DOI: 10.4149/km_2012_2_75

The influence of metallic charge on metallurgical quality and properties of ductile iron

Z. Glavaš*

Faculty of Metallurgy, University of Zagreb, Aleja narodnih heroja 3, 44103 Sisak, Croatia

Received 13 September 2010, received in revised form 1 August 2011, accepted 7 September 2011

Abstract

The effect of pig iron, steel scrap and ductile iron returns content in metallic charge on the nucleation potential and metallurgical quality of the base iron and ductile iron and the final microstructure and tensile properties of ductile iron is analyzed in this paper. The obtained results confirm the beneficial effect of pig iron addition on the nucleation potential of base and ductile iron producing an increase in nodule count and a decrease in chilling tendency of both base and ductile iron. The steel scrap has a price much more convenient than pig iron, but the use of high percentage of steel scrap in the charge was limited due to decrease in nucleation potential and increase of chilling tendency. Ductile iron returns also contributed to lower nucleation. Preconditioning did not completely correct the negative effect of high percentage of steel scrap in metallic charge. The results showed that the base iron must have had enough nucleation potential in order to obtain efficient inoculation. It was found that the tensile properties of ductile iron, especially the elongation, increased with the increase of the percentage of pig iron in metallic charge, due to increase of nodularity and nodule count.

Key words: ductile iron, metallic charge materials, metallurgical quality, nucleation potential, thermal analysis

1. Introduction

Ductile iron is cast iron in which the graphite is present as tiny spheres (nodules). In ductile iron, eutectic graphite separates from the molten iron during solidification in a manner similar to that in which eutectic graphite separates in gray cast iron. However, because of additives (magnesium) introduced in the molten iron before casting, the graphite grows as spheres, rather than as flakes of any of the forms characteristic of gray iron. Cast iron containing spheroidal graphite has better tensile properties and toughness than gray iron or malleable iron. Due to favorable combination of mechanical properties (relatively high tensile strength and toughness), ductile iron is used in many structural applications, such as pipes, various automotive parts, etc.

The most important factors that influence the properties of ductile iron are: chemical composition, the shape, distribution and amount of graphite, nodule count, matrix structure, the cooling rate during the solidification, the cooling rate through the eutectoid transformation range (solid state transformations), and the presence of other microstructural constituents (e.g. carbides, iron-phosphide eutectic, etc.) [1–8].

Chemical composition is one of the most significant factors in determining the metal matrix structure [1, 4–6]. Silicon is a ferrite promoter, while elements such as copper and tin are pearlite promoters. Manganese and chromium are a carbide forming elements. Phosphorus is a very harmful element because it has a strong embrittling effect and should be kept as low as possible. The presence of antispheroidizing (deleterious) minor elements (titanium, aluminum, arsenic, lead, etc.) may result in graphite shape deterioration, up to complete graphite degeneration.

The proportion and distribution of ferrite and pearlite in the metal matrix are very important to the mechanical properties of the ductile iron. If the

* Tel.: ++385 917368826; fax: ++385 44533381; e-mail address: glavaszo@simet.hr

continuous phase is ferrite, the material exhibits relatively high elongation and moderate strength, while a continuous pearlite matrix results in the opposite, i.e. high strength and low elongation.

The amount and shape of the graphite in ductile iron are determined during solidification and cannot be altered by subsequent heat treatment [5, 8]. It is common to attempt to produce more than 90.0 % of graphite in nodular form (> 90.0 % nodularity). Shapes which are intermediate between a true nodular form and a flake form yield mechanical properties that are inferior to those of ductile iron with true nodular graphite [8, 9]. The size and uniformity of distribution of graphite nodules also influence properties, but to a lesser degree than graphite shape. An optimum nodule density exists [10]. Small, numerous nodules are usually accompanied by high tensile properties and tend to reduce the likelihood of the formation of chilled iron in thin sections or at edges. Excessive nodules may weaken a casting to such a degree that it may not withstand the rigors of its intended application.

Nodule count affects the ferrite/pearlite ratio. As nodule count increases, the diffusional paths of carbon in the eutectoid transformation range decrease, which results in higher ferrite volume fraction in the microstructure for the same chemical composition and cooling conditions [2, 5, 7, 10]. Inoculation has an important influence on graphite nodularity and nodule count. Proper inoculation will improve the nucleation state of the melt, which results in higher nodule count and graphite nodularity [10–12].

The effects of the cooling rate on the microstructure and the properties of ductile iron are quite complex, since they affect both graphite morphology and the ferrite/pearlite ratio. Higher cooling rates during the solidification will increase graphite nodule count and graphite nodularity. However, higher cooling rates in the eutectoid transformations range result in higher volume fraction of pearlite in the microstructure [2, 5, 7].

