THE PERFORMANCE EVALUTION OF CERAMIC AND CARBIDE CUTTING TOOLS IN MACHINING OF AUSTEMEPERED DUCTILE IRONS

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Abstract: The aim of this research is to compare TiN (PVD) coated Al_2O_3+Ti[C,N] mixed alumina-based (KY4400) ceramic and CVD coated carbide TiC+AI_2O_3+TiN (ISO P25) cutting tools in turning austempered ductile irons. Ductile cast iron samples were austenitized at 927°C and subsequently austempered for 1 hour at 400°C. The hardness of the workpiece material was measured and found to be 43.5 HRC. In the present work a series of tests were conducted in order to evaluate the tool performances by adopting tool life. In all experiments cutting forces, flank wear and surface roughness values were measured throughout the tool life. No cutting fluid was used during the turning operations. Study of the tool life and failure modes shows that tool life was determined by the flank wear and surface roughness generated on the workpiece. The main conclusion is that tool life of ceramic insert was longer than the coated carbide insert although much higher cutting speeds were used.

Keywords: ceramics, wear, tool life, cutting force, ductile iron

Östemperlenmiş Küresel Grafitli Dökme Demirlerin İşlenmesinde, Seramik ve Karbür Kesicilerin Performanslarının Karşılaştırılması

Özet: Östemperlenmiş küresel grafitli dökme demirler, üstün mekanik özelliklerinden dolayı, son yıllarda, birçok endüstriyel alanda mühendislik malzemesi olarak kullanılmaktadır. Bu çalışmada, PVD kaplamalı aluminyum oksit esaslı seramik Al_2O_3+Ti[C,N] (KY4400) ile CVD kaplamalı karbür kesici takımların TiC+AI_2O_3+TiN (ISO P25), östemperlenmiş küresel grafitli dökme demirlerin işlenmesindeki performansları karşılaştırılmıştır. Deneylerde kullanılan ÖKGDD numuneler, ilk olarak 927°C'de 90 dakika östenitlemeden sonra, tuz eriyiğinde 400°C'de 1 saat östemperlenmiştir. Sertlik 43,5 HRC olarak ölçülmüştür. Deneylerde, takım ömrü süresince kesme kuvvetleri, serbest yüzey aşınması ve yüzey pürüzlülüğü değerleri ölçülerek karbür ve seramik kesici takımların performansları karşılaştırılmıştır. Seramik kesici takımlar ile talaş kaldırma işleminde daha yüksek kesme hızı kullanılmış olmasına rağmen, karbür kesici takımlardan daha yüksek yüzey kalitesi ve daha uzun takım ömrü elde edilmiştir.

Anahtar Kelimeler: Seramik, aşınma, takım ömrü, kesme kuvveti, dökme demir

1. INTRODUCTION

Ceramic cutting tools in recent years have been sought in many applications due to their improved properties like good thermal shock resistance, good high-temperature strentgh, creep resistance, low density, high hardness and wear resistance, electrical resistively, and better

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chemical resistance (Luttervelt et. al., 1998 and Camuscu, 2006) They have unique chemical and mechanical properties and these tools can offer increased metal removal rates, extended tool life and have the ability to machine hard workpiece materials like stainless steel and hardened steel. These properties have now enabled the ceramic tools to be used in the machining of various types of steel, cast iron, non-ferrous metals and refractory nickel based alloys at high speeds (Kamuscu, 2006 and Schneider et. al., 1999).

For machining on austempered ductile iron (ADI), the most widely used ceramic class is the alumina-based class. There are different classes of ceramic materials for cutting tools, each with different properties. The two main classes of ceramic for cutting tools are aluminum oxide (Al_2O_3)-based, and silicon nitride-based (Si_3N_4). The Si_3N_4-based ceramics are formed by crystals of Si_3N_4 with an intergranular phase of SiO_2, sintered with alumina (Yeckley, 2005). Compared to the Al_2O_3 class, the Si_3N_4-based ceramic has a higher toughness (except for the whisker reinforced Al_2O_3 ceramic), greater hardness, increased thermal shock resistance, but lower chemical stability with respect to iron (Sandvik, 1994).

