PERFORMANCE EVALUATION OF COATED CARBIDE CUTTING TOOLS WHEN TURNING HARDENED TOOL STEEL

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To my beloved parents and sister

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ABSTRACT

Hard turning is a more economical technology that is developed to substitute grinding in the finishing operations of hardened material (HRC 45 and above). However, the potential of this technology is limited due to the high cost of ceramics and cubic boron nitride (CBN) cutting inserts. In order for hard turning to be truly viable, the performance of more economical cutting tools must be justified. This research project was undertaken to investigate the performance of KC 5010 physical vapor deposition (PVD) titanium aluminium nitride (TiAlN) conventional and wiper geometry inserts during finish hard turning of Stavax Electro-Slag-Refining (ESR) stainless tool steel (HRC 47 - 48). Tool performance, tool failure modes and wear mechanisms were investigated under various cutting conditions. Machinability parameters namely tool life and surface roughness were evaluated. Response surface methodology (RSM) was used to model the relationship between the response of interest (tool life and surface roughness) and several variables (cutting speed and feed rate) for the conventional insert. It was found that flank wear near the nose in the minor flank region of the insert was the main wear form found on KC 5010 inserts as crater wear was not severe. The wear mechanisms responsible were mainly abrasion and adhesion. At high cutting speed (170 m/min), there was a strong tendency for the tools to fail catastrophically. Wiper geometry inserts were capable of producing better surface finish compared to conventional geometry inserts but with a shorter tool life for similar cutting conditions. The tool life and surface roughness models developed for conventional inserts were found to be statistically valid and adequate to predict the machining responses under certain cutting conditions. Only minimal discrepancy was found between the predicted and actual values. Based on this analysis, hard turning with coated carbide conventional and wiper geometry inserts is indeed promising.

ABSTRAK

Larik keras merupakan satu teknologi ekonomik yang dibangunkan sebagai alternatif kepada proses pencanaian untuk pemesinan kemasan keluli keras (HRC 45 ke atas). Walau bagaimanapun, potensi teknologi ini agak terbatas disebabkan oleh kos mata alat seramik dan boron nitrida kiub yang tinggi. Bagi memastikan teknologi larik keras benar-benar sesuai, kesesuaian penggunaan mata alat yang lebih ekonomik perlu disiasat. Kajian kerja ini bertujuan untuk menguji prestasi dan kelakuan mata alat konvensional dan "*wiper*" KC 5010 karbida yang disaluti titanium aluminium nitrida melalui proses deposit wap fizikal semasa larik keras kemasan keluli tahan karat "*Stavax Electro-Slag-Refining*" (HRC 47 - 48). Prestasi mata alat, mode tamat hayat dan mekanisme kehausan mata alat dikaji pada pelbagai parameter pemotongan. Parameter kebolehmesinan iaitu jangka hayat mata alat dan kualiti permukaan larik benda kerja melalui ukuran kemasan permukaan turut diperiksa. "*Response surface methodology*" digunakan untuk mendapatkan hubungan statistik di antara hasil keputusan pemotongan (jangka hayat dan kualiti permukaan) dan beberapa pembolehubah (halaju pemotongan dan kadar uluran) untuk mata alat konvensional. Hasil kajian menunjukkan kehausan rusuk di bahagian puncak penyayat samping merupakan bentuk kehausan utama pada mata alat KC 5010 di mana "*crater wear*" tidak teruk. Mekanisme yang mengakibatkan kehausan mata alat ialah "abrasion" dan "adhesion". Pada kelajuan pemotongan tinggi (170 m/min), didapati "*catastrophic failure*" mudah berlaku. Mata alat "wiper" berupaya menghasilkan kualiti permukaan yang lebih baik berbanding mata alat konvensional tetapi jangka hayat mata alat adalah lebih pendek untuk parameter pemesinan yang sama. Model jangka hayat dan kualiti permukaan bagi mata alat konvensional didapati sah dari segi statistik dan ramalan sahih dapat diperolehi. Berdasarkan kajian ini, disimpulkan bahawa larik keras menggunakan mata alat karbida bersalut konvensional dan "*wiper*" adalah berpotensi.

