Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v37i4.27460

Effects of different inoculants on the microstructural characteristics of gray cast iron gg-25, hardness and useful life of tools

Diego Ruben Martin[1], Joao Roberto Sartori Moreno[1*] and André de Albuquerque Vicente[2]

[1]*Programa de Pós-graduação em Engenharia Mecânica, Universidade Tecnológica Federal do Paraná, Avenida Alberto Carazai,1640, 86300-000, Cornélio Procópio, Paraná, Brazil.* [2]*Escola Politécnica, Universidade de São Paulo, São Paulo, São Paulo, Brazil. *Author for correspondence. E-mail: joaosartori@utfpr.edu.br*

ABSTRACT. Current study evaluated the machinability characteristics of parts, microstructure and mechanical properties when three different inoculants (IM-22 with FeSi-Ba/Zr; G-20 and FeSi-Ba; IMSR 75 with FeSi-Sr) were added in experiments carried out in a foundry. The research methodology was mailly based on the analysis of the machinability by the milling process of the specimens in gray cast iron GG-25, name according to DIN EN 1561.Evaluation of results is based on a thorough analysis of tool wear, surface finish, microstructural analysis, chemical composition and mechanical properties of the material. Results showed that among the studied inoculants strontium sulfide (SrS) was thermodynamically more stable than the others, because it leds towards a more negative free energy change of Gibbs and therefore more favorable to the formation of nuclei having greater critical radius (r_c), solidification with heterogeneous nucleation. Its inoculant was also more efficient in forming a more favorable microstructure, greater amounts of eutectic cells and, longer life of the insert when machined.

Keywords: machinability, strontium sulfide, tool wear, critical radius, eutectic cells.

Efeitos de diferentes inoculantes nas características microestruturais de ferro fundido cinzento gg-25, dureza e vida útil de ferramenta

RESUMO. Este estudo avaliou, por meio de experimentos realizados em uma fundição, a atuação na adição de três inoculantes diferentes (IM-22 com FeSi-Ba/Zr, G-20 e FeSi-Ba, e IMSR 75 com FeSi-Sr), para observar características de usinabilidade de peças, microestrutura e propriedades mecânicas. A metodologia da pesquisa é baseada, principalmente, na análise da usinabilidade pelo processo de fresamento dos espécimes em ferro fundido cinzento GG-25, nomeado de acordo com DIN EN 1561. As maneiras de avaliação dos resultados se basearam em uma análise aprofundada do desgaste da ferramenta, do acabamento da superfície, da microestrutura, da composição química e das propriedades mecânicas do material da peça de trabalho. Os resultados mostraram que, entre os sulfetos gerados na estrutura, o sulfeto de estrôncio (SrS) foi termodinamicamente mais estável do que outros, pois leva a uma mudança livre de Gibbs, mais energia negativa e, portanto, mais favorável à formação de núcleos com raio crítico (r_C) maior, levando e permitindo a solidificação com nucleação heterogênea. No entanto, a inoculação pelo IMSR 75 foi mais eficaz na formação de uma microestrutura mais favorável, com uma maior quantidade de células eutéticas e maior tempo de vida do inserto na usinagem.

Palavras-chave: usinabilidade, sulfeto de estrôncio, desgaste de ferramenta, raio critico, células eutéticas.

Introdution

Cast iron is traditionally selected in many industrial applications due to its flexibility comprising good melting point, low cost (between 20 and 40% less than steel) and a wide range of mechanical properties. A though gray cast iron is a material that provides easy machining, due to the great amount of parts and volumes of this type of material machined at world level, fast and economical machining is a continuous challenge, for foundries and for manufacturers machine tools.

Gray cast iron works at a strip tensile strength (150 to 400 MPa), and elongation is very small. Graphite is highlighted in the form of veins, which makes the gray cast iron material much used for components subject to thermal fatigue (JABBARI; HOSSEINZADEH, 2013).

The mechanical and structural properties of gray cast iron may be improved by adding iron-silicon alloys base prior to the molten casting of the iron. The main role of this technique, called inoculation, is the reduction of super-cooling during solidification by an increase in the number of eutectic cells to avoid, graphite of super-cooling and carbide graphite in the metal matrix, and prevents solidification by metastable eutectic system to obtain the graphite A type. It is also, a viable approach to improve the machinability of the material (COLLINI et al., 2008).

