ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 16, No. 4. 2010

Production of Ductile Iron Castings with Different Matrix Structure

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Received 30 October 2010; accepted 03 December 2010

The relation between the kind of inoculants, the castings size and matrix structure of ductile iron was investigated. Inoculation was performed by using 4 different inoculants. Ductile iron was cast in test bars with diameters from 3 mm to 50 mm. The study of the microstructure showed that the effect of the kind of inoculant on the content of pearlite is significant only for regular specimen sizes. The hardness value was found to decrease with decreasing pearlite content in the matrix structure of ductile iron. The time between spheroidizing treatment and pouring has strong effect on the ductility of ductile iron. Ce-bearing inoculant reduced this effect. Tests were also conducted to investigate the effects of kind of inoculants and the diameter of specimens on the microhardness of pearlite. It was found that the microhardness of pearlite of small size specimens is higher than this one of large size specimens. Ce-bearing inoculant slightly equalizes pearlite contents and its microhardness in various specimens sizes.

Keywords: ductile iron, matrix structure, section size, mechanical properties, microhardness.

1. INTRODUCTION

Every year, ductile irons find new fields of application, as steel substitute material, mainly as a result of their properties that, in most of the cases, are even better than those of low carbon steels. Although other ferrous castings may have superior individual properties, ductile iron offers, at lower cost, a unique versatility that can be obtained through microstructure control [1, 2]. Ductile iron may be considered as a composite in which spheroidal graphite particles are embedded into a metallic matrix. The mechanical properties of ductile iron are controlled primarily by their matrix structure. Therefore, modification in the amount or distribution of matrix phases or microstructures can modify mechanical properties. The matrix structure of ductile iron can be ferritic, pearlitic, ferritic-pearlitic, martensitic, austenitic or bainitic [3 – 5]. Ferritic, pearlitic, ferritic-pearlitic ductile irons are normally produced and usually used in the as-cast condition. The published reports review indicates that the matrix of as-cast ductile irons are determined by cooling rate, composition, inoculation, pouring temperature, addition of rare earth element and the content of pig iron in the charge [6 – 9].

The mechanical properties of ductile irons depend primarily upon the microstructures developed during solidification [8]. The cooling rate is largely determined by size of the casting in cross-section. Heat treatment may be used to overcome the difficulty, but is usually undesirable because of cost and the extra processing steps required. Faster cooling rates associated with thin sections promote pearlite formation; slower cooling rates favour ferrite formation [10]. The lower properties can be improved by the use of good inoculation practice, the selection of charges containing low levels of carbide forming elements and by additions of elements which improve nodule shape and nodule count in slow cooling sections [11].

Most ductile irons have a near-eutectic composition, extending far into strongly hypereutectic region for thin walled castings only. The foundries tend toward carbon levels of 3.40 to 3.84 percent and silicon levels of 2.45 to 2.64 percent. All ductile irons are low in sulfur (0.02 percent maximum) and in phosphorus (0.08 percent maximum) [12, 13]. The carbon equivalent affects the amounts of ferrite [14]. Copper and tin are elements most commonly used for pearlite promotion. Chromium is a pearlite promoter in ductile iron but its reaction depends up on the nodule count [15].

Inoculation is well known and very important step in foundry technology. This step defines the final microstructure and resultant properties and minimizes problems. Inoculation, if done correctly, controls the nodule count, reduces or eliminates carbides, produces the correct mechanical properties, improves machinability, and will decrease shrinkage. The most common inoculant used for ductile irons is foundry grade ferrosilicon, containing about 75 percent silicon. Inoculants often contain elements in relatively low concentration which are active inoculants, such as Ca, Al, Zr, Ba, Sr and Ti. But these elements are often very expensive so the problem is in choosing of the kind of inoculant. Inoculation can be accomplished in one or all of three ways: prior to the magnesium treatment, simultaneously with treatment, and after treatment. Normally the later in the process that inoculation is performed the more effective it will be [16, 17].

