Turkish J. Eng. Env. Sci.
33 (2009) , 147 – 157.

doi:10.3906/muh-0904-6

Performance of multilayer coated carbide tools when turning cast iron

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Received 15.04.2009

Abstract

The tool life performance of multilayer hard coatings was evaluated for machining of spheroidal graphite cast iron. TiCN+TiC+Al_2O_3+TiN and TiCN+TiC+Al_2O_3+TiN multilayered coatings with different thicknesses were fabricated on WC substrates using high temperature chemical vapor deposition (HTCVD). These cutting tools with hard multilayered coating systems were used in the longitudinal turning of spheroidal graphite cast iron under the cutting conditions encountered in the work. To investigate the tool life performance in cutting tools coated by HTCVD, cutting experiments were performed using a CNC turning bench with 3 different cutting tools having multilayered hard coatings and an uncoated insert with square edges, and a type of spheroidal graphite cast irons. The tests were done under various combinations of speed, feed, and depth of cut. Tool life based on flank wear was considered to compare the 3 cutting tools. Tool performance was evaluated with respect to tool wear, surface roughness, and cutting forces at 4 different cutting speeds in the range 125-200 m/min.

Key Words: Carbide tool; Spheroidal Graphite Cast Iron; Turning; Tool life; Surface finish.

Introduction

The developments in machine tools and cutting tool materials achieved over the last few decades have led to the use of higher cutting speeds compared with conventional machining. High-speed cutting does not only reduce machining costs by increasing production volume and rate, but also results in good surface quality of machined parts. Thus, final finishing operations are usually decreased or sometimes totally eliminated, resulting in further reductions in manufacturing costs (Fallböhmer et al., 1996).

Compared to grey cast irons, there is little published data on the machining of ductile irons in the literature. The machinability of ductile irons is reported to be poorer than that of grey cast iron. Graphite flakes in grey cast irons act as stress raisers at the shear plane and thus facilitate cutting (Camuscu, 2006). In ductile iron, on the other hand, the graphite spheres are less effective than the flake graphite in weakening the material in the shear plane, and the flow zone material may sometimes be extremely ductile. This, together with inherently enhanced mechanical properties of ductile irons, results in poorer machinability than that of grey cast irons (Trent, 1984). Constituents of microstructure such as pearlite, ferrite, austenite, martensite, graphite, and carbide affect the machinability of nodular cast irons. Alloying elements in cast iron also have an important influence on the machinability (Sandvik, 1997). It has been reported that alloying nodular cast iron with Ni and Cu improves the machinability by reducing cutting forces and surface roughness of the machined parts (Seker et al., 2003).

In addition to cemented carbide, high speed steel tools are also used in large quantities for machining steel. The coating of high speed steel with hard material layers also increases tool life. Practical examples are given that support the possibilities for high speed steel tools coated by high temperature chemical vapor deposition (HTCVD).

Chemical vapor deposition (CVD) is a chemical process in which precursor gases are introduced into a reaction chamber at near ambient temperatures and directed towards a heated substrate in order to induce controlled chemical reactions. The chemical reactions result in the deposition of a solid thin film material onto the substrate surface. The CVD process is also used to produce synthetic diamonds. This technology is not yet available, even though research on high temperature CVD (HTCVD) is under way (Trent, 1991; Zima, 1999; Fitzsimmons et al., 2001). Introduced in 1995, the concept of high temperature CVD (HTCVD) is based on the continuous feeding of purified gas precursors onto a seed crystal heated to a sufficiently high temperature (>1000 °C) to enable epitaxial growth rates of interest for bulk growth applications.

Finally an explanation is given of the HTCVD process. In this process a mixture of gases is injected into the growth chamber. The higher the temperature, the larger is the probability that the initial bonds will crack and the radicals will attach to the surface, thus leading to epitaxial growth. When temperature is increased, the probability of adhesion increases but also the etch rate from the surface enhances. The growth rate is therefore determined by the desorption of the reaction products, the etch rate of the surface, and the diffusion mass transport of the source molecules. Generally, the growth rates in CVD are too low to allow production, usually tens of micrometers an hour. By increasing the temperature the growth rate increases, but at the same time problems related to the controlling of the growth become more severe, and problems such as homogeneous nucleation in the gas phase may occur. These problems might be overcome by a very careful control of the thermal and thermodynamic conditions (Trent, 1991; Zima, 1999).

