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MICROSTRUCTURE AND PROPERTIES OF SILICON ALLOYED COMPACTED GRAPHITE IRONS (CGI)

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The microstructure, tensile properties and hardness of 25 mm thick compacted graphite iron samples alloyed with 3,01, 3,22, 3,61, 3,97 and 4,29 wt. % Si were analyzed in this paper. It was found that Si promotes and strengthens ferrite. Metallic matrix of compacted graphite iron sample alloyed with 3,01 wt. % Si consisted of 98,1 % ferrite and 1,9 % pearlite. Fully ferritic metallic matrix was obtained in compacted graphite iron samples alloyed with 3,22, 3,61, 3,97 and 4,29 wt. % Si. Nodularity varied from 8 to 13 %. Yield strength increased from 246 to 447 N/mm^2, tensile strength increased from 318 to 496 N/mm^2, hardness increased from 160 to 227 HBW, and elongation decreased from 3,6 to 1,6 % with an increase in Si content from 3,01 to 4,29 wt. %. Analyzed Si alloyed compacted graphite iron samples have a very uniform hardness and higher ratio $R_{p0,2}/R_m$ than conventional ferritic, ferritic-pearlitic and pearlitic compacted graphite iron grades.

Key words: compacted graphite iron, silicon, microstructure, tensile properties, hardness

INTRODUCTION

The properties of compacted graphite iron (CGI), also known as vermicular graphite cast iron, primarily depend on its microstructure, i.e., graphite morphology and structure of the metallic matrix [1 - 4]. The graphite morphology in CGI depends on the chemical composition, cooling rate during solidification and the amount of added inoculant [3, 5, 6]. Structure of the metallic matrix of CGI depends on the chemical composition, graphite morphology and the cooling rate after solidification [1, 3, 4, 7].

It is well known that Si strengthens ferrite through substitutional solid solution strengthening mechanism [8 - 10]. Increasing Si content progressively increases the strength of ferrite. This effect of Si is very successfully used in ductile iron production [11 - 13].

Considering that the strengthening of ferrite by Si was successfully applied in ductile iron production, it is useful to explore how this effect influences the properties of CGI. Recently published paper shows that alloying with 3,66, 4,09 and 4,59 wt. % Si significantly changes the mechanical properties of CGI plates with thicknesses of 7, 15, 30, 50 and 75 mm compared to conventional pearlitic CGI [14]. There are a lot of possibilities for further research in this field through variations of Si content, microstructure features and thickness of castings. This paper investigates the effects of alloying with 3,01, 3,22, 3,61, 3,97 and 4,29 wt. % Si on the microstructure, tensile properties and hardness of CGI samples with a thickness of 25 mm.

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EXPERIMENTAL

The base melts were prepared in a medium-frequency coreless induction furnace. The charge consisted of steel scrap, ductile iron returns, special low-manganese pig iron, foundry grade FeSi75 and recarburizer. Ratio mass of steel scrap : mass of ductile iron returns : mass of special low-manganese pig iron was 0,4 : 0,6 : 1,0.

Mg-treatment was carried out by Cored wire process. The chemical composition of FeSiMg treatment alloy is shown in Table 1. Inoculation was carried out in the ladle. Inoculant was added in an amount of 0,2 wt. %. Its chemical composition is shown in Table 1. Five CGI melts was made with the following targeted Si contents: 3 wt. %, 3,3 wt. %, 3,6 wt. %, 4 wt. % and 4,3 wt. %.

Table 1 **The chemical composition of FeSiMg treatment alloy and inoculant / wt. %**

	Mg	Si	Al	Ca	Ce	La	Ba
FeSiMg treatment alloy	29	42	0,9	1,4	0,5	0,2	
Inoculant		75	1	1			1

CGI melts were poured into CO_2 molds in order to obtain 25 mm thick Y-shaped samples (type II in accordance with standard ISO 16112:2006). The tensile test pieces with a diameter of 14 mm were machined from Y-shaped samples. The tensile test was carried out in accordance with standard ISO 6892-1:2009.

After completion of the tensile test, samples for hardness test and metallographic examination were cut from the tensile test pieces. Brinell hardness test was carried out in accordance with standard ISO 6506-1:2005 (load was 7,35 kN, steel ball with a diameter of 5 mm). The mean value of the hardness of each CGI sample was calculated from ten individual measurements.