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LIST OF SYMBOLS AND ABBREVIATIONS

AISI	-	American iron and steel institute
ANOVA	-	Analysis of variance
b	-	Shank width
BL	-	Length of groove backwall wear
BUE	-	Built-up-edge
BW	-	Width of groove backwall wear
C	-	Constant in tool life equation
CBN	-	Cubic boron nitride
CVD	-	Chemical vapor deposition
d	-	Depth of cut
et al.	-	and others
EDAX	-	Energy dispersive analysis by X-ray spectroscopy
ESR	-	Electro-Slag-Refining
f	-	Tool feed rate
FN	-	Finishing negative
FW	-	Finishing wiper
h	-	Shank height
HRC	-	Hardness Rockwell C
HSS	-	High speed steel
HTMF	-	Hard turning with minimal fluid
ISO	-	International Organization for Standardization
KB	-	Crater width
KI	-	Crater index

KM	-	Crater center distance
KT	-	Depth of the crater or depth of groove backwall wear
l	-	Tool length
MT-CVD	-	Medium temperature chemical vapor deposition
n	-	Slope of the tool life curve
N	-	Nose wear
PCBN	-	Polycrystalline cubic boron nitride
PCD	-	Polycrystalline diamond
PVD	-	Physical vapor deposition
r	-	Tool nose radius
RSM	-	Response surface methodology
SAE	-	Society of automotive engineers
SD	-	Depth of secondary face wear
SEM	-	Scanning electron microscope
SW	-	Width of secondary face wear
T	-	Tool life
TiAlN	-	Titanium aluminium nitride
TiC	-	Titanium carbide
TiCN	-	Titanium carbon nitride
TiN	-	Titanium nitride
V	-	Cutting speed
Al_2O_3	-	Aluminium oxide
C_e	-	End cutting edge angle
C_s	-	Side cutting edge angle
CH_4	-	Methane
F_c	-	Cutting force
F_r	-	Radial force
F_t	-	Thrust force
MoS_2	-	Molybdenum disulfide
NL_1	-	Notch wear length on main cutting edge
NL_2	-	Notch wear length on secondary cutting edge

NW_1	-	Notch wear width on main cutting edge
NW_2	-	Notch wear width on secondary cutting edge
R_a	-	Arithmetical mean surface roughness
R_t	-	Peak-to-valley height of the surface profile
Si_3N_4	-	Silicon nitride
TCl_4	-	Titanium chloride
VB_B	-	Average width of flank wear land in zone B
$VB_{B\ max}$	-	Maximum width of the flank wear in zone B
VB_C	-	Average width of flank wear land in zone C
$VB_{C\ max}$	-	Maximum width of the flank wear in zone C
α_b	-	Back rake angle
α_s	-	Side rake angle
θ_e	-	End relief angle
θ_s	-	Side relief angle

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CHAPTER 1

INTRODUCTION

Machining which includes turning is one of the most versatile processes in the manufacturing industry for processing, shaping or cutting various types of workpiece materials. The trend in the industry today is towards near net shape manufacturing. In turning of hardened material, this is known as finish hard turning or simply as hard turning. Previously, near net shape manufacturing of hardened material by turning is not possible and often secondary processes such as grinding or lapping are required. Parts are cut to a size close to the final dimension and shape before being heat treated and finish ground to the final dimension. However, with the advances in cutting tool materials, hard turning is able to be conducted with either cubic boron nitride (CBN) or ceramic tools which are of higher cost. The advances in tool coating technology allow for the investigation of the use of lower cost coated carbide tools which will results in significant economic savings.

1.1 Background

The investment in metal machining increases yearly despite the development of thermoplastics and near net processes or modern machining processes such as ultrasonic machining, chemical machining and electrical discharge machining (Childs *et al.*, 2000). This phenomenon is mainly due to the capability of machining to achieve high precision and complicated free-form shapes at a reasonable cost which is unrivalled by other processes. At the same instance, metal machining has undergone advances in machine tools and tool materials to keep pace with the current requirements such as better surface finish and higher hardness materials.

