Influence of inoculation on cast iron machinability: Case studies

Aurélie FAY

Ferroglobe, Chambéry, France

***Aurélie Fay**

She obtained her Master Degree in Metallurgy & Materials Science from the Polytechnic National Institute of Grenoble, France in 2002. She is now R&D Manager at Ferroglobe-France, in charge of the management of the foundry metallurgical laboratory, the Foundry technical support to plants of the Group & Sales Department, and management of patents. At this position, she has acquired strong knowledge about cast iron (DI and GI) metallurgy, foundry process, foundry defects, thermal analysis, slags management, as well as in electrometallurgy such as production of silicon, ferrosilicon alloys and inoculants. She is also involved in foundry process improvement solutions provided by inoculation, and in defect investigation on iron castings.

E-mail: aurelie.fay@ferroglobe.com

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Abstract: Machinability can sometimes be difficult to predict and be impacted by different characteristics of the castings. Inoculation, a key step in foundry process, is well-known to be a powerful tool to adjust the characteristics of castings in both grey and ductile irons. Some metallurgical cases were investigated to understand different machinability behaviors in correlation to their metallographic characteristics. Thus, two examples taken from grey iron processes are analyzed to illustrate how inoculation is required to adjust characteristics of iron castings, especially the modification of graphite characteristics and the prevention of micro-shrinkage, both parameters are well-known to have an impact on iron machinability. The study also illustrates the importance of the ratio Mn/S to guarantee the presence of manganese sulfides in the matrix, beneficial for iron machinability.

Key words: inoculation; foundry process; machinability; grey iron

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Machinability is a key step right at the end of foundry process. Most foundries are focused on its efficiency and the associated productivity resulting from this operation linked to cost reasons. Machinability can sometimes be difficult to predict and is impacted by different characteristics of the castings.

Inoculation corresponds to the practice of adding a material in a small amount to liquid cast iron just before pouring to modify the iron solidification process. This inoculation step is usually compulsory to guarantee the final requested material's mechanical properties. The inoculation materials are normally made of a FeSi-alloy doped with different elements to guarantee a specific action. Among the noticeable effects of inoculation, the formation of nuclei supporting graphite germination and matrix structure control are well-known to positively impact the mechanical properties of the casting. This vision is likely to be quite restrictive as there are many concomitant benefits for inoculation practice, and they are also increasingly becoming the key parameters to solve the challenges arisen by some emerging materials.

This study aims at illustrating how inoculation can be used as a powerful tool to adjust machinability by acting on iron castings' properties. The method used is as follows: a parallel has been drawn between industrial machinability properties as reported by foundries in different conditions of the inoculation process and the corresponding metallographic examination of the castings obtained in each case. Two case studies have in particular been developed to show the impact of the inoculation process on metallurgical characteristics that were identified to impact the machining process: microshrinkage and graphite characteristics.

1 Machinability and metallurgical factors impacting iron machinability – Link with inoculation

1.1 Attempt to definition the term “Machinability”

Finding a general definition for the term “Machinability” is quite challenging. The

two definitions hereafter were selected from the literature to illustrate how complex material machinability is:

(1) Machinability refers to the ease with which a workpiece can be machined and measured in terms of tool life, metal removal rate, surface finish, ease of chip formation, or cutting forces. It is not an intrinsic property of a material but is a result of complex interactions among the mechanical properties of the workpiece, cutting tools, lubricants used, and machining conditions^[1].

(2) Machinability is defined as the ease with which a material can be machined into satisfactory parts. In practice, machinability is a complex property with no universally accepted method of

quantification or measurement^[2].

These two definitions are interesting to show the numerous variables impacting the machining process, coming from both the material physical characteristics, working conditions (depth of cut, tool shape & material, cutting fluid, rigidity of machine tools, etc.) and process operating conditions^[1,3,4].

The cause-effect diagram presented in Fig. 1 illustrates efficiently, in the case of an aluminum casting, the incredible number of variables, that being considered, have impact on the material's machinability^[3]. This is thus easily understandable why machinability can be so difficult to predict and quite challenging for foundries.