Light metallographic microscope with a digital camera and the image analysis system was used for determining the graphite nodularity and the ferrite and pearlite content in the metallic matrix. Nodularity was determined in accordance with Annex B in standard ISO 16112:2006. Graphite particles with a maximum axis length greater than 10 μm [15] were analyzed and classified based on their roundness-shape factor, as shown in the Table 2.

Table 2 **Classification of graphite particles based on their roundness-shape factor (Annex B in standard ISO 16112:2006) [15]**

Roundness-shape factor	Graphite form
< 0,525	Compacted (form III according to standard ISO 945)
0,525 to 0,625	Intermediate (form IV and form V according to standard ISO 945)
0,625 to 1	Nodular (form VI according to standard ISO 945)

The roundness-shape factor is defined by the following equation [15]:

$$\text{Roundness} = \frac{A}{A_m} = \frac{4 \cdot A}{\pi \cdot l_m^2} \quad (1)$$

where A is area of the analyzed graphite particle, A_m is area of circle of diameter l_m and l_m is maximum axis length of the analyzed graphite particle (maximum distance between two points on the graphite particle perimeter).

Nodularity was calculated using the following equation [15]:

$$\text{Nodularity} = \frac{\sum A_{\text{nodules}} + 0{,}5 \cdot \sum A_{\text{intermediates}}}{\sum A_{\text{all particles}}} \cdot 100,\ \% \quad (2)$$

where A_{nodules} is the area of particles classified as nodular graphite, $A_{\text{intermediates}}$ is the area of particles classified as intermediate forms of graphite and $A_{\text{all particle}}$ is the area of all particles with a maximum axis length greater than 10 μm.

RESULTS AND DISCUSSION

The chemical compositions of analyzed CGI samples are shown in Table 3. Table 4 and Figure 1 show the results of metallographic examinations. It can be seen that the ferrite content in the metallic matrix increased with increasing Si content because Si promotes the formation of ferrite. All analyzed CGI samples fulfill the requirement of standard ISO 16112:2006 in terms of nodularity.

Table 5 shows that the tensile strength and yield strength increased with an increase in Si content due to increase in the intensity of strengthening of ferrite. The ratio $R_{p0,2}/R_m$ of analyzed solid solution strengthened ferritic CGI samples varies from 0,774 to 0,901, and increases with the increase of Si content (Table 5). The value of this ratio is ~ 0,7 for the conventional ferritic, ferritic-pearlitic and pearlitic compacted graphite irons according to standard ISO 16112:2006 [15]. This indicates that the analyzed solid solution strengthened ferritic compacted graphite irons have higher yield strength than conventional compacted graphite irons at the same

Table 3 **Chemical compositions of analyzed CGI samples / wt. %**

	CGI 1	CGI 2	CGI 3	CGI 4	CGI 5
C	3,4	3,25	3,14	3,09	3,02
Si	3,01	3,22	3,61	3,97	4,29
Mg	0,01	0,012	0,011	0,011	0,012
S	0,011	0,013	0,012	0,011	0,009
P	0,028	0,026	0,027	0,025	0,024
Mn	0,11	0,11	0,1	0,11	0,09
Cu	0,018	0,019	0,018	0,019	0,019
Sn	0,004	0,006	0,006	0,006	0,006
Sb	0,0002	0,0002	0,0002	0,0002	0,0002
Ni	0,018	0,016	0,015	0,014	0,014
Cr	0,029	0,026	0,026	0,025	0,026
Mo	0,0005	0,0005	0,0005	0,0005	0,0005
V	0,004	0,004	0,005	0,004	0,004

Table 4 **Microstructural features of examined CGI samples**

	Si content / wt. %	Nodularity / %	Metallic matrix	
			Ferrite content / %	Pearlite content / %
CGI 1	3,01	8	98,1	1,9
CGI 2	3,22	10	100	0
CGI 3	3,61	11	100	0
CGI 4	3,97	10	100	0
CGI 5	4,29	13	100	0

