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A Study on Cutting and Tribology Performances of TiN and TiAlN Coated Tools

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TiN and TiAlN coatings were deposited on the surface of AISI 5140 steel and cemented carbide YT15 by magnetron sputtering technique (MSP). The reciprocating sliding tests of TiN and TiAlN coatings on the surface of AISI 5140 steel were performed to investigate the friction coefficients of coatings affected by various normal loads with friction pair of 304 stainless steel balls. Dry machining tests on AISI 5140 hardened steel were carried out with the TiN and TiAlN coated tools on a CA6140A lathe. The effects of cutting speed on cutting forces and surface roughness of TiN and TiAlN coated tools were obtained and analyzed to assess the cutting performance of coated tools. The microcosmic micrographs of wear areas of coated tools were observed and investigated by scanning electron microscope and energy dispersive spectrum. The results show that the friction coefficients of TiN coatings are lower than that of TiAlN coatings. The cutting force of TiAlN coated tool decreases and flank wear resistance enhances in comparison with TiN coated tool. The wear form and mechanisms of TiN coated tool are mainly crater wear on the rake face and adhesive wear and abrasive wear on the flank face. The wear form and mechanisms of TiAlN coated tool are mainly adhesive wear, the breakage of cutting edge and the damage of tip, accompanied with diffusion and oxidation wear.

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1. Introduction

Dry turning technology has been developed rapidly since the 1990s. Without using cutting fluids, reduced pollution to the environment and less the machining cost, dry turning is becoming the main processing method in industry at present.[1]

The cutting forces, life and wear mechanism of tools must be taken into account when dry turning steels.[2,3] In dry machining, there will be more friction and adhesion between the tool and workpiece since they will be subjected to higher temperature. At the same time, dry turning will also dissipate more power than wet turning and make the tool wear aggravated.[4,5] As the result, the conventional cutting tool material and the design process are no longer suitable for dry turning. So, it is becoming a research topic to select proper tool material and design tool surface characteristics. One of the main methods is a layer or multilayer coatings, such as TiN, TiAlN, TiCN, CrN, are deposited on the surface of inserts to enhance the stiffness and wear resistance of the tools. Nowadays, 80% of all machining operations are performed with coated carbide cutting tools.[6]

Compared to the uncoated tools, the cutting performances of coated tools can be improved significantly. For example, as the earlier coating material used in cemented carbide surface, TiN coatings are featured by low friction coefficient, high hardness and excellent wear resistance against to metals, making them have been widely used in industry such as machinery and microelectronics, especially cutting tools. But the oxidation temperature of TiN coatings is low. Under high temperature (approximately 550°C), the oxygen existed at coating-workpiece interface could react with the titanium element to generate TiO_2, which easily wear off by rubbing action.[7]

This situation would aggravate the abrasion wear of the TiN coatings. In recent years, TiAlN coatings have been gradually developed as an alternative to TiN coatings, because the presence of Al in TiAlN coatings can formed a superficial layer of composite ceramic (Al_2O_3) at high temperature to improve the oxidation resistance and corrosion resistance.[8-10]

Cutting forces, surface roughness and tool wear are three important quantities in the machining of steels. Knowledge of the thrust force in cutting is important because the tool holder, the workholding devices, and the machine tool must be sufficiently stiff to minimize deflection caused by this force. At the same time, cutting force has an important influence on tool wear and cutting temperature. Surface finish influences not only the dimensional accuracy of machined parts, but also their properties. Whereas surface finish describes the geometric features of surfaces and surface integrity pertains to properties, such as fatigue life and corrosion resistance, which are influence strongly by the type of surface produced.[11] Tool wear mechanisms in cutting process have an efficiency on tool life. In order to achieve good machinability, to improve the product quality and to decrease the costs, it is necessary to have minimum values of cutting force, surface roughness and tool wear.[12,13]

AISI 5140 have been widely applied to making mechanical parts because of its excellent mechanical properties. However, the machining performances of TiN and TiAlN coated tools on the dry turning of AISI 5140 steel are less reported compared to the aluminium alloy and the stainless steel.[14,15] Therefore, in the current study, AISI 5140 steel is used as the workpiece material for investigating the machining performances of TiN and TiAlN coated tools.

