Performance Evaluation of Carbide Tool Coated with TiCN/Al₂O₃/TiN in Turning Alloy Steel Under Eco-Machining Technique

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Abstract
The test results show tool life of multilayer ceramic (TiCN/Al₂O₃/TiN) CVD-coated carbide tool when using in high speed turning of AISI O1 steel with 240 HV under eco-machining technique is majority determined by the maximum flank wear on zone C and excessive chipping on tool nose region. The results are due to the geometry of cutting tool, mechanical and thermal wears. The use of oil-based cutting fluid in wet gives longer tool life and better surface roughness, Ra, than dry cutting (the eco-machining technique). This result is due to the presence of cutting fluid in supporting the advantages of coating materials. When tool rejection criteria are attained, higher surface roughness under wet cutting is resulted. The rough surface and abused feed marks are observed. They occur since excessive chipping on wet is worse than dry cutting due to the occurrence of thermal shock on the substrate (WC-Co).

Keywords: chipping, flank wear, dry cutting, surface roughness, subsurface alteration.

Introduction
Alloy steel is a material that widely used in metal cutting industry such as die and mould making industries and automotive industries (Kalpakjian 1995). Especially when used for fabricating the automotive parts, machining operations of alloy steel are usually conducted with cutting fluids (Lahres et al. 1999). The method of applying cutting fluids in this sector is commonly by flood cooling which flow rates range from 10 L/min for single point tools and 225 L/min per cutter for multiple-tooth cutters (Kalpakjian 1995). When the cutting fluids’ service time is considered, the flow rates indicate that a bunch of used cutting fluids should be discarded regularly. For example, it was reported that about 650,000 tons used cutting fluids had to be disposed annually from Germany automotive industries (Tonshoff & Mohlfeld 1997; Klocke & Eisenblatter 1997). The decision to improve machinability of automotive materials by machining using cutting fluids in the past were mainly focused on increasing tool-life without considering ecological aspects. Today, when environmental law is closed to industry, it is realized that actually the use of cutting fluids entails high costs in production and their disposal, and they are hazardous to the environment and human health (Sreejith & Ngoi 2000; Graham 2000). As a result, the method of machining is shifted; cutting fluids-free machining or dry machining is the ultimate goal as a means of reducing the overhead costs while protecting the environment. In this research, the cutting fluids-free machining is called cutting under eco-machining environment.
The difficulty in cutting fluids-free machining is that high cutting temperature. The cutting temperature is high because the absence of cutting fluids means high heat generation at cutting zone and it is a prominent faktor to shorten tool life. Ideally, the cutting fluids-free machining is accepted when it’s achievement compete the achievement of machining with cutting fluids. In more specific, tool life and surface finish of cutting fluids-free machining is about the same or better than the results when machining using cutting fluids (Sreejith & Ngoi 2000; Graham 2000). If it is achieved, depending on the machined workpiece, cost savings of up to 17% of the total workpiece costs can be made (Zielasko et al. 1998).

In line with the last paragraph, the way out to overcome the difficulty caused by the absence of cutting fluid is the development of solid lubricant as coating materials for cutting tool (Derflinger et al. 1999). Some coating materials have been developed for the purpose. However, the published results about the success of the coating materials developed for eco-machining based on the fact that the cutting fluids-free machining is accepted when it’s achievement compete the achievement of machining with cutting fluids is not widely reported.

With regard to the passages in above, the objective of research is evaluating the performance of carbide tool coated with TiCN/Al2O3/TiN in turning of alloy steel under eco-machining environment. In detail, the scopes of research are the study on wear characteristic of carbide tool coated with TiCN/Al2O3/TiN, to define the tool performance in term of tool life, and the study on surface finish of alloy steel machined surface.

