MACHINABILITY OF AUSTEMPERED AND PEARLITIC DUCTILE IRONS IN DRILLING PROCESS

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Abstract. *Many materials have their mechanical proprieties improved by heat treatments, but they can worsen machinability, as the case of austempered ductile iron (ADI) that besides of presenting better mechanical proprieties it has poorer machinability when compared with the conventional ductile iron and steel of similar strength. Being presently an important engineering material investigations about the behaving of the ADIs have been intensified. The aim of this work is to contribute further with this, comparing the machinability of three materials: pearlitic ductile iron as cast (FE70003) and two grades of austempered ductile iron having different austenitizing routes (ISO 1.050-6 and ISO 800-10). The machinability was raised in drilling process by drill wear rates. A factorial planning 2^4 was used, consisting of two quantitative variables: cutting speed (Vc) and feed rate (f) and two qualitative variables: work material and cutting fluid application technique. The results showed that the ADI grade ISO 800-10 was the material with higher machinability, followed by the FE70003 ductile iron and then by the ADI ISO 1.050-6 grade.*

Keywords*: machinability, drilling process, wear rate, ductile cast iron, austempered ductile iron.*

1. INTRODUCTION

In industry, the increase in demand for new engineering materials is related with cost and “weight-efficiency”. In the effort to achieve these requirements metallurgists are either applying new materials with similar strengths but lower densities, or increasing the strength of traditional material by alloying or by heat treatment. The option chosen depends on parameters such as the mechanical and thermal loads or on boundary conditions such as manufacturing costs, recyclability, public acceptance and machinability (Klocke et al, 2007). In this list are the cast irons that almost always offer good machinability and low manufacturing cost.

Austempered ductile iron (ADI), is a heat treated ductile iron, which appeared recently as an important engineering material due to its attractive proprieties such as good ductility, toughness and high wear and fatigue strength. ADI has been very used, now-a-days, in many structural applications in automotive and military industry, agricultural machinery and other (Lussoli, 2003).

ADI compared with conventional ductile iron has increased difficulties to machine, due to its high hardness degree that is influenced by the microstructure formed during heat treatment. Another fact that can be responsible for the poorer machinability of this material is to the presence of untransformed retained austenite which can be transformed into martensite during machining (Seah and Sharma, 1994). Because of these facts researches on the machinability of ADI have been intensified.

The aim of this work is to contribute with this, comparing the machinability of three materials: as cast pearlitic ductile iron (grade ABNT FE70003) and two grades of austempered ductile iron having different austenitizing routes (ISO 1.050-6 and ISO 800-10). The grade ISO 800-10 was heat treated in the intercritically region of austenite + ferrite. The machinability was raised in drilling process monitoring the drill wear rates. A factorial planning 2^4 was used, consisting of two quantitative variables: cutting speed (Vc) and feed rate (f) and two qualitative variables: work material and cutting fluid application technique.

2. EXPERIMENTAL PROCEDURE

2.1. Workpiece and Cutting Tool

The samples used were produced in continuous casting by Tupy S.A., with 104 mm of diameter. The bars were cut in discs and they were faced in a lathe to maintain a standard thickness of 30 mm and alignment to avoid slippages of the drills during entrance into the workpiece at the beginning of the machining of each hole. Table 1 shows the microstructure phases and hardness of the three work materials studied. Figure 1 shows typical microstructures.

Table1. Microstruture and Hardness Brinell.

Material	**Microstructure**	**Brinell Hardness (HB 5/750)**
DI - FE70003	Pearlite with ~4% of ferrite	263
ADI - ISO 1.050-6	Ausferrite	288
ADI - ISO 800-10	Ausferrite with ferrite and fine perlite residual	207

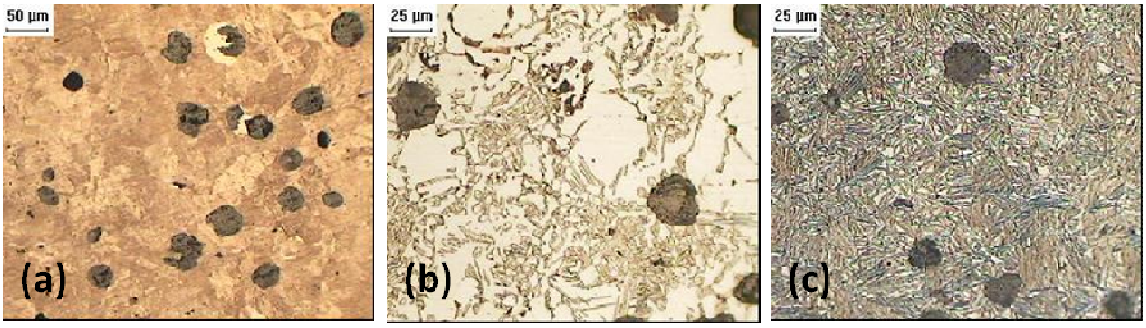

Figure 1 – Microstructures of tested materials: (a) pearlitic ductile iron (FE 70003), with pearlitic matrix; (b) ADI grade 800-10, with ausferrite and previous ferrite; (c) ADI grade 1050-6, with ausferrite matrix.

