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THE MACHINING OF HARDENED CARBON STEELS BY COATED CUTTING TOOLS

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ABSTRACT

The investigation of machining AISI 1050 carbon steels hardened to the 60 HRC hardness was carried out to determine the tool life and wear behaviour of the various cutting tools under different conditions. These experiments were conducted at using coated ceramic cutting tools and carbide cutting tools. The experimental results showed that the coated ceramic tools exhibited better performance than those of the coated carbide tools when machining the hardened steels. Moreover, wear behaviour of cutting tools were investigated in a scanning electron microscope. Electron microscopic examination also indicated that flank wear, thermal cracks on the tool nose combined with the nose deformation on the tools were responsible for the wear behaviour of the ceramic tools. For the carbide tools, however, removal of coated material from the substrate tool and combined with the crater wear were effective for the machining the hardened steel.

Key Words : Hardened carbon steels, Ceramic coated cutting tool, Carbide coated tool, Flank wear, Tool life

SERTLEŞTİRİLMİŞ KARBON ÇELİKLERİNİN KAPLAMALI KESİCİ TAKIMLARLA İŞLENMESİ

ÖZET

50 VSD-C sertliğindeki karbon çeliklerinin, değişik şartlarda kaplamalı kesici takımlarla, takım ömrü ve aşınma davranışlarını belirlemek amacıyla, işlenebilirliği incelendi. Bu deneylerde, kesici takım olarak kaplamalı seramik takımlar ve kaplamalı karbür takımlar ile talaş kaldırma işlemleri gerçekleştirildi. Sertleştirilmiş çeliklerin işlenmesinde seramik kaplamalı kesici takımlar, karbürlü kesici takımlardan daha iyi performans gösterdi. Bunun yanında, aşınmış takım uçları taramalı elektron mikroskobu altında incelendi ve bu inceleme ile seramik esaslı takımda yan kenar aşınması yanında burun aşınmasının etkili olduğu görüldü. Karbür esaslı takım yüzeyinde ise kaplama maddesinin koptuğu ve abrazyon şeklinde krater aşınmanın oluştuğu gözlendi.

Anahtar Kelimeler : Sertleştirilmiş karbon çeliği, Seramik takım, Karbür takım, Yan kenar aşınması, Takım ömrü

1. INTRODUCTION

Steels are generally regarded as “dificult-to-machine” at hardnesses greater than about 30-32 HRC. Consequently, workpiece materials above this limit are traditionally cut near-net-shape in the annealed condition, heat treated and finally electrical discharge machined, ground and/or hand polished to final dimensions and surface finish. Manufacturing costs can therefore be high and lead times excessive. Conventional cutting tools such as cementede carbide (WC) offer little scope for machining steels in the 35-65 HRC range, due to poor hot hardness performance. Coating are also used on cutting tools to provide improved lubrication at the tool/chip and tool/workpiece interfaces and to reduce friction, and consequently reduce the temperatures at the cutting edge. During machining, coated carbide tools ensure higher wear resistance, lower heat generation and lower cutting forces, thus enabling them to perform better at higher cutting conditions than their uncoated counterparts by Minevich, (1997)**.** The use of coated tools to machine difficult-to-cut materials actually represents state of the art machining technology and today's machining processes are becoming increasingly demanding upon cutting tool materials. More than 40 % of all cutting tools are coated in modern industry today according to market data (Grearson, 1992). The development of ceramic and polycristalline cubic boron nitride (PCBN) has expanded in recent years, particularly in Japan and Germany, England due to products capable of withstanding the extremely high temperatures and stresses imposed when rough and finish machining hardened ferrous components.