Fig. 1: Ishikawa diagram summarizing the main parameters impacting machinability of high silicon content aluminum castings^[3]

1.2 Machining operations: a key step in foundry process

There are many ways to evaluate the ease of a machining operation. Common criteria such as cutting insert life time, cutting forces encountered, speed of machining, power consumption, surface finish, and ease of chip disposal, etc. are often considered. At the end, these all always impact costs in the process and thus are absolutely to be considered by the foundry.

In the case studies presented hereafter, a specific focus will be done on the materials properties, stating that the machining process parameters are identical for each case study since these parameters are the ones of the foundry concerned by the study.

1.3 Metallurgical factors impacting on iron machinability

Small differences in chemical composition, inoculation practice, as well as section size differences or molding parameters can be expected to have relatively insignificant effects on hardness or tensile properties but significant effects on tool life when machining iron^[4]. That is why improving machinability properties leads to considering the metallurgical process.

Inoculant additions and solidification rates are of importance^[4].

These two factors have indeed significant effects on the eutectic cell structure, graphite characteristics and matrix structure, which in turn affect the chip forming characteristics of the cast iron at a microstructural level during machining.

In Table 1, the main iron characteristics known to impact the mechanical properties, and thus the machinability^[1-4], are listed. They are correlated to the main process factors able to create modifications in such characteristics. The characteristics designed with * can be modified through the inoculation process.

Table 1: Main metallurgical factors reported to have an impact on iron machinability^[1-4]

Iron characteristics	Process factors
Graphite* (size, shape, distribution)	Chemical composition
Matrix* (pearlite/ferrite ratio, carbides)	Cooling rate
Discontinuous structures*	Moulding type
Mechanical properties*	Inoculation practice
Microshrinkage*	
Inclusions* (macro and micro)	

Inoculation practice is helpful in adjusting many iron characteristics impacting the machinability. Thus, it seems essential to draw a direct parallel between the inoculation process and the resulting machinability properties as reported for instance in Ref. [4-5].

Figures 2 and 3 summarize what is mentioned hereafter how iron characteristics can influence the chips formation. Figure 2 represents a tool advancing through a metal part containing a variety of graphite flakes and abrasive macro- and micro-

Fig. 2: Schematic showing how iron characteristics influence the chips formation^[6]

Fig. 3: SEM Image of initial stages of chip formation ahead of the cutting tool during high speed machining on ductile iron^[4]

inclusions that might include oxides, carbides, nitrides, sand, and other materials. The advancing tool creates a compression zone below and ahead of the tool rake and flank faces^[6]. Machinability of ductile irons is dominated by the hardness of the matrix which is influenced primarily by the presence of pearlite and other hard micro-constituents^[4].

Two case studies are detailed hereafter, focusing on the correlation between materials' properties and machinability behavior, measured in terms of the life of the tool after machining.

2 Case studies

2.1 Case study-1

One foundry produces brake drums in grey iron. They state that about 40% of their castings are subject to microshrinkage (measured by ultrasounds). In the meantime, they want to improve their machining process to reduce costs. It was decided with the Foundry to focus on materials characteristics in order to understand the main parameters that would be helpful in reaching their target.

The Foundry tested two new inoculant practices: using Inoculant A & Inoculant C, in comparison to their standard practice with Inoculant B. For that trial in the Foundry, similar process conditions were used, as for instance: liquid iron chemistry, iron temperature, inoculant addition rate and the method of adding inoculant (in stream).

A metallographic examination was performed on one casting resulting from the testing of each kind of inoculant. The Foundry also gave industrial data about the machinability behavior for each series, making it possible to draw a link between microstructure and machinability properties.

As far as the metallographic examination is concerned, differences are observed between the three series, about graphite characteristics and the presence of microshrinkage. The micrographs before and after nital etching are shown in Fig. 4 and the presence of microshrinkage and its relationship with machinability are shown in Table 2.