Several types of carbides can be found in ductile iron. All are generally unacceptable and steps must be taken to get rid of carbides. Carbide content has both direct and indirect effects on the properties of ductile iron. Increasing the volume percent of hard, brittle carbide reduces the tensile strength and elongation of ductile iron. The formation of eutectic carbide (metastable eutectic) during solidification affects the volume fraction of graphite produced.

It is obvious that the shape, distribution and amount of graphite and nodule count significantly influence the properties of ductile iron. The precipitation of graphite in nodular form is not only controlled by magnesium content. The nucleation of graphite occurs through a heterogeneous process and preexisting nuclei compatible with crystallographic structure of graphite are needed [8, 11, 12]. The more suitable nuclei per unit volume (higher nucleation potential), the greater the number of graphite particles that start to grow. Nucleation potential and chemical composition determine the graphitization potential of the melt. A high graphitization potential will result in melts with graphite as the rich carbon phase.

Foundries often experience a situation where they get faultless castings on one occasion and unexpectedly high scrap rates on another, even though the chemical analysis, pouring temperatures and pouring times are identical in both cases. Such situations are often caused by the fact that the solidification process varied due to differences in the nucleation potential and metallurgical quality of the melts. Analysis of chemical composition of the cast iron melt does not give information about these essential properties.

Metallurgical quality of the melt is rather vague parameter, which is related to the composition of the melt and its processing, and becomes somewhat more meaningful if it is equated to graphite forming tendency as opposed to solidification with carbide. This does not mean that all ductile irons which are carbide-free as-cast are equal in metallurgical quality. Considerable quality differences exist. Probably the most sensitive quality indicator is nodule count.

There are a number of factors that affect the nucleation potential and metallurgical quality of cast irons melts. They are: the metallic charge, the type of melting equipment employed, melting and holding temperatures, holding time, chemical composition and inoculation.

The type of charge material, including the melt history and the liquid metal preparation prior to nodularization and inoculation treatment has an important effect on the final structure and properties of ductile iron castings. It has been found that high nucleation states and potential for nucleation are achieved in melts prepared with high percentage of pig iron in the metallic charge whereas the converse (low nucleation and low potential for nucleation) is experienced in melts prepared with high percentage of ductile iron returns and steel scrap in the metallic charge [13].

Improvements of the nucleation potential and metallurgical quality of the base irons, especially irons prepared with high percentage of steel scrap in the metallic charge, can be achieved with preconditioning (pretreatment) [13–16]. In foundry practice, different preconditioning agents are used, such as metallurgical silicon carbide, ferrosilicon, ferrosilicon based complex alloys, etc. Small additions of preconditioning agents give increased levels of nucleation in the base iron, thus reducing the variations between melts and giving more consistent casting properties.

Cupola melted irons exhibit a higher metallurgical quality than irons melted in induction furnace [13]. In cupola there is the contact between molten iron and the coke in the cupola well (nucleating effect), relatively short time at high melt temperatures and the presence of adequate oxides and sulfides as nucleation sites whereas the converse conditions are present in induction furnace. Due to that, induction melted irons generally require different charge ratios and additional amount and often times more potent inoculants.

High melting (superheating) temperatures and long holding times are detrimental. These conditions are very damaging to the nucleation state, even with highly suitable charge materials [13]. The stability of nuclei decreases with increasing temperature. As the holding time increases, nuclei tend to float to the surface of the melt and to be absorbed in the slag.

The chemical composition influences the graphitizing tendency of cast irons to a certain extent. Carbon and silicon promote graphitic freezing and must be carefully controlled. As the carbon equivalent decreases or the level of carbide stabilizing elements increases, the tendency to solidify with a more carbidic microstructure increases. Increasing carbon content reduces shrinkage tendency and increasing silicon content reduces carbide formation, but these effects are lost due to the loss of nucleation.

Inoculation increases the number of active nuclei in melt so that eutectic solidification, specifically graphite precipitation, can start with a minimum amount of undercooling [12]. It increases nodularity and the nodule count, improves distribution of graphite and tends to reduce the likelihood of the formation of carbides. As a result, mechanical properties improve.

The assessment of the nucleation potential of a graphitic cast iron can be achieved with chill wedge testing. By measuring the width of the chilled (carbidic) portion of the wedge, the foundryman could determine nucleating potential. As the chill width increases, the nucleating potential of melt decreases. However, many parameters and the experience of foundryman influence the results of assessment of nucleation potential with chill wedge testing.

The melt control method which gives the better insight into the nucleation potential and metallurgical quality of the melt is thermal analysis (TA). TA is a simple, quick and reliable method for the assessment of melt quality and observation of solidification process of cast irons. In the foundries, TA is performed by recording of cooling curves. The parameters which are identified and measured by TA could be applied in the assessment of influence of process parameters on solidification, i.e. for the assessment of metallurgical quality and nucleation potential of the melt.