Solidification starts with nucleation, which is strongly affected by undercooling. The eutectic undercooling increases with increasing the melt pouring temperature. Therefore, the molten melt must be poured at lower temperature in order to decrease internal tensile stress, increase nodule count, decrease pearlite content, increase eutectic cell count, decreased chill depth [18, 19]. The rare earth elements addition to the iron decreases the eutectic undercooling and led to a higher amount of ferrite. Therefore, the specimens with rare earth elements have the lower mechanical properties as compared to same thickness specimens without these elements [6, 9]. However, the optimum rare earth content varies significantly according to different investigators.

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Considering of the growing interest in the development of ductile iron production processes, the present work focuses on the study of the influence of the kind of inoculants and cooling rate on the ductile iron matrix microstructure and hardness.

2. EXPERIMENTAL

Ninety kilograms of melts was prepared by melting pig iron, ductile iron returns, steel scraps, carbon and 75 % foundry grade ferrosilicon (Table 1) together using an induction furnace. The processes for spheroidization and post-inoculation were performed on the melts, using separate ladles. The spheroidization process was performed by applying the sandwich method in the first ladle, and using Fe-Si-Mg alloy at a melt temperature of 1530 °C. Inoculation was performed in the second ladle by using various inoculants (Table 2) in the stream, after which the melts were poured into the green sand mold in which five specimens with equal height of 310 mm but unequal diameters, 3, 5, 10, 25, and 50 mm, respectively, were produced. Various diameters cylindrical bars were cast in order to observe the effect of cooling rate on the pearlite content and its hardness. The pouring temperature was about 1360 °C. The effects of the time after spheroidizing treatment and the type of inoculants on the ductility and tensile strength were been cared out on the standard specimens with a diameter of 14 mm were machined from Y-type samples (Fig. 1).

Table 1. The chemical composition of charge materials

Item	C, %	Si, %	Mn, %	Cr, %	S, %
Pig iron	4.5	0.8	0.08	0.02	0.008
Mild steel	0.3	0.3	0.6	0.2	0.003
Return scrap	3.6	2.6	0.2	0.05	0.012
Fero-silicon	–	75	–	–	–
Carbon	95	–	–	–	–

Table 2. The chemical composition of inoculants

Inoculant	Chemical composition / mas. %			
	Si	Al	Ca	Other element
Alinoc	70–75	~4.0	~1.0	–
Ultraseed	70–76	~1.0	~1.0	1.5–2.0 Ce <1 $S+O_2$
Germalloy	70–78	~3.8	~0.9	–
SB5	65–70	~1.2	~1.2	2.0–2.5 Ba

The temperature of molten iron was measured by Pt-Rh thermocouple. Ductile irons of specimens were tested in the as-cast state. Metallographic examinations were performed by optical microscope with a digital camera and image analysis system after polishing and etching using a Nital solution. Areas with shrinkage porosities were not used for analyzing microstructure. Pearlite microhardness was tested using Vickers indenter with 0.49 N load. Rockwell hardness measurements were also performed using scale B.

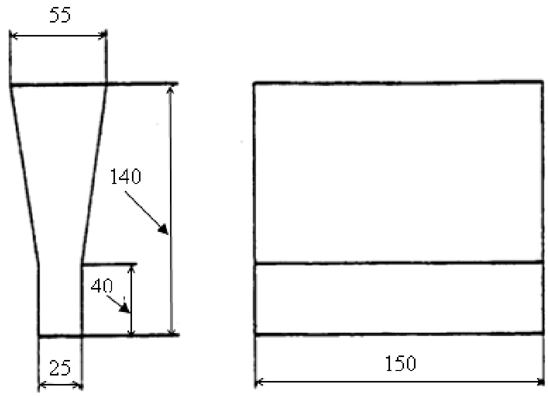

Fig. 1. Geometry of the Y-block ingot (dimensions in mm)

3. RESULTS AND DISCUSSIONS

Figure 2 shows that the thinner specimens contain more pearlite than thicker ones and the type of inoculant does not seem to affect the pearlite content for a thin and large specimen sizes. The kind of inoculant has noticeable effect for regular specimen sizes. It is so clear that Ce-bearing inoculant "Ultraseed" slightly equalizes pearlite contents in various specimens sizes. Ba-bearing inoculant "SB5" also reduces pearlite formation but to a lesser extent. It can be explained by the fact that the additions of cerium and barium promote nucleation of graphite nodules, resulting in the decrease of the pearlite formation in thin specimens [9, 20].