Fig. 4: Micrographs of each series using Inoculant A, B and C before and after nital etching

Table 2: Presence or absence of microshrinkage in the three series samples and its link with machinability

	Series with Inoculant A	Series with Inoculant B	Series with Inoculant C
Microshrinkage (Foundry observations by ink test on machined castings)	No microshrinkage	40% of castings with microshrinkage	No microshrinkage
Graphite distribution (metallographic observations using optical microscope)	Very thin graphite flakes The lowest concentration of graphite	Homogeneous distribution of graphite	The denser and more homogeneous graphite distribution & the highest concentration of graphite
Machinability behavior (Foundry observations measured in terms of wear tools)	Worse	Reference	Better

Comparing A to B: it seems that graphite distribution and characteristics are more important than the presence of microshrinkage since the machinability is better in Case B, even with the presence of microshrinkage.

Comparing B to C: it is not so easy to determine whether microshrinkage or graphite characteristics is the most important parameter. It is likely to be a complex combination of both parameters that at the end impacts positively the machinability behavior.

This study clearly indicates that the inoculation process can be directly correlated to the machinability behavior, since it plays a role in the iron characteristics: graphite characteristics and, in some specific cases, fighting against microshrinkage.

2.2 Case study – 2

One foundry is producing brake discs in grey iron, reference GJL250, in one plant and wants to extend this production with similar castings characteristics to a second plant. They did three trials using different inoculant practices, combining both ladle inoculation and late inoculation (B, C, D) and compared these results to the results of Plant A. From these trials, they investigated on the results and found that the three types of castings resulting from treatment with B, C, D showed different behaviors during machining compared to the reference grade coming from Plant A. The Foundry wants to understand the reasons for the observed differences so that at the end they could improve their process and reach their target.

For that study, a metallographic and scanning electronic microscopy investigations associated to a chemical analysis were realized on four samples resulting from the trials: A (reference), B, C and D. The idea was to check and report the differences between the castings and try to correlate them to the machinability behavior observed during the machining process as illustrated in Fig. 5. Pieces of castings resulting from the different trials were used for the metallographic investigation, as shown in Fig. 6.

2.2.1 Characteristics and distribution of graphite and matrix

Figure 7 shows the characteristics and distribution of graphite in the four castings. Regarding graphite characteristics and fineness, there is no significant difference, as both graphites of Types B and D are observed in the four castings. Thus, the machinability behavior may not be impacted by this parameter.

Fig. 5: Machinability results obtained and reported by the Foundry on Castings A, B, C and D, in terms of tools wear

Fig. 6: Pieces of castings resulting from the different trials and used for the metallographic investigation

Figure 8 shows the matrix characteristics of the four castings after nital etching. As far as matrix structure is concerned, the four castings show similar and fully pearlitic matrix. Thus, the machinability behavior may not be impacted by this parameter.

2.2.2 Presence of microshrinkage

Microshrinkages are found in all the four castings with an individual size measured between 50 to 200 μm . The number of microshrinkages in Casting C, and to a lesser extent in Casting D, is significantly higher than in Castings A and B.

2.2.3 Distribution of micro-inclusions

Figure 10 shows the distribution of micro-inclusions in the four castings. It can be seen that the Reference Casting A contains micro-inclusions smaller and more numerous than in Samples B, C and D.

Fig. 7: Graphite characteristics and distribution observed on the 4 castings, using optical microscope

Fig. 8: Matrix characteristics of the 4 castings after nital etching observed using optical microscope

The nature of these inclusions was investigated using scanning electronic microscopy associated to EDAX (Fig. 11). It was found that in all the castings the nature of the inclusions was similar and corresponding to MnS crystals.

Sulphur and manganese contents in grey iron have been reported to be critical factors associated with the high machinability of the material. Literature reports indicate that manganese sulfide stringers improve the machinability in iron as well as in steels, the provided manganese and sulfur are present in quantities large enough to combine with all the sulfur to produce

manganese sulfide instead of iron sulfide^[7-8]. Astakhov et al.^[7] explains that during cutting of grey iron, the MnS inclusions are believed to assist in the chip breaking process as well as to adhere to the cutting tool surface, forming a lubricating layer reducing friction, protecting against oxidation and diffusion and subsequently minimizing tool wear. Since MnS distribution is known to have an impact on the machinability of steel and iron, the difference in the distribution observed here might be part of the understanding of machinability difference.