The authors observed that the surface finish of the workpiece was not influenced by the tool wear, but rather by the cutting speed, feed rate, and depth of cut. Surface finish was improved with increasing cutting speed, and decreasing feed rate and depth of cut. It was also reported that the cutting process became more and more stable with increasing cutting speed. The vibration during cutting at the highest speed was the lowest (Tobias, 1965; Inasaki, 1993; Souza et al., 2004; Camuscu, 2006). The present paper details the results of an experimental investigation on the effect of cutting speed on the performance of multilayer-coated cutting tools when turning EN-GJS 1060 (spheroidal graphite cast iron).

Experimental Details

Cutting tools

The cutting tools used in the tests were uncoated carbide Tool 1 (T1) and multilayer coated tools Tool 2 and Tool 3 (T2 and T3), ISO SNMA 120408 (K10), clamped on tool holders PSBNL 25x25 K12. All tools are from the ISO HW–K10/15 grade with similar substrate of WC/Co (Figure 1). The conventional WC-(Ti, Ta, Nb, W)C-Co hard metal substrates and the tool specimens were provided by the Bohler Company.

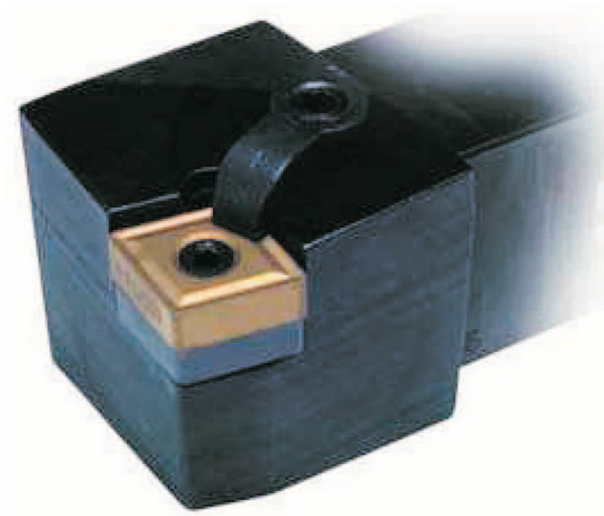

Figure 1. The substrate with a negative geometry.

The substrate was the conventional WC-(Ti, Ta, Nb, W)C-Co hard metal. The composition of the substrates is given in Table 1. Wear-resistant carbide substrate allows for machining of spheroidal graphite cast iron at high cutting speeds.

Table 1. Composition of the hard metal substrate in wt.%

Cutting tool	WC	(Ti, Ta, Nb, W)C	Co
T1	80.7	12.8	6.5
T2-T3	80.7	12.8	6.5

TiCN layers were deposited on WC substrates by CVD. On this basis layer one variant of a TiC–Ti(C,N)–Al_2O_3–TiN coating system was deposited in a HTCVD process at temperatures of about 1200 °C. As a result, 2 multilayered HTCVD coatings such as TiCN+TiC+TiCN+ Al_2O_3+TiN (Tool 2: T2) and TiCN+TiC+TiCN+ Al_2O_3+TiN (Tool 3: T3) were produced in different thicknesses. The total thicknesses of T2 and T3 coatings were totally equal to 7.5 μm and 10.5 μm, respectively. Details concerning deposition parameters of CVD/HTCVD coating systems are listed in Table 2.

Table 2. Information about the investigated CVD and HTCVD coating systems.

Coating	Thickness of layer (μm)	Deposition temperature ($^\circ$C)	Coating procedure
T2			
Ti(C, N)	1	800	CVD
TiC	1.5	1200	HTCVD
Ti(C, N)	1.5	1200	HTCVD
$Al_2\ O_3$	2	1200	HTCVD
TiN	1.5	1200	HTCVD
$\text{Thickness}_{\text{total}}$	7.5		
T3			
Ti(C, N)	1	800	CVD
TiC	3	1200	HTCVD
Ti(C, N)	1	1200	HTCVD
$Al_2\ O_3$	4	1200	HTCVD
TiN	1.5	1200	HTCVD
$\text{Thickness}_{\text{total}}$	10.5		

Machining process

Turning tests were carried out on a CNC machining center (Figure 2). All tests were conducted in dry conditions. Four different cutting speeds were employed throughout the experiments: 125, 150, 175, and 200 m/min. Feed rate (f) and depth of cut (a_p) were kept fixed at 0.25 mm/rev and 1.5 mm, respectively, throughout the experiments. During the tests, the effects of cutting speed (V_c), feed rate (f), and depth of cut (a_p) on tool life were investigated by changing each parameter, respectively.

