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The use of TiAlN coated carbide tool when finish machining hardened stainless steel

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Abstract: The introduction of hard turning has provided an alternative to the conventional processing technology used to manufacture parts made from hardened steels. Shorter product development time along with being more environmentally friendly are among the benefits offered by hard turning, which potentially results in lower manufacturing cost per part. However, common tool materials for hard turning applications are expensive. Due to the continuous developments in cutting tool materials and coating technology, inexpensive coated carbide cutting tools are being investigated to determine the potential of using them for use in extreme conditions as in hard turning. TiAlN coated carbide tool was selected to finish machine hardened steel. Performing hard turning dry at various cutting conditions, that is, cutting speed and feed rate, revealed that satisfactory tool life values and surface finish values that meet the strict range of finish machining were obtained when finish machining hardened steel of 47–48 HRC hardness.

Keywords: hard turning; coated carbide; tool life; surface roughness; wear mechanisms.

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1 Introduction

Components made from hardened steels are increasing in numbers driven by the need for high performance. Hardened steel's properties of high wear resistance and compressive strength meet the demands in automotive and tool and die industries. Machine shop being an integral portion of the manufacturing system needs to modify the machining process flow in order to be able to machine parts made from these hard-to-cut materials more effectively. The usual technique to manufacture hardened parts involves three sequential steps, that is, rough machining of unhardened steel, heat treating the steel to the required hardness and finish machining to the required dimensional accuracy. Normally, heat treatment is being done externally thereby leading to longer lead times.

The introduction of hard turning using tools with high hot hardness (Polycrystalline Cubic Boron Nitride (PCBN) and ceramic) has simplified the process flow by allowing the steel blank to be machined to its final dimension in the hardened state (Poulachon et al., 2003). Hard turning refers to the turning of hardened steels with a hardness of beyond 45 HRC. The hardness can even reach 68 HRC. This technique became a profitable alternative for finish machining due to advantages in economical and ecological aspects. High material removal rate and relatively low tool cost compared to the incumbent grinding as the finishing operation are some of the economical benefits. Additionally, stricter health and environment regulations and also post-production cost consideration led to the minimised use of coolant whenever feasible and hard turning has been successfully performed in dry condition (Mamalis et al., 2002).

Despite its significant advantages, the lack of data concerning surface quality and tool wear for the many combinations of workpiece and cutting tool impedes the acceptance of hard turning by the manufacturing industry (Pavel et al., 2005). Moreover, the common tools used in hard turning, PCBN and ceramic, are relatively high in price.

Some applications in the mould and die industry have been identified to require parts made of hardened steels within the moderate range of hard turning (45–48 HRC). Using advanced – and consequently expensive-cutting tools for these moderate hardness ranges may hinder the economical benefit of hard turning. Previous hard turning of stainless steel (43–45 HRC) has been successfully performed using coated carbide tool (Noordin et al., 2007). It is likely that coated carbide tool has the potential to turn steels of even higher hardness within the moderate range of hard turning. This is because of the continuous development of carbide tool taking place in the form of fine grained substrate, better binder that optimises strength and toughness and improved coating using Physical Vapour Deposition (PVD) technique. Therefore, the potential of using inexpensive coated carbide cutting tools needs to be investigated.

In order to encourage machine shops to fully adopt hard turning, assessments should be made to clarify the aspects of the tool life and machined surface's quality. The machining cost per part is a function of tool life and, thus, machine shops demand long tool life. Additionally, finish machining should produce fine surface finish as requested by the users of the machined parts to meet the specific requirements of certain application (Gillibrand et al., 1996). Therefore, in order to generate information on the performance of coated carbide tool and the resulting machined surface, hard turning was conducted using various cutting parameters within finish machining parameters.

2 Experimental details

The tests were conducted on a two-axis CNC lathe by the longitudinal turning process of a workpiece without using coolant. The selected conditions/values of the variables are given in the following section.