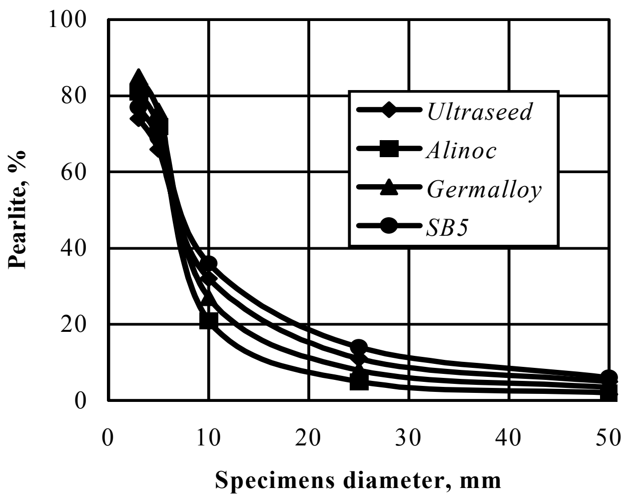

Fig. 2. Content of pearlite as a function of the kind of inoculant and the diameter of specimens

The hardness test results as a function of specimens' diameter are shown in Figure 3. It is shown that the hardness decreases with increasing specimens' size. These results reveal the remarkable consistency in relationships between hardness and pearlite content. Therefore, the influence of the kind of inoculants on the hardness is similar. Hardness is just only a parameter to predict some mechanical properties such as yield strength, tensile strength and elongation and is very easily measured [15, 21].

The effect of the kind of inoculants and the holding time after spheroidizing treatment on the elongation is shown in Figure 4. It is clear from this picture that the inoculant "Ultraseed" is more suitable for the decreasing of ductile iron ductility reduction during the holding time. The explanation for this is that "Ultraseed" reinstall good nucleation effectiveness from reactions with its sulphur and oxygen contributions [22]. The results of our investigation show that the tensile strength of ductile iron is less sensitive to the kind of inoculants then the elongation.

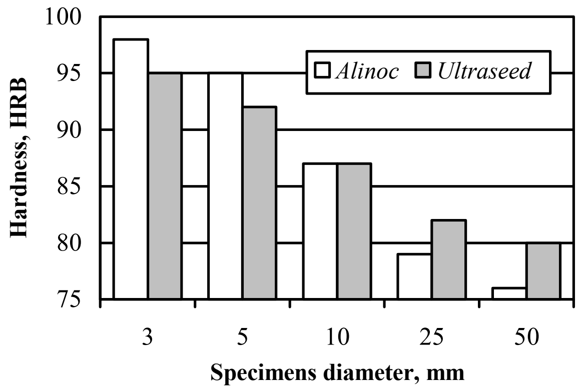

Fig. 3. Hardness of ductile iron as a function of the kind of inoculant and the diameter of specimens

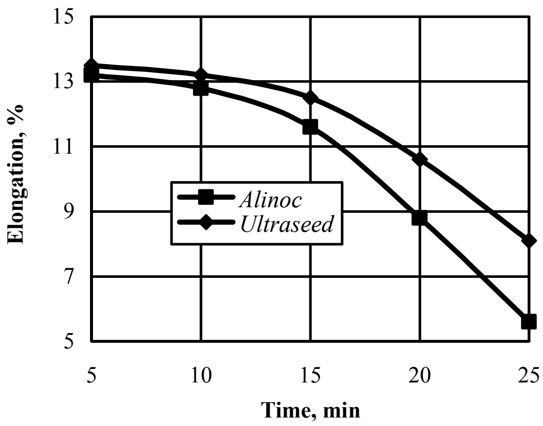

Fig. 4. Elongation as a function of the time after spheroidizing treatment and the kind of inoculants

