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Dry turning of tempered martensitic stainless tool steel using coated cermet and coated carbide tools

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Abstract

Turning trials were performed under dry cutting conditions with constant depth of cut in order to investigate the usability of coated TiCN based cermet (KT 315) and coated carbide (KC 9110) cutting tools to turn tempered martensitic stainless tool steel with hardness in the 43–45 HRC range. Cutting speed, feed and the side cutting edge angle (SCEA) of the tool were the independent variables considered. Regardless of the cutting tool material, cutting speed and feed expectedly have an effect on tool wear and tool life. Additionally, the SCEA is found to influence the tool life where the tool life increases, as the SCEA was changed from 0° to −5°. The longest tool life was attainable when cutting with KT 315 at low cutting speed and feed rate when using −5° SCEA. However, in all other instances, KC 9110 outperforms KT 315. This is particularly evident at medium and high cutting speeds and feed. The constant and exponent for the various Taylor tool life equations have been determined. Flank wear, end clearance wear and catastrophic failure were the main types of tool failure mode determining tool life. The wear mechanisms for the various tool failure modes were suggested. The results suggest that dry turning of hardened, stainless tool steel could be performed using coated TiCN based cermet and coated carbide cutting tools with −5° SCEA at suitably selected cutting speed and feed combination.

Keywords: Dry hard turning; Tempered martensitic stainless tool steel; Tool failure mode; Tool life; Wear mechanism

1. Introduction

Hard turning has been used increasingly in industry. Numerous studies have been reported on the successful implementation of hard turning. Most of these studies involve work materials with hardness values in the range of 52–62 HRC and also they involve the use of ceramic, CBN and PCBN cutting tools [1–8]. There are applications which require parts with hardness values within the range of 40–45 HRC and studies involving work materials within this hardness range are somewhat limited. The use of coated cermet and coated carbide tools in these applications are also somewhat limited. This is in spite of the introduction of cemented carbide and cermet tools with superior properties compared to those of their predecessors as a result of the continuous development carried out. These developments include the use of improved substrates, coating materials and coating technology. Therefore, there is a need to know whether the newer generation of carbide and cermet tools can be used for the applications in question. The geometry of a cutting tool that removes the metal in the form of small chips is vital to improve the quality of the part surface finish, to assure accuracy of dimensions and tolerance, and to increase tool life. One of the most important parameters in tool geometry is the SCEA. Previous studies on unhardened AISI 1018 have shown that SCEA has an effect on machinability parameters such as the tool life [9].

It is not known whether for the machining of hardened steel, the use of different SCEAs have a similar effect on the various machinability parameters.

Dry machining has been considered as the machining of the future due to concern regarding the safety of the environment [10]. It is the most logical measure that could be undertaken to eliminate all the problems associated with the use of cooling lubricants. In their keynote paper on dry cutting, Klocke and Eisenblatter [11] provided a wide range of examples of successful implementation of dry machining of cast iron, steel, aluminum and even super alloys and titanium. They also expounded that the introduction of dry machining necessitates the adoption of measures suitable to compensate the primary functions of the cooling lubricant and in turn calls for a very detailed analysis of the complex interrelationships linking the process, tool, part and machine tool (Fig. 1). Byrne et al. [12] have indicated that the turning of various types of steel can be performed under dry

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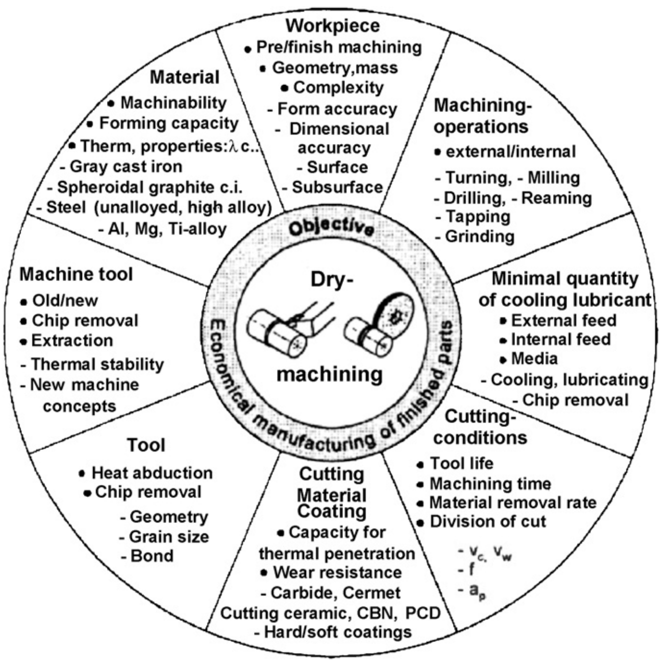


Fig. 1. Variables influencing dry machining.

cutting conditions in line with the concerns related to the environmental problems associated with cutting fluids and this trend of machining dry is set to continue.