1. *Workpiece material*: bars of stainless steel (modified AISI 420) with hardness of 47–48 HRC. The stainless steel was martensitic type with high carbon and chromium contents of 0.38 and 13.6%, respectively.
2. *Tool insert and holder*: commercially available coated carbide (3.0–3.5 μm TiAlN coating over a tungsten carbide substrate) with ISO designation of CNMG 120408. The coated carbide inserts were mounted on a tool holder with an ISO designation of MCLNL 1616-H12 giving −5° rake angle, 5° relief angle and −5° side cutting edge angles.
3. *Cutting parameters*: cutting speeds of 100, 130, 170 m/min and feeds of 0.1, 0.125, 0.16 mm/rev with a constant depth of cut of 0.4 mm.

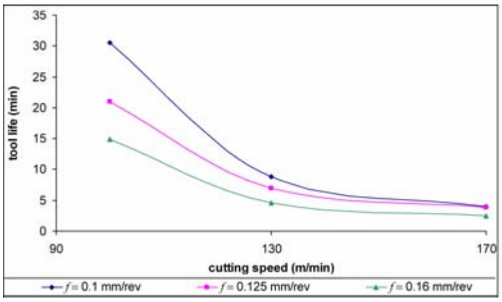
Evaluations were conducted on both the progressively worn tool and the generated machined surface. The tool wear was measured according to the ISO 3685, subjected to the flank wear width (VBmax) within the nose radius of the tool (zone C). The roughness values of machined surfaces were measured by portable surface profilometer using 0.8 mm cutoff length. Further examination was then applied on the worn inserts at the end of their life time by using Scanning Electron Microscope (SEM) attached with Energy Dispersive X-ray Spectrometer (EDS).

3 Results and discussion

3.1 Tool life and total material removal

The tool life criteria are set based on a maximum flank wear width of 0.14 mm or when the tool is severely worn (occurrence of catastrophic failure) or when the machined surface roughness is beyond 1.6 μm. The moderate range of finish machining parameters is advantageous for the coated carbide tool. As can be observed in Figure 1, the tool could withstand up to 30.5 min. The ability of the coated carbide tool to withstand over 10 min of service life indicated that coated carbide performed well for materials with hardness up to 48 HRC within the selected cutting parameters.

Figure 1 Tool life values at various cutting speeds and feeds



The coated carbide tool lasted longer when low cutting speed was applied. The longest tool life was achieved by combining low cutting speed and low feed. As expected, increasing the feed alone shortened the tool life. However, as the cutting speed increased, the tool lifetime became less sensitive to the changing of feed.

Clear drawback was evident when higher cutting speeds were selected. Covering PVD TiAlN coating over tungsten carbide substrate was actually intended to enable the tool to perform cutting at higher speed. Higher speed will increase the material removal rate, which is related to the process productivity. Material removal rate is a function of cutting speed, feed and depth of cut. Finish machining is characterised by low feed and depth of cut (Shaw, 2005). Thus, in order to improve the productivity, a cutting tool subjected to finish machining should be able to operate at high cutting speeds. In this case of hard turning using coated carbide, the tool was able to cut steel with high hardness. But, it was unlikely that it could go for high speed. This trade-off obviously might reduce the tool's productivity since the material removal rate would be low. However, this particular hard turning operation still has its niche in machining tasks where machining time per part is not a constraint.

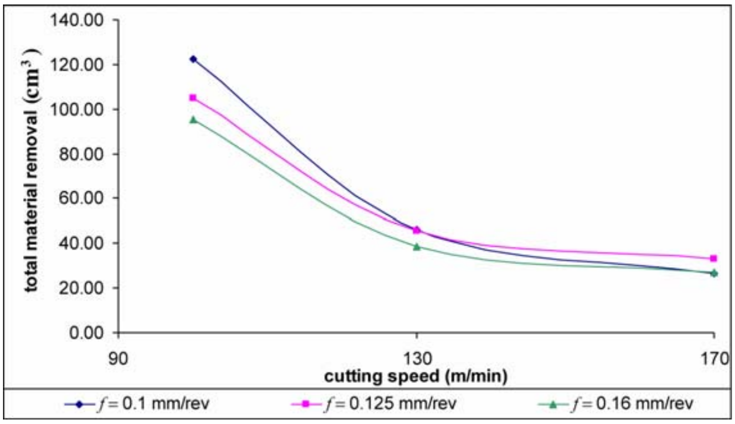
Economical consideration of a cutting tool can also be determined by the amount of excess workpiece material it can remove. The volume of metal removal, W, was calculated using equation (Arsecularatne et al., 2006):

$$W = TVfd \tag{1}$$

where T is the tool life, V is the cutting speed, f is the feed and d is the depth of cut.