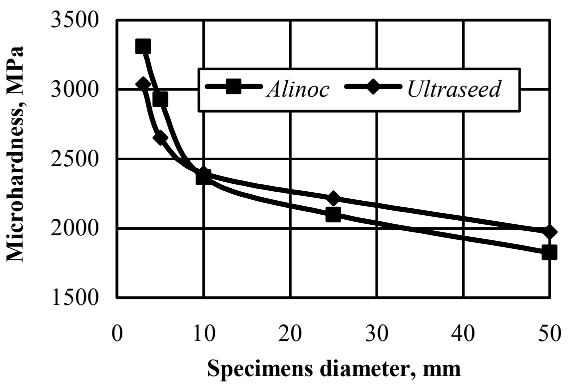

Fig. 5. Microhardness of pearlite as a function of the kind of inoculants and the diameter of specimens

Figure 5 shows results of Vickers microhardness tests of ductile irons inoculated with "Alinoc" and "Ultraseed" inoculants. From this picture it could be seen that the microhardness of pearlite of small size specimens is higher than this one of large size specimens. This could be explained by the analysis of lamellar spacing of pearlite as the change in the microhardness value reflects the change in pearlite spacing [23, 24]. A growth of pearlite is a diffusive process. The lamellar spacing depends on the transformation temperatures. At high temperatures (low undercooling below the A_1) the driving force is rather low, and the growth rate is low relative to the diffusion speed. This condition gives rise to the large pearlite spacing. At low temperatures (high undercooling below the A_1), the pearlite spacing is finer. Figure 5 indicates also that the inoculant bearing cerium equalizes microhardness of pearlite in various specimens sizes.

4. CONCLUSIONS

The effect of the kind of inoculants on both pearlite content and hardness of ductile iron castings is significant only for regular specimens sizes. Ce-bearing inoculant slightly equalizes these features in various specimens' sizes. Moreover, this inoculant reduces the effect of time between spheroidizing and pouring on the decreasing of elongation. In addition, it was found that that the tensile strength of ductile iron is less sensitive to the kind of inoculants then the elongation.

The microhardness of pearlite is affected by the specimens' size. The pearlite of small size specimens is higher than this one of large size specimens. The inoculant bearing cerium equalizes microhardness of pearlite in various specimens' sizes.

REFERENCES

1. **Bonora, N., Ruggiero, A.** Micromechanical Modelling of Ductile Cast Iron Incorporating Damage. Part I: Ferritic Ductile Cast Iron *International Journal of Solids and Structures* 42 (5–6) 2005: pp. 1401–1424.
2. **Labrecque, C., Gagne, M.** Review Ductile Iron: Fifty Years of Continuous Development *Canadian Metallurgical Quarterly* 37 (5) 1998: pp. 343–378.
3. **Celik, O., Ahlatci, H., Kayali, E. S., Cimenoglu, H.** High Temperature Abrasive Wear Behaviour of an As-cast Ductile Iron *Wear* 258 (1–4) 2005: pp. 189–193.
4. **Unkić, F., Glavaš, Z., Terzić, K.** The Influence of Elevated Temperatures on Microstructure of Cast Irons for Automotive Engine Thermo-mechanical Loaded Parts *RMZ-Materials and Geoenvironment* 56 (1) 2009: pp. 9–23.
5. **Luo, J., Bowen, P., Harding, R. A.** Evaluation of the Fatigue Behaviour of Ductile Irons with Various Matrix Microstructures *Metallurgical and Materials Transactions A* 33 (12) 2002: pp. 3719–3730.
6. **Stefanescu, D. M.** Solidification and Modelling of Cast Iron – A Short History of the Defining Moments *Materials Science and Engineering: A* 413–414 2005: pp. 322–333.
7. **Bočkus, S., Dobrovolskis, A.** Peculiarity of Producing Ferritic Ductile Iron Castings *Materials Science* (*Medžiagotyra*) 10 (1) 2004: pp. 3–6.
8. **Sheikh, M. A**. Production of Carbide-free Thin Ductile Iron Castings *Journal of University Science and Technology Beijing, Mineral, Metallurgy, Material* 15 (5) 2008: pp. 552–555.
9. **Choi, J. O., Kim, J. Y., Choi, C. O., Kim, J. K., Rohatgi, P. K.** Effect of Rare Earth Element on Microstructure Formation and Mechanical Properties of Thin Wall Ductile Iron Castings *Materials Science and Engineering: A* 383 (2) 2004: pp. 323–333.