The usability of coated cermet and coated carbide tools for machining hardened work material with hardness in the 43–45 HRC range using various SCEA under dry machining conditions is therefore the basis for the current investigation.

2. Experimental details

Coated TiCN based cermet and coated carbide insert with a nose radius of 0.8 mm and an ISO designation of CNMG 120408-FN and TNMG 120408-FN were used in this investigation. The coated cermet is a multi layered, PVD TiN/TiCN/TiN turning grade designated by KT 315 whilst the coated carbide is designated by KC 9110 and it is a specially engineered, cobalt enriched carbide grade with 18 μm thick K-MTCVD-TiCN inner layer, a fine grained thick α-Al_2O_3 intermediate layer, and outer layers of TiCN and TiN. Tool holders, having ISO designation of MCLNL, MTJNL and MTGNL, were used in order to obtain SCEAs of −5°, −3° and 0° respectively. The back and side rake angles are −5°.

The Stavax ESR, a premium grade stainless tool steel produced by UDDEHOLM AB was the work material selected for this investigation. It was delivered in the soft annealed condition and its composition is 0.38% C, 0.50% Mn, 0.90% Si, 13.60% Cr and 0.30% V. Its microstructure consists of a soft matrix in which carbides are embedded and the carbides compounds of carbon and alloying elements (such as Cr and V) are characterized by very high hardness. The work material was then heat treated to a hardness value of 43–45 HRC. Initially, the work material was gradually heated to a hardening temperature (austenitizing temperature) of 1030 °C in a vacuum furnace where the carbides are partially dissolved and the carbon and alloying elements from the carbides are dissolved in the matrix, which is transformed from ferrite to austenite thereby acquiring an alloying content that gives the hardening effect. The gradual heating in a vacuum furnace minimizes distortion. The heated work material was then cooled rapidly using N_2 gas with a 6 bar overpressure as the quenching media. Quenching in a vacuum furnace with gas eliminates problem associated with oxidized surfaces whilst the use of overpressure increases the quenching speed. Due to the rapid cooling, carbon atoms do not have time to reposition themselves for the re-formation of ferrite from austenite thus resulting in the formation of a hard martensitic structure. The matrix is however not completely converted into martensite and therefore some retained austenite is always present together with the undissolved carbides. The resulting microstructure contains inherent stresses that can easily cause cracking. Tempering was then performed in order to alleviate this problem and to obtain the desired hardness. In this particular case, the material was tempered four times. The temperature for the 1st three tempering cycle was 540 °C whilst the final tempering temperature was 550 °C. The resulting microstructure of the work material consists of tempered martensite, some retained austenite and carbides.

The edge of the heat-treated bar was premachined at the beginning of every pass by machining a slight chamfer using a separate tool holder corresponding to the SCEA investigated. The machining tests were carried out on a 5.5 kW CNC lathe machine and the cutting speeds (*V*) used were 100, 130 and 170 m/min whilst the feeds were 0.09, 0.16 and 0.28 mm/rev. The cutting conditions tested are listed in Table 1. The tool wear on the insert was measured at 10× magnification using a toolmakers microscope. The progression of the tool wear was also observed using an optical microscope. Additionally, the SEM was used to analyze the precleaned, worn inserts at the end of their tool life. Using ISO 3685-1977 (E) as a guide, the tool wear criterion used were when the maximum width of the flank wear land, $VB_{B\,max} = 0.2$ mm or when the maximum width of the end clearance wear, $VC_{max} = 0.2$ mm or the occurrence of catastrophic failure.

3. Results and discussion

3.1. Tool life

The physical appearance or chip form of the chips collected during the machining tests performed using KC 9110 is observed using a digital camera and presented in Fig. 2. In general, the resulting chip-form is strongly influenced by feed rate. Referring to the ISO-based chip-form classification [13], at high feed rate, loose arc chips are produced regardless of the cutting speed and