In this work, TiN and TiAlN coatings were deposited on the surface of 45 steel and YT15 carbide inserts by MSP. The average friction coefficient of TiN and TiAlN coatings had been obtained by dry sliding tests in the air. The dry turning experiments with various cutting speeds at constant depth of cut and feed rate were carried out on AISI 5140 steel with TiN and TiAlN coated tools. According to the experimental results, the effects of cutting speed on the cutting force and surface roughness were investigated. The SEM micrographs of the worn rake face of the TiN and TiAlN coated tool were observed by scanning electron microscope and the wear mechanisms were analyzed and discussed to assess the performance of coatings.

2. Experimental Details

The substrate was made of AISI 5140 steel whose chemical composition (wt. %) was C 0.39, Si 0.27, Mn 0.65, P 0.035, S 0.035, Cr 1.1, Ni 0.03 and Fe balance. The test blocks with the dimension of $\phi30\times2$ mm were designed for friction tests. The workpiece material was AISI 5140 steel with a hardness of 40 HRC in the form of a round bar, and part specimens were bars of 400 mm in length and 56.7 mm in diameter. The heat processing of the specimen included hardening and tempering.

Dry turning tests were performed on a CA6140A lathe with TiN and TiAlN coated cemented carbide YT15, which have the following tool geometry parameters: rake angle γ_0=15°, relief angle α_0=8°, inclination angle λ_s=-4° and side cutting-edge angle κ_r=75°.

Fig. 1 shows the diagram of cutting dynamometer experiential hardware. The arithmetic average surface roughness (Ra) of the workpiece was measured by surface roughness tester (JB-1C, China). The maximal flank wear was measured by an inverted metallurgical microscope (Axiovert200MAT, Zeiss, Germany). The wear graphs were observed using scanning electron microscope (JSM-6510, Japan).

It is generally agreed that the cutting speed is the most dominant factor influencing the tool life, followed by the feed rate and depth of cut. Hence, the cutting force and surface roughness tests were carried out at various cutting speeds (v) in a wide range, including 48, 61, 77, 98, 122, 137, 175 and 218 m/min.

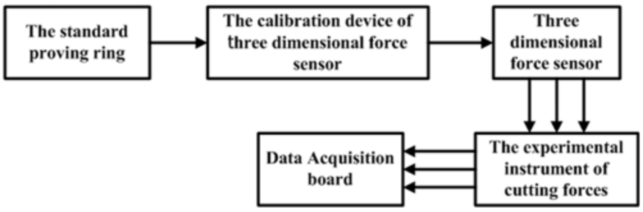


Fig. 1 Diagram of cutting dynamometer experiential hardware

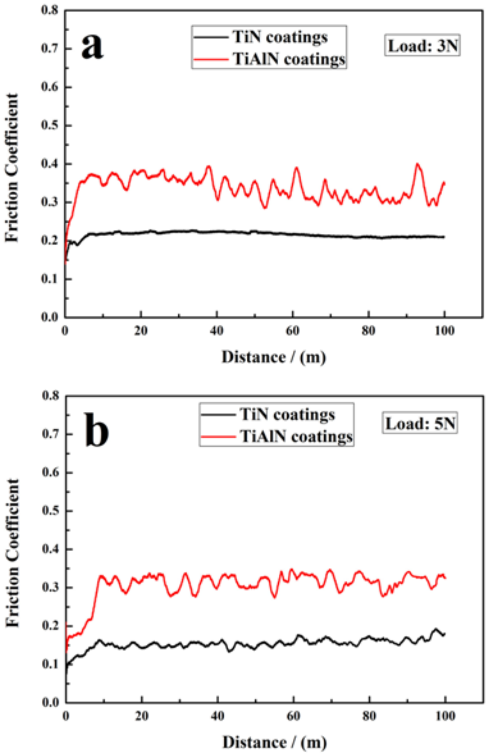


Fig. 2 Friction coefficients of TiN and TiAlN coatings at the load of 3 N and 5 N in air

3. Results and Discussion

3.1 Friction properties of TiN and TiAlN coatings

Sliding experiments were conducted in a ball-on-disk tribometer. Fig. 2(a) and (b) show the friction coefficients of different sliding couples of TiN and TiAlN coatings under the load of 3 N and 5 N at a dry sliding speed of 0.08 m/s. The sliding time was 1.5 hours. At the load of 3N (as seen in Fig. 2(a)), the magnitude of friction coefficients were in the increasing order of TiN and TiAlN. Their average friction coefficients were 0.22 for TiN and 0.33 for TiAlN. At the load of 5 N, (as shown in Fig. 2(b)), the friction coefficient of TiN was 0.15 and decreased approximately 0.07. However, the friction coefficient of TiAlN was decreased to approximately 0.30. The curve of friction coefficient of TiN was smoother than that of TiAlN. This could be explained as the follows: because of the higher hardness, TiAlN coatings would lead to the grinding of the stainless steel ball more serious and the contact size between the coatings and stainless steel ball became bigger than that of TiN coatings. As the result, the fluctuation of TiAlN coatings became