One clear difference in the machining process behavior of the materials is tool wear which depends on the cutting speed and mainly presence on the manganese sulfide (MnS) layer which it forms, acting as a lubricant and as a diffusion barrier when machining gray iron at high speed (MUHMOND; FREDRIKSSON, 2013).

The graphite morphology and the metallic matrix are furthermore mainly affected by the chemical composition, inoculation level and thickness of the section, as mentioned above.

However, since the matrix may be controlled in a similar way for different morphologies, the main difference in properties between the cast irons is due to graphite morphology.

The graphite flakes in gray iron have sharp edges which give the material its characteristic properties, as Table 1 demonstrates.

Table 1. Typical material and physical properties of gray iron and ductile iron

Property	Gray Iron	Ductile Iron
Tensile strength [MPa]	250	750
Elastic modulus [GPa]	105	160
Elongation [%]	0	5
Hardness[BHN10/3000]	179-202	217-255

Current assay was occasioned by the need of a foundry in Londrina - Paraná State (Brazil), to improve a piece of milling process made of gray cast iron, and to extend the life of the cutting tool.

It was then suggested to change the chemical composition of inoculants used in casting and through machinability tests conducted on the samples, to observe the effect of each addition in the milling properties of the material.

Three lots were produced using three different alternative inoculants (KIM et al., 2009) to pursue the improved machinability. Later, the mechanical and structural properties of manufactured parts were found. Machinability tests which consisted of the milling tool wear and finished the machined surface were then conducted.

Material and methods

Complying with DIN EN 1561, the material (gray cast iron GG-25) was chemically analyzed in the three compositions studied (inoculated with inoculants: G - 20; IM - 22 and IMSR75) by atomic absorption spectrometry with spectrometer Spectro Max coupled to Spark Analyzer MX Vision software.

The images for the metallographic analysis and eutectic cell count were generated by digital optical microscope Olympus BX 51 model with 100 x – 1000 x magnification capacity, specific attack for each requirement, and capture for image interpretation by software Image Pro-Plus .

Furthe, the hardness was measured by applying a load of 3000 kg f with a hard steel ball Ø10 mm during 20 s and scanned by Quick Brinell Metalab software. However, machinability tests (milling), were carried out in a vertical machining center CNC ROMI D 600 with insert SPHX1205 KY3500 and rotations of 5500 and 6366 rpm, to detect the useful life of the tool.

Results and discussion

Chemical composition

Table 2 shows the chemical compositions of samples with regard to run-off of gray cast iron GG-25 samples after different inoculations.

Table 2. Chemical composition GG 25 with inoculants.

Inoculants	C	Si	Mn	P	S	Cu	Ni	Sn
G-20	3.17	2.01	0.70	0.018	0.245	0.545	0.014	0.047
IM-22	3.17	1.90	0.66	0.020	0.205	0.546	0.012	0.043
IMSR75	3.15	2.00	0.65	0.022	0.229	0.533	0.007	0.045

The chemical composition rates did not differ significantly between the materials, but it should be noted that the amounts of silicon and sulfur exceeded the amount suggested by DIN EN 1561. Table 3 shows the composition of the inoculants used. It should be emphasize that silicon is present in greater amounts in the inoculant IMSR75, which also contains strontium.

Table 3. Chemical composition of the inoculants used.

Inoculants	Si	Mn	Ca	Al	Ba	Zr	Sr
G20	60.22	8.14	2.63	1.30	4.83	-	-
IM-22	65.21	5.52	1.49	1.06	2.19	5.74	-
IMSR 75	74.54	-	0.083	0.094	-	-	0.84

Metallographic analysis

Figure 1 shows the structures of the samples inoculated respectively with G-20, IM-22 and IMSR75, comprising the presence of graphite distribution size 4 in a flake form, type A and C, in the three pearlitic matrixes [2, 3]. However the cast iron inoculated with IM-22 showed a small of percentage super-cooling graphite (type D). The presence of type D graphite is due to the high cooling rate, shown small shafts. This type of graphite itself may not be regarded as harmful because of the low mechanical resistance that the structure of such graphite has and which primarily depends on the presence of a pearlitic matrix. Gray cast iron with graphite type D has generally good finish machining.