The aim of this paper was to determine the influence of metallic charge material, i.e. pig iron, steel scrap and ductile iron returns on the nucleation potential and metallurgical quality of base and ductile iron and the final microstructure and tensile properties of ductile iron.

2. Experimental

The base irons for the production of ductile irons melts were produced in a medium frequency coreless induction furnace. The charges consisted of special low-manganese pig iron (4.28 wt.% C, 0.124 wt.% Si, 0.019 wt.% Mn, 0.006 wt. % S, 0.029 wt. % P), steel scrap (0.12 wt.% C, 0.33 wt.% Si, 0.24 wt.% Mn, 0.023 wt.% S, 0.013 wt.% P, 0.03 wt.% Cu), ductile iron returns (3.65 wt.% C, 2.5 wt.% Si, 0.11 wt.% Mn, 0.008 wt.% S, 0.030 wt.% P, 0.08 wt.% Cu, 0.038 wt.% Mg), ferrosilicon (73.03 wt.% Si) and recarburizer (99.2 wt.% C). Pig iron portion of the metallic charge was varied from 10.0 to 60.0 wt.%, steel portion of metallic charge was varied from 10.0 to 80.0 wt.% and ductile iron returns portion of the metallic charge was varied from 10.0 to 50.0 wt.%. Preconditioning of the base irons was performed by addition of silicon carbide (63.0 wt.% Si, 30.0 wt.% C, 0.07 wt.% S) in amount of 0.90 wt.% of the metallic charge. In order to obtain exact (required) portions, all components of charges were carefully weighted before charging.

During charging, heating and melting the induction furnace followed the same power-time program as a means to keep the thermal history of the base irons as controlled as possible in the "furnace" phase.

Oxygen activity was measured by oxygen activity sensor. On each base iron, the oxygen activity was measured three times and the differences between the three measurements were in the range 3.2 to 10.4 %. After that, the average value of the oxygen activity was calculated for each base iron.

After oxygen activity measurement, TA was performed by the advanced TA system. A sample of the melt was poured into a standardized mold with a thermocouple. For each base iron one cooling curve was recorded and an advanced TA system calculated thermal parameters. After that, three chill wedge samples were cast from each base iron. The differences between the three measurements of chill width were in the range 2.7 to 8.9 % and the average value of chill width was calculated for each base iron. Dimensions of the chill wedge are specified according to the ASTM A 367.

The nodularization treatment was performed by Cored Wire method. Treatment alloy contained 15.40 wt.% Mg, 45.70 wt.% Si and 2.40 wt.% Ce_{MM}. Inoculation was performed with 0.3 wt.% of Ca/Al/Ba containing ferrosilicon. After the treatment and inoculation, the sample of melt was taken for TA and chill wedge sample and a Y-block were cast. The dimensions and the form of the Y-block are specified according to the EN 1563:2010. For each ductile iron one cooling curve was recorded and an advanced TA system calculated thermal parameters. Three chill wedge samples were cast from each ductile iron. The differences between the three measurements of chill width were in the range 3.1 to 7.7 % and the average value

Table 1. Thermal parameters, the results of measurements of chill width on chill wedge samples and oxygen activity in base irons

Base iron	The content of component in the metallic charge (%)			Thermal parameters						Chill width	a_O
	Steel scrap	Pig iron	Ductile iron returns	ϑ_{Elow} (℃)	ϑ_R (℃)	ϑ_S (℃)	GRF1	GRF2	$\frac{d}{dt}\vartheta_S$ (℃ s^{-1})	(mm)	(ppm)
1	10.0	60.0	30.0	1182.00	2.80	1139.50	84.00	18.00	–4.87	3.50	1.884
2	10.0	60.0	30.0	1175.70	2.50	1138.00	77.00	19.00	–4.99	4.00	2.011
3	30.0	60.0	10.0	1172.00	3.00	1130.40	72.00	21.00	–4.71	4.50	2.949
4	30.0	60.0	10.0	1172.10	2.80	1131.10	73.00	22.00	–4.76	4.50	2.463
5	27.0	48.0	25.0	1174.30	2.70	1133.60	63.00	23.00	–4.34	5.00	3.268
6	10.0	40.0	50.0	1175.10	1.70	1126.10	67.00	27.00	–4.52	5.50	3.227
7	44.5	35.5	20.0	1167.00	3.60	1124.80	61.00	32.00	–4.50	5.50	3.563
8	29.5	30.5	40.0	1164.80	6.10	1125.30	62.00	32.00	–4.37	6.00	3.650
9	57.0	23.0	20.0	1166.70	7.20	1128.90	61.00	37.00	–4.02	7.00	3.738
10	40.0	10.0	50.0	1164.20	7.80	1124.80	61.00	36.00	–4.16	7.00	3.754
11	40.0	10.0	50.0	1166.70	6.90	1122.70	60.00	35.00	–4.17	7.00	3.738
12	60.0	10.0	30.0	1163.10	10.90	1123.80	57.00	38.00	–3.98	7.00	3.659
13	80.0	10.0	10.0	1158.80	11.60	1113.20	53.00	45.00	–3.33	7.50	3.736
14	80.0	10.0	10.0	1154.20	12.30	1116.70	55.00	49.00	–3.44	8.00	3.974

of chill width was calculated for each ductile iron. Altogether, 14 melts were made.