**Literature Study**

**Tool Wear**

Tool wear is a phenomenon where the material used to construct the cutting tool gradually peeling off during machining process due to the combination of mechanical-thermal-chemical process (Cook 1973). The ISO 3685 (1993) standard also gives a definition for tool wear as the change of shape of the tool from its original condition shape, during cutting, resulting from the gradual loss of tool material or deformation. Tool wear determine the service time of cutting tool or well-known as tool life and Taylor (1907) is the pioneer to relate tool wear and tool life in mathematical model.

In machining using single-point cutting tool like turning process, ISO 3685 (1993) classifies tool wear into two categories, i.e. (1) flank wear, and (2) crater wear. In the meaning of providing further detail of both wear types, Dearnley and Trent (1982) provide illustration of them as a result of their study. In addition, Dearnley and Trent (1982) reported that they got another wear type called notch wear. The illustration of flank, crater and notch wear types is shown in Figure 1.

Source: Dearnley and Trent. 1982.

**FIGURE 1**: Wear scheme of cutting tool during machining process (A = crater wear, B = Flank wear, C and D = notch wear).
Surface Finish

Surface finish is a common criteria used to determine the quality of machined product. Originally, surface finish is only a part of surface integrity as the main aspect to determine all quality aspects of machined surface. The word “surface integrity” was firstly coined by Field in 1965. In his next publications (Field & Kahles 1971; Field et al. 1972), he tries to elaborate comprehensively all aspects in surface integrity that well-influenced the quality of machined surface.

In daily activity, the manufacturing engineers define surface finish by the roughness of machined surface and Ra is the famous parameter for it. In accordance with ISO 468 (1982), Ra is one of parameters that defined as the arithmetic mean value of machined surface profile. Formerly, Ra was identified as AA (arithmetic average) or CLA (center-line average) (Kalpakjian 1995). In the relation with tool wear, usually Ra and tool wear are used to determine tool life.

Eco-Machining

Recently, dry machining or machining without the present of cutting fluids is the hot topic in machining technology (Klocke & Eisenblätter 1997; Kress 1998; Derflinger et al. 1999; Graham 2000; Harris et al. 2000; Renevier et al. 2000; Sreejith & Ngoi 2000; MTA-SME 2001; Kim et al. 2001; Soković & Mijanović 2001; Nouari et al. 2003; Grzesik & Nieslony 2003). There are 4 faktors at least caused dry machining become interesting:

1. Dry machining is the only choice to overcome the problem of non-biodegradable used cutting fluids that potential to distort the environment. By this, dry machining can be called eco-machining technique.

2. Dry machining is potential to reduce production cost. The examination made in Germany automotive industries show that the cost of cutting fluids is about (7-20)% from the total production cost. This amount is 2 to 4 times greater than the cost of cutting tool (Tonshoff & Mohlfeld 1997; Klocke & Eisenblätter 1997; Kopac 1998; Lahres et al. 1999; Sreejith & Ngoi 2000; Harris et al. 2000; MTA-SME 2001). Due to the environmental law, the percentages of cutting fluids cost will increase when the used cutting fluids should be processed before dispose to environment. Processing of used cutting fluids meant in the environmental law needs cost about 2 to 4 times of the fresh cutting fluids price (Hong & Zhao 1999).

3. Dry machining is the suitable environment for the recent cutting tool material like coated carbide, ceramic, cermet, cubic boron nitride (CBN), and polycrystalline diamond (PCD) due to its natural behavior as brittle material. They are cracking, flaking or even fracturing easily due to the thermal stress caused by the present of cutting fluids during machining (Graham 2000; Sreejith & Ngoi 2000; Che Haron et al. 2001).


The main advantage of cutting fluids is to reduce thermal and friction that generated along the cutting zone. Moreover, cutting fluids is also benefit to flow chips away from the cutting zone. If cutting fluids do not use in machining process, thus, both of advantages are not available. As a result, the friction coefficient increased and the high cutting temperature (generated by high thermal / heat) will end with adhesive wear as well as diffusion-dissolution wear on the cutting tool. Both wear mechanisms show that cutting tool in dry cutting severe of high work load in terms of mechanical and thermal loads. On the other hand, in tool perspective as brittle material, dry cutting
gives benefit to avoid thermal shock / stress that usually indicated by comb-crack on cutting tool surface / cutting edge (Graham 2000; Sreejith & Ngoi 2000; Che Haron et al. 2001).