The wear behaviour of ceramic cutting tools has to be properly understood for their effective utilization in machining hard materials. Varieties of researches have been carried out focusing on the ceramic cutting tool materials in machining different work materials. Huang et al. 2001) studied the material fabrication and its cutting performance of Al_2O_3/TiC ceramic tool, El-Wardany et al. (1993) observed that the occurrence of plastic deformation of the ceramic cutting edge, triggered surface roughness deterioration, and eventually, edge fracture, while machining hardened steel using ceramic cutting tool materials. Chakraborty et al. (1990) carried out machining experiments with cast iron using several types of ceramic and carbide tools. Their results showed that the dominant wear mechanism for aluminum oxide-based ceramics was abrasion, while for silicon nitride-based ceramics the basic mechanism was diffusion. This comparison was made in terms of tool life and workpiece surface roughness and to understand the wear mechanism of silicon nitride-based ceramic tools and coated carbide tools in turning of ADI (Diniz et. al., 2008 and Grzesik et. al., 2009).

Nowadays, most coated carbide tools used in the machining of Austempered ductile iron (ADI) have microscopic coating layers. The main coating materials are titanium carbide, aluminum oxide (Al_2O_3), titanium nitride (TiN) and titanium carbonitride (TiCN). The chief purpose of these coatings is to increase wear resistance of the tool external layers which have contact with chips and workpiece, while the tool substrate keeps the toughness of the regular cemented carbide (Cakir et. al., 2005 and Diniz et. al., 2006). Other kinds of tool coatings are titanium/aluminum nitride (TiAlN), chromium nitride (CrN), titanium / zirconium nitride (TiZrN), titanium/aluminum carbonitride (TiAlCN) and titanium boride (TB_2), most of them presented in multi-layers coatings. These coatings have smaller grains than the coatings with just one layer that increases the wear resistance (Bhattacharyya et. al., 1989). Most of the coated carbide inserts used to machine on Austempered ductile iron (ADI) are coated with three layers of TiCN+Al_2O_3+TiN, using the chemical vapour deposition (CVD) technique (Grzesik et. al., 2009 and Santhanam, 2005).

The main goal of this research is to compare two different tool materials (ceramic and coated carbide) in the turning operation of austempered ductile iron (ADI). Some experimental results on the cutting performance of ceramic and coated carbide tool materials are reported and wear mechanisms are analyzed with microstructural observation.

2. MATERIALS AND MEDHOD

2.1. Material Properties

Cylindrical ADI bars in 87 mm diameter and 300 mm length that were austempered at constant temperatures and times were used as base materials. Ductile cast iron samples were austenitized at 927°C and subsequently austempered for 1 hour at 400°C. Before austempering treatment, the bar ends were cut off and the casting skin was removed leaving 87 mm of diameter and 300 mm of length for the workpiece. The hardness of the work-piece material was measured and found to be 43.5 HRC. The chemical composition of ductile iron before the austempering treatment is given in Table 1. Scaning electron microscope picture of the material is given in Figure 1.

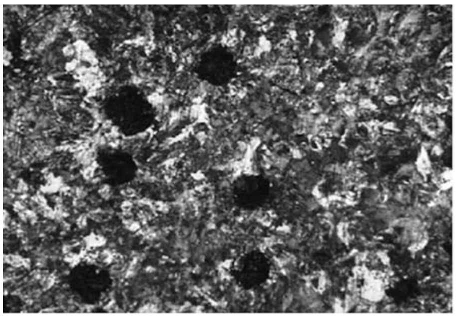


Figure 1:
Microstructure of ADIs at 400 °C for 1 hour

Table 1. Chemical composition of ductile iron

Element	C	Si	Mn	Ni	Cu	P	S	Mo
Amount (%)	3.72	1.95	0.198	0.015	0.582	0.0283	0.0093	0.0012

2.2. Machinability test

Machining tests were carried out according with Standard ISO 3685 (ISO, 1993) which involves turning of a bar at a constant cutting speed (V) and the identification of the cutting time (T_c) necessary to obtain a specific value of tool flank wear. The experimental conditions have been given in Table 2. Since conventional 5.5 KW TOSS lathe was used in the tests.

Two type of cutting inserts, namely TiN (PVD) coated Al_2O_3+Ti[C,N] mixed alumina-based (KY4400) ceramic and CVD coated carbide TiC+Al_2O_3+TiN (ISO P25) insert were used to machine the austempered ductile iron (ADI). Microstructure of the ceramic and carbide cutting tool materials is given in Figure 2. The specification and properties of the tool materials are given in Table 3. No cutting fluid was used during the turning operations.