Figure 2. CNC machining center.

An unalloyed spheroidal graphite cast iron, EN-GJS 1060, was selected as a workpiece material since it is the most commonly used grade in the automotive industries. The chemical composition and hardness values of the material are shown in Tables 3 and 4, respectively. The workpiece cylindrical bars were 250 mm long and 65 mm in diameter. The workpiece was premachined using a longitudinal turning cutter before mounting onto a Kistler piezoelectric dynamometer for forces measurement. Cutting forces were measured with a Kistler 3-component dynamometer 9257B linked via a multichannel charge amplifier (type Kistler 5019B) to a chart recorder.

Table 3. Chemical composition of the cast iron (EN-GJS 1060).

Chemical composition (wt.%)							
C	Si	Mn	P	S	Cu	Mg	Fe
3.60	2.70	0.20	0.10	0.02	0.60	0.055	Balance

Table 4. Average hardness values of the workpiece materials (BHN).

Test no.	EN-GJS 1060		
1	248	270	270
2	256	264	249
3	274	250	258
Column med.	259	261	259
BHN	260		

Measurement of tool wear

Flank wear was measured with an optical microscope and a mini optical measurement inspection system toolmaker's microscope. Five measurement samples were taken and the mean value was considered. Flank wear measurements were taken at an interval of every 100 mm length cut. With the workpiece diameter of 65 mm and employed depth of 1.5 mm cut, the cutting length of 100 mm corresponded to a machined metal volume of approximately 35 cm^3. Tests were stopped when the maximum flank wear value (VB$_{max}$) exceeded 0.3 mm. As explained in the literature (Lau et al., 2000), wear is always treated as a surface damage phenomenon; therefore study of the damaged surface contour is one of the best ways of analysis.

End of tool life criterion

End of tool life criterion based on tool flank wear distance (VB = 0.7 mm) was adopted, and to comply with requirements from the design of the workpiece rejection other criteria were also considered based on surface roughness parameters (maximum roughness average, $R_a = 6$ μm) and burr dimensions (maximum burr length, $h = 1.8$ mm).

In each test the roughness parameters R_a, maximum flank wear VB$_{Bmax}$, and burr length (h) were measured after machining the first 5 workpieces. Next, up to the 10th workpiece machined the intervals of measurements of these parameters were enhanced to 10 workpieces. From the 10th to the 60th workpiece machined the intervals of measurements were fixed in 10 workpieces and after the 60th workpiece the interval was increased to 20 workpieces machined until one of the tool life rejection criteria was reached.

Surface roughness measurements were recorded at every 100 mm length cut. Three readings were taken at 3 different points on the circumference, which were 120° apart. Surface roughness measurements were performed using a profilometer with a cut-off length of 0.8 mm and sampling length of 5 mm.

Results and Discussion

An optical microscope picture of the material is given in Figure 3. Spheroidal graphite cast iron contained graphite nodules in a matrix that is pearlitic. One of the nodules is surrounded by ferrite, simply because the region around the nodule is decarburized as carbon deposits on to the graphite. Etchant: nital 2%.

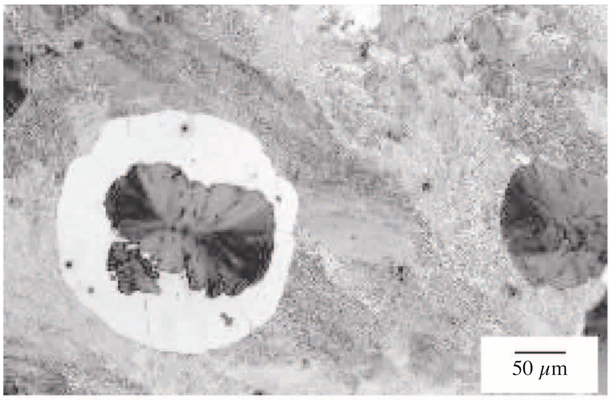

Figure 3. Micrograph of spheroidal graphite cast iron.