Table 1
Cutting conditions, failure mode and tool life for machining tests

No.	*V* (m/min)	Feed (mm/rev)	SCEA	KT 315			KC 9110	
				Mode of failure	Most prominent wear form prior to end of tool life	*T* (s)	Mode of failure	*T* (s)
1	100	0.09	−5	VC_{max} exceeded	VC_{max}	2014	VC_{max} exceeded	909
2	170	0.09	−5	Catastrophic	$VB_{B\,max}$	334	VC_{max} exceeded	670
3	130	0.16	−5	Catastrophic	VC_{max}	482	VC_{max} exceeded	680
4	100	0.28	−5	$VB_{B\,max}$ exceeded	$VB_{B\,max}$	219	VC_{max} exceeded	587
5	130	0.28	−5	$VB_{B\,max}$ exceeded	$VB_{B\,max}$	44	$VB_{B\,max}$ exceeded	253
6	170	0.28	−5	Catastrophic	$VB_{B\,max}$	23	$VB_{B\,max}$ exceeded	170
7	170	0.28	−3	$VB_{B\,max}$ exceeded	$VB_{B\,max}$	15	$VB_{B\,max}$ exceeded	157
8	170	0.28	0	$VB_{B\,max}$ exceeded	$VB_{B\,max}$	9	$VB_{B\,max}$ exceeded	100

(a) (b) (c)

Fig. 2. Chip-form for −5° SCEA when using KC 9110 at (a) 100 m/min, 0.09 mm/rev; (b) 130 m/min, 0.16 mm/rev; (c) 100 m/min, 0.28 mm/rev.

the SCEA used. On the other hand, at low feed rate, snarled cock screw chips are produced regardless of the cutting speed and the SCEA used. When cutting at 0.16 mm/rev, long, cock screw chips are obtained. In all instances similar trends are generally obtained when using KT 315.

The results on tool life (*T*) and failure modes for the turning tests are shown in Table 1. It can be clearly seen that the tool life decreases with increasing cutting speeds and feeds. The longest tool life of 2104 s is obtained when cutting with KT 315 at low cutting speed (100 m/min) and feed (0.09 mm/rev) using −5° SCEA. The histogram in Fig. 3 compares the performance of KT 315 and KC 9110 in terms of tool life when cutting with −5° SCEA. It can be seen that KC 9110 consistently outperformed KT 315 except when cutting under low feed and low cutting speed conditions. Additionally, at high feed of 0.28 mm/rev, the tool life for KT 315 is extremely short (less than 60 s) when machining at medium and high cutting speeds regardless of the SCEA used. This is consistent with observation made by Dawson and Kurfess [14] whereby in general, tool life increases as feed rate reduces. The histogram in Fig. 4 confirms that even for −3° and 0° SCEA, KC 9110 outperformed KT 315 when cutting at high feed and cutting speed. This figure also revealed that the best performance is attainable with −5° SCEA as its use resulted in the longest tool life. This confirms the superiority of tools with −5° SCEA when cutting hardened Stavax ESR tool steel with KT 315 and KC 9110 cutting tool material. This is because for a given feed and depth of cut, the area of cut is approximately constant, whilst the area of tool-chip engagement increases as the SCEA is changed from 0° to −5° [15]. This results in higher chip equivalent values, which lowers cutting temperature and increases tool life [16].

The longer tool life attainable by KC 9110, particularly at high speed, may be attributed to the coatings applied and the substrate used. The coatings applied on KC 9110 consist of three separate coating layers with a total thickness of 18 μm compared to a thickness in the range of 10–14 μm under normal circumstances. The TICN inner layer offers better protection against flank wear. This coating is applied using MT-CVD process, which allows for lower deposition temperatures (∼850 °C) compared to conventional CVD (900–1100 °C) and shorter coating cycle, thereby reducing the mismatch in thermal contraction rates between the coating and the substrate during cooling to provide fewer coating cracks and a tougher cutting edge. The tendency to form brittle η-phase at the coating-substrate interface is also reduced as a result of this. The MT-CVD technique employed also results in reduced residual stresses and improved edge toughness due to the lower deposition temperatures. The fine-grained alpha crystal structure Al_2O_3 intermediate layer offers protection against the elevated temperatures encountered during cutting and provided an abrasion resistant, chemically inert barrier. The alpha structure offers greater stability compared to the more commonly used kappa structure. It has been proven that Al-based coating materials provide the highest wear resistance to practically all wear mechanisms. The 2 μm TiN/TiCN layer outer layer provides additional wear resistance. Additionally, the polishing of the outer coating surface minimizes the chances of built-up edge formation. As usual, the substrate for KC 9110 primarily consists of WC in a Co binder. However, by using the nitrogen enrichment technology, the near

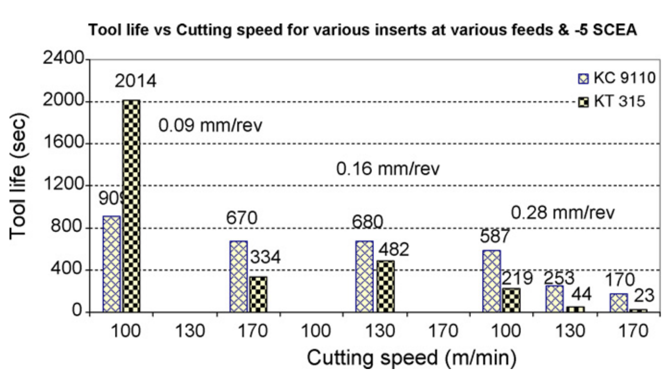


Fig. 3. Histogram of tool life for KT 315 and KC 9110 at various feeds, cutting speeds and −5° SCEA.

