the cutting speed.

![Figure 1. Variation of surface roughness, Rₐ of workpiece with cutting speed.](image-url)
Figure 2. Variation of wear rate of the cutting tool insert with cutting speed.

Generally, tool life of cutting tool insert is depends on the workpiece material and cutting parameters especially rotational cutting speed which is mainly focused in this study. Tool wear is one of the fundamental elements to determine tool life that is inversely proportional to it. In addition, surface roughness and tool fracture or excessive chipping also affect the tool life. In this work, the tool life (maximum allowable machining time) is calculated from the flank wear, $V_B$ as the wear is the most visualize wear on the cutting tool insert plus it is the most commonly used parameter to calculated the tool life (equation 2). The crater wear or nose wear are not considerably taken to calculate the tool life because these wear occurred on a very small scale in this study. Table 1 shows the experiment results used to calculate the tool life.

Figure 3 shows the tool life after turning 316L stainless steel under the dry cutting condition. The plotted graph shows that the increased of the cutting speed display the decreased in the tool life. As illustrated in the figure 3, the pattern of the graphs show that the tool life is effected by cutting speed on turning operation. It is clearly seen that the tool life of the TiCN cutting tool insert is higher at the lowest cutting speed (185 rev/min) compared to the tool life when using the 660 rev/min cutting speed. The maximum tool life is found at a low cutting speed. The graph shows the cutting speed proportional to tool life, as pointed out by Elmunafi et al. [13]. This condition is due to the high contact stress between cutting edge and machined surface at low cutting speed. This condition further developed flank wears. As a cutting speed increased, the development of temperatures is high enough to give impact on the wear processes. The flank wear, $V_B$ increases from low cutting speed to high cutting speed and indicated that wear curves is influenced by a large temperature requirement. The heat generated is higher and it has the tendency of the cutting tool to increase wear as the cutting speed increases. The researchers also have found that the tool life depends on the machine tool, tool material and geometry, work material and cutting conditions. In addition, Krolczyk et al. [14] was observed that the effectiveness was higher when turning operation occurred in the dry condition.

| Cutting speed (rev/min) | Uncoated tool Flank wear, $V_B$ (mm) | Coated TiCN tool Flank wear, $V_B$ (mm) | Uncoated tool machining time (min) | Coated TiCN tool machining time (min) |
|------------------------|-------------------------------------|----------------------------------------|-----------------------------------|-------------------------------------|
| 185                    | 0.100                               | 0.100                                  | 5.405                             | 5.410                               |
| 415                    | 0.125                               | 0.115                                  | 2.410                             | 2.410                               |
| 660                    | 0.220                               | 0.180                                  | 1.515                             | 1.670                               |
4. Conclusions
Producing a better surface finish at low to high cutting speed is essential in metal cutting. The surface finish of AISI 316L stainless steel work piece, wear rate and tool life of uncoated and coated TiCN insert in turning of stainless steel was investigated. The higher the cutting speed applied produced a smoother surface finish for the workpiece. Cutting speed have affected the wear rate, the flank wear length and tool life of the cutting tool insert.

As the cutting speed increased, the wear rate increased practically while the increment in the cutting speed caused the decreasing on the surface roughness of the work material. The results shows that the surface quality of the work material become smooth even though the wear rate increase and tool life decrease. The changing of the cutting speed, whether increase or decrease, will gives a significant impact to the results of tool wear and tool life of uncoated and coated TiCN cutting tool and also to the surface finish quality of AISI 316L stainless steel work material.

Acknowledgments
This research financial was supported by Ministry of Science, Technology and Innovation, Malaysia (MOSTI) with Sciencefund grant No. 06-01-01-SF0702. The author would like to thank Universiti Teknologi MARA and SIRIM Berhad for providing research and characterization facilities.

References
[1] Zhang L, Chen S, Cheng X, Wu H P, Ma Y and Xiong X J 2012 Effects of cubic carbides and La additions on WC grain morphology, hardness and toughness of WC-Co alloys Transactions of Nonferrous Metals Society of China (English Edition) 22 1680–85
[2] Jianxin D, Jiantou Z, Hui Z and Pei Y 2011 Wear mechanisms of cemented carbide tools in dry cutting of precipitation hardening semi-austenitic stainless steels Wear 270 520–27
[3] Canteli J A, Cantero J L, Marín N C, Gómez B, Gordo E and Miguélez M H 2010 Cutting performance of TiCN–HSS cermet in dry machining Journal of Materials Processing Technology 210 122–28
[4] Manoj Kumar B V, Kumar J R and Basu B 2007 Crater wear mechanisms of TiCN–Ni–WC cermets during dry machining Int. Journal of Refractory Metals and Hard Materials 25 392–99
[5] O’Sullivan D and Cotterell M 2002 Machinability of austenitic stainless steel SS303 Journal of Materials Processing Technology 124 153–59
[6] Fatin, M. N., Hadzley, A. M., Izamshah, R. A. R., & Amrand, M. A. 2018. An Experimental
Study of Wear Mechanism on High Speed Machining of FC300 Gray Cast Iron Using TiAlN Coated Carbide Cutting Tool Applied Mechanics and Materials 761 257–61

[7] Ciftci I 2006 Machining of austenitic stainless steels using CVD multi-layer coated cemented carbide tools Tribology Int. 39 565–69

[8] Korkut I, Kasap M, Ciftci I and Seker U 2004 Determination of optimum cutting parameters during machining of AISI 304 austenitic stainless steel Materials and Design 25 303–5

[9] Gokkaya H and Taskesen A 2008 The effects of cutting speed and feed rate on Bue-Bul formation, cutting forces and surface roughness when machining Aa6351 (T6) alloy Journal of Mechanical Engineering 54 521–30

[10] Nurul Amin A K M, Ismail A F and Nor Khairusshima M K 2007 Effectiveness of uncoated WC-Co and PCD inserts in end milling of titanium alloy-Ti-6Al-4V Journal of Materials Processing Technology 192–193 147–58

[11] Gu J, Barber G, Tung S and Gu R-J 1999 Tool life and wear mechanism of uncoated and coated milling inserts Wear 225–229 273–84

[12] Arsecularatne JA, Zhang LC and Montross C 2006 Wear and tool life of tungsten carbide, PCBN and PCD cutting tools Int. Journal of Machine Tools and Manufacture 46 482–491

[13] Mohamed Handawi Saad Elmunafi, Noordin MY and Kurniawan D 2015 Tool life of coated carbide cutting tool when turning hardened stainless steel under minimum quantity lubricant using castor oil Procedia Manufacturing 2 563–67

[14] Krolczyk GM, Nieslony P and Legutko S 2013 Determination of tool life and research wear during duplex stainless steel turning Archives of Civil and Mechanical Engineering 15 347–54