Proceedings of COBEM 2007
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19th International Congress of Mechanical Engineering
November 5-9, 2007, Brasília, DF

ANALYSIS OF THE CUTTING TOOL'S WEAR BEHAVIOR FOR TURNING MACHINING OF AUSTEMPERED DUCTILE IRON

Prof. Valter Vander de Oliveira, oliveira@sociesc.com.br
Prof. Marcelo Teixeira dos Santos, *Ph.D*, teixeira@sociesc.com.br
Sociedade Educacional de Santa Catarina, R Albano Schmidt, 3333. Boa Vista. Joinville. Santa Catarina.
Prof. Paulo André de Camargo Beltrão, *Ph.D*, beltrao@utfpr.edu.br
Universidade Tecnológica Federal do Paraná, DAMEC/ PPGEM, Avenida Sete de Setembro, 3165. Rebouças. Curitiba. Paraná.
Cássio Luiz Francisco de Andrade, *Msc*, cássio@tupy.com.br
Tupy Fundições Ltda, R Albano Schmidt, 3333. Boa Vista. Joinville. Santa Catarina.

Abstract: The austempered ductile iron (ADI) could be used in various segments of mechanical industry, mainly in automobilist due to their proprieties, technical advantages and the combination between resistance and ductility that could be getting from this material. ADI has also been used with success in gears, in chain roulettes, crankshafts, as well as in engine blocks manufacturing, once blocks made in cast iron can't support the performance requirements of modern engines. The main technical limitation of austempered ductile iron attached to machinability is relatively low in austemperated state. This problem happen by austenite transformation, which is characteristic of ADI microstructure, and triggered due to material deformation, which affects the steps of manufacturing process. This is more common to happening between the heat treatment sequence and the finishing machining. This article describe a study about the wear behavior of three materials used to cutting tools (cemented carbide, ceramic and CBN) in external turning of ADI through a comparative analysis of tool life in function of cutting speed, using as final criteria of life a flank wear of 0,3 mm. The cemented carbide tools coated with a layer of aluminium oxide showed up the better performance among the tools used due to the combination of abrasion resistance and the high tenacity of the substratum.

Keywords: turning process, austempered ductile iron, flank wear and cratering.

1. INTRODUCTION

The austempered ductile iron (ADI) was described by Goldberg et al (2000) as a material applied in substitution of other casting irons. Therefore it presents improvement of the mechanical properties such as wear resistance, hardness, tenacity, the easiness of manufacture with an acceptable cost, considering the most ecological technology. ADI has been used since 1972, and its use is increasing in a significant way in the last few decades due to the automobile industry. The ADI technical advantages are the combination between mechanical resistance and the ductility that can be gotten in this material and could be compared with the casting steel higher resistance. Among others properties its capacity of damping, wear resistance and good thermal conductivity, became this material less inclined to mechanical distortions during the thermal treatment when compared with other ferrous materials. Goldberg et al (2000) esteem that production of ADI in the North America in about 150.000 tons per year, with a projection of 20% growth for 2005. There are about 200 industries working with casting of ADI, being that the majority of the parts produced in the North American market manufactured before thermal treatments. The main limitation to work with austempered ductile iron is attributed the low machinability relatively to its austempered state, being common to occur through the looping before the thermal treatment and the final finishing during the production sequence. The development of new ADI materials with finer granular structure improved the tenacity, keeping intact the other properties such as hardness and wear resistance. Tool materials such as ceramics and cubic boron nitride (CBN) have been used in the manufacturing industry of hard materials such as the ADI due their properties, of high hardness in high temperatures and wear resistance. Moreover, the cutting tools coating technology acquired basic importance in the process of manufacture hard materials, where coating helps the separation function between tool substratum and the working material of the part, where the substratum can be tenacious to support shocks and coating in fine layers could reduce wear, decreasing the friction coefficient on the face surface and acting as a thermal isolating of the substratum. Beyond these coating advantages for cutting tools the process of coating deposition can be choose between chemical vapor deposition (CVD) or physical vapor deposition (PVD) with the advantage that in the physical process the application of a new layer can be carried out some times without modifying the dimensions and the format of the tool. Diniz, et al (2000) presents an initial idea that to ADI machining it's necessary to have the adequate cutting tool, and to get that, is vital to analyze a series of situations which had assisted in the ideal choice of the process and cutting tool for machining this material. The aspects to be considered in this choice includes: *i*) the material to be machined by its hardness and chip morphology; *ii*) equipment characteristics such as power, speeds and state of conservation; *iii*) the exactly cost of the tool. These choices could produce positive points, such as extended tool life and/ or greater production, but in some situations could not cause a reasonable relation cost/ benefits. Machining conditions such as cutting speeds, feed rate and depth of cut must be tested in operation conditions of rough and finish machining. Beyond these, geometry of the cutting tool such as forms, angles and dimensions must be settled. The objective of this paper is compare the performance of cemented carbide, ceramic and CBN cutting tools and to analyze the wear behavior in function of the cutting speed applied in the external finishing turning of the austempered ductile iron.