A good surface finish can lead to longer service life and improved efficiency of the engineering component. Previously, this can only be done by secondary processes such as grinding. However, the idea today is to eliminate this step by replacing it with finish hard turning which is capable of producing a similar surface roughness. Finish hard turning is a process in which hardened steels with hardness Rockwell C (HRC) 45 and above are finish turned. Such hardened steel especially stainless tool steel has wide applications in the mold and die industry. This is mainly due to the properties of the material that has good corrosion resistance, polishability, wear resistance, machinability, stability in hardening and high surface finish. The roughness average, R_a value to be achieved in finish turning is 1.6 μm and below. This value is consistent with the requirement found on many engineering drawings. Gillibrand *et al.* (1996) performed the turning of medium carbon steel with this criterion in mind and found that titanium nitride (TiN) coated carbide tools gave an improvement in tool life of between 250 and 300 percent, during finish turning, compared to uncoated carbide tools.

Titanium carbide (TiC) coated tool is one of the very first coated carbide tools introduced by Sandvik. Ekemar (1982) showed that TiC coated tool performs better than cemented carbide in terms of tool life and cutting forces when machining steel and cast iron. Sandvik then came up with the alumina titanium carbide coated cemented carbide a few years later. The tool consists of 6 μm of TiC and 1 μm of aluminium oxide (Al_2O_3). When machining steel, Ekemar (1982) has successfully used the insert at low as well as high cutting speeds. Colding (1982) demonstrated that the wear rate, cutting forces and cutting edge temperature are considerably lower in these coated tools compared to uncoated carbide. Kalish (1982) also obtain the same conclusions when the TiC coated inserts are compared to cemented titanium carbide during machining of AISI 1045 steel.

Hale and Graham (1982) investigated the crater and flank wear of Al_2O_3, TiC and TiN coated carbide tools when turning AISI 4340 steel (HRC 29). It was found that the crater wear increases significantly after the coating is penetrated due to increasing contact between the chip and the substrate material. The crater wear resistance is directly proportional to the thickness of the coating. The influence of coating thickness indicates that flank wear first increases with increasing coating thickness and then levels off at thickness greater than about 4 to 6 μm. Gates Jr. and Peters (1982) investigated the use of chemical vapor deposition (CVD) coatings when turning AISI 4140 steel of hardness values between HRC 30 and 32. It was found that multilayer coatings of Al_2O_3, TiC and TiN performed well with respect to flank and crater wear.

Lim *et al.* (1999) investigated the wear mechanisms of TiC coated carbide during dry turning of hot-rolled carbon steel. It was found that the mechanisms responsible for the wear of TiC coating on cemented carbide tools are discrete plastic deformation, cracking, attrition and abrasion. Perry *et al.* (1999) successfully tested physical vapor deposition (PVD) TiN coated carbides which have been subjected to pulsed intense electron beam treatments on 4130 steels with hardness value of HRC 15. It is shown that the flank wear is halved due to the treatment at low energy level. Prengel *et al.* (1997) demonstrated the superiority of high-ionization sputtered titanium aluminium nitride (TiAlN) coating during turning, milling and drilling of several workpiece materials. Jindal *et al.* (1999) evaluated ion-plated PVD TiN, titanium carbon nitride (TiCN) and high-ionization sputtered PVD TiAlN coated carbides in turning Inconel 718 (HRC 35.5), medium carbon SAE 1045 steel (HRC 17) and ductile iron (HRC 22.5) at low and high cutting speeds. It was found that TiAlN coated tools showed the best metal cutting performance followed by TiCN and TiN coated tools.