Ref.	Evaluation defects number (microshrinkage)
A	21
B	23 (coarser size)
C	42
D	37

Fig. 9: Distribution of microshrinkage in castings. An additional effort was made by counting the number of microshrinkages detected on a picture taken at x100 to compare further

Fig. 10: Distribution of micro-inclusions, as observed using an optical microscope

2.2.4 Coarse inclusions

The presence of coarse inclusions were observed in Castings C and D, with the presence of degenerated graphite forms around the contamination (Fig. 12). This is likely to be also detrimental to machinability.

2.2.5 Chemical analysis

A chemical analysis was done on the four castings, as shown in Table 3. To further investigate the possible reasons that would explain the difference in the distribution of the microinclusions observed in the four castings, the balance

Mn/S has been considered^[9] and calculated and compared for the 4 castings according to the formula proposed by Norbury^[10]: $\%Mn = 1.72 \times \%S + 0.3$ for grey iron.

It seems that except for Casting A, the amount of Mn found in Castings B, C and D is in excess towards the calculated amount of Mn obtained from the Norbury formula considering the amount of sulfur available in the iron. A coefficient “a” has indeed been calculated: $\%Mn = 1.72 \times \%S + a$, to illustrate this point. It appears that this balance Mn/S should be reconsidered, as shown in Table 4.

Fig. 11: Observation and composition determination of inclusions found in Castings A and C, using SEM associated to EDAX. All inclusions are corresponding to MnS

Fig. 12: Coarse contamination (probably slag particles) detected in Castings C and D, using an optical microscope

Table 3: Comparison of chemical compositions (%) of the four castings studied

Casting No.	C	Mn	Si	P	S	Ti	Ni	Cu	Sn
A	3.33	0.56	1.87	0.039	0.12	0.022	0.025	0.063	0.079
B	3.37	0.64	2.05	0.038	0.094	0.019	<0.020	0.047	0.076
C	3.33	0.64	2.01	0.028	0.077	0.017	<0.020	0.034	0.092
D	3.38	0.64	1.85	0.031	0.12	0.025	<0.020	0.047	0.10

Table 4: Comparison between %Mn values calculated by Norbury Formula and analyzed by chemical analysis, and estimation of “a” factor in the formula: $\%Mn = 1.72\%S + a$

Castings	Calculated %Mn	Analysed %Mn	a
A	0.51	0.56	0.35
B	0.46	0.64	0.47
C	0.43	0.64	0.50
D	0.51	0.64	0.43

Referring to the differences observed in the Castings A, B, C, D, it is not possible to say which parameter is the predominant one. However, it is possible to help the Foundry as follows:

(1) Presence of microshrinkage: well-known to be detrimental to machinability. A much higher amount of microshrinkage was found in Castings C and D. This problematic situation for the Foundry can be reduced by using the correct inoculant practice (correct inoculant and addition rate).

(2) Distribution of the MnS: MnS are beneficial to machinability when they are well distributed in the matrix and numerous enough. This is to be linked to the ratio Mn/S

in grey iron. In this study, the presence of the micro-inclusions MnS was directly correlated to the chemical composition of the melt. It has been found that Mn was in excess in relation to the S present in the iron. Referring to Fig. 6, this could be the main difference between the machinability behavior of Casting B and Reference Casting A, thus may be critical in the machinability process. The solution for the Foundry was to adjust the %S in the melt to be sure to catch all available Mn in the melt to form manganese sulfides.

(3) The combination of a high amount of microshrinkage, poor distribution of MnS and the presence of coarse slag inclusions are explaining the poor machinability results for Castings C and D, compared to B and A – the reference.

3 Conclusions

Metallurgical characteristics are necessary to understand machinability behavior. In parallel, inoculation is a powerful tool to adjust metallurgical characteristics. Thus, it makes sense to adjust machinability properties by inoculation process. Results of the case studies presented here tends to show that:

(1) Inoculation process is beneficial to promote better graphite characteristics and distribution, which is essential to promote a good machinability.

(2) Inoculation is helpful to prevent microshrinkage, as the correct choice of inoculant has been made, thus is also critical to increase iron machinability.

(3) Mn and S ratios are of importance and need to be considered to provide a sufficient amount of manganese sulfides distributed in the matrix, to avoid the formation of FeS. Manganese sulfides are indeed beneficial for iron machinability.

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