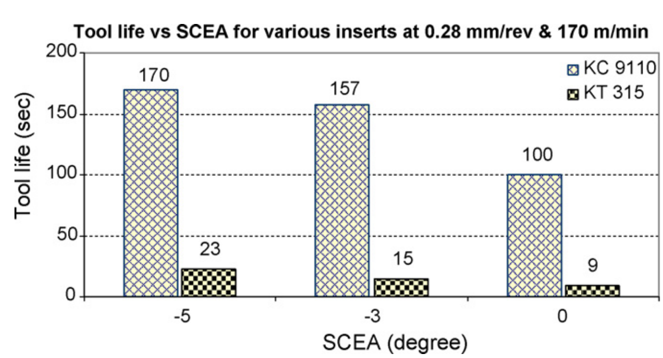


Fig. 4. Histogram of tool life for KT 315 and KC 9110 at various SCEAs, 0.28 mm/rev and 170 m/min.

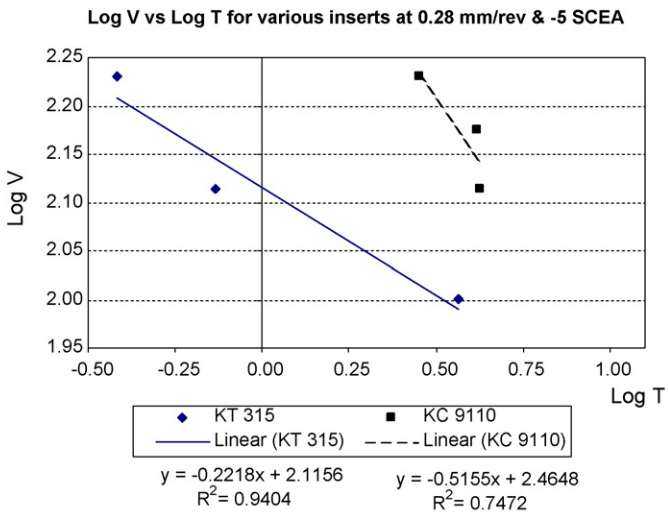


Fig. 5. Graphical representation of Taylor tool life equation for KT 315 and KC 9110 at 0.28 mm/rev and −5° SCEA.

surface Co content is between 1.5 and 2 times that of the core. This enables the toughness at the surface to be increased consistent with the higher Co content at the near surface whilst the core will have greater deformation resistance attributed to the lower Co content [17–19]. Additionally, cermets have a lower resistance to mechanical and thermal shocks, which are characteristics associated with turning hardened tool steel, compared to cemented carbides due to their lower thermal conductivity, tensile strength and higher coefficient of thermal expansion [20].

Fig. 5 attempts to compare the relationship between tool life and cutting speed for KT 315 and KC 9110 under similar cutting condition of 0.28 mm/rev and −5° SCEA. It is clear that the linear trendlines for KT 315 and KC 9110 were not parallel and the n values were 0.22 and 0.52, respectively. This confirmed the assertion made by Degarmo et al. [21] that the value of n depends mostly on tool material. The extent of the difference in the n values obtained for the various cutting conditions tested also indicate that the feed rates have a primary effect on the relationship between the tool life and cutting speed. The rather small n values for KT 315 indicate that cutting speed has greater effect on tool wear and tool life. This is unlike KC 9110 where the n values were bigger. An examination of the Taylor constant values revealed that the C values were 131 and 292 m/min and therefore the use of KC 9110 generally resulted in longer tool life.

The typical rapid-uniform-rapid wear profile corresponding to zones A–C can be observed when using both KT 315 and KC 9110. Fig. 6 attempts to compare the wear profile of KT 315 and KC 9110 when using −5° SCEA at 130 m/min and 0.16 mm/rev. It can be seen that KC 9110 outperforms KT 315. Upon entering zone C after approximately 350 s, KT 315 wears rapidly and the weaken tool fails catastrophically with the work material being welded at the cutting edge (Figs. 6 and 7a). The relative positions of the curves depend on cutting conditions and the cutting tool material. Rapid wear rates are initially experienced possibly due to the running-in process caused by a very small area of contact between the tool and the work material, the presence of extraneous substances at the interface and a transient surface roughness.