There are many aspects taken into account to ensure dry machining can be performed. First of all is the cutting tool. Cutting tool should be optimized with emphasize in the substrate material selection, tool geometry and coating material selection. The high hot hardness and high wear resistance of carbide, cermet, ceramic, CBN, and PCD are placing those substrate materials as the suitable choices of cutting tools for dry machining. For the purpose of increasing the original substrate performance and reduce the friction coefficient, today many coating materials have been invented and those are also promising to be added to ensure the success of dry machining. Secondly, dry machining needs the rigid machine tool. The high cutting temperature, friction coefficient and cutting condition are potential to drive machine tool for vibrating and even chattering.

Literature study indicates that the first publication counted care to the effect of used cutting fluids to environment is Klocke and Eisenblatter (1997). They reported that dry machining could be performed with promising results on cast iron, carbon and alloy steels, and aluminum. In line with the results, Graham (2000) was also reported the switch from wet to dry cutting could be done for some metals such as cast iron, steels and aluminum. Moreover, in the meaning of providing the comprehensive opinion for dry cutting, Sreejith and Ngoi (2000) in their paper entitled “Dry Machining: Machining of The Future” also stated that results.

Klocke and Eisenblatter (1997), Graham (2000), Sreejith and Ngoi (2000), and Harris et al. (2000) reported that cast iron was machining successfully under dry cutting. The coated carbide cutting tool, CBN, Sialon and PCD were recorded in dry cutting of cast iron. The CBN and PCD were used even up to the high speed machining technique that was 1000 m/min. In case of alloy steel, some researchers reported that coated carbide, ceramic, CBN and PCD were potential to be used (Klocke & Eisenblätter 1997; Derflinger 1999; Lim et al. 1999; Graham 2000; Sreejith & Ngoi 2000; Che Haron et al. 2001; Kim et al. 2001; Grzesik & Nieslony 2003).

Unfortunately, none of the publications in the above discusses the success of switching from the basis of “cutting fluids-free machining is accepted when it’s achievement in terms of tool life and surface finish compete the achievement of machining with cutting fluids”. By the fact, it is hard to accept the success of dry machining because no evidence available to prove it clearly yet. In short, they seem only perform examination and provide information of the performance of such cutting tool in machining of certain workpiece material under dry cutting. Consequently, nobody can guarantee that the dry result competes or may be better than dry or eco-machining result.

With regard to the above passages, objective of research in this report is to study the machinability of automotive material AISI 1045 under eco-machining environment. In particular, the carbide tool wear characteristic, tool life and surface finish of the machined workpiece are studied. To meet the ideal accepted condition of eco-machining, the experiment in this study will be carried out with and without cutting fluids. The results of tool life and surface finish when machining with cutting fluids will be used as the basis to measure the achievement of eco-machining.

Materials and Methods

Materials

AISI 01 is selected as the workpiece material in this study. It has hardness of 23 HRC and the chemical composition is 0.95%C, 1.2%Mn, 0.30%Si, 0.5%W, 0.1%V, 0.5%Cr, and Fe is the rest. The workpiece material used has a dimension of 330 mm in length and 100 mm in diameter. In commercial application in automotive industry, this material is used for fabrication of axle and spline shaft by utilizing turning operation (Kalpakjian 1995; Oberg & Green 1996).
Coated carbide tools are selected to employ the eco-machining process for AISI 01. The cutting tools are also the common cutting tools used in automotive industry for the machining quality of medium or semi-finish to finish. The CVD-coated WC-Co(TiCN+Al2O3+TiN) is selected. The tool has ISO designation VBMT 160408 and they will be mounted on tool holder with ISO designation SVJBR 2525 M16 to provide tool geometry of 0,5,52,3,0,5,0.8.