10. **Caldera, M., Rivera, G. L., Boeri, R. E., Sikora, J. A.** Precipitation and Dissolution of Carbides in Low Alloy Ductile Iron Plates of Varied Thickness *Materials Science and Technology* 21 (10) 2005: pp. 1187 – 1191.

11. **Lacaze, J., Boudot, A., Gerval, V., Oquab, D., Santos, H.** The Role of Mn and Cu in the Eutectoid Transformation of Spheroidal Graphite Cast Iron *Metallurgical and Materials Transaction* 28A 1997: pp. 2015 – 2025.

12. **Karsay, S. J.** Ductile Iron Production Practices, American Foundrymen's Society, Inc., Des Plaines, Illinois, 1994.

13. **Csonka, J. M., Muratore, E. C., Woods, J. E.** Survey on Ductile Iron Practice *Transactions of the American Foundry Society* 110 2002: pp. 1099 – 1112.

14. **Rivera, G., Boeri, R., Sikora, J.** Influence of the inoculation Process, the Chemical Composition and the Cooling Rate, on the Solidification Macro and Microstructure of Ductile Iron *International Journal of Cast metals Research* 16 (1 – 3) 2003: pp. 23 – 28.

15. **Gonzaga, R. A., Landa, P. M., Perez, A., Villanueva, P.** Mechanical Properties Dependency of the Pearlite Content of Ductile Iron *Journal of Achievements in Materials and Manufacturing Engineering* 33 (2) 2009: pp. 150 – 158.

16. **Popovski, V., Misterik, C., Kaiser, L.** Metallurgical Comparisons between Operating Conditions, Inoculant Types and Fade Effects in Gray Iron *Proceedings of AFS Cast Iron Inoculation Conference* Schaumburg, Illinois, September 29 – 30, 2005: pp. 57 – 68.

17. **Jezerski, J., Bartocha, D.** Properties of Cast Iron Modifying with Use of New Inoculants *Journal of Achieving in materials and Manufacturing Engineering* 22 (1) 2007: pp. 25 – 28.

18. **Kanno, T.** Effect of Pouring Temperature, Composition, Mould Strength and Metal Flow Resistance on Shrinkage Cavities in Spheroidal Graphite Cast Iron *International Journal of Cast Metals Research* 21 (1 – 4) 2008: pp. 2 – 6.

19. **Edalati, K., Akhlaghi, F., Nili-Ahmadabadi, M.** Influence of SiC and FeSi Addition on the Characteristics of Gray Cast Iron Melts Poured at Different Temperatures *Journal of Materials Processing Technology* 160 (2) 2005: pp. 183 – 187.

20. **Salazar, R. F., Herrera-Trejo, M., Castro, M., Mendez, J. N., Torres, J. T., Mendez, M. N.** Effect of Nodule Count and Cooling Rate on As-cast Matrix of a Cu-Mo Spheroidal Graphite *Journal of Materials Engineering and Performance* 8 (3) 1999: pp. 325 – 329.

21. **Gonzaga, R. A., Carrasquilla, J. F.** Influence of an Appropriate Balance of the Alloying Elements on Microstructure and on Mechanical Properties of Nodular Cast Iron *Journal of Materials Processing Technology* 162 – 163 2005: pp. 293 – 297.

22. **Warrick, R. J.** Spheroidal Graphite Nuclei in Rare Earth and Magnesium Inoculated Irons *AFS Cast Metals Research Journal* 9 1996: pp. 97 – 108.

23. **Sosa, A. D., Echeverria, M. D., Moncada, O. J., Mingolo, N., Sikora, J. A.** Influence of Nodule Count on Residual Stresses and Distortion in Thin Wall Ductile Iron Plates of Different Matrices *Journal of Materials Processing Technology* 209 2009: pp. 5545 – 5551.

24. **Xiao-Feng Peng, Fan, J., Pi, W.** Effect of Interlamellar Spacing on the Constitutive Behaviour of Pearlitic Steels via Damage and Multiscale Analysis *International Journal for Multiscale Computational Engineering* 3 (2) 2005: pp. 161 – 176.

Presented at the National Conference "Materials Engineering'2010" (*Kaunas, Lithuania, November 19, 2010*)