2. WEAR MECHANISM OF CUTTING TOOLS

The mechanisms of tool wear constitute an important study for machining processes optimization. Therefore a way to increase tool life is acting to reduce the wear mechanism. Ferraresi (1977), point out that the knowledge of the wear mechanism is basic for a chosen tool criteria and to the machining conditions. The behavior of the wear phenomenon can be better analyzed through the curve of tool wear against cutting speed. According to Stemmer 1995, the main causes of the wear phenomena are:

2.1 Built-up-edge

Many times a chip layer that remaining adhere to the cutting edge is formed, in the faying surface between chips and the tool face, modifying its behavior in relation to the cutting force, superficial finishing and tool wear. The detachable edge of cut tends to grow gradually until at a certain moment it is pulled brusquely, causing a dynamic disturbance. The cutting force diminishes forming the built-up-edge. Therefore, tool face angle changes.

2.2 Abrasion

The abrasion mechanism is one of the main causes of tool wear, as much of the flank and face wear can be generated by abrasion. The wear generated by abrasion is stimulated by hard particles presented in working materials and cutting temperatures that could reduce tool hardness. The higher is the tool material hardness and resistance to temperatures, the greater is its resistance to abrasive materials. Sometimes hard particles pulled out from other regions of the cutting tool and could be dragged by the movement of the working material, causing abrasive wear in an adjacent area of the tool (Diniz et al, 2000).

2.3 Adhesion

Diniz et al (2000) said that if two metallic surfaces are in contact under moderate loads, low temperatures and decreasing cutting speeds, a metallic contact could cause material welding. The resistance of this welding is raised to such point that in the attempt to separate the surfaces, rupture in one of them will occur. Thus, particles of the metal surface go from one surface to the other. The phenomenon of this welding is present in the cutting edge, but wear for same weld without the formation of the built-up-edge can be seen. In general, the zone of slipping (on the contrary of the tack zone), during the interrupted cutting, promote the chips to flow irregularly and facilitate the mechanism of wear for adhesion due to the depth of the irregular machining or the lack of rigidity.

2.4 Diffusion

The diffusion consists of chemical transference from one material to another which causes property variations on superficial layer of the cutting tools. These chemical reactions produce complex carbides formation that are less resistant and could be rapidly removed by abrasion. The diffusion is responsible for the crater wear in higher cutting speeds. Therefore it is occurring on cutting tool faces if high temperature and time of contact chip-tool are happened, which are the necessary conditions for diffusion, (Diniz et al, 2000).

2.5 Oxidation

High temperatures with presence of air and water could generate oxidation for the majority of metals. The wear generated by oxidation is formed in the extremity of the chips/ tool contact through the air access in the region. The wear generated for oxidation is formed especially in the extremities of the contact chip-tool due to the excess of air in this region, being this a possible explanation for the sprouting of the notch wear (Diniz et al, 2000).

2. EXPERIMENTAL PROCEDURE

For this study external cylindrical turning of a cast iron pipes of ADI were used. The chemical composition of the ADI specified by Tupy casting was: C = 3.65%; Si = 2.85%; Mn = 0.18%; S = 0.005%; P = 0.027%; Cu = 0.97%; Ni = 0.04% and in agreement Mg = 0.041%. The systematic tests of machining had followed the methodology of ISO 3685 norm and the identification and classification of the material had been carried out according to the SAE J24770 norm. The machining was done using a lathe CNC FEELER, model FTC10 with installed power of 10 kW.