**Method**

Method of research is by machining experiment using turning machine tool. Turning tests will be carried out by using CNC turning machine. The experimental method is designed based on two stages:

1. The sensitivity stage. This stage is experimental cutting at the common cutting speed as recommended by the tool manufacturer.
2. The testing stage. At this stage, the possibility of increasing the cutting condition will be tried. The optimum cutting condition that can be achieved by the cutting tools is examined. It is made to observe the possibility of cutting tools used for eco-high speed machining of steel.

The CVD-coated carbide is used up to the tool rejection criteria: the maximum flank wear (VB_{max}) of 0.4 mm and the excessive chipping, flaking or fracturing caused the significant changes of tool cutting edge (Kalpakjian 1995; ISO 3685 1993). Flank wear is measured at various cutting intervals using a toolmakers microscope. Data obtained from measurement are collected to produce the graph of tool wear progression.

Prior to turning test, all workpiece materials are machined in order to peel off the outer surface to avoid the inconsistent hardness as the result of bar production. Moreover, to avoid excessive damage on entry to the cut, a 5 mm precut is made on the outer edge of each first cutting pass prior to commencing the turning tests.

**Cutting Condition**

For the purpose of addressing the statement “cutting fluids-free machining is accepted when it’s achievement in terms of tool life and surface finish compete the achievement of machining with cutting fluids”, trials were performed under dry and wet cutting with steady stream oil-based cutting fluid: density (15°C) 0.868 g/ml, viscosity (40°C) 3.8 cst and flashpoint 216°C.

From the result of study on sensitivity stage, it was resulted that cutting speed of 250 m/min was the lowest speed in this study. At this speed, Chubb and Billingham (1980) reported that this speed can be classified as high speed machining. The highest speed in this study in which experiment is done on performance stage is the speed that provides tool life approximately 5 minutes (ISO3685 1993). Feed rate of 0.16 mm/rev and depth-of-cut of 1 mm were not varied.

**Experimental Techniques**

All high speed turning tests were carried out on a CNC turning Avenger 200T of Cincinnati Milacron. Tool life of cutting tool was determined based on the ISO 3685 (ISO3685 1993) where the wear on the flank face was the main concern. The tool rejection criteria stipulated for the machining trials were:

1. Maximum flank wear (VB_{max}) ≥ 0.6 mm.
2. Excessive chipping (flaking) or fracture of the cutting edge.

Flank wear was measured at various cutting intervals using a digital vernier microscope, namely Absolute Digimatic of Mitutoyo, with magnification power ranging from 5-10. To avoid excessive damage on entry to the cut, a 5 mm precut entry phase
was created on the outer edge of each pass prior to commencing the machining trials.

The international standard of quantitative method of measurement for two-dimensional surface topography was referred in this study and $R_a$ parameter was selected to carry out (ISO 468 1982). This parameter is most often specified on engineering drawings and universally recognized as the arithmetic mean of the absolute departures of the surface profile from the mean line. It was measured using Surftest 402, a surface profilometers of Mitutoyo, with a 0.8 mm cut-off length. Measurements were taken at least of 3 times in feed direction at the time of the measurement on the flank wear and the average values were then recorded.

Results and Discussions

Discussion of Trial

At the initial stage of trials under dry and wet cutting for all cutting speeds tested (250-350 m/min), the width of cutting tools flank wear was observed uniform within depth-of-cut (Figure 2). However, in further machining, the maximum flank wear on zone C (Figure 3) and excessive chipping of cutting tool nose region were found as the dominant rejection criteria when machining AISI O1 steel with KC9025 (Figure 4). These results are believed due to the geometry of cutting tool where the contact area of 35°-diamond insert shape is concentrated on its nose region. Moreover, as shown in Figure 4, the excessive chipping is suspected as the result of the breaking away of chips that, because of high cutting temperature, adhering strongly on the tool nose region during machining. When broken, chips also pull out some coating as well as substrate materials along.