For each ductile iron three standard test pieces for the estimation of tensile properties (R_m, $R_{p0.2}$, A) were machined from Y-blocks. The dimensions and the form of the test pieces are specified according to the EN 1563:2010. The tensile test was performed in accordance with EN ISO 6892-1. The differences between the three measurements of R_m were in the range 2.1 to 6.5 %, the differences between the three measurements of $R_{p0.2}$ were in the range 2.0 to 6.9 %, and the differences between the three measurements of A were in the range 2.7 to 6.3 %. Average values of R_m, $R_{p0.2}$, A of each ductile iron were calculated on the basis of individual measurements.

Metallographic examinations were performed after tensile test by a light metallographic microscope with a digital camera and the image analysis system. On the each ductile iron sample, five measurements were carried out for each analyzed microstructure features (nodularity, ferrite content, pearlite content, nodule count). The differences between the three measurements of nodularity were in the range 3.2 to 7.4 %, the differences between the three measurements of ferrite content (and pearlite content) were in the range 2.8 to 5.6 %, and the differences between the three measurements of nodule count were in the range 4.7 to 10.1 %. Average values of microstructure features of each ductile iron were calculated on the basis of individual measurements.

3. Results and discussion

Carbon content in the base irons varied from 3.68 to 3.82 wt.% and silicon content varied between 2.17 and 2.35 wt.%. The content of pearlite promoting elements and carbide forming elements was low (manganese – from 0.12 to 0.17 wt.%, cooper – from 0.015 to 0.048 wt.%, nickel < 0.05 wt.%, chromium < 0.03 wt.%, molybdenum < 0.004 wt.%). This helps to promote a ferritic metal matrix in ductile irons. Phosphorus content varied from 0.018 to 0.033 wt.% and sulfur content varied from 0.010 to 0.018 wt.%. Extremely low sulfur base iron (< 0.005 wt.%) is undesirable since such base irons exhibit poor response to nodularization and post inoculation [8, 13].

The results of TA, chill wedge testing and oxygen activity measurements in the base irons are given in Table 1. Only those thermal parameters that are most relevant for assessment of the nucleation potential and metallurgical quality of the melts are given.

The TA data indicate that the nucleation potential and metallurgical quality of the base irons vary from heat to heat (Table 1).

The lowest eutectic temperature (ϑ_{Elow}) is directly related to the nucleation status of the melt [17]. The higher ϑ_{Elow} values (lower undercooling) indicate a well-nucleated iron with a low tendency to form chill (higher nucleation potential). The obtained results show that the increase of the percentage of pig iron in the metallic charge results in increasing of the lowest eutectic temperature. As the percentage of steel scrap or ductile iron returns in the metallic charge increases, the lowest eutectic temperature decreases. Chill width decreases with the increase of the lowest eutectic temperature.

Recalescence (ϑ_R) represents the difference between the highest eutectic temperature (ϑ_{Ehigh}) and the lowest eutectic temperature (ϑ_{Elow}). Recalescence is the indicator of the eutectic growth, i.e. the amount of austenite and graphite that are precipitated during the early stage of eutectic solidification [17]. High recalescence indicates the poor nucleation status of the melt. Data on recalescence indicate that the increasing of the percentage of pig iron in the metallic charge lowers the recalescence. The increase of the percentage of steel scrap or ductile iron returns in the metallic charge results in increasing of recalescence.

Solidus temperature (ϑ_{S}) shows the end of the solidification. The increase of the nucleation potential of the melt results in increasing of the solidus temperature [17]. Moreover, solidus temperature is greatly influenced by the segregation of carbide forming elements. The results of examinations show that the solidus temperature increases as the percentage of pig iron in the metallic charge increases. The increase of the percentage of steel scrap or ductile iron returns in the metallic charge produced the opposite effect. Chill width decreases with the increase of the solidus temperature.