Che Haron *et al.* (2001) investigated the wear behavior of multilayer TiCN, Al_2O_3 and TiN coated carbide when turning tool steel with a hardness value of HRC 23. It was found that wear progression of carbide tools are generally in three stages: at the initial stage, followed by the gradual stage and finally the abrupt stage of wear. Noordin *et al.* (2001) evaluated the suitability of various coated carbide tools when finish turning AISI 1010 steel through cutting forces, microstructure and surface finish parameters. Noordin *et al.* (2004) in their study on the performance of coated carbide when turning AISI 1045 steel utilized response surface methodology (RSM). It was found that feed rate is the most significant factor in influencing the cutting force and surface roughness.

Many researchers investigated the advantages of using coated carbide as compared to uncoated carbide. Agrawal *et al.* (1995) also studied this aspect with stainless steel and found an increased in cutting forces when TiN coated carbide was used. However, Venkatesh (1984) demonstrated that TiN coated tools outperformed uncoated carbide during turning of mild steel. Kudapa *et al.* (1999) successfully used medium temperature chemical vapor deposition (MT-CVD) coated tools to machine AISI 4340 steel with a maximum hardness of HRC 32. This success is attributed to the increased edge toughness, smoothness and the absence of thermal cracks in the coatings. Pfouts (2000) identified that PVD coatings offer advantages over CVD in certain operations and workpiece materials such as titanium, nickel-base alloys and non-ferrous materials.

From the literature reviewed, coated carbide tools are commonly used for either conventional rough or finish turning of steels with hardness values of HRC 32 and below. The workpiece hardness value can be slightly higher with a chromium-based coating that serves as a thermal barrier (Scheerer *et al.*, 2005). Varadarajan *et al.* (2002) used multicoated hard metal carbide inserts for turning AISI 4340 steel with a hardness value of HRC 46. However, the experiments were conducted in hard turning with minimal fluid (HTMF) condition. The results showed a reduction in cutting forces and surface roughness and an increase in tool life. It is also noted that Kang *et al.* (2003) was able to use PVD TiAlN coated tool for die steel with a hardness of HRC 62 during high speed milling. Sharif *et al.* (2000) demonstrated that TiAlN coating outperformed uncoated tools during drilling of titanium alloy. In short, coating technology gives various combinations of materials and possibilities. It is clear that the major weakness of a cemented carbide tool is related to its lower toughness. Deshpande *et al.* (1996) tried to bridge this gap with high speed steel by experimenting with an iron-based binder for carbide. Preliminary testing had shown positive results when turning steel with hardness of HRC 20. It resulted in higher cutting speeds, longer tool life and better chipping resistance. The potential of using coated carbide tool for higher hardness workpiece is there but is yet to be explored.

Presently, ceramic and cubic boron nitride (CBN) cutting tools are widely used for finish turning of hardened workpiece material. Konneh (1997) successfully used alumina TiC based ceramic tool for finish turning of various tool steels. At higher hardness stainless tool steels of between HRC 45 and 50, Balakrishnan (2003) demonstrated the success in using whisker reinforced ceramic inserts which is normally applicable to nickel based alloys. The tool life constant was obtained as 0.7478 and reduced with increasing cutting speeds. Zhao *et al.* (1999) successfully tested silicon nitride (Si_3N_4) ceramic cutting tool material against stainless steel using pin-on-disk method. Venkatesh *et al.* (2000) found that a higher negative side cutting edge angle gave better surface finish and lower cutting forces when using alumina TiC based ceramic on tool steels. Kevin Chou and Song (2004) found that large nose radius gave finer surface finish with ceramic inserts when turning HRC 61 AISI 52100 steel.

Cubic boron nitride (CBN) inserts are commonly used to turn hardened steels of very high hardness values. Experiments conducted with high speed steel as workpiece showed that at this particular range of hardness, CBN inserts are superior compared to carbide as carbide inserts worn out rapidly. CBN is used to replace grinding to produce crankshaft in the automotive industry (Colding, 1982). Poulachon *et al.* (2001) identified a limiting value of hardness at HRC 50 with polycrystalline cubic boron nitride (PCBN) inserts where above this limit cutting temperature decreases but cutting forces increases. Kevin Chou (2003) obtained satisfactory results in terms of cutting forces and wear with CBN-low inserts during intermittent cutting of steel bars (HRC 62 to 64). Most researchers noted the formation of a white layer when machining hardened steel. According to Ramesh *et al.* (2005), this hard and brittle layer associated with tensile surface residual stresses is found to be detrimental to fatigue life.

