WEAR BEHAVIOR OF CARBIDE TOOLS WHEN TURNING ADI UNDER ROUGHING AND FINISHING CONDITIONS

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Abstract. *As ADI behaves different from both common cast irons as steels, there is not yet a commercial tool designed for its machining. In this context, it was studied the tool life, according to ISO 3685, consumed power, cutting forces, chip formation and the wear mechanisms of tools under roughing and finishing conditions. These tests were performed with three grades of ADI (grades 2, 3 and 4, according to the old ASTM 897-90) and also with the as-cast iron, as a reference condition. For the roughing tests, it was analyzed the wear behavior of tools designed for the roughing turning of three different materials: cast iron, steel and stainless steel. For the finishing tests, it was analyzed the wear behavior of tools designed for the finishing turning of two different materials: cast iron and steel. The tool life tests were carried in a CNC lathe, and it was possible to notice that for the roughing turning, the tools designed for cast irons presented better tool life than the tools designed for steels and stainless steels. On the other hand, for the finishing tests it was different, once that the tools designed for the steels presented better tool life. The chip formation was studied using a Quick-Stop device, and it was possible to determine that abrasion and adhesion were the mainly mechanisms that drove the tool wear. In the roughing tests, for all the three tools with the four materials, the adhesion takes place rather than the abrasion mechanism, and for the finishing tests, for the two tools with the four materials, the abrasion mechanism was more marked. It was also noticed evidences of the occurrence of BUE during both tests.*

Keywords*: Austempered Ductile Iron, Tool Life, Quick Stop*

1. INTRODUCTION

Throughout the last three decades, Austempered Ductile Iron (ADI) has been rapidly adopted and exploited worldwide for manufacturing primarily automotive products. It was first commercially applied in 1972 and by the mid 1970's was employed in Chinese military trucks and commercial truck applications among European industries. Towards the end of the 70's ADI had been used for light cars and trucks and was favorably looked upon by the US automotive industries. At the turn of the last century, the worldwide consumption of ADI was estimated at 150,000 tons per year, with a projection forecast of 20% annual growth (Hayrynen, 2002).

ADI exhibits remarkable properties, such as high toughness, relatively light weight, good heat conductivity and good vibration damping, as well as a high level of ductility and wear resistance (Keough, 1991). These useful mechanical properties are arrived at via a unique process of heat treatment that provides designers with further manufacturing flexibility and effective cost reduction compared to comparative forged steel components. ADI is continuously being incorporated into the ferrous application market (Kovacs, 1987; Cakir, 2005).

In contrast to conventional "as cast" ductile irons, ADI gains its mechanical properties by the heat treatment process and not by a specific alloy combination. Thus, the only condition for obtaining a desirable ADI component is a good quality ductile iron material (Hayrynen, 2002).

Regarding mechanical properties, Kovacs (1987) reported that among many beneficial features, ADI has the advantage of offering manufacturing flexibility presenting the designer the option to alter significantly the casting mechanical properties by applying various modes of heat treatment.

The microstructure of ADI was first called bainite as in steels, however, later on work carried out by Kovacs and Hayrynen, it was shown that the microstructures of steel and ADI are not the same. They stated that the structure of ADI is an ausferritic structure composed of ferrite plus carbon-enriched austenite. This finding was also supported by other researchers.

When a steel part is replaced with ductile iron, better machinability is considered to be the most important gain. Although there is no definite information in the published literature that ductile iron has better machinability than steels, data obtained from manufacturers like General Motors shows that parts manufactured from ductile iron leads to improvement in tool life by 20–900% when compared to the heat treated forged steels (Katuku *et al.*, 2009; Klopper, 2007).

It can be reckoned that ADI poses certain problems during machining due to its enhanced strength and wear resistance when compared to the other types of cast iron. It was previously reported that unreacted (or untransformed) retained austenite can decrease the machinability of ADI due to stress induced transformation to martensite during machining. However, the machinability of the softer grades of ADI is same as or better than that of steels which is similar to ADI in strength (Ahmadabadi, 1997; Daber *et al.* 2008; Garin *et al.* 2003).