The chemical composition of the cast iron was also affected by ferrite/pearlite ratio. It strongly affected the material physical properties and, therefore, the machinability/tool life.

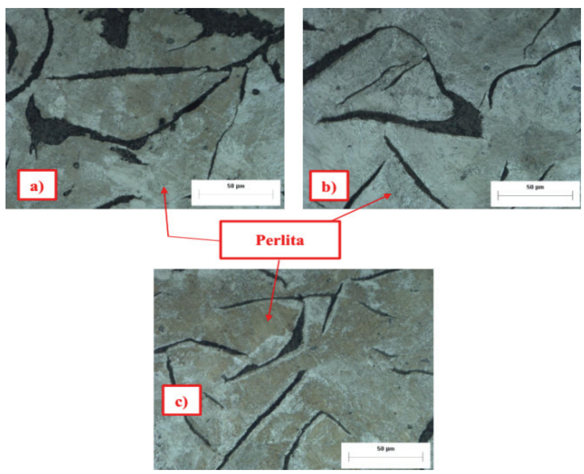

Figure 1. Microstructures of metal matrix with (a) G-20, (b) IM-22 and (c) IMSR 75; 1000x magnification and etched with 4% Nital.

Figure 2 (a), (b) and (c), show the microstructure after attack by Stead reagent that accelerates the development of the contour of eutectic cells due to inoculation (KIM et al., 2009).

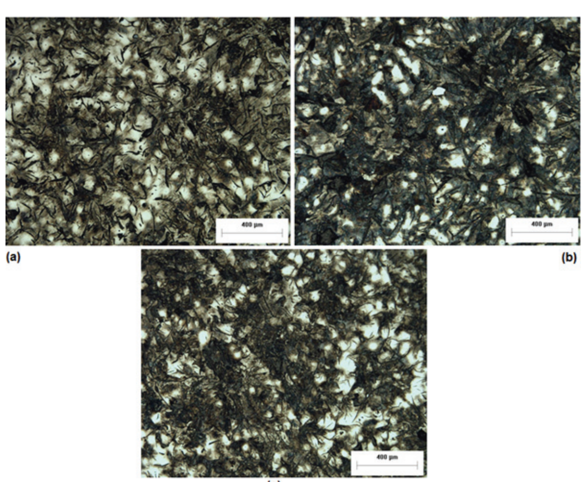

Figure 2. Eutectic cells as inoculant (a) G-20; (b) IM-22 and (c) IMSR75.

All the three differently inoculated irons had graphite in flake form with a pearlitic matrix in their microstructure. However, cast iron inoculated with IM-22 (FeSi-Ba/Zr) showed undercooling solidification graphite type D, which, in turn did not occur with the inoculated G 20 (FeSi-Ba). Moreover, IMSR 75 (FeSi-Sr) showed that graphite type A and C had, better mechanical properties and workability.

Counting of eutectic cells

Five counts were made in the region of the middle radius of the molten samples and an average of eutectic cells per sample was calculated, as demonstrated in Table 4.

Table 4. Counting of eutectic cells.

Identification	Number of eutectic cells mm^{-2}					
	Counting 01	Counting 02	Counting 03	Counting 04	Counting 05	Average
Sample 01 (G20)	1.6	1.2	1.4	1.4	1.9	1.5
Sample 02 (IM-22)	1.1	0,7	0.9	0.9	0.9	0.9
Sample 03 (IMSR 75)	1.6	1.8	2.8	2.1	1.8	2.0

Inoculation produces type A and graphite pearlitic matrix, together with relatively high number of eutectic cells. The greater the number of eutectic cells, greater mechanical strength and ductility tend to increase (FRÁS; GÓRNY, 2012). Inoculated material with IMSR75 showed most of these cells per mm^2, with higher performance of the inoculant in current analysis.

Nevertheless, the cell growth rate was caused by eutectic transformation in the inoculation, which tended to increase the number of eutectic cells, as occurred with IMSR75, with graphite structure, favoring the formation of pearlitic matrix and alterations in trend for shrinkage cavities in cast iron (FRÁS; GÓRNY, 2008).