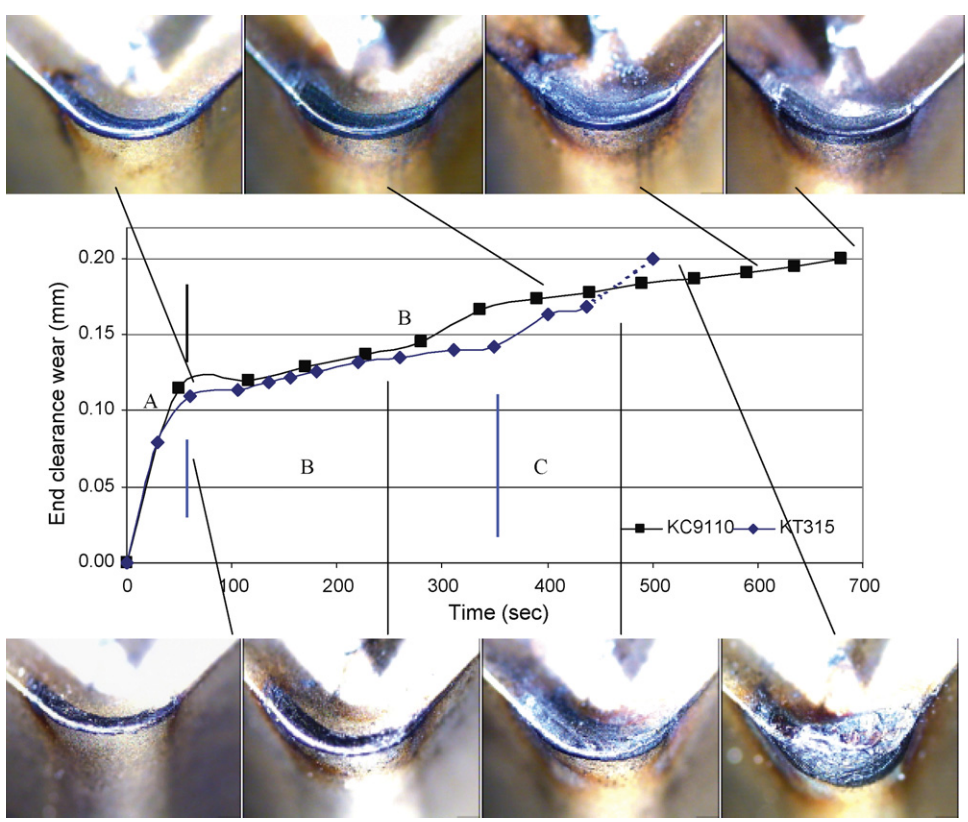
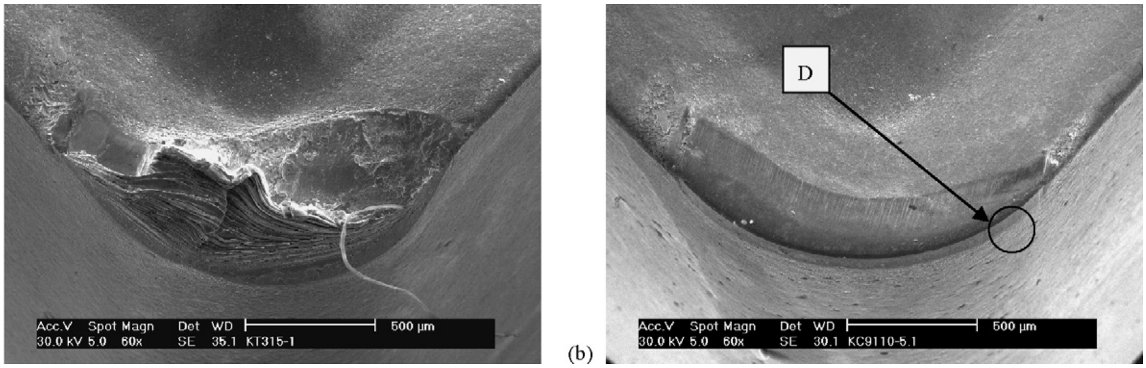


Fig. 6. End clearance wear growth comparison between KT 315 and KC 9110 when using −5° SCEA at 130 m/min and 0.16 mm/rev.



(a) (b)

Fig. 7. SEM image of inserts (a) KT 315 (b) KC 9110 at the end of their tool life corresponding to final optical micrograph images for the respective cutting tool materials of Fig. 6.