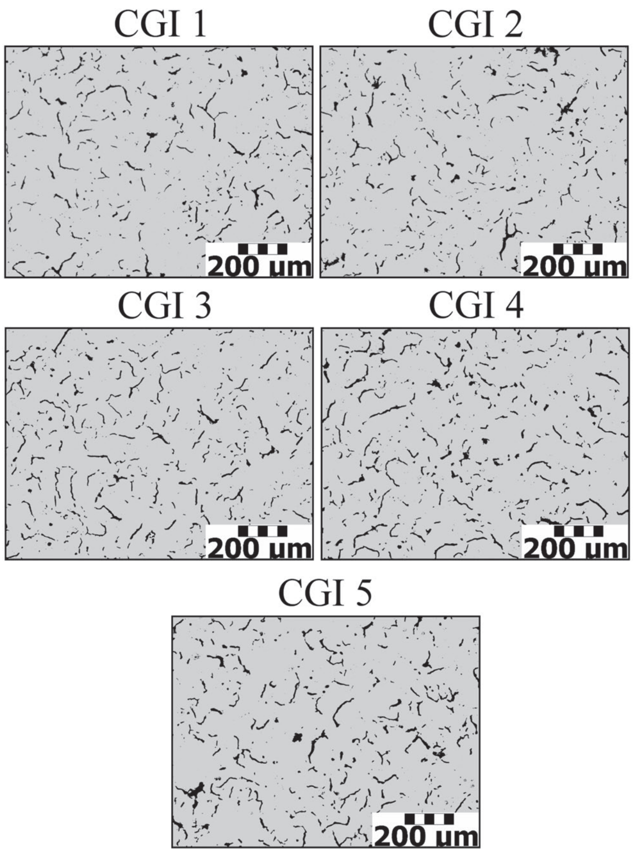

Figure 1 Graphite structure in examined CGI samples

Table 5 **Tensile properties and hardness of examined CGI samples**

	CGI 1	CGI 2	CGI 3	CGI 4	CGI 5
Si content / wt. %	3,01	3,22	3,61	3,97	4,29
$R_{p0.2}$ / N/mm^2	246	334	366	414	447
R_m / N/mm^2	318	379	412	462	496
$R_{p0.2}/R_m$	0,774	0,881	0,888	0,896	0,901
A / %	3,6	3	2,5	2	1,6
Brinell hardness	160	166	172	193	219

level of the tensile strength. It is obvious that strengthening of ferrite by Si has a greater effect on yield strength than the tensile strength of CGI.

The embrittlement of ferrite increases and ductility decreases with increasing intensity of strengthening. For this reason, the elongation decreased with the increasing Si content (Table 5). At the same level of the tensile strength, elongation of analyzed solid solution strengthened ferritic compacted graphite irons exceeds the minimum required elongation of conventional compacted graphite irons according to standard ISO 16112:2006 [15].

The hardness increased with increasing Si content due to increase in the intensity of strengthening of ferrite (Table 5). Brinell hardness of CGI 1 and CGI 2 are located in the typical Brinell hardness ranges for conventional compacted graphite irons that have similar tensile strength. Brinell hardness of CGI 3, CGI 4 and CGI 5 are slightly lower than the typical Brinell hardness ranges for conventional compacted graphite irons with a similar tensile strength.

CONCLUSIONS

Obtained results indicate that Si promotes and strengthens the ferrite in CGI. The intensity of strengthening of ferrite increases with increasing Si content. For this reason tensile strength, yield strength and hardness increase, and elongation decreases with increasing Si content. Strengthening of ferrite by Si showed the strongest effect on the yield strength. Because of this, solid solution strengthened ferritic compacted graphite irons have higher yield strength than conventional ferritic, ferritic-pearlitic and pearlitic compacted graphite irons at the same level of tensile strength. This allows the reduction of the wall thickness of the casting. The ratio $R_{p0,2}/R_m$ of analyzed solid solution strengthened ferritic compacted graphite irons increases with increasing Si content. Single-phase ferritic metallic matrix results in a uniform hardness, which has a beneficial effect on machinability of the castings.

Considering the achieved tensile properties, analyzed solid solution strengthened ferritic compacted graphite irons can replace several conventional ferritic, ferritic-pearlitic and pearlitic compacted graphite iron grades specified in standard ISO 16112:2006. Tensile properties of CGI 1 alloyed with 3,01 wt. % Si exceed the minimum required tensile properties for grade ISO 16112/JV/300/S. Tensile properties of CGI 2 alloyed with 3,22 wt. % are higher than the minimum required tensile properties for grade ISO 16112/JV/350/S. Tensile properties of CGI 3 alloyed with 3,61 wt. % Si exceed the minimum required tensile properties for grade ISO 16112/JV/400/S. Tensile properties of CGI 4 alloyed with 3,97 wt. % Si and tensile properties of CGI 5 alloyed with 4,29 wt. % Si are higher than the minimum required tensile properties for grade ISO 16112/JV/450/S.

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