FIGURE 2: The typical Uniform Flank Wear at The Initial Stage of Trial (300 m/min, wet, ~ 1 minute).
The statistical regression V-T curves of the average three trials of dry and wet cutting are shown in Figure 5. These curves clearly show wet cutting gives the best overall performance, in terms of tool life, at the cutting conditions investigated. At the highest speed tested (350 m/min), wet cutting gave average tool life of 15.02 minutes, while dry cutting was approximately half of it that is 7.52 minutes.

The principal reasons of why oil-based cutting fluid used under wet cutting gives longer tool life than dry cutting lie in fact that:

1. Coolant reduces the cutting temperature.
2. Coolant acts as a lubricant and reduces friction in wet cutting (presented in discussion of surface roughness).
The evidence to support the first reason is given by the most obvious indication of cutting temperature that is the colours of chips (Trent 1991). It was observed during machining trials that the colour of chips under dry cutting was dark blue rather than burnished to light blue under wet cutting. Thus, it can be concluded that the cutting temperature when machining under dry is higher than wet cutting and shorter tool life under dry cutting is probably due to thermal stresses that attributed by the high cutting temperature. In the relation with wear on the cutting tool flank face, thermal stresses crack the coating layers and the rate of removing the coating layers under dry is higher than wet cutting due to the high cutting temperature itself and relatively high friction coefficient when machining under dry cutting.

**Surface Finish**

Those graphs in Figure 6 are plots of the average surface roughness values, $R_a$, recorded from the machining trials. The duration of cutting time represents tool life and the last $R_a$ data is recorded when the rejection criteria are attained.

The surface roughness values measured during trials are the sum of the ideal and the natural surface roughness values. The ideal surface roughness values is caused by the given tool geometry and feed rate and, for turning operation (Boothroyd & Knight 1989), is expressed as a function of the feed rate ($S$) and nose radius ($r$) of a tool:

$$R_a = \frac{0.0321 \cdot S^2}{r} \quad \ldots (1)$$

Natural surface roughness is caused by the irregularities in the cutting operation such as the occurrence of built-up-edge (BUE), chatter, defects in the structure of the workpiece and inaccuracies in the machine tool movement.
Initial wear on the flank face (Figure 2) was observed followed by the distortion of nose radius (Figure 7). Nose radius was reduced because some of coating materials were removed when the initial wear was formed. Based on this relation and referring to equation (1), the values of $R_a$ should be increased and the plots in Figure 6 show a good agreement with that. However, in further machining, a gradual improvement in surface roughness generally is observed. From the trials, when wear on cutting tool flank face was gradually increased, it was observed that some of chips adhered on the region where the coating materials had been removed. This case was continuing until the tool rejection criteria were attained (Figure 4). Before the case in Figure 4 that excessive chipping occurred, chips were laminating the nose region of cutting tool and sometimes covered the worn region on the flank face. These are probably the reasons of why the values of $R_a$ are gradually improved before again increasing until the cutting tool is totally failure.

For duration of cutting time under wet is as long as dry cutting, $R_a$ produced under wet is lower than dry cutting for all cutting speeds tested (Figure 6a-c). In further machining, on the contrary, when the cutting time duration under wet surpasses the duration of cutting time or tool life of dry cutting, $R_a$ increases significantly and the values are higher than the highest $R_a$ value of dry cutting (significant evidence shown in Figure 6b-c). Higher surface roughness values recorded when machining at this duration can be directly related to the excessive chipping of the cutting tool nose region in which rough surface and abused feed mark are generated (Figure 8).

As mentioned previously, oil-based cutting fluid also acts as a lubricant and prolongs tool life. From the plots in Figure 4.5, clearly, the steady stream oil-based cutting fluid successfully lubricates the machining process; thus, surface roughness produced is better than under dry cutting. Lubrication reduces the mechanical wear (abrasion) and as a result, reduces the rate of cutting tool flank wear and prolongs tool life. Although tool life can be extended longer than tool life that resulted under dry cutting but when the quality of machined surface is referred, $R_a$ increases significantly, hence surface finish is poor. From the results can be concluded that as long as the quality of machined surface is the main concern, the use of cutting fluid in prolonging tool life does not useful.