Three different materials as cutting tools were used: cemented carbide, ceramic and cubic boron nitride. The codified tools used in these tests according to the ISO norm were: CNMG 120408, for cemented carbide inserts; CNGA 120408 for ceramic and CBN inserts. The inserts rhomboid form presents a tip radius of 0,8 mm. The cemented carbide inserts had an aluminum oxide CVD (chemical vapor deposition) coating and the cubic boron nitride inserts had a coating of titanium nitride. The tool supports identified as DCLNL 2020 K12, specification responsible for the tool angles, was used in this work. For inserts of ceramic and CBN it is present one bevel of 0,2 mm to protect the edges and to increase the tool edge resistance. The completed geometric information of the tools is presented in table 1.

Table 1. Cutting Tools for Turning Process - Cutting Geometry

Tool	Coating	Class	α_o	χ	γ	λ	ε	r_ε
Cemented Carbide	TiN + Al_3O_2 + TiCN	K15	4	95	18	-4	80	0,8
Ceramic	TiC	K15	4	95	-4	-4	80	0,8
CBN	TiN	K05	4	95	-4	-4	80	0,8

The turning tests were performed without cutting fluid, keeping the feed rate and the depth of cut fixed and varying tool materials and cutting speeds. The cutting speed used was established for supplier recommendation for a tool life of thirty minutes. The applied depth of cut used was of 1,6 mm, therefore the norm recommends that the depth in this type of test should be around two times of the tool tip radius. The feed rate of 0,3 mm/rev was selected due to the manufacturer recommendation. Two factors with three level experiments had been established for the tests, resulting in nine rounds with three repetitions for each round. Tool wear behavior, power of cut and sample superficial finishing were measured. The turning length was determined so that the balance, distance of the part for is of the chuck not exceeded the relation of three times the diameter of the part.

The CNC machine program was elaborated in a manual way, and this allows that each cutting pass had an interval of time for measurement. The machine has a Mitsubishi command, Meldas 50L, and it employed ISO language that allowed a larger autonomy of the operator.

Twenty seven samples for the machinability and metallographic tests had been prepared with dimensions of 120 in diameter and 140 millimeters of length. Through figure 1 it can be observed the preparation of the form and dimensions of the samples for tests without thermal treatment. One lower in the extremity of the pipe improved the nesting and the rigidity of the setting system.

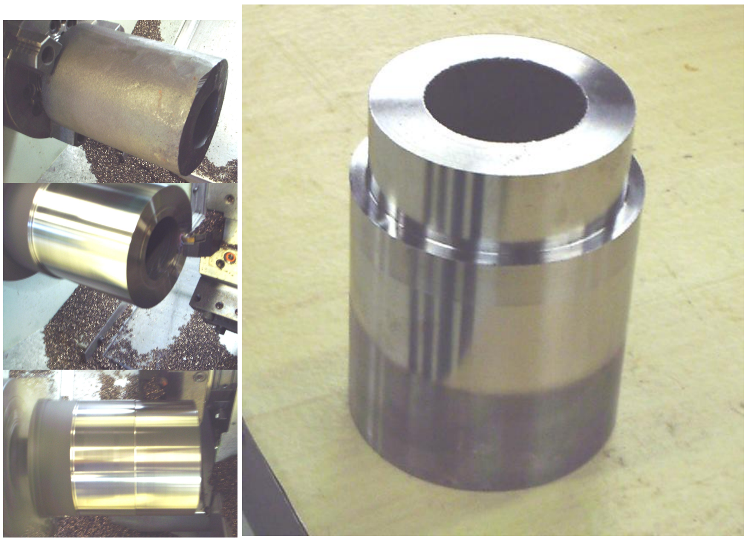

Figure 1 Setting of ADI sample for tests.

All parts had been submitted to the thermal austempered treatment at SOCIESC labs. The samples had been identified and had their hardness data registered. The dispersion they had been used to separate the test samples for each tool. A table of the test samples was used in the array, as sample hardness varied from 285 to 321 Brinnel Hardness (HB), and separated for different tool materials. Each tool worked with a significant range of material hardness, and the first experiments were performed with lowest hardness values materials until the last ones with the highest hardness values materials.