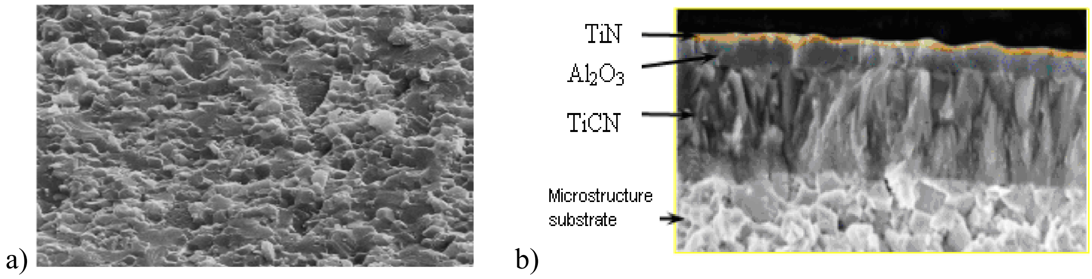


Figure 2:
Microstructure of the materials a) PVD coated alumina-based ceramic (Al_2O_3+Ti[C,N])
b) CVD coated carbide inserts (TiC+Al_2O_3+TiN)

Table 2. Experimental condition

Machine tool	: TOSS, 5.5 KW, Lathe
Work specimen's materials	: Austempered Ductile Iron (ADI)
Size	: (Cylindrical workpieces ∅87×300 mm)
Cutting tools	:PVD TiN coated AI_2O_3+Ti[C,N] mixed alumina-based ceramic (KY4400), CVD coated carbide TiC+AI_2O_3+TiN cutting tool, DNMG 150608
Tool holder	: CDBNR 2525 M12
Working tool geometry	: Inclination angle:6, rake angle:6, clearance angle:6, edge angle:75
Principal nose radius	: 0.8mm
Force dynamometer	: Kyowa TD-500
Microscope	: Nikon104 with a magnification of X10
A profilometer	: Taylor Hobson Talysurf 10
Process parameters	
Cutting velocity, V	: 128 m/min for carbide, 192 m/min for ceramic inserts
Feed rate, f	: 0.12 mm/rev
Depth of cut, a	: 1.0 mm
Environment	: Dry

Table 3. The composition and properties of cutting tool materials

Details of tool material	Unit	CVD coated carbide TiC+AI_2O_3+TiN (ISO P25)	TiN (PVD) coated AI_2O_3+Ti[C,N] mixed alumina-based ceramic, (KY4400)
Composition		90% W, 6% Ni, 4% Cu	$AI_2O_3$70% TiN 22.5% TiC 7.5%
Insert specification		DNMG 15 06 08 T01020	DNMG 15 06 08 T01020
Density	g/cm3	11.6	4.26
Vickers hardness	(HV10)	1500	1800
Transverse rupture Strength	MPa	2150	550
Young's modulus	GPa	530	400
Fracture toughness	MPa-m1/2	13	4.0
Thermal conductivity	W/mK	42	24
Coefficient of thermal Expansion	$K^{-1}x10^{-6}$	12.4	8.6

In all experiments, depth of cut (a) was 1.0 mm, feed rate (f) was 0.12 mm and cutting speeds (V) were 128 m/min for carbide tool and 192 m/min for ceramic tools (which is an acceptable cutting speed for ADI materials (Lin, 1995). It was obvious that the ceramic tool would present very long tool life (or the coated insert would come to end much sooner) if the same cutting speeds were used for both tool materials. This is why the different cutting speeds were used (Grzesik et. al., 2009)

As the tool life criteria, a value of 0.3 mm of average flank wear land (VB_B) that was established by ISO 3685, was used (Figure 3). ISO DNMG 150608 (K10), clamped on tool holder CDBNR 2525 M12 was used in the tests. Cutting forces, flank wear and surface roughness values were measured until the tool expires. The cutting forces were measured by a three-dimensional force dynamometer, Kyowa TD-500, the flank wear of the tool was measured by Nikon104 microscope and the workpiece surface roughness was measured by a profilometer (Taylor Hobson Talysurf 10).