The use of cutting fluid also supports the advantages of coating materials in producing surface finish. The outer coating TiN that known has low coefficient of friction, only detected producing $R_a$ better than wet cutting at 250 m/min (the first data) but at higher cutting speeds, the data show that the presence of cutting fluid supporting TiN to produce better $R_a$ (Figure 6b-c). The thick intermediate layer Al$_2$O$_3$ is also supported by the cutting fluid since the data after initial cut show that $R_a$ under wet is better than dry cutting. The steady stream cutting fluid supplied to cutting tool during machining prevents the occurrence of thermal shock on Al$_2$O$_3$ but as expected not on WC-Co and that is why the excessive chipping occurs under wet is worse than under dry cutting even at the same cutting speed (Figure 4). A gradual chipping of Al$_2$O$_3$ was observed during data collections when the maximum flank wear was not attained. The process is suspected because Al$_2$O$_3$ is very stable (not chemically reactive), thus, oxide coatings generally bond weakly with the TiCN as the inner layer before the substrate WC-Co. The wear protection advantages of TiCN coating are not only a result of increased hardness, higher toughness and abrasion resistance, but also due to an extremely low coefficient of friction at low temperature coupled with the good heat transmission behaviour. Although there is no microanalysis performed to prove which layer is being activated but it is suspected that TiCN is supported well by cutting fluid at cutting speed of 250 m/min since the data before cutting tool is totally failure still provides $R_a$ lower than under dry cutting. It occurs because the cutting temperature at 250 m/min is relatively lower than 300 or 350 m/min and as previously stated, TiCN has extremely low friction coefficient at low cutting temperature.
FIGURE 6: $R_a$ vs. cutting time when machining of AISI O1 tool steel with multilayer ceramic (TiCN/Al$_2$O$_3$/TiN) CVD-coated grade KC9025 at feed rate of 0.16 mm/rev, depth-of-cut of 1 mm, cutting speeds of: (a) 250, (b) 300, (c) 350 m/min.
FIGURE 7: Coating material is removed from tool nose region in initial wear and it distorts the shape as well as reduces tool nose radius (300 m/min, wet, ~1 minute).

FIGURE 8: AISI O1 machined surface produced at 300 m/min and wet cutting:
(a) initial cut (basis of comparison),
(b) final cut. Legend: $\Phi$ and $\Theta$ are feed marks and their vertical distance is feed 0.16 mm, arrow is feed direction. (Magnification 20x)

Conclusions

From the analysis of results that obtained through the experiment, some points can be extracted to be the conclusions of the research and they are listed as follows:

1. Life of multilayer ceramic (TiCN/Al$_2$O$_3$/TiN) CVD-coated carbide tool when using in high speed turning of AISI O1 steel is majority determined by the maximum flank wear ($V_{B_{max}} \geq 0.6$ mm) on zone C and excessive chipping on tool nose region due to the geometry of cutting tool, mechanical and thermal wears.

2. The use of oil-based cutting fluid in wet gives longer tool life than dry cutting due to its function as a coolant in reducing cutting temperature and as a lubricant in reducing mechanical wear.
3. For duration of cutting time under wet is as long as dry cutting, $R_a$ produced under wet is lower than dry cutting for all cutting speeds tested. This result is due to the presence of cutting fluid in supporting the advantages of coating materials.

4. Although longer tool life is possible to achieve under wet cutting; however, when tool life of wet surpasses the dry cutting, higher surface roughness are recorded.

5. When tool rejection criteria are attained, higher surface roughness values under wet cutting are resulted. The rough surface and abused feed marks are observed. They occur since excessive chipping on wet is worse than dry cutting due to the occurrence of thermal shock on the cutting tool substrate (WC-Co).

References

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