The following is merely an overview of the work reported in the literature. Xiao (1990), studied hardened AISI H13 hot-work hardened steel (43-48 HRC) using series of different ceramic tools. It was found that the tool life was limited mainly by crater wear when using Si-Al-O-N, whisker reinforced alumina and CBN. Alumina based ceramic tools showed superiour crater wear resistance whisker reinforced alumina tools showed microfracture during cratering, CBN tools revealed evidenced of diffusion wear. Enomoto et all. (1987), indicated that CBN tools had the shortest life when the Cr-Mo steel was rather soft (HRC35) whereas carbide tools showed shorter tool life with the increasing the hardness of work materials. Similar studies with various hardness were conducted by Gane and Stephens (1983); Matsumoto et all. (1987); König et all. (1990). Ohtani, (1991) indicated that Al_20_3/TiC based ceramic tools had as long as a tool life as CBN tools for the continuous machining of hardened steels. Takatsu et all. (1983), found that minimum flank and crater wear occurred when using tools with 55 % CBN tools on SUJ2 bearing materials hardened to 62 HRC. Similar studies were carried out by König et all., (1990) and Osihi and Nishida (1992), when using CBN and mixed alumina tools. In the former work it is suggested that when rough cutting the CBN tool is preferable, based on a tool life criterion, while for finishing the mixed alumina is superior. In the latter one, the use of lower cutting speeds and optimimum corner radii was shown to delay the onset of fracture in mixed alumina. Their study showed that the critical speed was higher for CBN than for mixed alumina tool.

According to Xiao, (1990), tool wear induced normal and shear stresses leading to surface and subsurface deformation while Watson and Murphy (1979), reported that low speeds can result in built up edge damage. Most reported data has been obtained using cemented carbide tooling, particularly coated products (Ezugwu and Soh, 1997). In recent study carried out by Abrao et all. (1995), showed several aspects of finish turning against grinding of hardened bearing steel. The findings suggested that for the operating parametres tested the microstructural alterations observed were confined to an untempered martenzitic layer often followed by an overtempered martenzitic layer. In addition, the best fatique resistance was obtained when turning by using PCBN cutting tools, followed by turning using mixed alumina tools and finally by grinding. Gülyaz et all. (1996), studied the final machining operations of the hardened components which has a 60 HRC hardness using CBN cutting tools. based on the selected cutting conditions. The effects of cutting parametres on surface roughness of the hardened carbon steel were determined, using the Response Surface Method and the surface roughness became worst with increasing the depth of cut and feed rate while it became better with increasing the cutting speed. More recently, Platin et all. (1998), developed the mathematical model for tool life of ceramic tools but for Inconel 718 süper alloys. It is found that the maximum permisable speeds for A_20_3-SiC and Sialon inserts were 360 m/min and 270 m/min respectively. Brant (1986), observed that cratering in alumina and mixed alumina tools involved plastic deformation of a thin layer. Crater wear of mixed alumina was more sensitive to cutting speed than that of alumina as the content of Ti (C, N) was worn by diffuson into the workpiece material within the secondary shear zone. A similar phenomenon was reported by Chattopadhyay and Chattopadhyay (1984). Nakayama et all. (1988), compared the soft and high strength of hard materials and tool wear due to abrasion and high temperature. Ohtani and Yokagawa (1988), stated that the main wear mechanism of CBN and ceramic tools in the machining of cold work tool steel SKD11 was abrasion by hard alloy carbide particles contained in the workpiece. The life span of carbide tools decreased as workpiece hardness increased while the lifespan of CBN and ceramic tools showed the opposite results. Luo et all. (1999), also observed that the main wear mechanism was abrasion in machining of the AISI 4340 steel using CBN tool. For the ceramic tools, however, there was adhesion wear and abrasion wear. Matsumoto et all. (1987), found compressive residual stresses near the machined surface, shifting to tensile stresses as to the hardness of the workpiece decreased when turning hardened the same steels using mixed alumina tools. Narutaki et all. (1979), showed that average cutting temperature of CBN tools was lower than that of carbide tools. It decreased with the increase of workpiece hardness when the hardness exceeds a particular limit. According to (Hooper and

Brookes, 1984; Hooper et all. (1989) the wear of CBN tools occurred as a result of chemical wear caused by interactions with the enviroment and formed a protective layer on the surface of the tool at high temperature. The authors suggested that the improved tool wear performance by DBC50 over Amborite when finishing is due to the its lower thermal conductivity.