Graphite factor 1 (GRF1) is a parameter that is defined as the relative time for the temperature to drop 15 ℃ from the highest eutectic temperature ($\vartheta_{\mathrm{Ehigh}}$). This parameter reflects how much eutectic, i.e. eutectic graphite, is precipitated during the second part of the solidification process (from $\vartheta_{\mathrm{Ehigh}}$ to ϑ_{S}) [17]. The obtained results show that the graphite factor 1 increases with increasing the percentage of pig iron in the metallic charge and decreases with increasing the percentage of steel scrap or ductile iron returns in metallic charge.

Graphite factor 2 (GRF2) is calculated from the cooling rate before and after solidus. This parameter is the angle observed in the first derivative curve at the solidus temperature (ϑ_{S}). Parameter $\frac{\mathrm{d}}{\mathrm{d}t}\vartheta_{\mathrm{S}}$ is the value of the first derivative at solidus temperature or the depth of the first derivative (angle) at solidus temperature. Low value of graphite factor 2 and value of the first derivative at solidus temperature indicate the high nucleation potential of the melt and high amount of graphite at the end of the solidification [17]. The obtained results show that the increase of the percentage of pig iron in the metallic charge results in decreasing of graphite factor 2 and the value of the first derivative at solidus temperature. These thermal parameters increase as the percentage of steel scrap or ductile iron returns in the metallic charge increases.

Data analysis shows that there is a correlation between the percentage of steel scrap in metallic charge and the chill width. The increase of the percentage of steel scrap in metallic charge results in increasing of the chill width, due to low nucleation potential.

The obtained results show that the different charge materials can supply various oxygen contents to the base iron. Oxygen activity is the highest in the base irons prepared with high percentage of steel scrap in metallic charge.

With carbon content in the treated (ductile) irons in the range from 3.46 to 3.52 wt.% and silicon content in the range from 2.51 to 2.69 wt.% carbon equivalents in the range from 4.31 to 4.42 % were achieved. This corresponds to eutectic and slightly hypereutectic compositions. Phosphorus content varied from 0.015 to 0.031 wt.% and sulfur content varied from 0.007 to 0.012 wt.%. Magnesium content varied between 0.035 and 0.039 wt.%.

Table 2 summarizes the results of thermal analysis and chill wedge testing of ductile irons. The thermal analysis data indicate that the nucleation potential and metallurgical quality of the ductile irons also vary from heat to heat (Table 2). The lowest eutectic temperature ($\vartheta_{\mathrm{Elow}}$), solidus temperature ($\vartheta_{\mathrm{S}}$) and graphite factor 1 (GRF1) decrease with the increase of the percentage of steel scrap and ductile iron returns in the metallic charge. Recalescence (ϑ_{R}), graphite factor 2 (GRF2) and the value of the first derivative of the cooling curve at solidus $\left(\frac{\mathrm{d}}{\mathrm{d}t}\vartheta_{\mathrm{S}}\right)$ increase with the increase of the percentage of steel scrap and ductile iron returns in the metallic charge. Increase of pig iron content in the metallic charge produced an opposite effect, i.e., improved the nucleation potential, and the cooling curves show higher values for $\vartheta_{\mathrm{Elow}}$, ϑ_{S} and GRF1 and lower values for ϑ_{R}, GRF2 and $\frac{\mathrm{d}}{\mathrm{d}t}\vartheta_{\mathrm{S}}$. TA data show the correlation between the changes in values of thermal parameters of the base iron and those of ductile iron. For example, an increase of the lowest eutectic temperature of the base iron produced an increase of the lowest eutectic temperature in ductile iron and vice versa. Other thermal parameters show the same trend.

The ductile irons made with high percentage of steel scrap in metallic charge exhibit a higher chill level than ductile irons prepared with high percentage of pig iron.

The results of metallographic examinations and tensile tests are given in Table 3.

Data analysis shows that there is a correlation between the thermal parameters and microstructure features of ductile irons. The obtained results show that the increase of the lowest eutectic temperature ($\vartheta_{\mathrm{Elow}}$) results in increase of nodularity and nodule count and decrease of chill width. Low $\vartheta_{\mathrm{Elow}}$ indicates poor nucleation potential of the ductile iron melt, i.e. a low number of active sites for nucleation of graphite.

The results of examinations show that the increase of recalescence (ϑ_{R}) results in decreasing of the nodule count and nodularity. High recalescence indicates poor nucleation potential of the ductile iron melt.