However, the eutectic cell count with IM R75 inoculant had the best results with 2.0 cells mm^{-2}; followed by inoculation with G-20, with an average of 1.5 cells mm^{-2} and followed by inoculation with IM- 22 with 0.9 cells mm^{-2}. The best mechanical properties and machinability occurred with the IMSR75 inoculant.

Hardness tests

Hardness tests were conducted at six sites distributed in the sample. Inoculation with IM-22 and IMSR75 had the highest rates when compared hardness rates in the inoculated material with G-20 (Figure 3). However all materials complied with hardness range specified by DIN EN 1561 (180HB - 250HB).

Inoculation usually has better mechanical properties such as tensile ductility and toughness (COLLINI et al., 2008; SELIN et al., 2009).

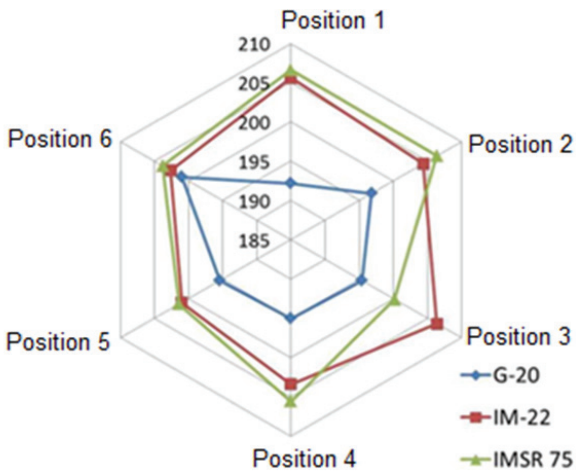

Figure 3. Brinell's hardness test in six positions of the samples.

Tool life tests

The end of tool life may be perceived when the average maximum flank wear of the insert reaches 0.3 mm, and when a maximum flank wear of any of the cutting inserts reaches 0.3 mm (BERGLUND, 2011). It is known that the tool wear may occur during machining, plastic deformation, spalling, oxidation or breakage of the tool. Cutting parameters comprised the dominant wear mechanism of the tool related to the abrasive wear on the flank face of the inserts. The flank wear was evaluated and employed as a quantitative response to determine the useful life of tools (DIAS; DINIZ, 2013).

Figure 4 shows that at the highest cutting speed of 1000 m min.$^{-1}$, tool wear was not as equally distributed throughout the inferior flank face (BERGLUND, 2011) as at the slower speed of 864 m min.$^{-1}$ of machinability, where the dominant wear mechanism was abrasive in the tool's flank face.

Results of the machining tests clearly showed the higher level of difficulty in the machining of compacted graphite iron when compared to the machining of standard gray cast irons for the cutting forces (KARABULUT; GÜLLÜ, 2013) and tool wear.

The percentage of ferrite and pearlite in the matrix, the amount, size, form, and distribution of the graphites and the presence of inclusions are directly related to parameters indicative of the material machinability similar to the tool life of the work piece (SELIN et al., 2009).

Therefore, the wear of the insert´s flank (V_B) was evaluated to analyze the tool´s life time. The, end of life criterion was V_B = 0.3 mm, when results from the three tested inoculants and different machining practices are compared (DIAS; DINIZ, 2013), as Figures 5 and 6 show.