Similar trend of material removal rate with that of tool life results was noticeable (Figure 2). The highest productivity was achieved by employing the low speed-low feed combination. Increasing the feed while maintaining the cutting speed resulted in higher material removal than increasing the cutting speed by keeping the feed constant.

Figure 2 Total volume of material removal



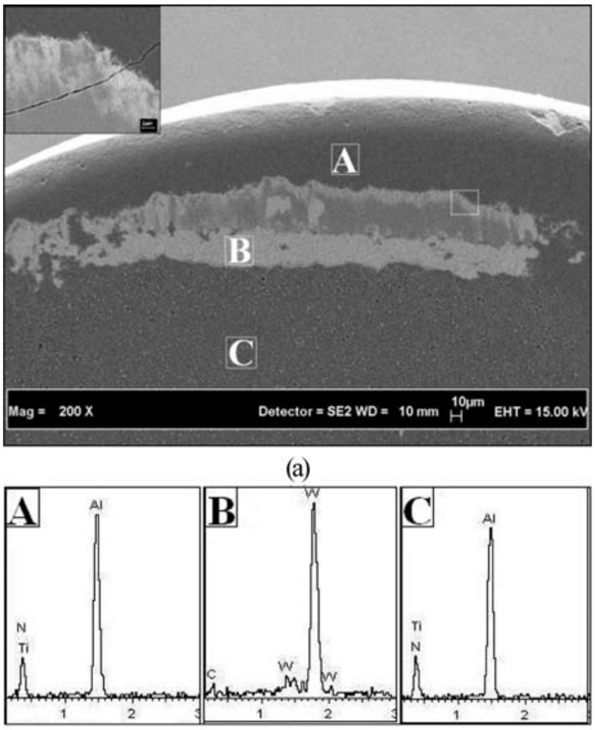
By considering the tool life and material removal, the use of the high speed-high feed combination was found unsuitable. Using such a combination would burden both machinist, since tool changing would be extremely frequent and the management, since the process low productivity resulted in an increased cost per part. Another factor that should be taken into account is the fact that the hard turning tests were performed without using coolant. Carbide tools are often used in conventional turning where coolant is an integral part of the process. Coolant, in the form of flooding fluid, sprayed mist or cryogenic substance has a positive impact on the tool life of carbide cutting tools (Hong, 2001; Varadarajan et al., 2002), especially in low cutting speeds. Being intended to be an alternative to higher priced tools to perform hard turning, the coated carbide tool was forced to cut hardened steel dry. This economically and environmentally beneficial dry cutting was likely sacrificing the coated carbide tool life. Yet, at some cutting parameters, the coated carbide tool satisfactorily showed its potential to present those benefits by its lengthy service lifetime.

3.2 Wear mechanisms

While cutting, a cutting tool undergoes changes from its original shape until a certain criterion is met, where it is no longer machining effectively. It is the gradual loss of its materials that is measured to determine its life time. Assessing how a tool wears as it reacts to the loading during machining will complement the recognition of the overall cutting process. Common method for this purpose is by evaluating the tool at the end of its life.

Most of the inserts considered, attained their end of life after reaching the maximum flank wear width criterion. Images of the coated carbide tool at the end of its life as in Figures 3(a) and 4 typically show the condition at the rake and flank faces, respectively.