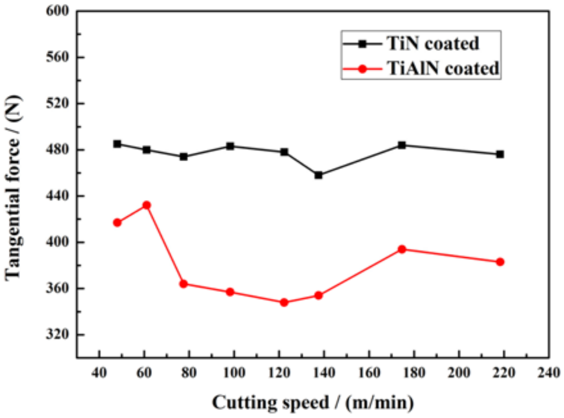


Fig. 3 Evolution of tangential forces at different cutting speeds

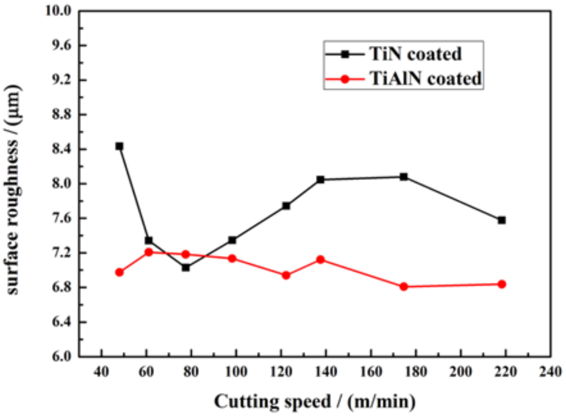


Fig. 4 Evolution of surface roughness at different cutting speeds

more volatile. The friction coefficient at every load was found to be lower at the beginning than that of at the end of scratch. At the beginning of scratch, less resistance was encountered to plough the coating because of some adsorbates such as oil, dirt and other impurities adsorbed on the coatings surface. Comparatively more resistance would be exhibited by the abrasive ahead of the indenter.

3.2 Cutting forces

Fig. 3 illustrates the evolution of the tangential force (also named main cutting force) as a function of cutting speed in dry turning of AISI 5140 steel. It should be noted that the variation tendency of the main cutting force is different. When cutting speeds are less than 140 m/min for TiN coated tool and 120 m/min for TiAlN coated tool, the main cutting force decreases with the increase of cutting speed, but the decrease range is different. When the cutting speeds are more than 140 m/min for TiN coated tool and 120 m/min for TiAlN coated tool, the main cutting forces increase again. The variation in the evolution of cutting forces at different cutting speeds could be attributed to the fact that the increase of cutting speeds generated more heat and thus raised temperature in the deformed regions. This behavior would aggravate the thermal softening of workpiece and decrease the tool-chip interface friction, leading to the reduction of machining deflection and main cutting forces. When the cutting speed are more than 140 m/min for TiN coated tool and 120 m/min for TiAlN coated tool, the high strain hardening rate of the workpiece plays a determinate role in the machining. As the result, the main cutting forces have a tendency to increase. This tendency agrees with the extension of Oxley's predictive analytical model for forces, temperatures and stresses exposed by Lalwani D. I.[16] Regardless of the trend, the main cutting forces of TiAlN coated tool were decreased by 10-27.2% in comparison with TiN coated tool.

3.3 Surface roughness

Fig. 4 shows the average surface roughness obtained at different cutting speed with TiN and TiAlN coated tools. The surface roughness of TiAlN tool reduces with the increase of cutting speed. However, this reduction becomes smaller and smaller at higher cutting speed. When the cutting speed is greater than 175 m/min, the surface roughness values reach a steady state, about 6.8 μm. As the ductility of AISI 5140 steel is high, there existed large and unstable built-up edge (BUE) on the rake face when the cutting speed is low (v=68 m/min). BUE would substitute the main cutting edge to perform cutting process, which lead to the high cutting force and poor surface. When the cutting speed is high (v=175 m/min), the BUE fall off from the tool due to the high temperature and as a result, the surface finish is improved.