Machining of ADI in its austempered condition is highly desirable because it can yield the tight tolerances and surface finishes generally required, save machining time and thus reduce costs. In depth fundamental understanding of interactions involved in this particular machining of ADI in its austempered condition should show the way to the optimum cutting tool material and or coating as well as optimum machining parameters (productive cutting speeds and feed rates, etc.). These outcomes would be among the last obstacles to be overcome before intensifying the use of this material in the automotive industry.

After this study, it is expected to know and to understand the tool wear behavior and to give some helpful information to tool manufacturers aiming to develop specific tool geometry to improve its resistance when machining ADI.

2. EXPERIMENTAL EQUIPMENT, MATERIALS AND PROCEDURE

This material was standardized into five group materials in ASTM 897-90, after Hayrynens effort. These five groups are better known as ADI grades and are numbered from 1 to 5. Nowadays, the ASTM 897M-06 classifies this material in six different groups, according to its mechanical properties and covers the various strength levels, as shown in Tab. 1, relating the new groups with the previous namely grade number.

Table 1. Mechanical property requirements of grades (SI Units).

Grade	750/500 /11	900/650 /09	1050/750 /07	1200/850 /04	1400/1100 /02	1600/1300 /01
→ namely grade number	---	1	2	3	4	5
Tensile strength, min, MPa	750	900	1050	1200	1400	1600
Yield strength, min, MPa	500	650	750	850	1100	1300
Elongation in 50 mm, min, %	11	09	07	04	02	01
Impact energy, J⁽¹⁾	110	100	80	60	35	20
Typical hardness, HBW, kg/mm²⁽²⁾	241-302	269-341	302-375	341-444	388-477	402-512

(1) : Unnotched charpy bars tested at 22 ± 4°C.
(2) : Hardness is not mandatory and is shown for information only.

To carry out these experiments 4 different materials were tested. An as-cast ductile iron (DI), which one was the basis to obtain the ADI's, and three (3) different types of ADI, named here by grade two (G2), grade three (G3) and grade four (G4). These materials were provided all in billets (600 X D150 mm).

The turning center used for these experiments is installed at CCM/ITA. This machine-tool has an available capacity of 11 kW with maximum velocity of 4000 rpm and maximum feed speed of 30 m/min.

Using an optical microscope, the initial conditions of the cutting tools as well as the angles, which define their geometry, were verified. Any defect observed at the edge, flank or face of the tool was enough to consider this tool unavailable to the tests. To improve the reliability of results, three (3) tools were used in each condition.

It was used interchangeable inserts in many ISO specifications, already commercially available. These inserts have edge angle of 80º, side cutting edge angle of 7º and radius peak of 1.6 and 0.4 mm. The support used for all the experiments has the specification of DWLNL 2020K 08.

2.1. Procedure

For tool wear measurement, analyses and photographies were obtained through an universal microscope for subsequent measurement and projection. A Wild M3C type S microscope by Herrbrugg Switzerland, with magnification capacity of 6.4, 16, 25 and 40X, and the software Leica Qwin Pro were used to measure the inserts wear.

The tool support was always kept in the same position. Only the interchangeable insert was removed to allow the measurement of the tool wear. Before its replacement, the cleaning of the seat was guaranteed with a jet of compressed air, thereby ensuring adequate positioning of the insert.

For tool efforts measurement, data of the effective spindle power were acquired through a CP5611 plate and recorded by a routine of the software Labview for data acquisition in a computer.

The machine-tool dynamic characteristic evaluation was performed using acquisition in real time via OPI (Operator Panel Interface). This interface port was connected to a PCI plate through a MPI cable. Most part of the information available in HMI (Human Machine Interface), became available in a personal computer (PC), using a communication converter CNC-PC.

For this converter, already in the DDE (Dynamic Data Exchange) format, a routine developed at Labview application package was used, which can be used as entrance to monitor and collect the data. The routine provides and stores data in text file format that can be moved to be analyzed in different softwares (graphic plots, tables, etc.).