From the above literature review, it is seen that most of the study has been focused on hardened hot work die steel and bearing steel using ceramic and CBN cutting tools and no study on machining of the hardened carbon steel using coated cutting tool materials has been reported. The aim of the present investigation was, therefore, to compare the wear behaviour of conventional coated ceramic and carbide cutting tools used for turning hardened AISI 1050 steel under various cutting conditions. Attempts were also made to analyze the worn tool in order to determine factors responsible for wear of coated tools.

2. EXPERIMENTAL PROCEDURE AND METHODS

2. 1. Material Details

The machine used for the turning tests was a Johnford TC 35 Industrial type CNC lathe machine. The lathe equipped with continuously Computer Numerically Controlled (CNC) lathe variable spindle speed from 50-3500 rpm, and a 10 KW motor drive was used for the machining tests. The cutting tools tested were coated carbide tools (TP15) and coated ceramic tools (LX11). The material selected for the tests according to the insert number CNMA120408 are reported in Table 1. These inserts were mounted on a commercial tool-holder having the following geometry: rake angle, $\gamma = -6^o$, clearance angle, $\alpha = 6^o$, side cutting angle, $\Psi = 75^o$, inclination angle, $\lambda = -6^o$ dir. All the inserts tests had been coated using a CVD technique. In the coating process, TP15 grade is also known CVD coated grades. Coating substance takes place on the P20 tungsten carbide substrate for this one and consists of four layer of Ti (CN)+TiC+Al_20_3+TiN compound materials. In the case of LX11 ceramic tool, it is coated ceramic one, but coated only a layer of TiN compound. In the deposition proces, the substrate (tungsten carbide or ceramic) is heated in a chemical reactor and a gas or mixture is passed through the reactor to cause deposition.

The work material for this investigation is an AISI 1050 steel having the following chemical composition: C = 0.53 %, Mn = 0.68 %, Si = 0.24 %, P = 0.011 %, S = 0.013 %. The steel bar stock was 60 mm diameter and 400 mm in length and these bars are hardened to 50 HRC under at water coolant.

Table 1. Properties of Cutting Tools Used in the Experiments

Types of Cutting Tools	Tool Designation	Chemical Composition of Coating Materials	Cutting Fluids
Coated carbide tools (TP15)	CNMA 120408	Ti (C, N) + TiC + Al_20_3 + TiN	Dry
Coated ceramic tools (LX11)	CNGA 120408	TiN	Dry

2. 2. Cutting Conditions

Preliminary tests were carried out to determine suitable depths of cut, feed rates and cutting speeds. The flank cutting conditions program is given in Table 2.

Table 2. Experimental Cutting Conditions

Cutting Conditions	
Cutting speed, V (m/min)	200, 250, 300, 350
Feed rate, f (mm/rev)	0.05, 0.075
Depth of cut, t (mm)	0.6, 1.0, 1.4

Tool flank and crater wear was measured by means of a tool makers microscope, with an error of 0.005 mm. Tool life criterion was either the average width of flank wear land, V_{BB} = 0.3 mm, the depth of the crater, KT = 0.12-0.15 mm, depending on the feed rate or breakage, whichever was reached first. Flank wear was monitored at suitable interval, using a special microscope-assisted device. Crater wear was measured with a surface analyser. Worn inserts were also inspected by scanning electron microscope. All of the inserts were consecutively tested for a period of 2 min in order to overcome systematic wear variations.

2. 3. Metallography

To determine the wear mechanisms of the ceramic and carbide coated cutting tools used in these tests, the wear areas were observed in a scanning electron microscope. Before observation of the tool wear, it is cleaned by acetone or methane gas, however, HCL acid can be used for removing the adhered materials on the cutting tools.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3. 1. Tool Life Curves