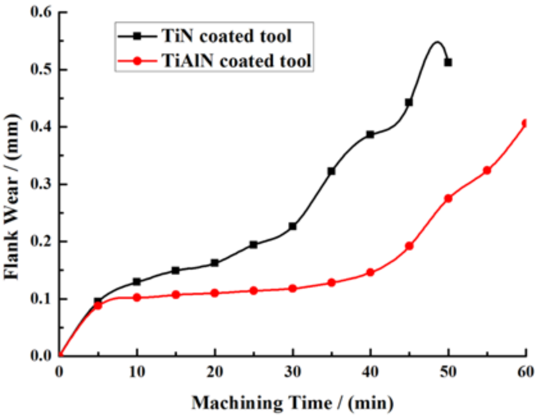


Fig. 5 Growth of flank wear with machining time

For the TiN coated tool, the surface roughness is more sensitive to cutting speed than that of TiAlN coated tool. As the cutting speeds increase, the Ra value for lower speeds quickly decreases to 7.03 μm and then increases to 8.08 μm at 175 m/min. When the cutting speed is greater than 175 m/min, the surface roughness reduces again. It should be noted that the surface roughness with TiN coated tool is generally higher than TiAlN coated tool whether at low cutting speed or high cutting speed.

3.4 Flank wear

Fig. 5 illustrates average flank wear with machining time of the two inserts. The maximum flank wear and VB of TiN and TiAlN coated tools were measured after each 5 minutes using the fixed cutting parameters of v=122 m/min, f=0.2 mm/r and a_p=1 mm. It can be seen in Fig. 5 that the worn stages of TiN coated tool is similar to that of TiAlN coated tool and includes initial worn stages, normal worn stages, acutely worn stages. Both the two worn curves rise with the increase

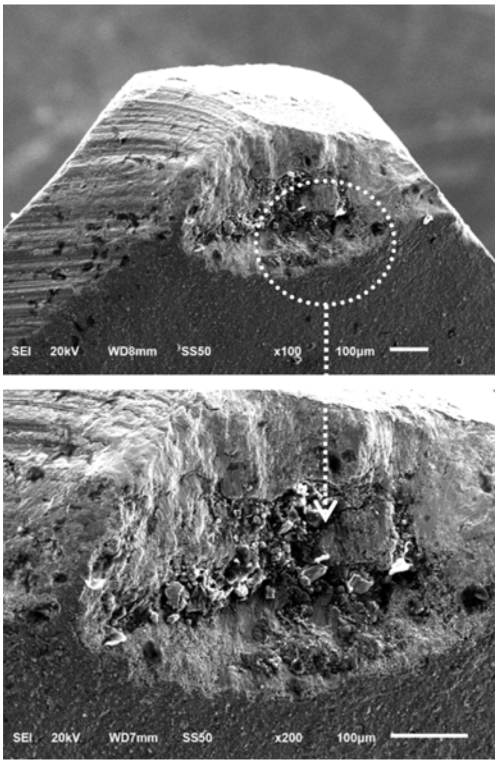


Fig. 6 SEM micrographs of the rake face of TiN coated inserts

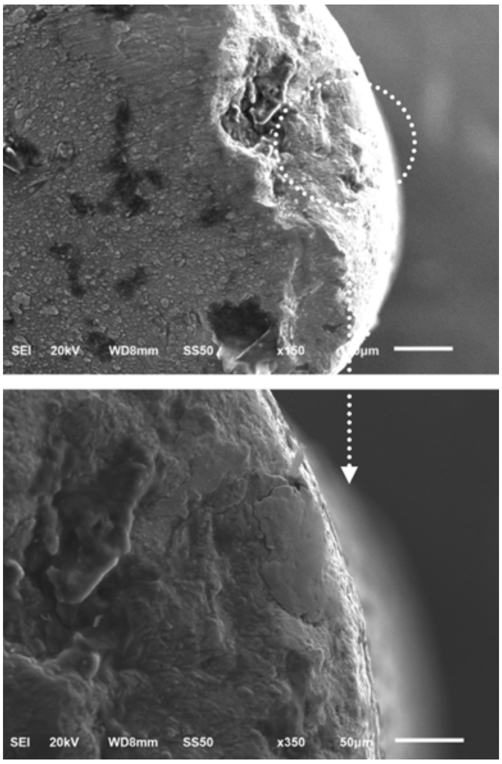
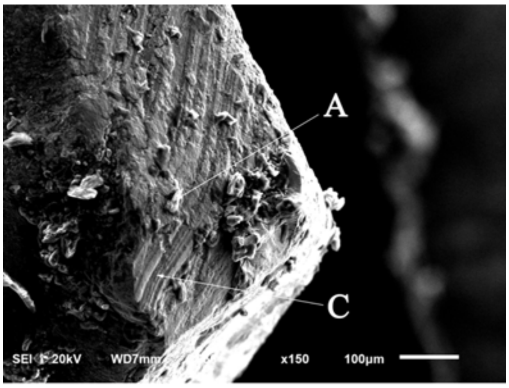