Turning tests were conducted with the objective of raise comparative information among materials. The following tests were performed: power consuming acquisition during cutting of each material; tool life tests, by monitoring of flank wear (VB).

Although the most common is to show graphics of the cutting forces against one specific cutting condition, in these tests the parameter presented is the “consumed power”, in terms of a percentage of the available lathe capacity (11 kW). This was performed like this because of the available conditions to compare the cutting forces in real time during the experiments.

For turning tests, the length/diameter ratio of test specimens should be enough to avoid machining vibrations. At the end of each test, this ratio should not exceed the value of 10. Aiming a good use of material during the tests, the sample dimensions were defined as 300 mm in length, and diameters of 145 and 73 mm at the beginning and at the end of the experiment, respectively.

With these dimensions, the new test specimen can yet be handled without the necessity of auxiliary equipment during loading and unloading of the machine. The test specimens were pre-machined to remove the rough surface generated in the foundry (iron scales).

The metal working fluid used for all tests was a commercial emulsion directed to the cutting tool, with concentration of 7.9% and pH of 8.6.

Measurements of wear were made under regular intervals of time, being carried out every minute for each variation of level of wear and every three (3) minutes in stabilization points of the cutting edge. The objective of so many measurements, since a series of standard numbers could be used instead, was to verify the variation in levels of stabilization of the edge, and verify the behavior of cutting through the inclination of tools edge wear curves, to assess the repeatability of tests.

3. RESULTS

3.1. Tool class for roughing operations

In this test it was studied the tool life behavior and the consumed power versus the machining time, during lathe operations in roughing conditions. The condition to consider the test finished was the flank wear of VB = 0,3 mm or its breakage, according to ISO 3685. Three recommended ISO classes of tool were tested: KR 3205(designed for ductile iron); PR 4225 (designed for steel) and MR 2025 (designed for stainless steel).

The cutting conditions were chosen according to previous studies and research data, and they were: cutting speed of v_c = 60 m/min, depth of cut of a_p = 1.5 mm and feed rate of f = 0.2mm/rev. The obtained results for “tool life” are presented in Fig. 1 and the results for “power consumption” are presented in Fig. 2:

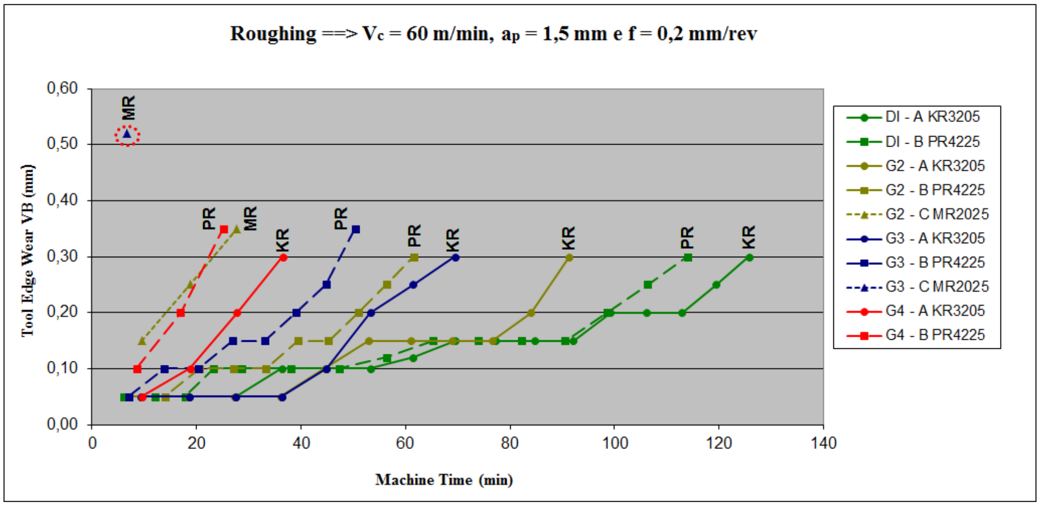

Figure 1. Tool life in roughing conditions.