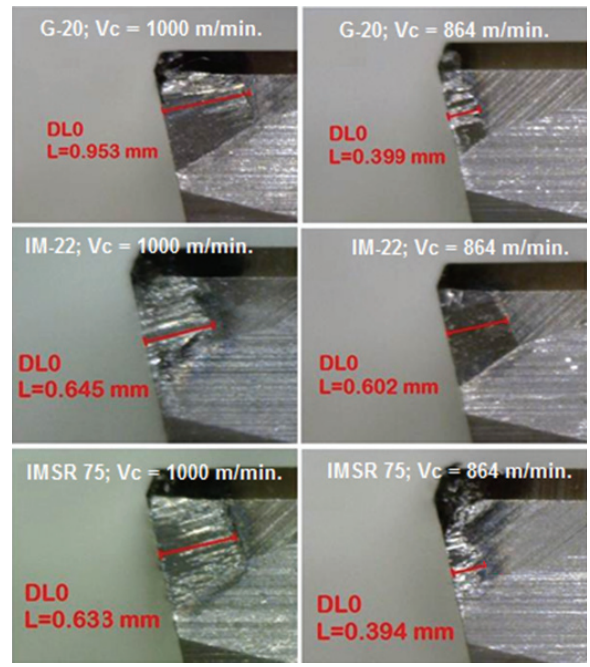

Figure 4. Flank wear of three samples with V_c at 864 and 1000 m min.$^{-1}$.

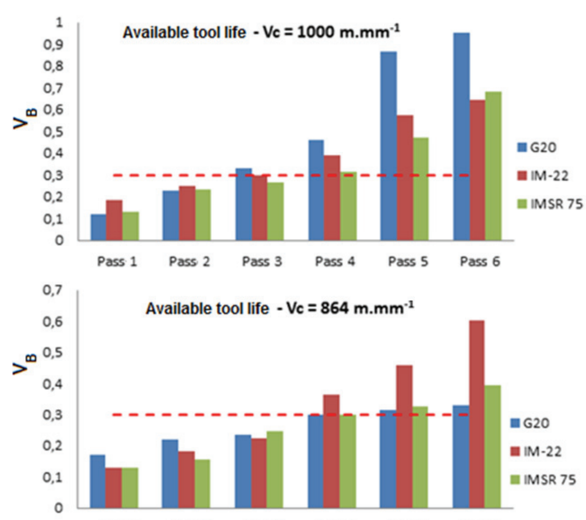

Figure 5. Tool wear for all inoculated cast and machined at two different VC cutting rates.

In the case of three inoculants used, the tool flank wear rate used in the milling of gray cast iron GG-25 decreased as shear rate decreased, with increased lifetime of the insert for lower cutting speeds (GASTEL et al., 2000; REN et al., 2009).

Therefore, the cutting speeds of the inoculated material IMSR 75, provided the insert a smaller flank wear and prolonged its useful life (KIRBY, 2010); this was, followed by IM-22 inoculated material for the cutting speed at 1000 m $min.^{-1}$ and by inoculum with G-20 for the cutting speed at 864 m $min.^{-1}$.

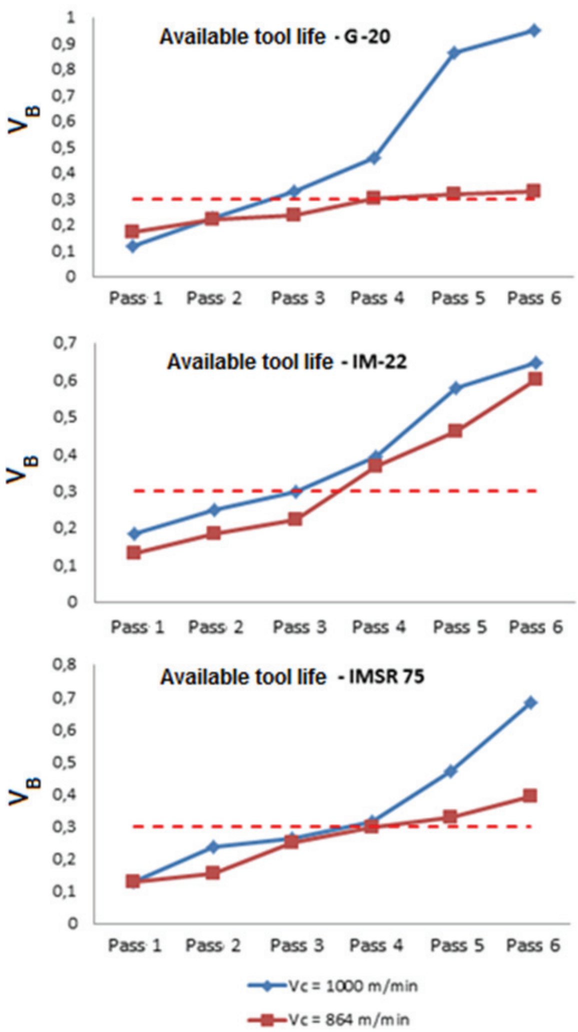

Figure 6. Flank wear in gray cast iron GG25 inoculated with G-20, IM22 and IMSR75.