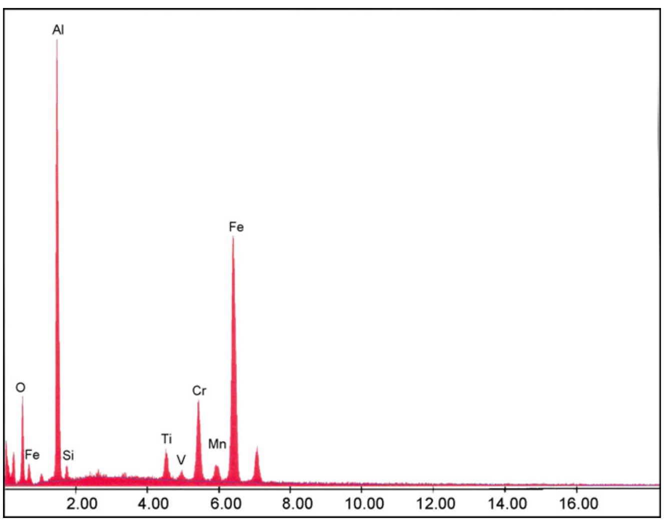


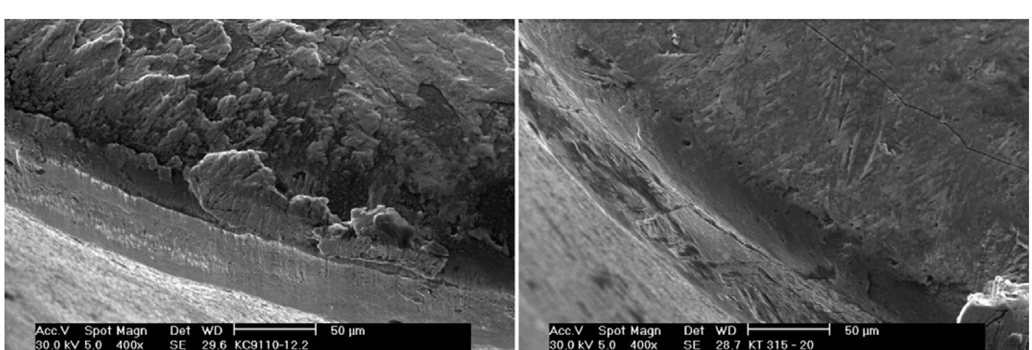
Fig. 8. EDAX analysis after cutting for 680 s at 130 m/min, 0.16 mm/rev, −5° SCEA when using KC 9110 whereby Al and Ti from the coated tool are mainly detected at location D of Fig. 7b.

During this period, high points in the asperities are quickly worn away. This is followed by a period of relatively constant wear rate where the coating is being worn away. This continues until the substrate is partially exposed as the wear scar size attains a certain critical value. As the substrate has lower wear resistance than the coating, the wear rate increase rapidly as more substrate material is being exposed. This will finally lead to the eventual failure of the cutting tool. Profiles limited to zone A are obtained in a number of instances when using KT 315. This indicates that the wear undergone is rapid where a single pass of cutting results in the wear criterion being exceeded or results in catastrophic failure and is not associated with the running-in process described previously. On the other hand, when using KC 9110, profiles with only zones A and B are obtained in most of the instances even though the tool life criteria has been exceeded (Fig. 6). This suggests that the tools can still be use, as the substrate has not been penetrated (Fig. 7b). The EDAX analysis in Fig. 8 confirms that apart from work material, elements associated with the coating materials such as Al and Ti predominate and elements associated with the substrate material is absent.

3.2. *Types of tool failure mode*

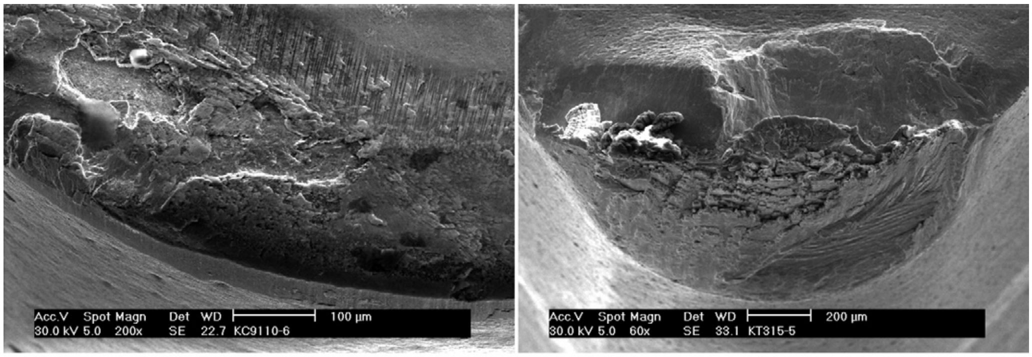
From the various SEM images of the inserts at the end of their tool life for the cutting conditions tested, there are generally four main types of tool wear/tool wear form/tool failure mode that can be clearly identified, viz. flank wear, end clearance wear, catastrophic failure and crater wear. Flank wear and catastrophic failure are the dominant tool wear forms determining the tool life when machining hardened Stavax ESR steel with KT 315. On the other hand, end clearance and flank wear are the dominant tool wear forms determining the tool life for KC 9110.