These plotted results can clear show that DI provides a greater tool life when compared with ADI. It is also easy to see how the machine time decreases for the same tool (KR or PR or MR) when comparing ADI G2, G3 and G4. This show how the machinability in roughing operations of these ADI decreases when the grade number increases.

Analyzing each material separately, it is possible to conclude the same behavior for all of them. For roughing operations in ADI, the inserts designed for machining ductile iron presented better results, in terms of tool life, than the inserts designed for steel. And they both presented better behavior than the inserts designed for stainless steel.

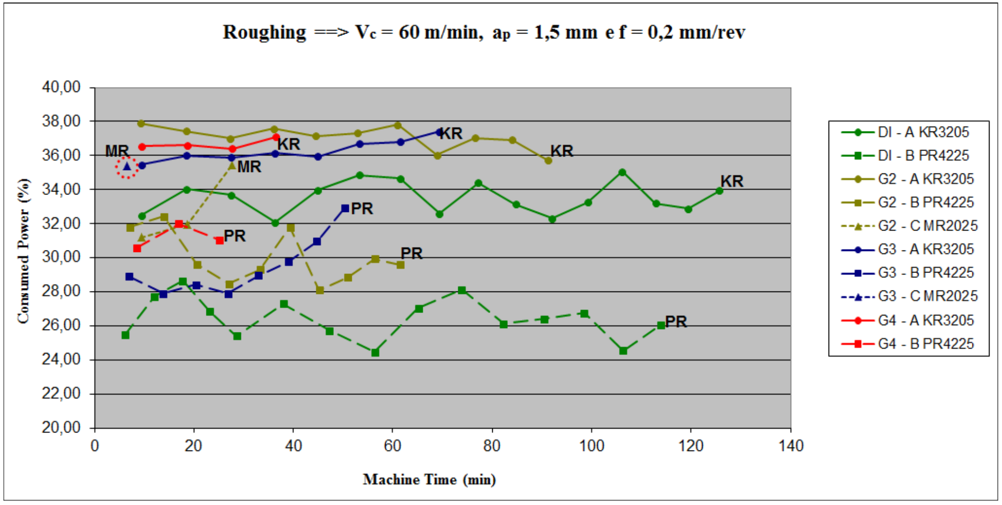

Figure 2. Consumed Power in roughing conditions.

The obtained results for consumed power can show how the consumed power increases when comparing DI with ADI. It is possible to notice that the three tested ADI demand the same level of power consumption. Analyzing the tool behavior, it is possible to see that the inserts designed for machining steel (PR) presented lower power consumption than the tools designed for ductile iron and for stainless steel. Actually, this is an expected result, once the geometry of ISO P class provides a greater angle to facilitate the chip removal.

Analyzing the tool classes studied, it is possible to notice that either for G2 and G3 the better condition was with class K tool. It is also possible to recommend some geometry improvements on the tool edge aiming to reduce the power consumption. All inserts had their wear progress monitored during the tool life tests and it was possible to notice that the main wear mechanism were abrasion and adhesion. Figure 3 presents an example of one tool used in these tests.

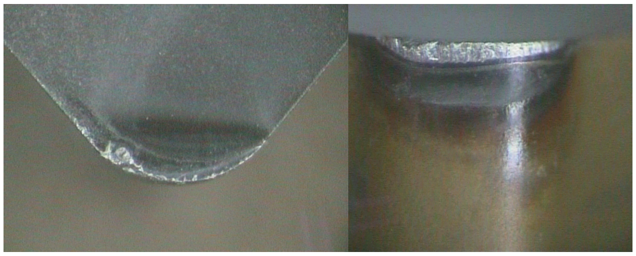

Figure 3. Tool wear on insert KR 3205 when rough turning ADI G3.

The great flank wear and the data acquired during the test evidence the abrasion mechanism occurred in this tool. This mechanism was present in all the tools tested. The crater wear was also present and this fact evidences the high intensity of adhesion mechanism. This wear mechanism can earlier damage the tool and this is an alert to take care of the tool coating.