The results of the flank wear, power of cut and surface roughness had been collected to each two samples so that with the ending of the tests, the results of the three cutting tools were compared. The norm recommends between six or ten measurements for each experiment. A preliminary array determined the number of intervals for measurement, the adjustments in cutting parameters and for ceramics inserts it resulted in the selection of a more tenacious material for the experiment. The tool the flank wear (Vb = 0,3mm) or the notch wear (Vn = 0,6mm) had been used as criterion to determine the end of the tool life and to evaluate the performance of them. Other fails in tools had been observed such as cracks. The measurements had been carried through in a microscope with magnifying of 20 times and in some times they had resulted in interruption of the experiments.

3. EXPERIMENTAL RESULTS

During samples turning tests it was observed that the chips produced had been presented in the form of small curves and the heat generated for the friction between tool and the worked material liberated some sparks next to the tool edge, due the hardness of the material. The tests done using cemented carbide tools identified by the manufacturer as multi-layer class cemented carbide classified by ISO as K15. This insert has an aluminum oxide coating acts as an effective thermal barrier to distribute heat evenly. Wear on flank surface caused probably by abrasion was observed in first the ten minutes of cut and after that crater wear helps to remove part of the edge. During the tests, the presence of vibrations generated for inclusions, formed by carbides, was also observed. That fact had been responsible for the tool flank wear in such a way that cratering in these tests diminishing the tool life time. In some tests that fact resulted in cracking of the edge. The tests with the ceramic tools were performed with inserts identified for supplier as K15. These inserts presented problems of edge chipping in the cut edge when the flank wear increase. The vibrations observed during machining tests were produced by inclusions which are points with higher hardness on the working material surface. Therefore a change of the ceramics class for one more tenacious was done from class K05 to K15. The tool presented flank wear in the main edge and next to Vb = 0,3 mm vibrations and cutting power increase their values, having as consequence the chipping of the edge, driven the tests to be repeated some times. The tests with the CBN tool had been carried through using inserts identified for manufacturer as K05 class with a coating of titanium nitride applied through PVD. The experiments showed better results when compared to ceramics. However the characteristics of the tool wear behavior was similar to ceramic inserts presenting flank wear in the main edge. For cutting speed analysis of each tool material were compared when final life was reached for flank wear of 0,3mm.