T a b l e 2. Thermal parameters and the results of chill wedge testing of ductile irons

Ductile iron	The content of component in the metallic charge (%)			Thermal parameters						Chill width (mm)
	Steel scrap	Pig iron	Ductile iron returns	$\vartheta_{\mathrm{Elow}}$ (°C)	ϑ_{R} (°C)	ϑ_{S} (°C)	GRF1	GRF2	$\frac{\mathrm{d}}{\mathrm{d}t}\vartheta_{\mathrm{S}}$ (°C s^{-1})	
1	10.0	60.0	30.0	1178.10	2.00	1131.80	95.00	22.00	–4.24	2.50
2	10.0	60.0	30.0	1170.60	2.10	1129.80	89.00	26.00	–4.15	2.50
3	30.0	60.0	10.0	1168.20	2.80	1121.20	90.00	28.00	–4.02	3.00
4	30.0	60.0	10.0	1165.90	3.30	1125.90	91.00	27.00	–4.06	3.00
5	27.0	48.0	25.0	1165.30	2.70	1130.30	85.00	30.00	–3.82	3.50
6	10.0	40.0	50.0	1168.00	2.10	1124.70	88.00	30.00	–3.90	4.00
7	44.5	35.5	20.0	1164.50	3.40	1119.30	83.00	35.00	–3.62	5.00
8	29.5	30.5	40.0	1160.00	4.30	1121.30	86.00	40.00	–3.70	4.50
9	57.0	23.0	20.0	1160.70	5.20	1120.70	80.00	44.00	–3.36	4.50
10	40.0	10.0	50.0	1160.30	5.80	1115.00	77.00	45.00	–3.58	5.00
11	40.0	10.0	50.0	1158.20	5.50	1116.00	78.00	43.00	–3.61	5.00
12	60.0	10.0	30.0	1158.50	5.90	1120.60	72.00	44.00	–3.51	5.00
13	80.0	10.0	10.0	1150.20	6.40	1111.70	70.00	51.00	–2.93	5.50
14	80.0	10.0	10.0	1152.70	6.20	1112.20	67.00	50.00	–3.10	6.00

T a b l e 3. Microstructure features and tensile properties of ductile irons

Ductile iron	The content of component in the metallic charge (%)			Microstructure				Tensile properties		
	Steel scrap	Pig iron	Ductile iron returns	Nodularity (%)	Ferrite content (%)	Pearlite content (%)	Nodule count	$R_{\mathrm{p0.2}}$ (N mm^{-2})	R_{m} (N mm^{-2})	A (%)
1	10.0	60.0	30.0	84.00	96.97	3.04	198	322.0	452.0	19.7
2	10.0	60.0	30.0	82.00	96.86	3.14	190	326.0	453.0	19.3
3	30.0	60.0	10.0	81.00	95.66	4.34	176	306.0	441.0	19.7
4	30.0	60.0	10.0	80.00	95.92	4.08	173	310.0	445.0	19.0
5	27.0	48.0	25.0	80.50	95.55	4.45	167	310.0	439.0	17.9
6	10.0	40.0	50.0	80.00	94.96	5.04	169	309.0	438.0	17.3
7	44.5	35.5	20.0	77.50	95.13	4.87	168	308.0	443.0	17.9
8	29.5	30.5	40.0	77.00	94.82	5.18	162	302.0	434.0	17.0
9	57.0	23.0	20.0	75.50	94.90	5.10	153	296.0	425.0	16.5
10	40.0	10.0	50.0	74.00	94.55	5.45	146	298.0	420.0	16.3
11	40.0	10.0	50.0	73.00	94.79	5.21	150	293.0	418.0	16.9
12	60.0	10.0	30.0	71.00	94.83	5.17	145	292.0	420.0	15.6
13	80.0	10.0	10.0	68.10	93.31	6.69	120	286.0	434.0	13.9
14	80.0	10.0	10.0	69.00	94.25	5.75	116	289.0	432.0	14.5

Moreover, high value of recalescence is related to the non-continuous precipitation of graphite during the solidification. A too high amount of graphite precipitated in the early stage of eutectic solidification results in a small amount of available graphite during the later solidification. Due to that, secondary sites of nucleations are not activated, which may result in a low nodule count.

The obtained results show that the increase of the nodule count results in increasing of the solidus temperature (ϑ_{S}). By increasing nodule count during solidification, the rate of release of latent heat due to graphite precipitation increases, and the solidus temperature is raised above the metastable temperature ($\vartheta_{\mathrm{Ewhite}}$), preventing carbide formation. Increasing the nodule count is an important goal, because a higher nodule count is associated with less chilling tendency.

Data analysis shows that the graphite factor 1 (GRF1) increases with the increase of nodule count and nodularity. A high graphite factor 1 value indicates continuous precipitation of eutectic graphite, which is related to the high nucleation potential of the ductile iron melt and activation of secondary nucleation sites. This results in the moving of the eutectic reaction toward longer times. This mode of eutectic