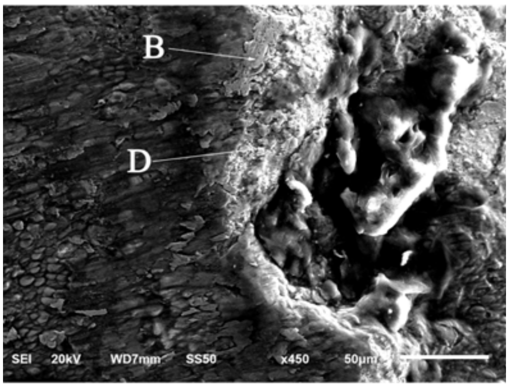
Fig. 7 SEM micrographs of the rake face of TiAlN coated inserts

of machining time.

In the initial worn stages, the flank wear values of TiN and TiAlN coated tool are 0.095 and 0.088 mm, respectively. After machining 5 minutes, both the coated tools turn into normal worn stages. The flank wear values of TiN coated tools increase at the rate of about 15% each 5 minutes. However, the wear tendency of increase of TiAlN coated tool is slower, about 4% each 5 minutes. When the machining time is 40 minutes, the VB of TiAlN coated tool is only 0.146 mm, which is far below the VB (about 0.386 mm) of TiN coated tool. The machining time of TiN turning into acutely worn stages is 25 minutes, while the machining time of TiAlN is 40 minutes. The flank wear values are 0.194 and 0.146, respectively. As the dry turning continues, the flank wear of TiN coated tool increases steeply with increasing machining time. It should be noted that when the machining time reached 50 min, the flank wear of TiN coated tool is about 0.512 mm, approaching to the tool failure criterion. However, it is interesting to found that the flank wear of TiAlN coated tool is only 0.406 mm when the machining time is 60 min. It is obvious that the wear resistance of TiAlN coated tool is better than TiN coated tool in dry turning of AISI 5140 steel, especially at longer machining time.



(a) TiN coated tool



(b) TiAlN coated tool

Fig. 8 SEM micrographs of flank wear of coated tools

3.5 Tool wear

Figs. 6 and 7 show the SEM micrographs of the rake face after 40 minutes' machining with the TiN and TiAlN coated inserts at the following parameters: v=122 m/min, f=0.2mm/r, a_p=1mm. As seen in Fig. 6, the wear form of TiN coated tool on the rake face is characterized as broad and deep crater, which starts at a few distances away from the cutting edge. There are some visible adhesive materials in the crater. And most of coatings have broken off from the substrate. After the coating broke off, the instantaneous heat generated can softens the