The cutting tools were K20 grade of cemented carbide twist drills with 10 mm of diameter, coated with multilayers of TiN/TiAlN.

2.2. Tool Life Tests

The tool life tests were developed in drilling process following a full factorial planning 2^4. The cutting speed (Vc), feed (f), work material and cutting fluid application technique (flood and minimum quantity – MQF, both externally applied) were the variables considered. Primarily the two ADIs grades were compared, and then they were confronted against the ductile iron as cast. Table 2 presents the two levels of the input variables.

Table 2. Input variables at two levels.

Variable	Level (-1)	Level(+1)
Vc [m/min]	110	140
f [mm/rev]	0.15	0.25
Material	ADI II/DI	ADI I/DI
Cutting Fluid	Flood (982 l/h)	MQF (50 ml/h)

The experimental tests were carried out in a Discovery 760 - Romi CNC machine center. Through holes were machined with a total tool feed curse (Lf) of 35 mm to allow the main cutting edges of the drill to exit completely out from the button face of the discs (5 mm). Each test consisted of drilling holes equally distributed on the disc as illustrated in Fig 2.

Tool flank wear was monitored using a stereo microscope by Olympus and an image analyzer system, Image-Pró Express. Measurements were taken at the end of each drilling cycle programmed according to Fig.2. The size of the tool flank wear measured at the end of the last cycle, hole number 54, was adopted as the machinability output parameter of each test. This strategy was adopted because the number of workpiece discs of the three work materials available was limited.

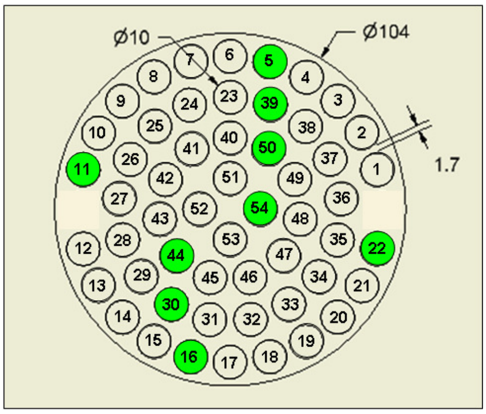

Figure 2. Holes highlighted in green indicate the end of machining cycles used for tool wear measurements

3. RESULTS AND DISCUSSION

Table 3 presents the maximum tool flake wear (VBBmax) measured after machining the last hole of each test. Figs 2 and 3 show the comparison of the machinability of the materials with different cutting fluid application techniques for various cutting conditions used.

Table 3. Tool wear (VB_{Bmax}) after machining the last hole in each test.

Material	Vc [m/min]	f [mm/rev]	Cutting Fluid Application Technique	VB_{Bmax} [mm]
DI - FE70003	110	0.15	Flood	0.103
DI - FE70003	140	0.15	Flood	0.479
DI - FE70003	110	0.25	Flood	0.114
DI - FE70003	140	0.25	Flood	1.282
DI - FE70003	110	0.15	MQF	0.558
DI - FE70003	140	0.15	MQF	0.604
DI - FE70003	110	0.25	MQF	0.347
DI - FE70003	140	0.25	MQF	0.604
ADI - ISO 1.050-6	110	0.15	Flood	0.536
ADI - ISO 1.050-6	140	0.15	Flood	0.832
ADI - ISO 1.050-6	110	0.25	Flood	1.590
ADI - ISO 1.050-6	140	0.25	Flood	2.229
ADI - ISO 1.050-6	110	0.15	MQF	0.701
ADI - ISO 1.050-6	140	0.15	MQF	2.319
ADI - ISO 1.050-6	110	0.25	MQF	1.436
ADI - ISO 1.050-6	140	0.25	MQF	1.567
ADI - ISO 800-10	110	0.15	Flood	0.040
ADI - ISO 800-10	140	0.15	Flood	0.068
ADI - ISO 800-10	110	0.25	Flood	0.068
ADI - ISO 800-10	140	0.25	Flood	0.068
ADI - ISO 800-10	110	0.15	MQF	0.089
ADI - ISO 800-10	140	0.15	MQF	0.080
ADI - ISO 800-10	110	0.25	MQF	0.063
ADI - ISO 800-10	140	0.25	MQF	0.080

Figures 3 and 4 show that for all cutting conditions tested the ADI - ISO 800-10 grade was the material with the best machinability followed by the pearlitic ductile iron (FE 70003) and the material which presents the worse machinability was the conventional ADI grade ISO 1.050-6. These graphics also show that when applying flood cooling the tests with higher flank wear were when using the most severe cutting condition (higher cutting speed and feed rate), and this is further illustrated for the ADI ISO 1.050-6 grade in Fig.5, which shows the evolution of the maximum flank wear of the tool for all cutting conditions tested.