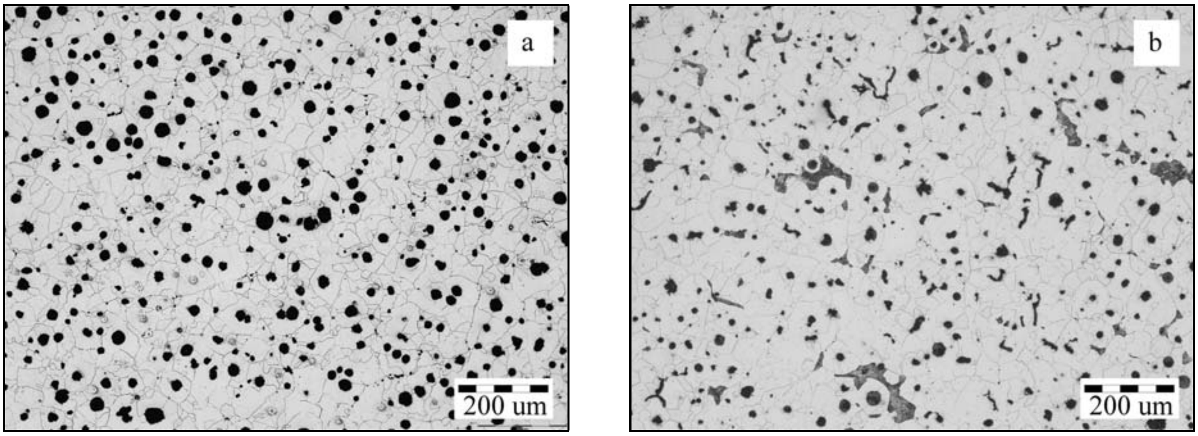

Fig. 1. Optical micrograph of microstructure of ductile iron sample number 1 (a) and 14 (b). Etched, natal.

solidification, when the nucleation and the growth of eutectic occur in longer times, results in a higher distribution of sizes of the precipitated graphite, i.e. a higher density of graphite particles in the metal matrix.

Graphite factor 2 combined with the value of the first derivative at solidus temperature is a sensitive indicator for heat conductivity and thereby for graphite shape and nodule count. The obtained results show that the decrease of graphite factor 2 (GRF2) and value of the first derivative at solidus temperature $\frac{\mathrm{d}}{\mathrm{d}t}\vartheta_{\mathrm{S}}$ result in increasing of nodule count and nodularity.

The microstructures of ductile irons made with high percentage of pig iron and high percentage of steel scrap in metallic charge are different (Fig. 1). The use of high percentage of pig iron in metallic charge gives significant change in the microstructure.

The obtained results show that the metallic components of the charge have pronounced effects on nodularity and nodule count. As the percentage of pig iron increases and the percentage of steel scrap and ductile iron returns decreases, the nodule count and nodularity increase (Fig. 1).

The percentage of ferrite in metallic matrix is the highest in ductile irons prepared with high percentage of pig iron in metallic charge, due to the high nodule count. A higher number of graphite particles during the eutectoid transformation enable the formation of a higher fraction of ferrite in the microstructure. It is obvious that the increase of nodule count influences the properties of ductile iron.

The results of tensile test indicate that the increase of the percentage of pig iron in metallic charge results in increase of elongation, due to the increase of nodularity, nodule count, and ferrite content. Nodularity and nodule count have a direct influence on the tensile properties. The presence of irregularly shaped graphite spheroids affects the mechanical properties. All properties relating to strength and ductility decrease as the proportion on non-nodular graphite increases. The form of non-nodular graphite is important, because the graphite with sharp edges has a more adverse effect on tensile properties than the form of graphite with rounded ends. Poorly shaped nodules act as flaws (or stress raisers) that facilitate crack initiation and propagation. Better graphite morphology allows more efficient use of the mechanical properties of the metal matrix.

All the ductile iron melts were inoculated. The results indicate that the inoculation improves the nucleation state of the melt. But, the final nucleation potential of the ductile iron melts before pouring is dependent on the whole metallurgical history of the melt preparation and treatment. It is obvious that the inoculation does not correct problems that result from incorrectly prepared base irons. It is important to create and preserve the conditions to achieve a high number of stable nuclei prior to inoculation.

Oxygen plays a role in the nucleation and growth of graphite and to have a significant influence over the ultimate structure and, thereby, properties of the ductile iron castings. Oxides are directly related to the heterogeneous nucleation sites for graphite nucleation. The obtained results show that the increase in total oxygen content in the base iron is not sufficient to cause an increase of nodule count in ductile iron.

4. Conclusions

The obtained results indicate that the metallic components of the charge and melt history have a significant effect on the nucleation potential and metallurgical quality of the base and ductile iron. These parameters affect the final microstructure and mechanical properties of ductile iron castings.

Increasing percentage of pig iron and decreasing of percentage of steel scrap and ductile iron returns in the metallic charge lead to high nucleation potential, lower chill values in both base and ductile iron and higher nodule count and nodularity in treated and inoculated ductile iron. The reason for this effect is the steel and ductile iron return components of the charge contribute very little in the way of nuclei for the growth of graphite.