3.2. Tool class for finishing operations

In this test, the experiments were carried out with the same method, but now during lathe operations in finishing conditions, also according to ISO 3685. Two recommended ISO classes of tool were tested: WF 3215 (designed for ductile iron) and WF 4215 (designed for steel).

The cutting conditions were: cutting speed of v_c = 60 m/min, depth of cut a_p = 0,4 mm and feed rate of f = 0,2 mm/rev. Although the cutting speed is very low for finishing conditions, this value was chosen in order to preserve the machine-tool. Other tests with cutting speeds values high as 1000 m/min were carried out in others experiments. The obtained results for "tool life" are presented in Fig. 4 and the results for "power consumption" are presented in Fig. 5:

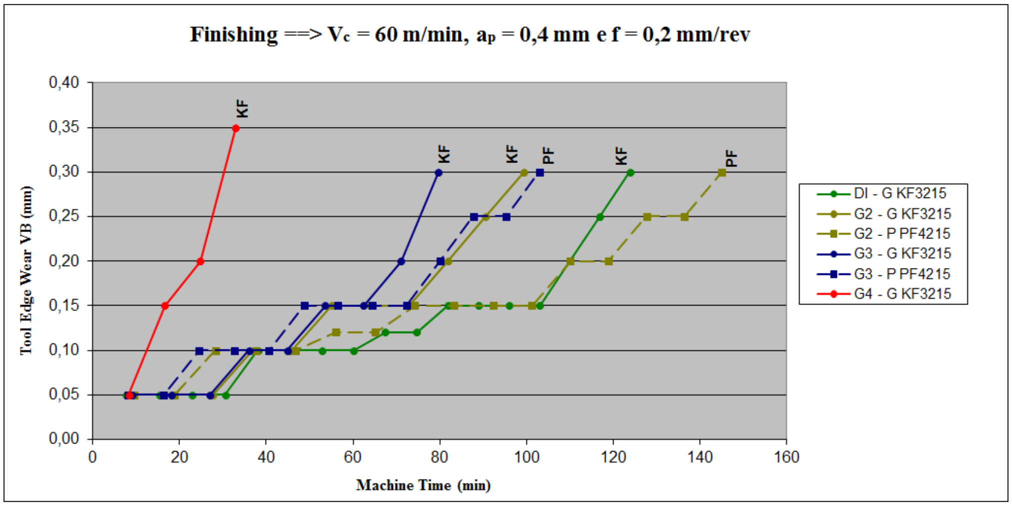

Figure 4. Tool life in finishing conditions.

Looking at the KF tool results, it is possible to notice that DI provides greater tool life than ADI once more. It is also possible to notice (now looking at each tested material) that the inserts designed for steel presented better results than the ones designed for ductile iron, either for G2 as for G3. This result evidences the influence of the work penetration (a_p) on the tool wear behavior, once that this is the main difference between rough and finish conditions.