Figure 4. shows the flank wear curve with increasing cutting length for all 3 tools at 4 different cutting speeds.

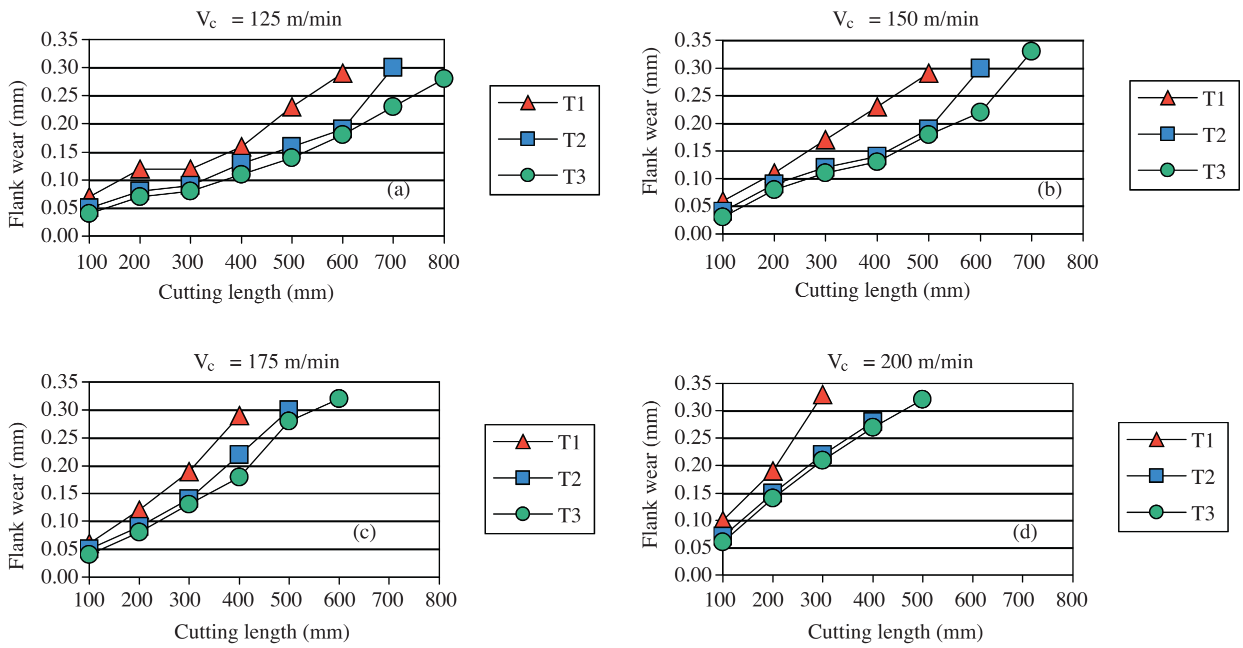

Figure 4. Flank wear versus cutting length curves obtained at the speed of (a) 125 m/min, (b) 150 m/min, (c) 175 m/min, and (d) 200 m/min.

At all cutting speeds, the uncoated cemented carbide tool (Tool 1) performed worse than multilayer coated tools (Tools 2 and 3). This was more obvious at the cutting speed of 200 m/min than other cutting speeds, as seen in Figure 4d. Tools 2 and 3 exhibited similar wear behavior at all cutting speeds with the former performing slightly better than the latter. These can be seen more clearly in Figure 5, which shows the average flank wear rates obtained by dividing the peak VB_{max} values (in μm) in Figure 4 by the corresponding maximum cutting length (in mm). It is clearly seen in Figure 5 that flank wear rate curves for Tools 2 and 3 are almost exactly parallel to and very near each other, indicating that Tools 2 and 3 have similar flank wear characteristics. At all other speeds Tool 3 behaved slightly better than Tool 2. When the flank wear rate curves are examined, it can be seen that this is the case.