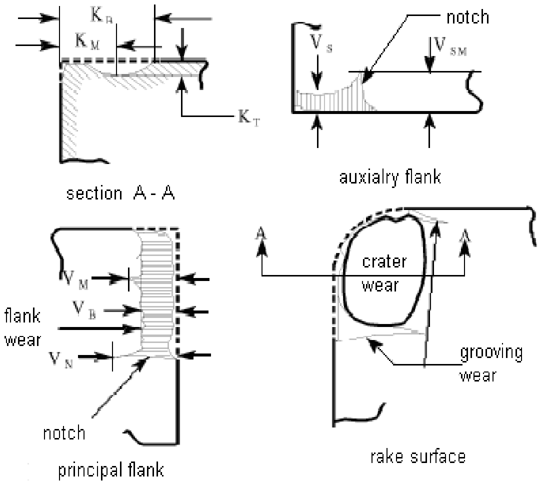


Figure 3:
*Geometry of wear of turning tools (*Dhar, 2001)

3. RESULTS AND DISCUSSIONS

3.1. Flank wear

Flank wear is a major form of tool wear in metal cutting. When machining using tools under typical cutting conditions, the gradual wear of the flank face is the main process by which a cutting tool fails (Luo et. al., 2005, Haron et. al., 2001 and Arsecularatnea et. al., 2006). The flank wear in the ceramic cutting tools is a mechanically activated wear usually by the abrasive action of the hard workpiece material with the ceramic cutting tools. It occurs on the relief face of the cutting tool and is generally attributed to the rubbing of the tool along the machined surface and high temperatures causing abrasive and/or adhesive wear, thus affecting tool materials properties as well as work piece surface Seker et. al., 2006 and Sornakumar et. al., 1995).

Tool life estimation involves a number of tests to be carried out at constant cutting conditions till the failure of the cutting tool. In general, as the tool life criterion, amount of flank wear is used. The cutting test was started with a new cutting tool, and the machining process was stopped at certain intervals of cutting length in order to measure the width of flank wear. Flank wear curve of the ceramic and coated carbide tools in machining ADI is shown in Figure 4. It indicates that ceramic tool material has good wear resistance. Under the experimental conditions, and ceramic tool has uniform flank wear.

3.2. Surface finish

One of the important parameters in evaluating the performance of a cutting tool is the surface quality. Theoretically, surface roughness is a function of feed rate and nose radius. But in practice; cutting speed, cutting depth and tool wear have influence on surface roughness as well. The advantage of machining using ceramic cutting tools is generally seen in higher levels of surface finish obtained compared to that of other conventional tools such as cemented carbides (Seker et. al., 2006).

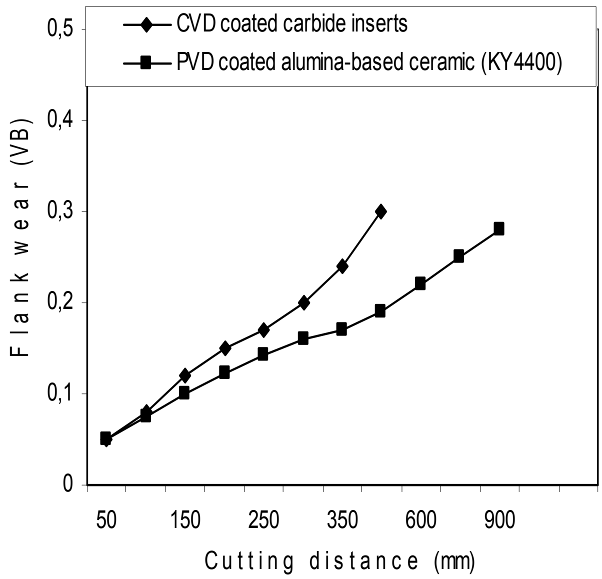


Figure 4:
Tool wears comparisons groups of ADI. V=128 m/min (carbide tool), V=192 m/min (ceramic tool), f=0.12 mm/rev, a=1 mm)

Surface finish is one of the most stringent requirements placed on finish operations; its degradation is usually due to the tool wear. For this reason, the workpart surface finish and the tool flank wear were used to evaluate the tool performance. In particular, the wear criterion adopted in the finish turning tests was based on a maximum allowed value imposed to the average surface roughness (Ra) (Cakir et. al., 2008).

Surface roughness values that were measured by a profilometer (Taylor Hobson Talysurf 10) 10 mm from the chuck first, in every 75 mm, were compared. Figure 5 depicts the surface roughness values (Ra) of each one. In X axis of the diagram the distance from the chuck of lathe is given in millimeters, and in Y axis surface roughness values (Ra) in microns.