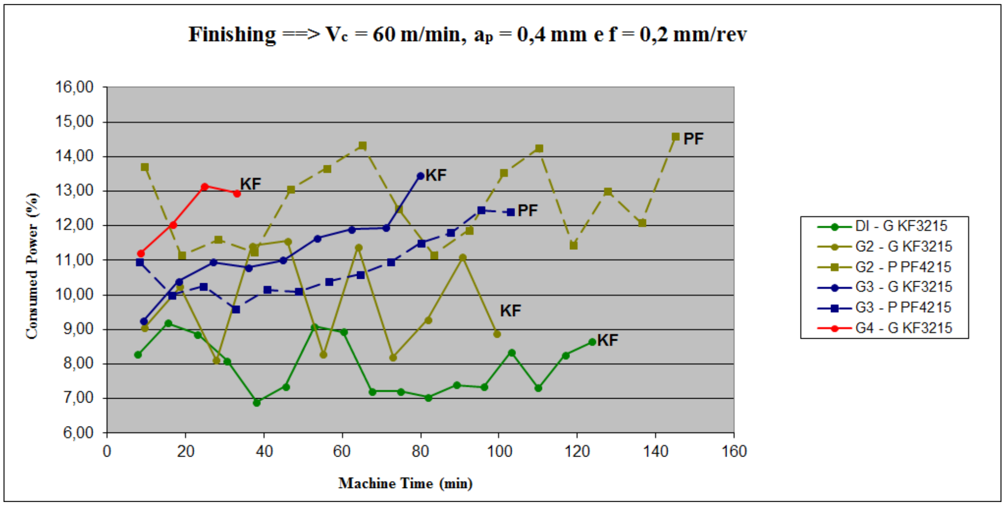

Figure 5. Consumed Power in finishing conditions.

The results obtained for consumed power didn't present significant difference that enables further considerations. It is only possible to perceive a little tendency of lower power consumption of the KF tools when compared with the PF tools. And it is also possible to notice the expected tendency of increase on this parameter when changing the materials from DI to ADI.

All inserts had their wear progress monitored during the tool life tests and it was possible to notice that the main wear mechanism was abrasion. Figure 6 presents an example of one tool used in these tests.

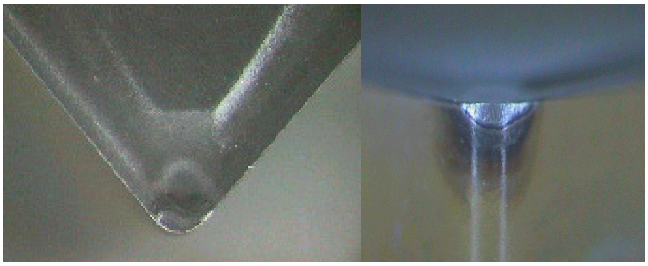

Figure 6. Tool wear on insert KF 3215 when finish turning ADI G3.

The great flank wear and the data acquired during the test evidence the abrasion mechanism occurred in this tool. This mechanism was present in all the tools tested. There was no presence crater wear, and this evidences the lower intensity of adhesion mechanism when comparing to roughing tests.

3.3 Quick-Stop tests

The quick-stop test aims to investigate the tool-chip interface and analyze the chip formation during the cutting process. This investigation gives the opportunity to understand some mechanical process and to forecast the behavior of the material and of the tool edge under certain cutting conditions.

The equipment consists in a mechanical device built to a dedicate lathe and that allows the tool to come out of the cutting process in a velocity between 2 or 3 times higher than the cutting speed. The objective of this test is to stop the chip formation process and keep the chip joined to the test piece before its breakdown, Fig. 7. In this way, it is possible to “freeze” mechanical transformations in the chip and analyze each zone that the material is forced to pass through to form the chip.

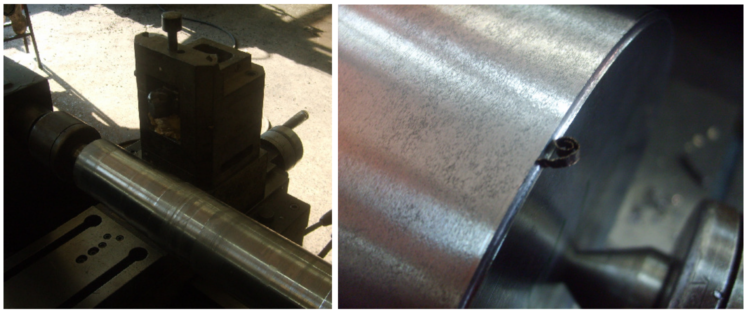

Figure 7. Quick-stop device and ADI G2 chip still joined to the test piece after quick-stop test.

It was tested three different billets, one of nodular cast iron, other of ADI grade 2 and one more of ADI grade 3. The ADI grade 4 wasn’t tested because of its machinability. The billets were turned to a specific diameter and then assembled to the quick-stop machine. The test was not successful for the nodular cast iron (DI), once it was not possible to keep the chip joined to the test piece. This was somehow expected, once this material is too brittle and presents fragmented chip.