Tool life data recorded at various cutting conditions when machining hardened AISI 1050 steel are presented in Figure 1. The variation of tool life for each tool with the increase of cutting speed in the turning of the HRC50 steel, tested at a feed rate of 0.05 mm per revolution and a depth cut of 1.0 mm, is shown in Figure 1(a). There was an appreciable reduction at higher cutting speeds for both of the inserts. It can be seen that the LX11 tool material gave the more wear resistance performance in all the cutting conditions tested. This may be the result of chemical stability of these ceramic tools. However, the tool life's for TP15 and LX11 tools are decreased with increasing the cutting speed. The reason for this may be due to high cutting temperature generated. In other words, an increase in cutting speed usually causes a reduction in the tool/chip contact length, therefore, shifting the zone of intense heat closer to the cutting edge. This increases in temperature coupled with the high compressive stresses near the cutting edge, could accelerate tool wear and led to the shorter tool life at high speed. In addition, tools with a response curve towards the top of the graphs proving the better results but there is only two line. Tool life also changed when the experimental conditions are changed. For example, TP15 tool lasted at 0.43 min while LX11 tool showed them approximately 18 min life when the test conducted at a speed of 250 m/min and at 1.0 mm depth of cut. The best performance in terms of tool life was observed for both inserts at cutting speed of 250 m/min for the test condition used. Other cutting parameters also affect the tool life and a considerable reduction was evidenced in Figure 1 (b). This work indicated that here was no obvious difference between two types of the cutting tools used in terms of the tool exponents. Similar study was carried out on AISI 8660 alloy steels using the same cutting tools (Şahin, 2001).

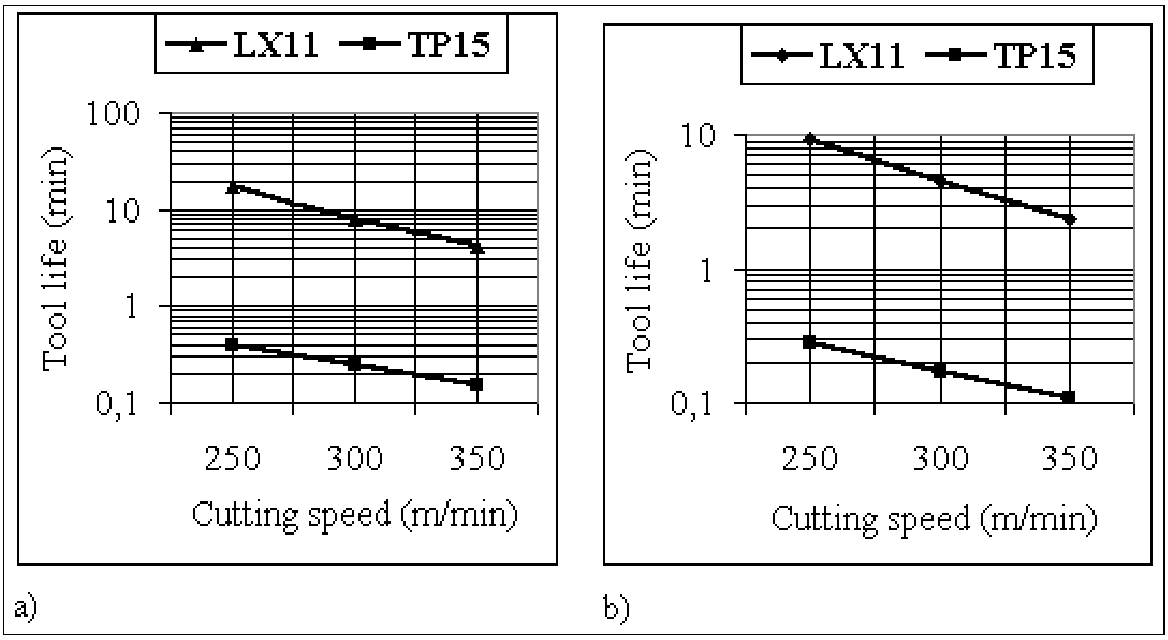


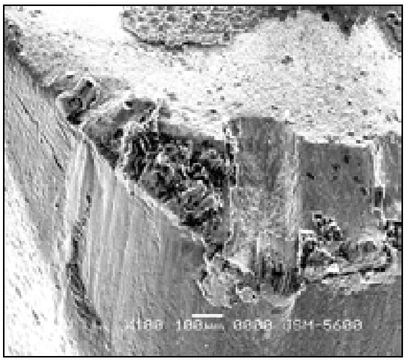
Figure 1. Tool life curves of TP15 and LX11 coated cutting tools when machining the AISI 1050 steel at various test conditions. a) V-T curves for cutting with 1 mm depth of cut and 0.05 mm/rev feed rate, b) V-T curves for cutting with 1.4 mm depth of cut and 0.05 mm/rev feed rate.