The values in the roughness figures of this work are an average values obtained throughout the whole experiment. Figure 5 shows the flank wear versus surface roughness for different cutting inserts. It can be observed that surface roughness values for workpieces machined by ceramic tools were somewhat lower. Since cutters, carbide and ceramic had the same cutter geometry and the same cutting edge microgeometry, the lower roughness obtained with ceramic tools must be attributed to the higher cutting speed used when ceramic tools were employed. The surface quality gets worse not only as the tool wears but also as the tool moves away from the chuck, therefore this should be considered in surface quality evaluations.

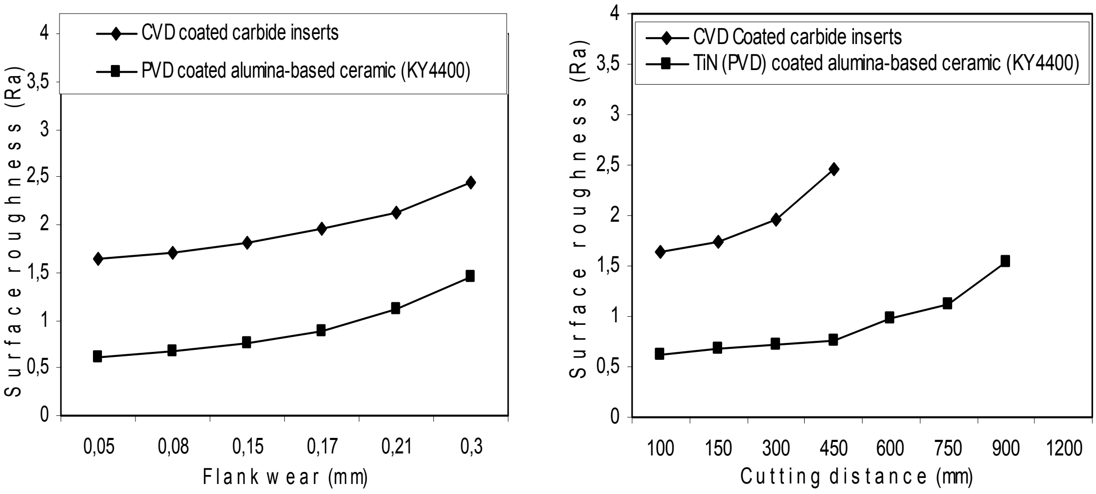
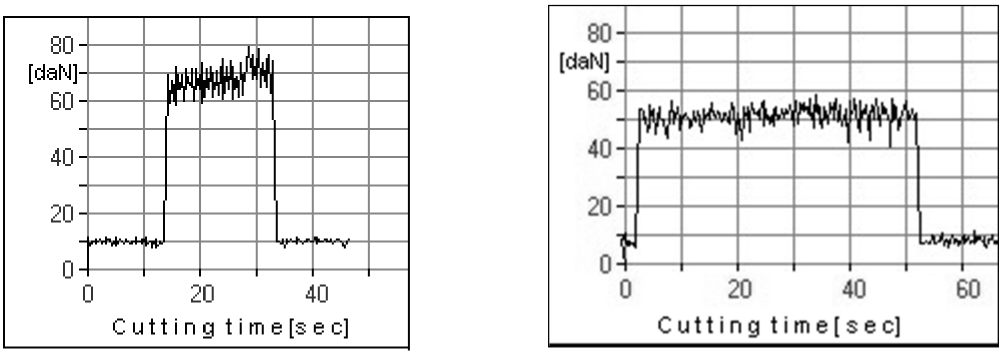


Figure 5:
Flank wear vs. surface roughness machining time at different cutting inserts V=128 m/min (carbide tool), V=192 m/min (ceramic tool), f=0.12 mm/rev, a=1 mm)

3.3. Cutting forces

The magnitude of the cutting forces is one of the most important machinability indices as it plays vital roles on power and specific energy consumption, product quality and life. Force signals are highly sensitive carriers of information about the machining process. The force displays were also reported to provide evidence of the nature of the relationship between force and wear which means the increase in cutting force indicates the increase of wear on the tool. Tangential cutting force versus cutting time is shown in Figure 6. The tangential cutting force values at the beginning of the cut and at the end of the tool life when the tool wear reaches to its critical value were used in comparisons.