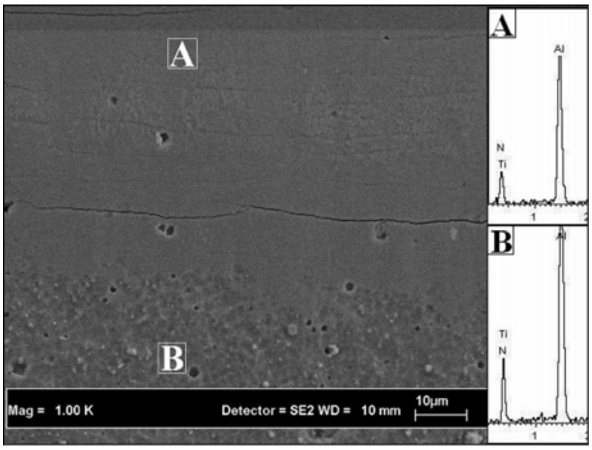
Figure 3 Images of (a) worn rake face (inset: crack) and (b) the corresponding EDS spectra of the particular regions



(a)

(b)

Figure 4 Images of flank face and the EDS spectra of the particular regions



A crater was formed on the rake face. The TiAlN coating no longer covered the carbide substrate. However, at the cutting edge, presented by region A in Figure 3(a), the coating remained, as indicated by the corresponding EDS spectra in Figure 3(b). Region C (fresh coating) and A are both identified as the coating even though they appear differently. There are colonies of remaining coating in the crater region. A closer look at a particular part of the crater region reveals the appearance of crack across both substrate and coating.

The whole area of the flank face was identified as coating. Figure 4 shows an area about 0.14 mm from the cutting edge such that both cutting and non-cutting regions appear in one frame. The cutting region of the flank face can visually be differentiated with the fresh coating since the former has smoother morphology than the latter. Cracks on the flank formed in the direction perpendicular to cutting speed direction.

A note can be taken that crater wear dominated the coated carbide tool's wear progression. It is likely that the rake face was subjected to higher loading than the flank. Jindal et al. (1999) analysed that crater wear was resulted from combination of chemical dissolution and/or diffusion wear and abrasive wear. The TiAlN coating was the actual contacting substance of the tool in both tool-chip (at the rake) and tool-workpiece (at the flank) interaction areas. Thus, it was the mechanical, chemical and thermal properties of the coating that determine the tool's resistance to wear and these properties are temperature dependent (Jindal et al., 1999). The effective rake angle of the tool assembly was 10°, having cutting region within the chip breaker groove. When cutting with a positive rake angle, the cutting edge which is subjected to higher mechanical load should be more severely worn. Since that was not the case, it means that the tool was strong enough to resist the mechanical load, at least until the coating got worn-off. Then, it should be the temperature generated at the rake face that was higher than the temperature at the flank face which was responsible to the more severe wear at the former than the latter.

Some reports regarding temperature distribution along a cutting tool provide clues to explain the phenomenon. Rech (2006) stated that a 'hot zone' was observable at the tool-chip interface at a certain distance from the cutting edge and another 'hot zone' in the rubbing zone on the flank face. Sutter et al. (2003) found when performing high speed machining, the maximum chip temperature is located at a distance of 300 μm from the tool tip (2/3 of the depth of cut). Also finite element analysis at the tool-chip interface of Al_2O_3 by Al Huda et al. (2002) found that the temperature distributions at the tool-chip interface is a function of the distance from the cutting edge, is maximum at a distance of about 0.6 mm from the cutting edge (the depth of cut was 0.8 mm). It was the higher local temperature at some distance from the cutting edge that adversely wore the coating leading to the initial exposure of the substrate. Once the coating got worn-off, the tool will be more susceptible to wear. The crater wear would then propagate through diffusion and abrasion mechanisms since the exposed substrate had lower mechanical, chemical and thermal properties than the coating.

The different morphology between the fresh and used coating appeared to be an effect of coating's plastic deformation. The TiAlN softened as its hardness decrease at high cutting temperature (Jindal et al., 1999). The high compressive stress through cutting (at rake face) and rubbing actions (at flank face) deformed the coating plastically, as suggested by Lim et al. (1999) when observing discrete plastic deformation of TiC coated carbide.