The negative impact of cutting speed on tool wear is obvious in Figure 5. As the cutting speed increases, all tools undergo more flank wear. This is more pronounced for Tool 1 than the others, as there is a sudden jump in flank wear rate bar at 200 m/min for Tool 1. At lower speeds (at 125 m/min and 150 m/min) for Tool 1 and at all speeds for Tool 2 and Tool 3, more steady increases in flank wear rates are observed with increasing cutting speed. Flank wear rates for Tool 2 and Tool 3 remain almost constant between all speeds. Taking the flank wear value of 0.3 mm as the tool life criterion, the maximum metal volumes machined with Tool 1 were 186 cm^3 at 125 m/min, 152 cm^3 at 150 m/min, 123 cm^3 at 175 m/min, and 87 cm^3 at 200 m/min; those machined with Tool 2 were 210 cm^3 at 125 m/min, 177 cm^3 at 150 m/min, 148 cm^3 at 175 m/min, and 123 cm^3 at 200 m/min; those machined with Tool 3 were 248 cm^3 at 125 m/min, 205 cm^3 at 150 m/min, 154 cm^3 at 175 m/min, and 129 cm^3 at 200 m/min.

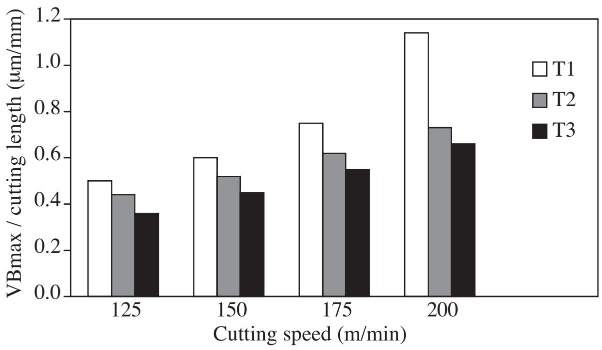

Figure 5. Flank wear rate versus cutting speed.

These results show that the high hardness of TiN coating considerably improves the wear resistance of Tools 2 and 3 multilayer cemented carbide tools when machining spheroidal graphite cast iron (Pashby et al., 1993). Under the various cutting speed when machining spheroidal graphite cast iron for the same test duration, the wear resistance of the Tool 1 is lower than the wear resistance of the Tools 2 and 3. Notably, the wear resistance of the Tool 3 is the highest of all the specimens as seen in Figure 5.

Figure 6 shows the variation in average surface roughness values with increasing cutting speed. Average surface roughness values were obtained by taking the average of surface roughness values plotted on each curve in Figure 6. Even though this approach ignores the variation in surface roughness with cutting length and related flank wear, it is very effective for visualizing the effect of cutting speed on surface roughness.

It is seen in Figure 6 that at all cutting speeds the best surfaces were produced with Tool 3, which was the best performing tool in terms of flank wear. Tools 2 and 3 produced surfaces having similar qualities at all cutting speeds. The superior performance of Tool 3 in terms of producing better surfaces becomes more apparent at 150 and 200 m/min. These results show that multilayer-coated tools (T2 and T3) perform better than the uncoated carbide tool (T1) as far as surface quality is concerned. The fact that Tools 3 and 2 produced better surfaces than Tool 1 indicates that the TiN coating on Al_2O_3 + TiCN multilayer-coated tools helps in improving the quality of machined surfaces.

The poor quality of machined surfaces obtained at 125 m/min is thought to be due to the formation of a built up edge (BUE) at low cutting speeds. As explained in Koshy et al. (2002), at high cutting speeds, on the other hand, BUE formation is suppressed, resulting in a better surface finish. The best surface quality was obtained when a cutting speed of 200 m/min was employed. The results obtained at 175 m/min were only slightly worse than those obtained at 200 m/min. In fact, at 175 and 200 m/min, all 3 tools exhibited similar behavior in terms of surface finish. At 200 m/min, the results were in the range 1.76-3.28 μm for Tool 1, 1.55-2.99 μm for Tool 2, and 1.35-2.99 μm for Tool 3. At 175 m/min, the surface roughness results were in the range 2.45-3.99 μm for Tool 1, 1.79-3.15 μm for Tool 2, and 1.69-3.05 μm for Tool 3.