At a high feed rate of 0.28 mm/rev, flank wear was generally the dominant failure mode regardless of the cutting tool material used (Fig. 9a). The development of flank wear land was



(a) (b)

Fig. 9. Flank wear when cutting at 170 m/min, 0.28 mm/rev, 0° SCEA using (a) KC 9110 after 104 s and (b) KT 315 after 10 s.



(a) (b)

Fig. 10. (a) Flaking on the rake face extending into the flank wear land after cutting for 257 s at 130 m/min, 0.28 mm/rev, −5° SCEA using KC 9110. (b) Catastrophic failure when using KT 315 after cutting for 25 s at 170 m/min, 0.28 mm/rev, −5° SCEA.

generally gradual and uniform. However, when cutting with KT 315 using 0° SCEA resulted in the flaking of the cutting edge (Fig. 9b). When using KC 9110 at 130 m/min, 0.28 mm/rev, −5° SCEA, flaking on the rake face extended into the flank wear land (Fig. 10a) revealing the substrate. It is observed that there is localized adherence of workpiece material on the cutting edges. Localized adherence also occurred when cutting at 170 m/min, 0.28 mm/rev, using −5° and 0° SCEA (Fig. 9a) and also when cutting with KT 315 (Fig. 9b).

End clearance wear is generally the dominant failure mode at low and medium feed rates (0.09 and 0.16 mm/rev), particularly when using KC 9110 (Fig. 7b), regardless of the cutting speed used. At a high feed rate of 0.28 mm/rev, it is dominant only at low cutting speed of 100 m/min. End clearance wear determines the tool life for KT 315 for one of the conditions tested (100 m/min, 0.09 mm/rev, −5° SCEA). The end clearance wear land developed is generally uniform regardless of the cutting speeds and feeds used. Catastrophic failure of the cutting tool determines the tool life for three of the cutting conditions tested. In two of the cases, flank wear is the most prominent tool wear form prior to failure whilst in the other case it is the end clearance wear. In both instances, the width of flank wear prior to failure were well below the criteria values used confirming that the deterioration of the cutting edge was rapid and resulted in the catastrophic failure on the major flank side (Fig. 10b)/minor flank side of the cutting tool as well as in the adjacent areas. Catastrophic failure is seen to occur exclusively when using KT 315.

3.3. Wear mechanism

Flank and end clearance wear probably occur by both abrasive and adhesive wear mechanisms with abrasive wear being the major source of material removal since the temperatures at the tool flank are lower than that on the rake face. Abrasive wear is mainly caused by the hard, martensitic structure of the hardened work material. The relative motion between the newly cut surface and the flank of the cutting tool in the presence of hard particles results in the development a flat of the flank faces of the cutting tool. Tool material is removed by mechanical action (ploughing, scoring, microcutting or grooving) with the said hard particles. The fragments of the hard tool materials removed by attrition wear from the tool surface, the highly strained–hardened fragments of an unstable built-up edge or the abrasive chips produced when machining the hardened workpiece material are other possible sources of the hard particles. The morphology associated with this wear mechanism is characterized by the formation of fine and uniform grooves on the tool flank. Adhesive wear mechanism also comes into play in instances where flank wear is severe (Fig. 9b) as a result of the fracturing of the adhering work material at the tool flank/edge. As a result of fracture, fragments of the tool material can be torn out and carried away on the underside of the chip or on the new work material surface.

Catastrophic failure exclusively occurred when using KT 315 in a number of instances. Vandierendonck and Van Stappen [22] also found that the use of coated and uncoated cermets in severe application (such as cutting depth too high or cutting feed too high) could result in the breakage of the cutting edge. This could be associated with a combination of abrasion, adhesion, diffusion, fracture and plastic deformation wear mechanisms. Initially, the coating on the tool flank, end clearance and rake face would wear off as a result of the abrasion and adhesion wear mechanisms described previously. With the partial revelation of the tool substrate, the remaining wear mechanisms become active and result in rapid wearing of the substrate. At this stage, the tool is sufficiently weakened causing it to fail catastrophically. Confirmation of the rapid deterioration of the tool is based on the fact that the flank and end clearance wear values prior to failure are well below the criteria values used. A brief discussion on these wear mechanism are given in the following paragraphs.