It is interesting to note that the investigation of finish hard turning is limited to ceramic and CBN cutting tools although claims are made by various cutting tool manufacturers that certain coated carbide tools are suitable. In addition, there is also very limited research work done for wiper inserts for turning operation that is claimed to be able to produce the same surface finish at twice the normal feed rate. Only de Souza Jr. *et al.* (2005) investigated the use of PCBN wiper inserts during face milling of cast iron. This project is designed in such a way to investigate these claims. If they are proven to be true, this will be a breakthrough for carbide tools in hard turning.

The response surface methodology (RSM) approach that is proven to be successful in developing machinability models will also be undertaken to avoid one-factor-at-a-time study (Tan, 2003). Currently, most RSM works are done by Alauddin *et al.* (1996a) and are concentrated on the drilling and milling process. Alauddin *et al.* (1996b, 1997a and 1997b) made a lot of studies on the tool life, surface finish and cutting forces of the end milling process using RSM. Onwubolu and Kumar (2005) investigated the drilling forces using RSM approach. It is noted that with the exception of a few investigators, RSM is not widely used for modeling the performance of cutting tools especially for turning. However, response surface methodology is known to be useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response (Montgomery, 1991).

1.2 Problem Statement

Ceramic and cubic boron nitride (CBN) cutting tools or inserts are mainly used for hard turning of steels. These inserts performed relatively well but the associated cost is significantly higher. Coated carbide tools which are relatively lower in cost are seen as a possible replacement especially with the introduction of new coatings such as physical vapor deposition (PVD) titanium aluminium nitride (TiAlN). Furthermore, wiper inserts are also claimed to be able to produce the same surface quality at higher feed rate and better surface finish at a feed rate of the conventional insert.

Currently, there are no or little studies done to support these claims, particularly for the application of coated carbide in hard turning. This led to a strong and widespread resistance to the use of coated carbide during finish hard turning which is a waste of opportunity to reduce operation cost.

1.3 Objectives

The ultimate aim of this work is to evaluate the performance and behavior of physical vapor deposition (PVD) titanium aluminium nitride (TiAlN) cutting tool (KC 5010) during the finish hard turning of Stavax ESR stainless tool steel (HRC 47 to 48). The specific objectives of this project are:

1. To apply response surface methodology (RSM) in developing empirical machinability models which include tool life model and surface roughness model.
2. To investigate the performance of the insert at various cutting speeds and feed rates during hard turning.
3. To compare the performance of conventional and wiper inserts at various cutting speeds with the feed rate fixed at a certain value.

1.4 Scope

The scope of this project covers the following:

1. The study concentrates on the use of conventional PVD TiAlN coated carbide for hard turning. Wiper PVD TiAlN coated carbide inserts will only be used for comparison purposes.

2. The use of Stavax ESR stainless tool steel of hardness value between HRC 47 and 48 as the workpiece material.
3. The evaluation of the performance of the cutting inserts is limited to the tool life, tool failure modes, tool wear mechanisms and surface finish of the workpiece.
4. The use of Response Surface Methodology (RSM) to develop empirical machinability models.

1.5 Significance of the Study

It is expected that the results from this study would provide better understanding of the characteristics, performance and application of the conventional and wiper geometries of KC 5010 coated carbide inserts in the manufacturing industries particularly those involved in the machining of hardened materials and in the mold and die industries. Predictable tool performance will improve the productivity and minimizes tool cost. It is also hoped that grinding operations can be substituted by coated carbide turning at a significantly lower cost by reducing power consumption and cycle time. Furthermore, it is hoped that coated carbide inserts are capable of replacing ceramic inserts which are two to four times higher in cost. Last but not least, it is expected that this study will be useful towards achieving effective and economical machining processes.