Obviously, when machining spheroidal graphite cast iron with coated and uncoated cutting tools, the combination of a depth of cut of 1.5 and feed rate of 0.25 mm/rev results in the best surface quality when the cutting speeds in the range 175–200 m/min are employed. Surface roughness values obtained at 125 m/min with all 3 tools were considerably higher than those obtained at 150, 175, and 200 m/min. At 150 m/min, the surface roughness results were in the range 2.49-3.75 μm for Tool 1, 2.09-3.05 μm for Tool 2, and 1.95-2.99 μm for Tool 3.

The worst surface quality was obtained at 125 m/min with all 3 tools studied in this work. At this speed, the surface roughness results were in the range 3.42-4.38 μm for Tool 1, 2.09-3.55 μm for Tool 2, and 1.99-3.55 μm for Tool 3. This supports the argument explained in the paragraph above, i.e. the formation of BUE at low cutting speeds improves surface quality. The present results show that this argument is true up to a certain limit of cutting speed, above which it has no validity. This limit for cutting speed may change with respect to the other cutting parameters used, i.e. depth of cut and feed rate, and with respect to material properties.

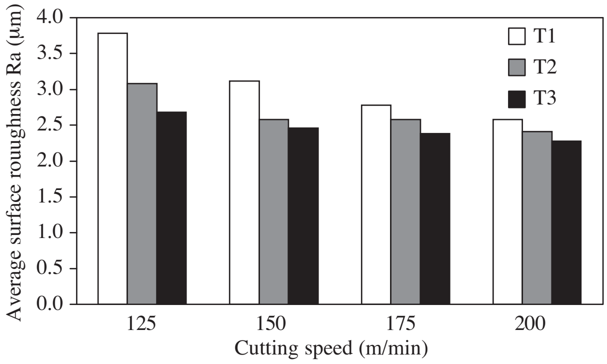

Figure 6. Average surface roughness versus cutting speed graphics.

Figure 7 depicts the change in average cutting forces with various cutting speeds. The average cutting force values were found by taking the average of cutting force values plotted on each curve in Figure 6. It can be clearly seen in Figure 7 that the increase in the cutting speed results in decreases in cutting forces for all 3 tools. Other researchers reported similar results previously (Tonshoff et al., 1999; Ko et al., 2001). The decrease in cutting forces with increasing cutting speed can be related to the increase in cutting temperature in the shear zone that results in the reduction of the yield strength of the workpiece material, chip thickness, and tool chip contact length as reported in DeGarmo et al. (1984) and Aspinwall et al. (1999).

When the 3 tools are compared, it can be seen that the average cutting forces obtained with Tool 1 were higher than those obtained with Tools 2 and 3 at all cutting speeds. The results obtained with Tools 2 and 3 were nearly the same at 125 and 175 m/min. At 125 m/min, Tool 2 resulted in the same average cutting force as Tool 3. At all cutting speeds, on the other hand, Tool 3 resulted in a lower average cutting force than Tools 1 and 2. This indicates that the TiN coating on the multilayer-coated tool results in higher cutting forces at low cutting speeds and lower cutting forces at high cutting speeds. A similar result was reported by Tonshoff et al. (1999).

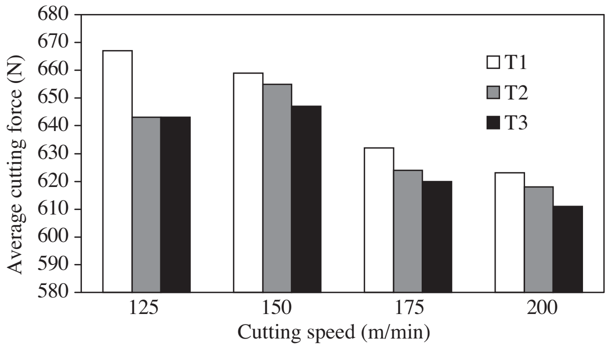

Figure 7. Average cutting force versus cutting speed.