However, this early study showed that slope were considerably different from TP15 and LX11 cutting tools. It is suggested that slope changes reflected tool materials differences. The longest tool life was obtained for both tools at 150 m/min cutting speed, the tool life of 35 min being recorded for these test conditions. As point out above, this work was not consistent with the previous researchers work in terms of the slope changes of the graphs obtained from our early experimental study carried out and some other researchers work. For example, Aspinwall and Wise (1991), studied the machining of hardened AISI H13 hot work die steel using advanced ceramic tools. The maximum flank wear was about 0.99 mm after cutting at 50 m/min cutting speed for 1 min. For sialon tools, the tool life was also short after cutting at 100 m/min speed for 0.7 min. However, the tool life of the pure alumina tools lasted about 16 min after cutting at 125 m/min speed.

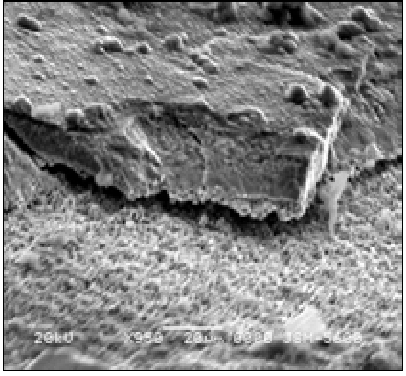
3. 2. Tool Wear

Tool life of the TP15 tools, was basically controlled by one or a combination of broken layer of the coated layer on the rake face, crater and nose wear, and chipping. In all the tests, $V_{BB} = 0.3$ mm was taken as a tool life criterion. Fracture mainly occurred at higher cutting speeds where higher temperature and stresses are generated. For the machining trials, the test carried out at 250 m/min cutting speed with ceramic tool, tool life was approximately 9.9 minute without exceeding any of the rejection criterion. SEM photographs showing the wear on the rake face and flank faces of the cutting tools after reaching the tool life criterion are presented in Figure 2. a slightly chipping and broken layer on the rake face and crater wear are the two major failure modes when machining the AISI 1050 steel with both grades of coated tools at the cutting conditions investigated. However, these failure modes can be associated with one or a combination of attrition, abrasion, crater and and nose wear mechanisms. Figure 2 (b) shows the wear of TP15 cutting tool under high magnification. This high magnification micrograph indicates very clearly broken layer of the coated material over the tool rake face. This might be due to forcing of the chips to the rake face of the cutting tool during machining process. This action resulted in mismatch of the thermal expansion of the coated layer and substrate material. Early study carried out on AISI 8660 alloy steels using the same coated cutting tool materials showed that abrasion wear and broken layer was evident for the TP15 tool (Tuncay, 2000; Şahin, 2001). For the LX11 ceramic tools, however, the flank face and rake face grooved by the workpiece due to hard particles such as crom, nicel and molibdenum in the alloy steel used in this experiment. Therefore, grooving and notching wear were observed under high magnification more clearly for the machining the hardened alloy steel. Because of its improved hardness, strength and chemical stability as well as the fine microstructures of the ceramic tools, the grooves were shallower. This is not the case for the machining of the hardened carbon steels due to not involving the hard particles. Figure 2 (c) also shows the crater wear observation although test condition was slightly higher than the previous one. The test conducted at 2.5 mm depth of cut and 0.15 mm/rev feed rate. A larger abrasion besides the removal of coated layer on the rake face were more clear in this figure. A rough surface of the TP15 tool is shown in Figure 2 (d) in addition to nose wear. Figure 3 shows the wear surface of the LX11 cutting tool when machining hardened 1050 carbon steel. The test was carried out at 200 m/min cutting speed with 0.05 mm/rev feed rate.