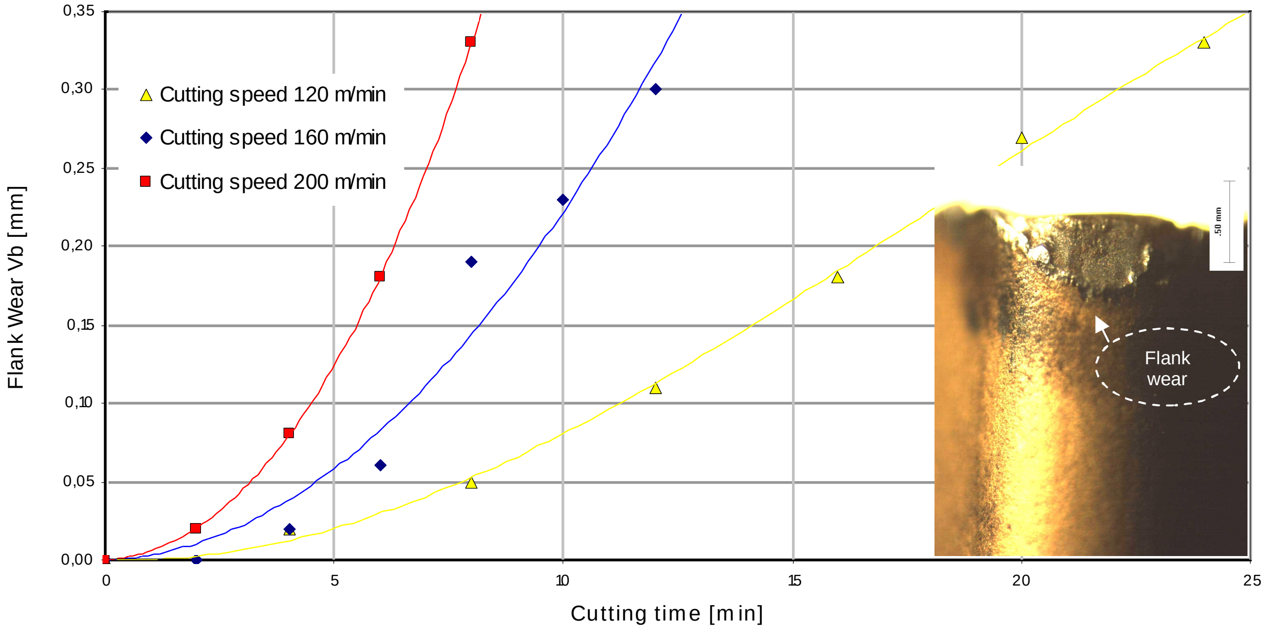

Figure 2 Flank wear in cemented carbide tool for cutting speeds of 120, 160 and 200 meters per minute.

The predominant mechanism of tool wear for cemented carbide measured in flank and face of the tools surfaces was abrasion as it can be seen in the figure 2. In tool tests with ceramic inserts life was compared with time. The best tool performance was reached, at cutting speed of 200m/min. The vibrations increased gradually as well as the increase of the cutting edge wear.

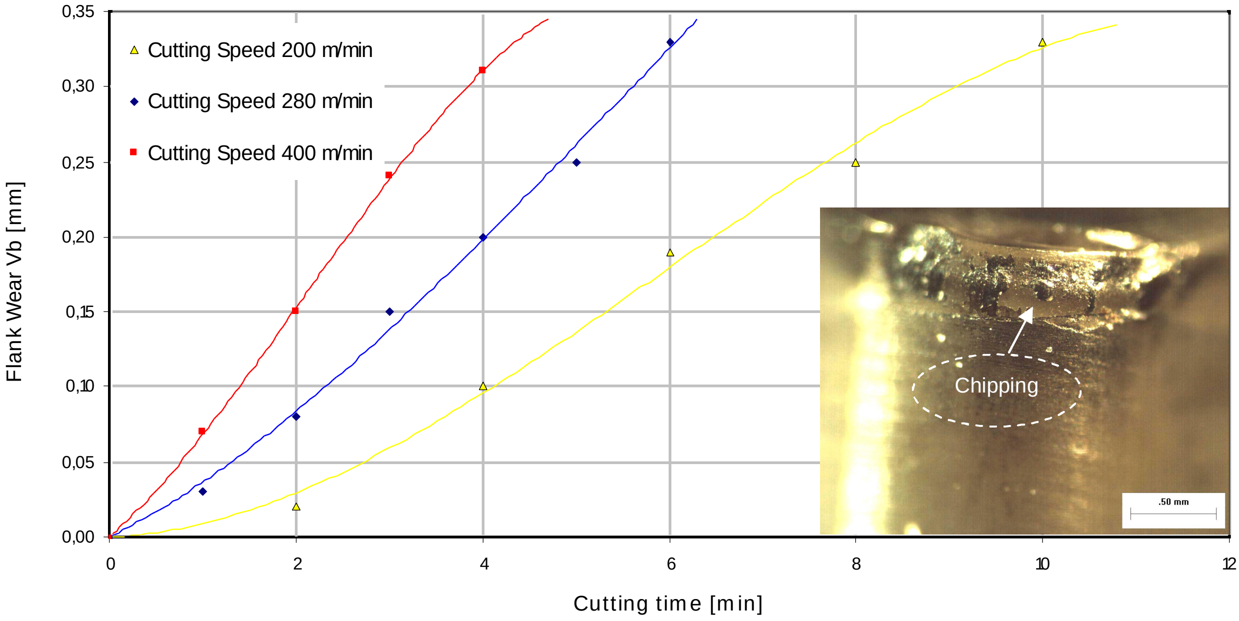

Figure 3 Flank wear in ceramic tools for cutting speeds of 200, 280 and 400 meters per minute.

The turning with ceramic tools presented problems such as chipping in the cutting edge as it can be seen in the figure 3. Notice oxides formation in the cutting edge and there are sparks during the machining. These factors were not objected of this study but they apparently had affected the behavior of the tool. The flank wear is observed next to edge and in cutting speed of 400 m/min tool face presented signals of oxide formation.