Like main cutting forces, feed and radial forces generally increased with increasing cutting length and subsequent tool wear, and also the feed and radial forces obtained with Tool 1 were found to be generally more sensitive to tool wear than those obtained with Tools 2 and 3. It can also be seen that in some cases feed and radial forces exceeded the main cutting force. In fact, it is usually expected that the main cutting force should be the highest and the radial force should be the lowest in magnitude. This expectation was validated only by Tool 2 at 175 m/min and Tool 3 at 150 and 175 m/min. At higher cutting speeds, the magnitudes of average feed and radial forces were near or slightly in excess of the main cutting forces obtained with the same tools. Tool 1, on the other hand, conformed to this expectation. The magnitude of average radial forces obtained with Tool 1 was the highest and that of average feed cutting forces was the highest at all cutting speeds (compare Figures 7, 8, and 9). The reason for this could not be clearly understood.

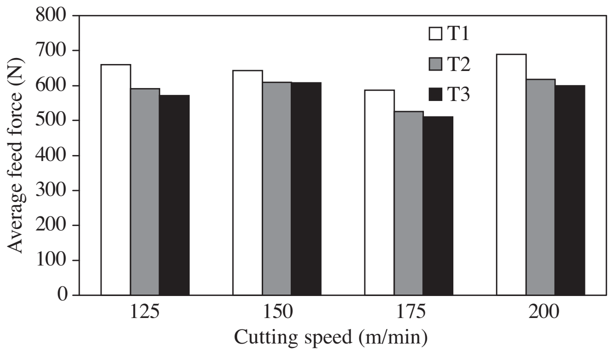

Figure 8. Average feed force versus cutting speed.

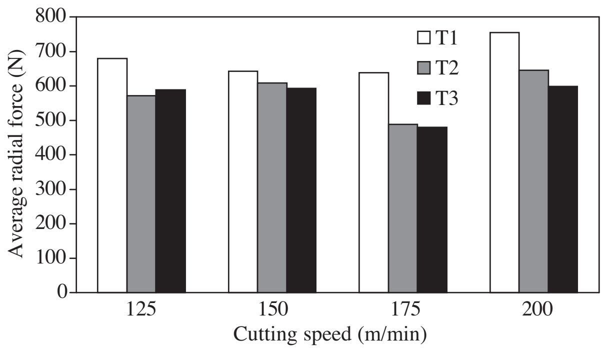

Figure 9. Average radial force versus cutting speed.

Multilayer-coated carbide tools (T2 and T3) perform better than uncoated carbide tools (T1) as far as generated forces are concerned. At all cutting speeds, the average magnitudes of main, feed, and radial forces obtained with the uncoated carbide tool were higher than those obtained with multilayer-coated carbide tools. In particular, very high radial force values were obtained with Tool 1. Among the 3 force components, the main cutting force acting in the direction of the cutting velocity is the most important one in determining the energy and power requirements, as the speeds in the feed and radial directions are negligibly small compared to the cutting speed.

Conclusions

The main conclusions drawn from this investigation are as follows:

1. The wear behavior of multilayer-coated carbide tools and the uncoated carbide tool are nearly the same in the cutting speed range (125-200 m/min) studied. However, the former performed slightly better than the latter.

2. The best surface quality was obtained with the multilayer-coated carbide tool (T3) for all the cutting speeds. The surface qualities obtained with the multilayer-coated carbide tools and the uncoated carbide tool are comparable, with those obtained with the latter being slightly better than the former. This indicates that TiN coating on multilayer-coated carbide tools adversely affects the surface quality of machined surfaces.

3. The 3 force components, i.e. the main cutting force, feed force, and radial force, generated by the TiN coated carbide tools are less than those generated by the uncoated carbide tool at all cutting speeds, indicating that turning with the former tools is more economical than the latter in terms of energy and power requirements.

4. The main cutting force usually decreases with increasing cutting speed owing to the high temperatures generated at the cutting zone. The decrease in the main cutting force obtained with multilayer carbide tools is greater than that obtained with the uncoated carbide tool. This, together with the results obtained for flank wear and surface roughness, indicates that, among the 3 tools used for the work, the one with the 10.5 μm thick multilayer TiCN+TiC+Al_2O_3+TiN coating with an external TiN layer is the most suitable tool for the turning of spheroidal graphite cast irons at high cutting speeds.

5. In this study, the tool life performance of multilayer hard coatings was evaluated for machining of spheroidal graphite cast iron. A similar study can be carried out to determine tool life, optimum cutting parameters, suitable tool grades, and their geometry.

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