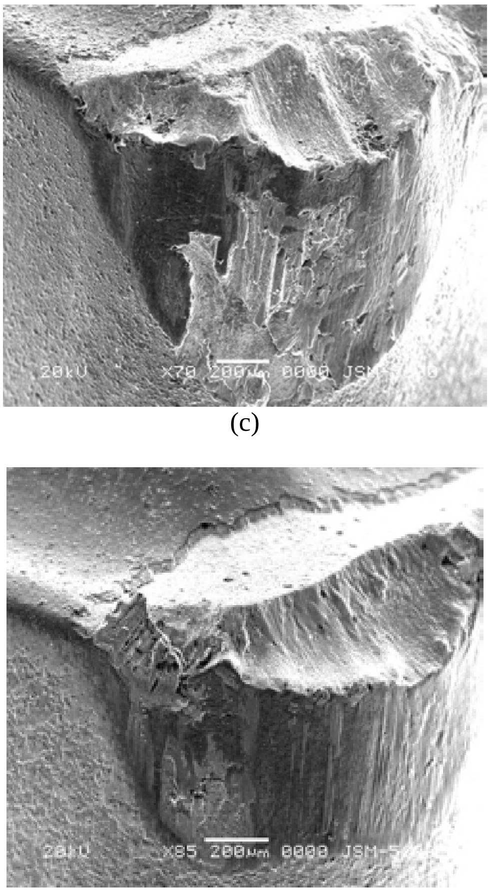
Flank wear, increased gradually was observed on the tool. The flank face was grooved by the workpiece slightly. It had a slightly smooth appearance indicating that in the smoothly grooved worn area the grains were uniformly abraded, especially on the flank face of the tool. This might be due to hard particles of the steel. It also suggest that the alumina based tools can resist wear satisfactorily. Figure 3 (b) shows the similar wear surface of cutting tool, but taken at high magnification. This high magnification also more clearly shows the deformation of structure on the rake face of the tool due to high temperature generated because of high cutting speed application. In addition to, chips on the tool nose were also observed. In another words, the wear area on the LX11 tool wear, had a similar appearance to that of the previous one, but deformation of structure on the rake face was evidenced more clearly. The test conducted at 250 m/min cutting speed with a 0.05 mm/rev feed rate and 0.6 mm depth of cut.



(a)



(b)

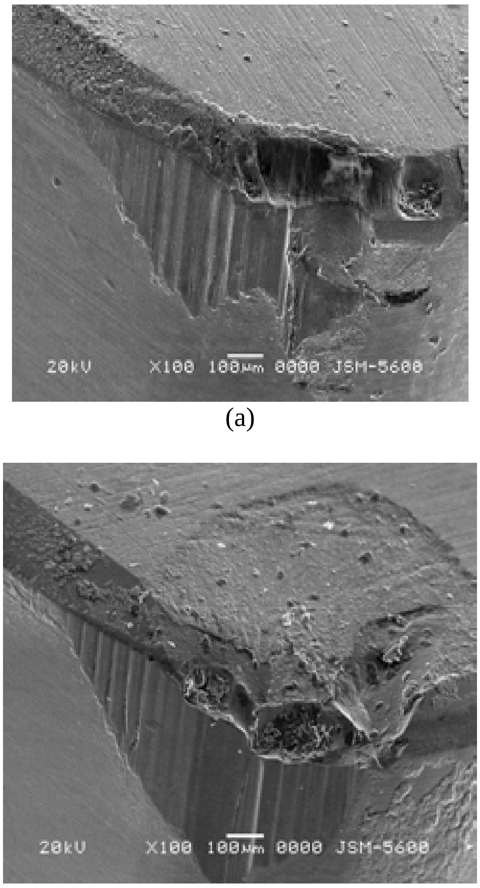


(c)

(d)

Figure 2. Tool wears of TP15 cutting tools when machining hardened AISI 1050 steel taken SEM fotographs. a) Chipping and removal of broken layers, b) Removal of coated material and rough structure, c) Crater wear and nose wear of cutting tool, tested at 300 m/min speed), d) Crater wear and broken layer on the cutting tool taken at high magnification