Table 1 TiN coated tool

Element	Weight percentage (%)
Fe	35.2
O	34.1
N	28.5
Ti	0.8
Cr	0.7
Si	0.6
W	0.1

Table 2 TiAlN coated tool

Element	Weight percentage (%)
Fe	30
O	22.3
W	21.2
N	17.2
Al	4.8
Co	2.4
Ti	2.2

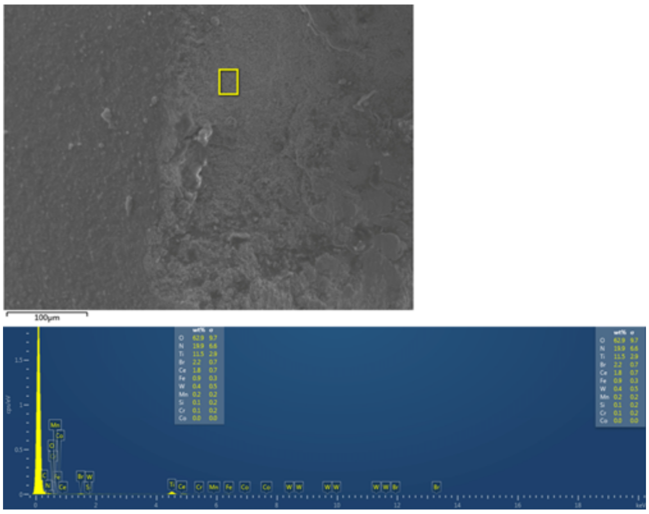


Fig. 9 EDS results of the edge near the rake face wear region of TiN

substrate's bonding phase, which results in intense wear of substrate. As seen in Fig. 7, the wear form of TiAlN coated tool is mainly the breakage of cutting edge on the rake face and the damage of tip. Some coatings near cutting edge are broke off and presented stratified structure. There are some craters on the rake face of TiAlN coated tool (as seen in Fig. 7), but they are smaller than that of TiN coated tool. And therefore, the tool wear performance of TiAlN coated tool is better than that of TiN coated tool.

Fig. 8(a) shows the SEM micrograph of flank wear of TiN coated tool. There are a lot of adhesion materials in wear region. And many scratches like furrow can be seen on the flank face. This indicates the main wear mechanisms are abrasive wear and adhesive wear. Table 1 and 2 present the EDS analysis results in the worn region A and B shown in Fig. 8(a) and (b). The worn region A and B exist large amounts of Fe, which comes from workpiece, indicating there are many chipping materials and impurities in these areas. As the cutting continued, shearing tensile stress of the adhesion materials would increase. When these adhesion materials are detached from the surface, the coatings will be also torn away from the tool caused by adhesive wear.

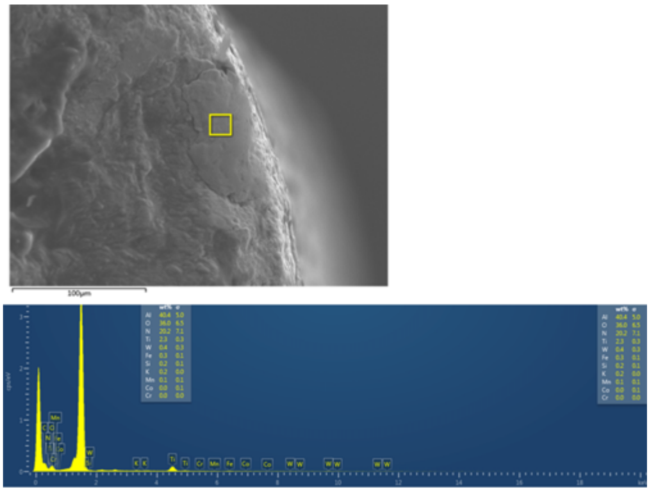


Fig. 10 EDS results of the tool nose wear region of TiAlN coated tool

Fig. 9 shows the EDS results of the edge near the rake face wear region of TiN coated tool. Fig. 10 indicates the EDS results of the tool nose wear region of TiAlN coated tool. Apparently, the high temperature generated in dry turning would lead to two types of diffusion at the tool-chip interface (diffusion of cutting tool constituents into the workpiece and diffusion of workpiece material components into the cutting tool).

4. Conclusions

In this research, TiN and TiAlN coatings had been deposited on the surface of AISI 5140 steel and cemented carbide YT15 by magnetron sputtering technique. Dry turning experiments at various cutting speeds at constant depth of cut and feed rate were performed on AISI 5140 steel using TiN and TiAlN coated tools. The cutting force, surface roughness, tool wear and wear mechanism were particularly investigated. The following conclusions are drawn from this study:

(1) The friction coefficients of TiN coatings are observed to be lower than that of TiAlN coatings, especially at the higher normal load.

(2) The main cutting forces of TiAlN coated tool are decreased by 10-27.2% in comparison with TiN coated tool. The surface roughness obtained with TiN coated tool is more sensitive to cutting speed than that of TiAlN coated tool, especially at higher cutting speed.

(3) The wear resistance of TiAlN coated tool is better than TiN coated tool in dry turning of AISI 5140 steel, especially at longer machining time.

(4) SEM observation and EDS analysis of worn TiN coated insert indicate that the wear mechanisms for the damage to the TiN coated tools during dry machining of AISI 5140 steel are mainly abrasive and adhesive wear. The wear form and mechanisms of TiAlN coated tool are mainly adhesive wear, the breakage of cutting edge and the damage of tip, accompanied with diffusion and oxidation wear.

(5) From this study, we find the effect of cutting and tool wear performance of TiAlN coated tool is better than that of TiN coated tool.

So, we expect more and more TiAlN coated tools are going to use in the area of metal processing.

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