The experiment with the CBN inserts showed better results of cutting time with cutting speed of 200m/min presenting a uniform wear. As well as with ceramic tools, the inclusions on the working material surface resulted in tool wear of the edge. The flank wear in the initial stage of the machining can be observed, and titanium nitride coating also did not resist the abrasion showing crater tool wear and after that tool edge cracks. Amongst the wear mechanisms it is gradually observed the oxidation and wear of the tool face surface.

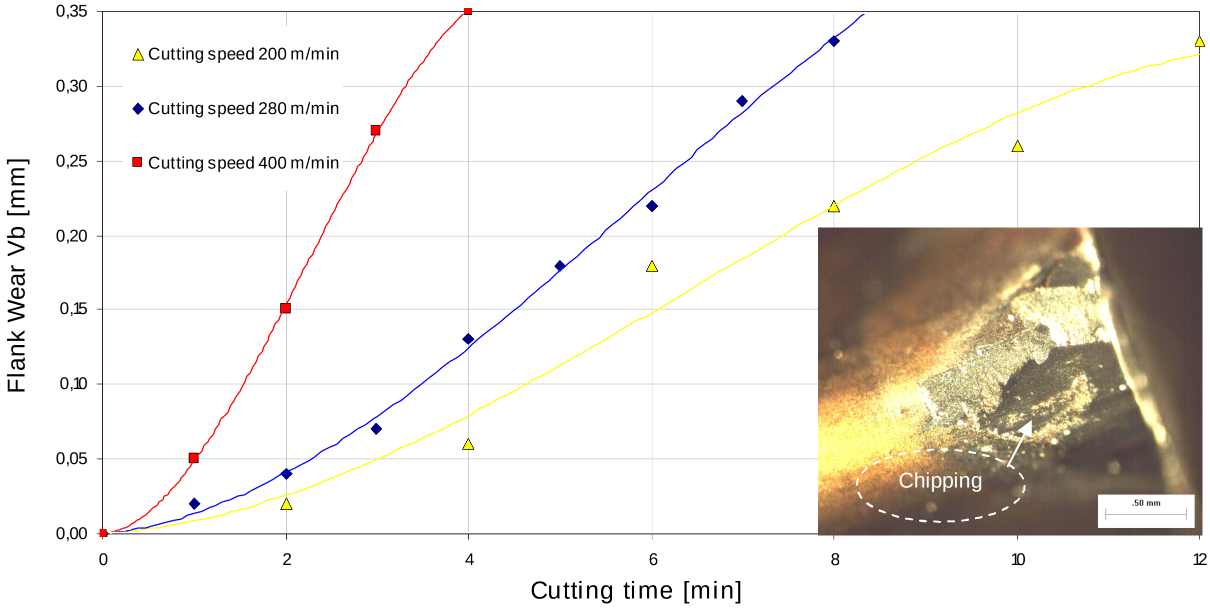

Figure 4 Flank wear in CBN tools for cutting speeds of 200, 280 and 400 meters per minute.

Comparing these three materials studied, cemented carbide tools, which had higher tenacity and aluminum oxide coatings presented the longest machining length for a cutting speed of 120m/min. However the ceramic and CBN tools presented good material removal rate, demonstrating its potential for application in the machining of parts manufactured in ADI.