Because of its improved hardness, strength and chemical stability as well as the fine microstructures of the ceramic tools, the grooves were shallower. However, melting wear due to generation of high temperature and slightly cracks on the coated layer were observed. Smooth surface of the coated ceramic tooling was also evidenced in Figure 3 (a, b), compare to the carbide cutting tooling in Figure 2 (b, d). The nose deformation of the LX11 ceramic cutting tools can be appeared when the cutting parametres changed. For example, depth of cut is increased up to 1.4 mm and cutting speed is about 350 m/min. The catastropic nose deformation observed because of the application of high cutting conditions and high temperature generated during the machining of hardened steel (Tuncay, 2000). It is suggested that ceramic tools were sensitive to depth of cut. This has also been reported with the previous study (Şahin, 2000).



(a)

(b)

Figure 3. Tool wear of HX11 coated cutting tools when machining hardened AISI 1050 carbon steels. a) Flank wear and nose wear, b) Flank wear and deformed microstructure of the tool

As shown in the above figures that ceramic cutting tools provide adequate hardness for the machining of hardened steels when compared to the TP15 coating tools. For work materials with lower hardness, the chip formed during the cutting process is mainly produced by plastic deformation, the energy required during cutting process is increased proportionally with the increase of hardness. This would cause the cutting temperature to increase with the increase of workpiece material hardness. However, when the workpiece hardness exceeds about 50HRC, the chip produced becomes thinner and its shape changes. This phenomenon has also been reported by (Narutaki et all., 1979; Xiao, 1990). But there is no full agreement with the wear behaviour and wear mechanisms of various cutting tools when machining tests were carried out on hardened such as hot work steel and die steel. For example, it was found that the tool life was determined mainly by crater wear when using sialon, whisker-reinforced alumina and CBN when machining the 62HRC Rc hardened AISI H13 steel. Alumina-based ceramic tools showed superior crater wear resistance while whisker-reinforced alumina tools indicated microfracture during cratering. Similar work carried out by Abrao et all. (1995), on the hardened AISI E52100 bearing steel (62 HRC) using CBN and mixed ceramic tooling, SEM observations of worn tools suggested that diffusion and abrasive wear were the principal causes of tool failure. No evidence of built-up-edge or notching was observed over the operating range. This is the case for the present study on the machining of hardened carbon steels. The fracture characteristics studied when machining type SUJ2 hardened steel with CBN, cermet and ceramic cutting tools by Osihi and Nishida (1992) showed that normal tool wear occurred when using Al_20_3-TiC based ceramic cutting tools to machine HSUJ2 at lower cutting speeds, but fracture occurred suddenly during the first minute of cutting time when the cutting speed exceeds a critical value. The critical speeds of early fracture is increased by reducing the feed rate and depth of cut as well as by increasing the corner radius. Such a behaviour was also observed with the present results obtained here when the coated carbide tools were used..

To summarize, tool wear of SEM investigation showed that the LX11 cutting tools were found to be more resistant than those of the coated carbide tools when machining the hardened AISI 1050 steel under similar conditions tested. The reason may be due to the chemical stability of the ceramic tools, its improved hardness, strength and thermal conductivity as well as the fine microstructures of the ceramic tools.

4. CONCLUSIONS

AISI 1050 carbon steels with hardness of 60 HRC was machined by using coated ceramic cutting tools and carbide cutting tools under various cutting conditions. The alumina-based coated ceramic tools are more wear resistant than those of the carbide coated tools when machining the hardened steels. Tool life of the both cutting tools decreased with increasing the cutting speed more effectively. Among the other parametres, depth of cut was more sensitive for the ceramic cutting tool, whereas, feed rate was important for the coated carbide tool. Moreover, SEM investigation showed that flank wear and nose cracks were effective mechanisms for the LX11 ceramic tools in the machining of carbon steels with hardness 60 HRC while broken layer on the rake face of the substrate material and crater wear were responsible failure mechanisms for the carbide tools.

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