When the melt is prepared with suitable charge materials (such as pig iron), capable of producing a liquid iron of a composition which will solidify with a naturally graphitic freezing tendency, then the conditions are correct for promoting good and consistent nucleation potential and metallurgical quality. When the melt is prepared from charge materials (such as steel scrap and ductile irons returns) and processing additives which result in a liquid melt composition of reduced graphite formation tendency and/or preferred carbide forming characteristics then problems can be expected to arise, linked to a resulting poor nucleation potential and metallurgical quality.

The high nucleation potential results in a higher number of small, uniformly dispersed and sized nodules, which has the beneficial effect on the tensile properties of ductile iron. The ferrite content in the metallic matrix is the highest in ductile irons prepared with high percentage of pig iron in metallic charge, due to the high nodule count.

If the base iron does not possess enough nucleation potential, inoculation cannot enhance it sufficiently and lower nodule count and nodularity will result. Small amount of residual sulfur in the base iron (0.008–0.012 %) as well as a minimum oxygen concentration assist in achieving a good response to inoculation and thereby contribute to the elimination of carbides. If the charge material is further oxidized, the resulting iron will exhibit a higher chill value.

Preconditioning is a proven and reliable technique for controlling base iron nucleation potential. Preconditioning improves the nucleation potential of the base irons prepared with high percentage of steel scrap in metallic charge. But, preconditioning does not completely correct the negative effect of high percentage of steel scrap in metallic charge. The effect of preconditioning on the nucleation potential is not efficient as the effect of a high percentage of pig iron in metallic charge.

In order to produce a cast iron melt that has a good nucleation potential and that responds well to inoculation and exhibits the lowest potential for carbide formation during solidification, the percentage of ductile iron returns should be limited to no more than 45.0 % and the steel content should be limited to 40.0 % maximum. The composition of metallic charge is an important process parameter and must be adapted depending on the required microstructure and mechanical properties of ductile iron castings.

References

[1] VENUGOPALAN, D.: Metallurgical Transactions A, *21*, 1990, p. 913.

[2] GUO, X.—STEFANESCU, D. M.: In: Proceedings of the 101st Annual Meeting. Ed.: Dienst, H. W. Des Plaines, Illinois, American Foundrymen's Society 1997, p. 533.

[3] PAN, E. N.—HSU, W. S.—LOPER, C. R.: In: Proceedings of the 92nd Annual Meeting. Ed.: Dorfmueller, A. Des Plaines, Illinois, American Foundrymen's Society 1988, p. 645.

[4] VENUGOPALAN, D.: In: Proceedings of the 94th Annual Meeting. Ed.: Agin, J. Des Plaines, Illinois, American Foundrymen's Society 1990, p. 465.

[5] SKALAND, T.—GRONG, Ø.: In: Proceedings of the 95th Casting Annual Meeting. Ed.: Agin, J. Des Plaines, Illinois, American Foundrymen's Society 1991, p. 153.

[6] VENUGOPALAN, D.—ALAGARSAMY, A.: In: Proceedings of the 4th International Symposium on the Physical Metallurgy of Cast Iron. Eds.: Ohira, G., Kusakawa, T., Niyama, E. Tokyo, Materials Research Society 1989, p. 321.

[7] MRVAR, P.: Materials Science Forum, *508*, 2006, p. 287.

[8] DAVIS, R. J.: Cast Irons. Ohio, Materials Park, ASM International 1999.

[9] VOKÁL, V.—NILSSON, K. F.—MINNEBO, P.: Kovove Mater., *46*, 2008, p. 39.

[10] UNKIĆ, F.—GLAVAŠ, Z.—TERZIĆ, K.: Strojarstvo, *50*, 2008, p. 231.

[11] LOPER, C. R.: In: Proceedings of the 103rd Annual Meeting. Ed.: Moore, J. R. Des Plaines, Illinois, American Foundrymen's Society 1999, p. 523.

[12] SKALAND, T.—GRONG, Ø.—GRONG, T.: Metallurgical Transactions A, *24*, 1993, p. 2321. http://dx.doi.org/10.1007/BF02648605

[13] GAGNÉ, M.: The Sorelmetal Book of Ductile Iron. Montreal, Rio Tinto Iron & Titanium Inc. 2004.

[14] BENECKE, T.: The Foundryman, *87*, 1994, p. 355.

[15] COPI, K. W.—LERNER, Y. S.—LAUKHIN, N. S.: Modern Casting, *93*, 2003, p. 29.

[16] ZAVADIL, R.—POPESCU, M.—SAHOO, M.: Modern Casting, *98*, 2008, p. 33.

[17] GLAVAŠ, Z.—LISJAK, D.—UNKIĆ, F.: Kovove Mater., *45*, 2007, p. 41.