High temperatures and compressive stresses can be expected when turning at high speeds and feeds. A tool temperature of about 900 °C is attainable when machining low strength, En 8 steel with coated carbide steel at a cutting speed of 183 m/min, feed of 0.25 mm/rev and a depth of cut of 1.27 mm [23]. In this particular investigation, even higher tool temperatures are expected when turning hardened Stavax tool steel due to the higher workpiece hardness. At temperatures above 900 °C, dissociation of the coating materials into their atomic component could occur and their subsequent removal by the fast flowing chip hasten the diffusion of metallic, e.g. Fe and Co, and non metallic, e.g. carbon, atoms across the tool–chip interface. Upon prolonged machining, the coating layers wear out thereby exposing the tool substrate to more severe diffusion wear. Diffusion being a strongly temperature-dependent process in which atoms diffused in the direction opposite to the concentration gradient, resulting in KT 315 inserts to have higher diffusion wear since they have higher Co content, which induces a higher concentration gradient between the tool material and the chip.

The combination of adhesion and diffusion wear mechanisms is particularly active on the rake surface. Crater formation due to adhesive wear process is believed due to the chip which alternately slips and sticks on the rake face. During the sticking phase, interdiffusion of Fe and Co occur resulting in the weakening of the binder. When the chip breaks free, it is able to fracture segments of the tool and subsequently small chunks of the tool are being removed resulting in the formation of a rough or irregular profile in the crater (Fig. 10a).

The presence of hairline cracks (Fig. 9b) on the rake face even before the substrate is being penetrated seems to suggest the coming into play of fracture mechanism, particularly through coating fracture resulting in edge chipping, flaking and rapid growth of crater wear, which considerably weaken the tool, accelerate the wear process and consequently lead to the catastrophic failure of the tool. The fracture observed may be due to the extremely high shear stresses produced by the moving chips or because of thermal stresses generated by the steep temperature gradient experienced by the tool as a result of cutting the hardened steel or even as a result of a defect in the substrate.

The cutting edge deforms plastically when the tool is unable to support the cutting pressure over the area of contact between the chip and the tool due to the high concentration of the compressive stresses at the tool rake face close to the cutting edge as well as due to the expected high tool temperatures. Deformation of the cutting edge usually occurs at high feed rates, which resulted in high cutting edge loads or at high cutting speeds since the hardness of the tool decreases with increasing cutting speed and temperature. An acceleration of the various wear processes occurs as a result of the downward deformation of the tool edge. Cutting tools subjected to compressive stresses tend to deform plastically if the elastic limit is exceeded. KC 9110 tools with a lower Co content will probably have higher resistance to plastic deformation relative to KT 315.

4. Conclusion

Cutting speed and feed have an effect on tool wear and tool life. It was observed that longest tool life was attainable when cutting using KT 315 at low cutting speed and feed rate using -5° SCEA. However, at other cutting conditions, KC 9110 outperformed KT 315. This is particular evident when cutting at high feed rate. Results also seemed to indicate that the SCEA also influenced the tool life as it increases, when the SCEA was changed from 0° to -5°.

Based on the linear trendlines, the constant and exponent for the Taylor tool life equations have been determined. The linear trendlines for KT 315 and KC 9110 are not parallel and the n values were 0.22 and 0.52 whilst the C values were 131 and 292 m/min, respectively. These point to the fact that the use of KC 9110 generally resulted in longer tool life.

The typical rapid-uniform-rapid wear profile corresponding to zones A–C can be observed when using both KT 315 and KC 9110. Profiles terminating in zone A are obtained in a number of instances when using the KT 315 whilst when using KC 9110, profiles with only zones A and B are obtained in most of the instances. Flank wear and catastrophic failure are the two main types of tool failure mode when machining hardened Stavax ESR steel with KT 315 at the various cutting conditions investigated. On the other hand, end clearance and flank wear are the main types of tool failure mode with KC 9110.

Flank and end clearance wear probably occur by both abrasive and adhesive wear mechanisms with abrasive wear being the major source of material removal since the temperatures at the tool flank are lower than that on the rake face. Catastrophic failure could be associated with a combination of abrasion, adhesion, diffusion, fracture and plastic deformation wear mechanisms. The results suggest that dry turning of hardened, stainless tool steel could be performed using coated TiCN based cermet and coated carbide cutting tools at suitably selected cutting conditions.

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