On the other hand, the tests with ADI grades 2 and 3 were successful and it was possible to collect samples to be analyzed at the microscope. It was tested three different values of cutting speed, 60, 80 and 100 m/min, aiming to verify the influence of the cutting temperature into the metallic matrix of the chip. The samples were sawed from the billet and then embed in resin to allow the metallographic analysis (Fig. 8).

Figure 8. Test specimens ready for metallographic analysis.

The test specimens were first observed without any chemical etching and after etched with Nital 5%. Besides the observation of the chip itself, it was also observed the characteristic of the machined surface. The etched specimens were observed in a magnification of 320X, resulting in images that present some difficulty to be understood each one individually. In Figure 9 it can be seen the photo of the most important region of each specimen, the chip root, observed without etching in a lower magnification (160X).

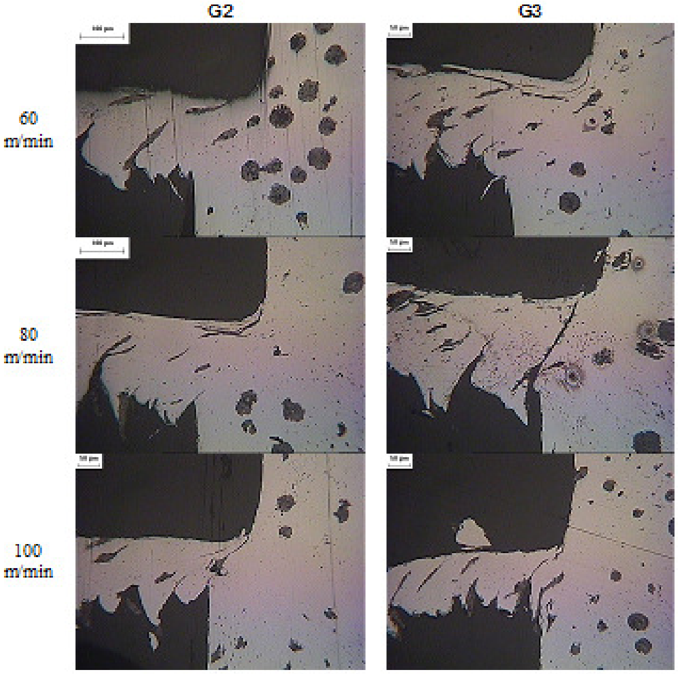

Figure 9. Test specimens photos with 160X of magnification, without etching.

There are many features to be observed and analyzed in these figures. For example, the figure obtained for a cutting speed of 60 m/min in the ADI G3 present a portion of a smashed material just before of the chip root. This is a strong evidence of the occurrence of Build-up Edge (BUE), what is surprising if it is true, once BUE is commonly formed for cutting speeds high as 70 m/min. BUE is one of the worst problems to be found when machining any material.

Besides of these considerations, many others can be made based on the etched specimens' observations. Metallographic changes in the microstructure evidences that occurred some thermal or mechanical phenomenon, and in the ADI case, that can prove if one specific cutting condition is harmful to the desired ausferritic structure.

Figure 10 present an assembly of many photos made in ADI G2 specimens for a better visualization. The region that goes horizontally to the left is the chip itself. The vertical region just above the chip is the recent machined surface. The region of the radius showed in each picture corresponds to the tool radius. Each photo was individually analyzed in metallographic terms and the considerations were summarized just below.