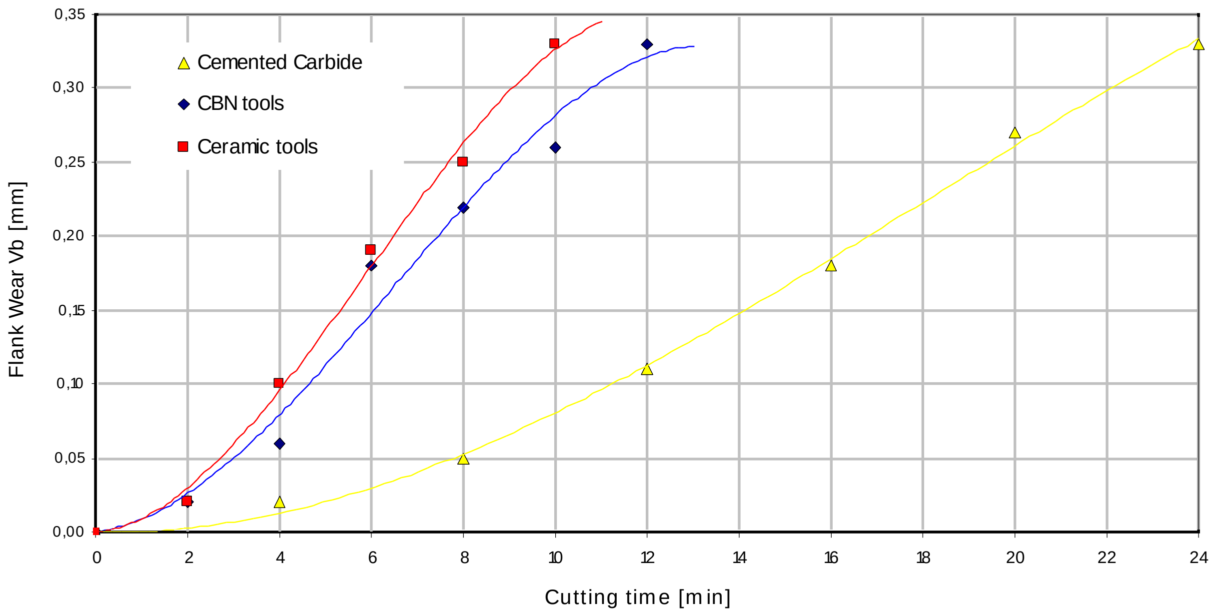

Figure 5 Comparison of the tool materials used in tests with greater performance.

Figure 6 shows tool life behavior, demonstrating that although the good performance of the cemented carbide tool, the inclination of the life curve of this material indicates that many alterations in cutting speed has great significance in tool life time.

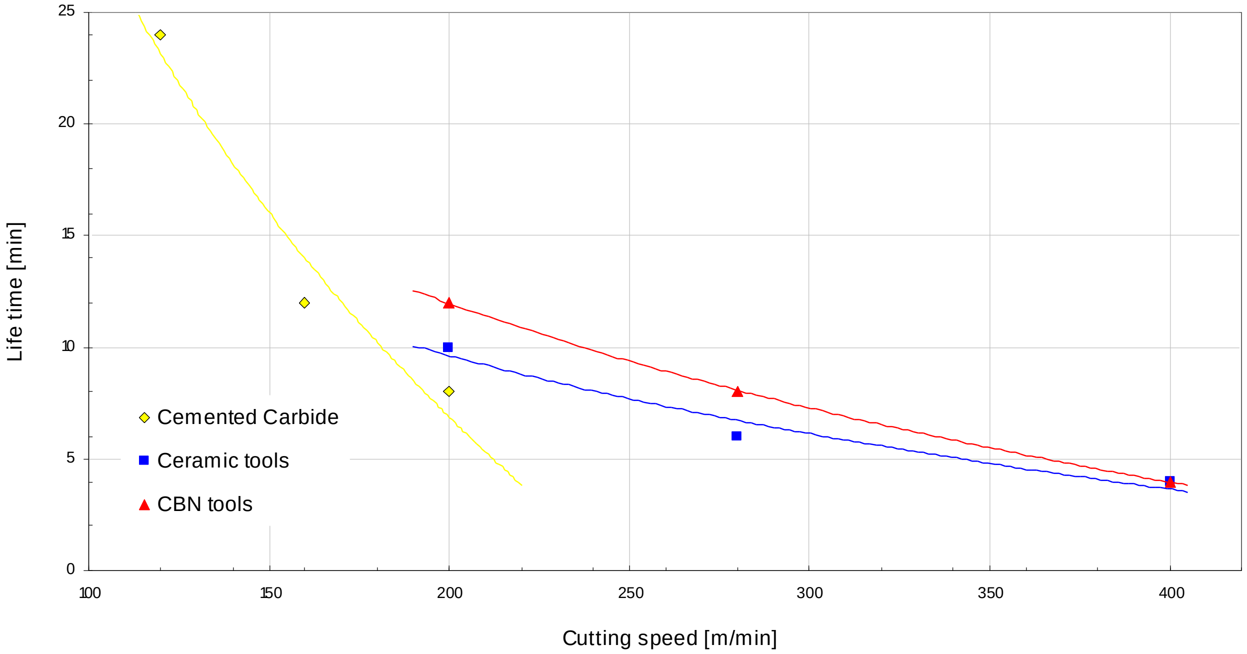

Figure 6 Comparison of tool life for the three tool materials.