However, when applying the cutting fluid using the MQF technique the smaller feed rate of 0.15 mm/rev was more critical than the higher feed rate of 0.25 mm/rev.

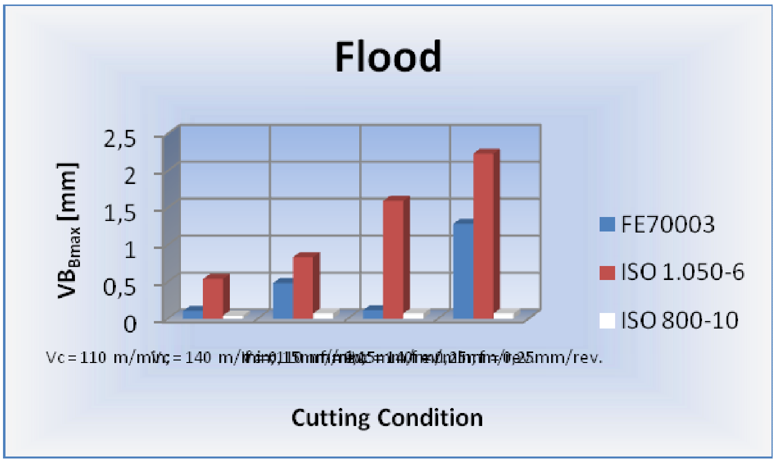

Figure 3. Machinability Comparative Graphic with flood cutting fluid application technique

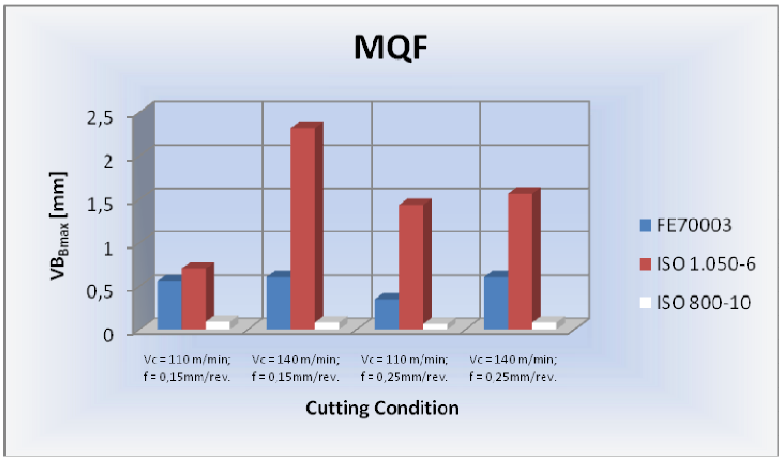

Figure 4. Machinability Comparative Graphic with MQF cutting fluid application technique

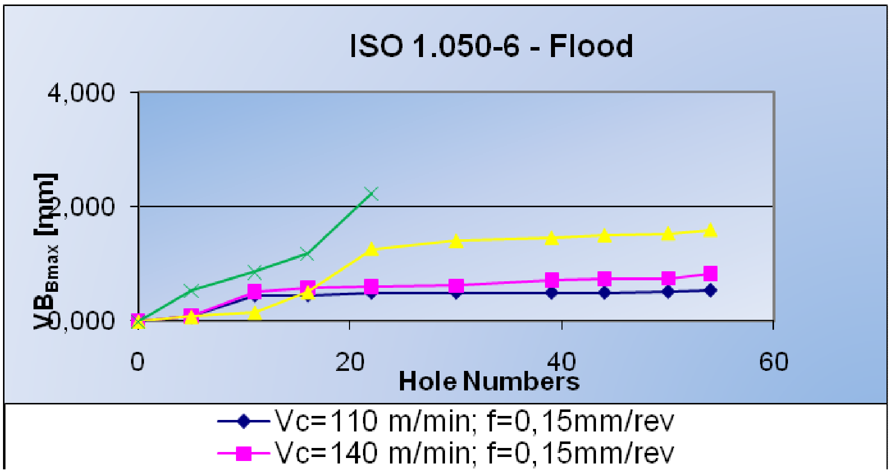

Figure 5. Maximum Flake Wear (VB_{Bmax}) evolution for different cutting conditions

Tables 5 to 7 present the significance analysis of the results with a confidence interval of 95% and 5% of significance level for the three materials tested.