The comparison of initial and the final forces was illustrated in Figure 7. It can be shown that the highest increase in the tangential cutting force (that is %16) is for CVD coated carbide tool and as expected, PVD coated alumina-based ceramic tool has lower increase (that is %12).



a) CVD coated carbide insert *b) PVD coated alumina-based ceramic insert*

Figure 6:
Tangential cutting force vs. cutting time

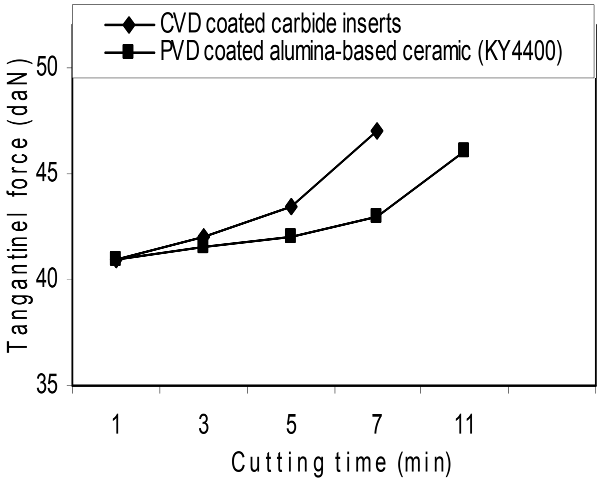


Figure 7:
Tangential cutting force vs. cutting time V=128 m/min (carbide tool), V=192 m/min (ceramic tool), f=0.12 mm/rev, a =1 mm)

In tool life evaluation turning processes were paused in every 75 milimetres and the average flank wear was measured. If the tool was not expired (which means it does not reach to a value of 0,3 mm of average flank wear land) at the end of the first bar, second bar of the same structure was used for the rest of the process. This was necessary for the constant cutting speed as explained previously. The ends of bars were chamfered to ease the entry of the tool to the workpiece. Machined workpieces (∅87x300 mm) are heavy. No matter how well they were supported by the tailstock, the stability problem was encountered in some cases which affect the surface quality. This means the surface quality gets worse not only as the tool wears but also as the tool moves away from the chuck, therefore this should be considered in surface quality evaluations.

Figure 8 shows the average chip volume removed per tool life in the experiments. As can be seen in this figure, the ceramic tool attained a much longer tool life than carbide tool, even under higher cutting speed. It must be remembered that the cutting speed used for ceramic tools was 1.5 times higher than for carbide tools, making cutting 1.5 times faster too. Thus, in this kind of operation, ceramic tools are much more suitable than carbide tools.

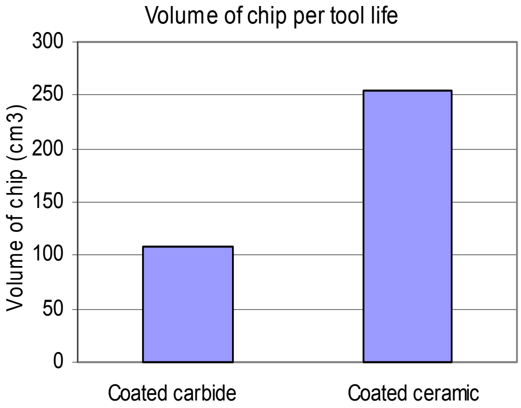


Figure 8:
Chip volume removed per tool life for each tool material V=128 m/min (carbide tool), V=192 m/min (ceramic tool), f=0.12 mm/rev, a=1 mm)

4. CONCLUSIONS

The paper describes a machinability evaluation of austempered ductile iron (ADI) with PVD coated alumina-based ceramic and coated carbide inserts. The experimental results showed that there are strong correlation between tool wear, cutting force, and surface finish. Tool life models were developed using the wear data. Based on the results obtained in this work, it can be concluded that:

(a) Flank wear increase over tool life influence surface roughness, which remained nearly constant throughout tool lives, especially for the experiments with alumina-based ceramic tool.
(b) TiN (PVD) coated AI_2O_3+Ti[C,N] mixed alumina-based ceramic cutting tool presented longer tool lives than CVD coated carbide tool although much higher cutting speeds were used.
(c) Machining with ceramic tools presented average surface roughness values lower than those obtained with carbide tools and also with smaller dispersion.
(d) The newly developed TiN (PVD) coated AI_2O_3+Ti[C,N] mixed alumina-based ceramic cutting tool material has good wear resistance in dry machining of austempered ductile iron.
(e) Flank wear in TiN (PVD) coated Al_2O_3+Ti[C,N] mixed alumina-based ceramic cutting tool is lower than CVD coated carbide TiC+AI_2O_3+TiN cutting tool on machining austempered ductile iron (ADI).

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