In this way it could be said that, with these cutting parameters used, the tool more adjusted for the machining of the austempered ductile iron is the cemented carbide insert using cutting speed of 120 meters per minute. However analyzing the figure 7 showing machining with each one of the tools, it is possible to notice that the difference among the costs of these tools is low, around 20%, which means that the higher cost of the ceramic and CBN tools could be overcome by reduction in time machining, due higher cutting speeds. This can represent economy in the final cost of the process when the value of the machine time is high.

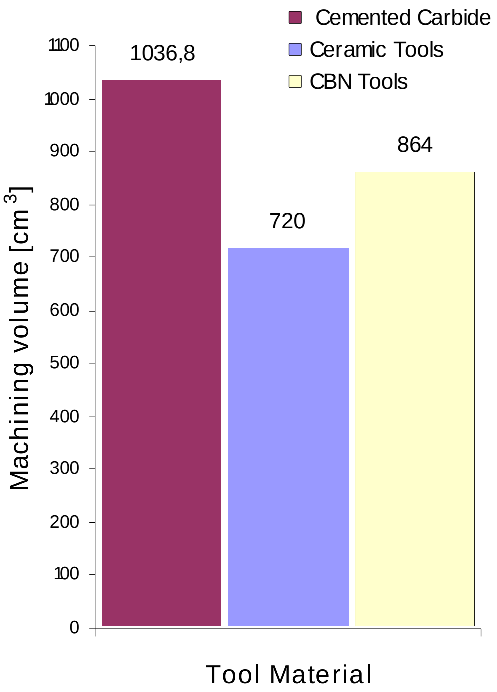

Figure 7 Comparison of machining volume for the three tool materials.

4. CONCLUSION

The austempered ductile iron has being used in the industry with a trend of growth, which had its mechanical properties as ductility and resistance to the wear, allowing its use in diverse applications, becoming a product that can substitute others with also a correct ecological trend. However, its relatively low machinability, due to the presence of a bainitic matrix structure, causes an impact directly in the machining process. During the tests it was noticed variability of its machining characteristics. Tool wear observations and the determination of its life beyond cutting expectations indicate that the behavior of this material presents a variation during the phase. This would influence tool life and machining repeatability that were determined by factors such as material hardness, cutting uniformity, tool heat diffusion and other diverse chemical and physical factors. In tested tools, inserts of cemented carbide got better costs, with more critical conditions of machining. Using materials with more tenacious class, the presence of inclusions and vibrations of the machine tool were better supported. Another factor that justifies these better results is the use of an aluminum oxide CVD coating on the inserts. Cutting speed of 120 m/min provide the longer life of the tools tested. This lower cutting speed produces little heat which generates little tool wear. The inserts of CBN material presented higher wear resistance, but did not support the abrasion and vibrations of the cutting process, generating micro-cracks that due to higher cutting speed was little observed and confused with abrasive tool wear. However its results of machining volume were 55% minor of what the cemented carbide tool. Its low tenacity was one of the main factors to get these results. Also the negative face geometry of the tool and the higher cutting speeds had contributed for the tool temperatures increase becoming sometimes the cutting edge incandescent. In these cases titanium nitride coatings could not support the friction generated on tool face causing coating removal which was deposited through a physical vapor deposition process (PVD). The worse result happened with the ceramic inserts where the tenacity of the tool changes from K05 to K15 material. Thus the substitute class presented tool chips and low feeds evidencing the presence of high temperatures causing deformations on inserts or tool and working material surface burning. The importance of this study was to obtain the knowledge to respect of hard materials machining. The wear behavior of the different cutting tool materials during turning of the ADI allows to validate that the work with materials such as CBN for cutting tools is technologically viable, although its higher costs the reduction of the stages of production.

5. ACKNOWLEDGEMENTS

We thank to the Sandvik and the Tupy Fundições companies for the aid in the development of the study.

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