The crack at the tool's rake face was likely initiated at the substrate that became brittle since losing its metal binder due to diffusion or dissolution, as clued by the non-existence (or unidentifiable) of Co at region B in Figure 3. The cracks occurred at the flank face could not be identified whether being surface (coating) or deep-beneath-the-substrate cracks. The crack that stretched across the substrate and coating at the rake face might indicate that these initial cracks were substrate deep as a result of plastic deformation of the substrate. On the other hand, coating cracks could also take place when deformation mismatch occurred due to different coefficient of thermal expansion between the two.

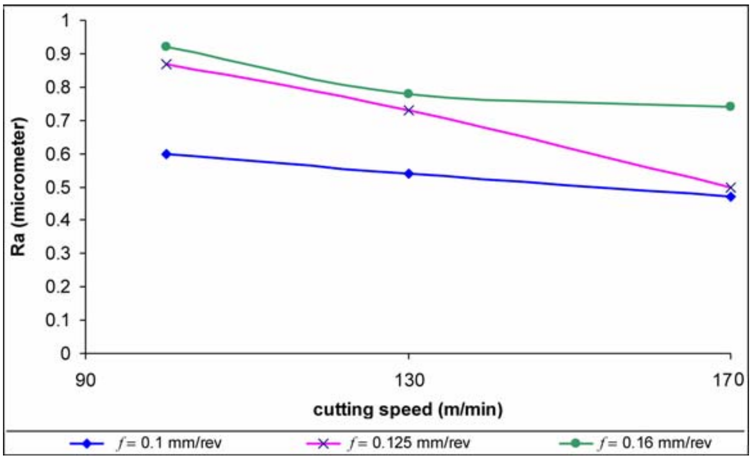
3.3 Surface finish

In finishing operations, as in hard turning, the end of tool life is commonly-based on a predetermined damage level of the machined surface. Surface roughness value of a part which quantifies its damage level has an important effect upon the life of many engineering components. Low value of roughness is essential to engineering components since it will reduce the coefficient of friction and wear rates and will improve corrosion resistance and aesthetic properties (Gillibrand et al., 1996).

The range of roughness values to be expected in finish machining is Ra = 0.75 – 1.5 μm (Shaw, 2005). As described in Figure 5, all of the Ra values are below the upper limit and even most of them were one level better, being lower than 0.8 μm. Low feed resulted fine surface finish with the lowest surface roughness of 0.47 μm was achieved at the combination of low feed-high cutting speed. The fine surface finish values are expected to fulfil the specific requirements by the mould and die industry. High feed setting resulted similar to and better Ra values than the predicted ones. The decrease in feed improved the Ra values. Cutting speed which is not considered in the theoretical expression slightly affected the achieved Ra.

The ability of the coated carbide tool to achieve finish machining criterion on surface roughness value was partially contributed by the sharp edge radius provided by the PVD coating technique and positive rake angle of the tool. The common negative rake angle setup in hard turning operation is intended to prevent the chipping of the cutting edge (Nakayama et al., 1988). The coated carbide tool, however, showed that it was able to resist against severe chipping when positive rake angle was set. The positive rake angle assembly was essential in making such smooth surface finish in addition to the sharp edge resulted by PVD process on the coating which is considered beneficial in resulting surface finish. Increasing the cutting speed might help improving the surface finish. Yet, referring to the life time of the tool, higher cutting speed is not a good option for overall performance.

Figure 5 Average surface roughness values at various cutting speed and feed



The quantitative surface finish examination would be benefitted further by measurement of the residual stress of the machined surface. This will complement the justification on whether hard turning performs better than grinding as finishing operation in terms of surface integrity. However, several researchers have evidenced that hard turning produced the preferred compressive residual stress (Mamalis et al., 2002; Matsumoto et al., 1999).