Table 5. Significance Analysis of full factorial planning 2^4 with the ADI - ISO 800-10 and ADI - ISO 1.050-6 materials.

	Effect	Std. Err.	p
Mean	0.735375	0.106546	0.000978
Vc [m/min]	0.340000	0.213093	0.171476
f [mm/rev]	0.304500	0.213093	0.212395
Cutting Fluid Application Technique	0.113000	0.213093	0.618611
Material	1.331750	0.213093	0.001537
Vc x f	-0.143250	0.213093	0.531237
Vc x Cutting Fluid Application Technique	0.099250	0.213093	0.660972
Vc x Material	0.331000	0.213093	0.181059
f x Cutting Fluid Application Technique	-0.315250	0.213093	0.199099
f x Material	0.304000	0.213093	0.213034
Cutting Fluid Application Technique x Material	0.096000	0.213093	0.671207

It can be verified from Tab. 5, that the type of material is the only significant parameter ($p < 0.05$) that influences the maximum flank wear developed after machining the 54 holes. The change of the material from ADI - ISO 800-10 (hardness of 207 HB) to ADI - ISO 1.050-6 (hardness of 288 HB) leads to an average increase in the flank wear of 1.33 mm. The differences of the material's hardness and microstructure are strongly responsible for this behavior.

Table 6. Significance Analysis of full factorial planning 2^4 with the DI - FE 70003 and ADI - ISO 800-10 materials.

	Effect	Std. Err.	p
Mean	0.290438	0.047039	0.000267
Vc [m/min]	0.235375	0.094078	0.036832
f [mm/rev]	0.075625	0.094078	0.444709
Material	0.441875	0.094078	0.001548
Vc x f	0.125125	0.094078	0.220182
Vc x Cutting Fluid Application Technique	-0.157625	0.094078	0.132371
Vc x Material	0.226375	0.094078	0.042758
f x Cutting Fluid Application Technique	-0.134875	0.094078	0.189577

From the results presented in Tab. 6, it is observed that there is significant difference between the DI - FE 70003 and ADI - ISO 800-10 materials. Using pearlitic DI instead of ADI it is expected an average increase of 0.44 mm in the tool wear. The cutting speed and interaction between cutting speed and work material have also significant influences on the tool wear developed. Increasing the cutting speed from 110 m/min to 140 m/min (-1 to +1 level) the tool wear will increase in 0.23 mm average. Finally changing the cutting speed and the work material interactively from level (-1) to level (+1) an average increase in the tool wear of 0.22 mm will occur.

When machining at high cutting speeds high cutting temperatures are developed and together with the properties of the work materials they are responsible for increasing the tool wear rates. Besides accelerating the thermally activated wear mechanisms (mainly diffusion and oxidation) high temperatures reduces the tool wear resistance and increase the tool wear rate (Machado at al, 2009 and Trent and Wright, 2000). In drilling process with the same tool diameter increase in the cutting speed will occur only by increasing the spindle speed and this can increase vibration whish in turn may induce tool microchipping that further contributes to tool deterioration.

Table 7. Significance Analysis of full factorial planning 2^4 with the DI - FE 70003 and ADI - ISO 1.050-6 materials.

	Effect	Std. Err.	p
Mean	0.956312	0.092426	0.000003
Vc [m/min]	0.566375	0.184852	0.013485
f [mm/rev]	0.379625	0.184852	0.070195
Cutting Fluid Application Technique	0.121375	0.184852	0.527863
Material	0.889875	0.184852	0.000955
f x Cutting Fluid Application Technique	-0.436625	0.184852	0.042460
f x Material	0.228875	0.184852	0.246982

Tab. 7 shows the significance analysis considering the DI - FE 70003 and ADI - ISO 1.050-6 work materials with a confidence interval of 95% and 5% of significance level. Again, the work materials significantly influence the tool wear at the end of the 54 holes machined. Other variables with significant effect are cutting speed and the interaction between feed and cutting fluid application technique. Change of work material from level (-1) to level (+1) causes an average increase in the flake wear of 0.89 mm and this is due to the higher hardness and different microstructure of the ADI - ISO 1.050-6 material. the increase of the cutting speed form level (-1) to level (+1) will cause an average increase in the maximum flank wear of 0.57 mm, and the reason for that has been already commented. Finally, the interaction between feed rate and cutting fluid application technique decreases the flake wear in average of 0.44 mm, probably due to a better lubrication condition.

4. CONCLUSIONS

The material that presented the best machinability is the austempered ductile iron ISO grade 800-10 (207 HB) followed by pearlitic ductile iron as cast grade FE70003 (263 HB) and the material with poorer machinability was the ADI ISO grade 1.050-6 (288 HB). Material hardness and microstructure differences implies in different machining response in drilling.

5. ACKNOWLEDGEMENTS

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