Conclusion

Tool life showed a better wear performance and surface finish in the cast iron inoculated with IMSR75, since the presence of strontium increased the number of eutectic cells with finer pearlite and graphite.

It has also been observed, that the surface finish with IMSR 75 was rougher with decreasing cutting rate.

Current study demonstrated that the use of IMSR75 (Fe-Si-Sr) to produce gray cast iron, when compared to inoculants G-20 (usual) and IM-22 (FeSi-Ba/Zr), was more efficient, since the presence of strontium proved to be more effective in the formation of a microstructure with more eutectic cells, and favored a longer wear life for the insert.

Acknowledgements

The authors would like to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) for the scholarship. Thanks are also due to Multimetal Fundição S/A Londrina Paraná State Brazil which requested the current study.

References

BERGLUND, A.; GRENMYR, G., KAMINSKI, J. and NICOLESCU,C.M. Investigation of Tool Wear Mechanisms in CGI Machining, **International Journal Mechatronics and Manufacturing Systems**, v. 4, n. 1,p. 3-18, 2011.

COLLINI, L.; NICOLETTO, G.; KONECNA, R. Microstructure and mechanical properties of pearlitic gray cast iron, **Materials Science and Engineering A**, v. 488, n. 1-2, p. 529-539, 2008.

KIRBY, E.D., Optimizing the Turning Process Toward an Ideal Surface Roughness Target, **Journal of Industrial Technology**, V. 26, n. 1, p. 1-11, 2010

DIAS, L. R. D.; DINIZ, A. E. Effect of the gray cast iron microstructure on milling tool life and cutting force. **Journal of the Brazilian Society of Mechanical Sciences and Engineering**, v. 35, p. 17-29, 2013

FRÁS, E.; GÓRNY, M. Eutectic cell and nodule count as the quality factors of cast iron, **Archives of Foundry Engineering**, v. 8, n. 3, p. 353-358, 2008

FRÁS, E.; GÓRNY, M. Inoculation effects of cast iron. **Archives of Foundry Engineering**, v. 12, n. 4, p. 34-46, 2012

GASTEL, M.; KONETSCHNY, C.; REUTER, U.; FASEL, C.; SCHULZ, H.; RIEDEL, R.; ORTNER, H. M. Investigation of the wear mechanism of cubic boron nitride tools used for the machining of compacted graphite iron and grey cast iron. **International Journal of Refractory Metals and Hard Materials**, v. 18, n. 6, p. 287-296, 2000

JABBARI, M.; HOSSEINZADEH, A., Numerical modeling of coupled heat transfer and phase transformation for solidification of the gray cast iron. **Computational Materials Science**, v. 68, p. 160-165, 2013.

KARABULUT, Ş.; GÜLLÜ, A.; Wear model in milling compacted graphite iron with different lead angle using ceramic cutting tools, **Solid State Phenomena**, v. 199, p. 371-376, 2013.

KIM, S.; COCKCROFT, S. L.; OMRAN, A. M. Optimization of the process parameters affecting the microstructures and properties of compacted graphite iron, **Journal of Alloys and Compounds**, v. 476, n. 1-2, p. 728-732, 2009

MUHMOND, H. M.; FREDRIKSSON, H. Relationship between inoculants and the morphologies of MnS and graphite in gray cast iron, **Metallurgical and Materials Transactions B**, v. 44B, p. 283-298, 2013.

REN, F.; LI, F.; LIU, W. M. A. Z.; TIAN, B. Effect of inoculating addition on machinability of gray cast iron, **Journal of Rare Earths**, v. 27, n. 2, p. 294-299, 2009.

SELIN, M.; HOLMGREN, D.; SVENSSON, I. L. Influence of alloying additions on microstructure and thermal properties in compact graphite irons, **International Journal of Cast Metals Research**, v. 22, n. 1-4, p. 283-285, 2009.

Received on April 17, 2015.
Accepted on September 27, 2015.