4 Concluding remarks

From the tests conducted, the TiAlN coated carbide tool performed satisfactorily when hard turning stainless steel (47–48 HRC) in dry condition. The longest tool life of 30.5 min and the highest volume of material removal were achieved at low cutting speed-low feed combination. Increase in cutting speed and feed decreased the tool life, with cutting speed as the more influential factor. The rake face suffered more wear than the flank face as crater area of exposed substrate was formed while coating remained in other areas. The crater wear was suggested to be caused by local high temperature occurred. Fine surface finish was generated at low feed with 0.47 μm as the finest.

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References

Al Huda, M., Yamada, K., Hosokawa, A. and Ueda, T. (2002) 'Investigation of temperature at tool-chip interface in turning using two-color pyrometer', *Journal of Manufacturing Science and Engineering*, Vol. 124, pp.200–207.

Arsecularatne, J.A., Zhang, L.C., Montross, C. and Mathew, P. (2006) 'On machining of hardened AISI D2 steel with PCBN tools', *Journal of Materials Processing Technology*, Vol. 171, No. 2, pp.244–252.

Gillibrand, D., Sarwar, M. and Pierce, C.T. (1996) 'The economic benefit of finish turning with coated carbide', *Surface and Coatings Technology*, Vols. 86–87, pp.809–813.

Hong, S.Y. (2001) 'Economical and ecological cryogenic machining', *Journal of Manufacturing Science and Engineering*, Vol. 123, pp.331–338.

Jindal, P.C., Santhanam, A.T., Schleinkofer, U. and Shuster, A.F. (1999) 'Performance of PVD TiN, TiCN, and TiAlN coated cemented carbide tools in turning', *International Journal of Refractory Metals and Hard Materials*, Vol. 17, pp.163–170.

Lim, C.Y.H., Lim, S.C. and Lee, K.S. (1999) 'Wear of TiC-coated carbide tools in dry turning', *Wear*, Vols. 225–229, pp.354–367.

Mamalis, A.G., Kundrak, J. and Gyani, K. (2002) 'On the dry machining of steel surfaces using superhard tools', *International Journal of Advanced Manufacturing Technology*, Vol. 19, pp.157–162.

Matsumoto, Y., Hashimoto, F. and Lahoti, G. (1999) 'Surface integrity generated by precision hard turning', *Annals of the CIRP*, Vol. 48, No. 1, pp.59–62.

Nakayama, K., Arai, M. and Kanda, T. (1988) 'Machining characteristics of hard materials', *Annals of the CIRP*, Vol. 37, No. 1, pp.89–92.

Noordin, M.Y., Venkatesh, V.C. and Sharif, S. (2007) 'Dry turning of tempered martensitic stainless tool steel using coated cermet and coated carbide tools', *Journal of Materials Processing Technology*, Vol. 185, pp.83–90.

Pavel, R., Marinescu, I., Deis, M. and Pillar, J. (2005) 'Effect of tool wear on surface finish for a case of continuous and interrupted hard turning', *Journal of Materials Processing Technology,* Vol. 170, Nos. 1–2, pp.341–349.

Poulachon, G., Bandyopadhyay, B.P., Jawahir, I.S., Pheulpin, S. and Seguin, E. (2003) 'The influence of the microstructure of hardened tool steel workpiece on the wear of PCBN cutting tools', *International Journal of Machine Tools and Manufacture*, Vol. 43, No. 2, pp.139–144.

Rech, J. (2006) 'A multiview approach to the tribological characterisation of cutting tool coatings for steels in high-speed dry turning', *International Journal of Machining and Machinability of Materials*, Vol. 1, No. 1, pp.27–44.

Shaw, M.C. (2005) *Metal Cutting Principles*, 2nd edition, New York: Oxford University Press, Inc.

Sutter, G., Faure, L., Molinari, A., Ranc, N. and Pina, V. (2003) 'An experimental technique for the measurement of temperature fields for the orthogonal cutting in high speed machining', *International Journal of Machine Tools and Manufacture*, Vol. 43, No. 7, pp.671–678.

Varadarajan, A.S., Philip, P.K. and Ramamoorthy, B. (2002) 'Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning', *International Journal of Machine Tools and Manufacture*, Vol. 42, pp.193–200.