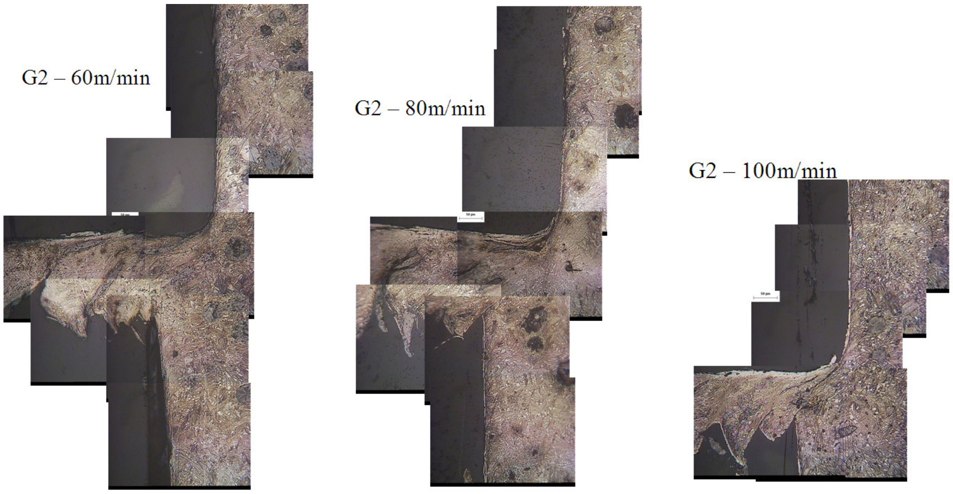

Figure 10. Assembly of test specimen photos of ADI G2 machined with 60, 80 and 100 m/min, etched with Nital 5%.

It was possible to observe that in the chip region, a plastically induced transformation of retained austenite to martensite takes place (Fig 11). When this is observed in the chip, it is not a problem. But if this transformation can be observed in the machined surface that is evidence that high mechanical stress is harming the ADI structure and it can compromises the mechanical behavior of the machined part.

Analyzing the machined surface it is also possible to verify if there are some discontinuities, these can be also evidences of BUE occurrence. But the most important conclusion that can be made by these photos is to identify the primary and secondary shear planes and to measure their inclination. This measurement gives an idea of the intensity of the mechanical mechanisms that takes place during the chip formation and this is important information to design more adequate tool geometry.

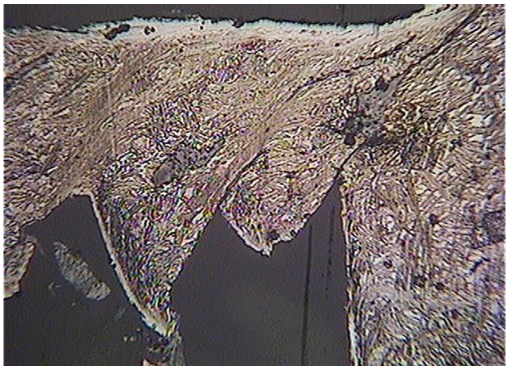

Figure 11. One of the photos made at ADI G2 specimen with 100 m/min showing the plastically induced transformation of the retained austenite to martensite inside the chip.

4. CONCLUSIONS

It can be concluded that as higher the number of the ADI grade, most difficult this material is to be machined. It was proven that the Ductile Iron is much easier to be machined than the tested ADI's. It was also observed that the ADI G4 present an enormous difficulty to be machined, been an alternative that gives very low productivity.

It can be also concluded that ADI G2 is easier to be machined than the ADI G3, considering the tested tools. But it is also possible to say that improvements in tool geometry can place these two materials in very similar levels of machinability, once that the obtained results presented here were not so different.

For roughing operations in ADI, the inserts designed for machining ductile iron presented better results, in terms of tool life, than the inserts designed for steel. And they both presented better behavior than the inserts designed for stainless steel. After monitoring the tools wear progress, during the tool life tests, it was possible to notice that the main wear mechanism for roughing operations were abrasion and adhesion.

On the other hand, for finishing operations, it was possible to notice that the inserts designed for steel presented better results than the ones designed for ductile iron, either for G2 as for G3. This result evidences the influence of the work penetration (a_p) on the tool wear behavior, once that this was the main difference between rough and finish conditions in these tests. For these finishing tests, after monitoring the tools wear progress, it was possible to notice that the main wear mechanism was abrasion.

Although the tools used in these tests were commercial solutions already available for machining common industrial materials, these tests allowed a better understanding of the tool wear behavior when machining ADI. Now it is possible to recommend some improvements on the tool geometry in order to get a tool dedicated for ADI machining.

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