THE PROPERTIES OF SILICON ALLOYED FERRITIC DUCTILE IRONS

In this paper the influence of silicon content of 3,1 to 5,4 wt. % on the tensile properties, hardness and impact energy of ferritic ductile iron was analysed. It was found that silicon strengthens the ferrite, resulting in an increase in yield strength and tensile strength with increasing silicon content up to 4,22 wt. %. Elongation and impact energy decreases and the hardness increases with increasing silicon content. Since ferritic ductile irons alloyed and strengthened by silicon have a higher $R_{p0,2}/R_m$ ratio and a higher elongation than conventional ferritic, ferritic/pearlitic and pearlitic ductile irons at the same level of tensile strength, we can expect an increased demand for these materials in applications where high resistance to impact load and low temperature impact properties are not required.

Key words: ductile iron, microstructure, tensile properties, impact energy, hardness

INTRODUCTION

The properties of ductile iron primarily depend on its microstructure [1, 2]. The microstructure of a conventional ductile iron in the as-cast condition is composed of graphite nodules which are surrounded by a ferritic and/or pearlitic metal matrix.

Proportion of ferrite and pearlite in the metal matrix significantly affects the mechanical properties of ductile iron. In general, ductile iron with ferritic metal matrix exhibits lower yield strength and tensile strength, but higher elongation and toughness. Pearlitic metal matrix has the opposite effect.

The chemical composition has a very big influence on the graphite morphology and metal matrix structure [1, 3 - 9]. Silicon is graphitizing element and promotes ferrite. Conventional ductile irons contain of 2 to 3 wt. % Si. Moreover, silicon is an effective element for strengthening of ferrite [1, 10, 11]. This effect progressively increases with increasing silicon content.

Silicon atoms replace iron atoms in the crystal lattice of iron and form a substitutional solid solution [12]. Due to difference in the size of the iron atoms and silicon atoms, crystal lattice is distorted. The movement of dislocations through such material is restricted, and plastic deformation does not occur [13, 14]. A higher level of stress is needed to allow dislocations to move again. It is obvious that the strength of ferrite increases with increasing silicon content. However, the brittleness increases at the same time, which means that there is an upper limit of silicon content.

The aim of this paper was to determine the influence of silicon content of 3,1 to 5,4 wt. % on the tensile prop-

erties, hardness and impact energy of ferritic ductile iron.

EXPERIMENTAL

Melting and preparation of the base irons for the production of silicon alloyed ferritic ductile iron melts were carried out in a medium frequency coreless induction furnace. Special low-manganese pig iron (50 %), ductile iron return (30 %) and steel scrap (20 %) were used to prepare the metallic charge. Targeted silicon contents in base irons were achieved by the addition of foundry grade FeSi. Preconditioning of the base irons was carried out by addition of commercial preconditioner (63 - 69 wt. % Si, 3 – 5 wt. % Al, 0,6 – 1,9 wt. % Ca, 3 - 5 wt. % Zr) in an amount of 0.1 wt. %.

The nodularization was carried out by Cored Wire process using FeSiMg treatment alloy (29 wt. % Mg, 42 wt. % Si, 0,9 wt. % Al, 1,4 wt. % Ca, 0,5 wt. % Ce, 0,2 wt. % La). Inoculation in the ladle was carried out by addition of commercial inoculant (67 – 72 wt. % Si, 1,9 wt. % Al, 1,5 wt.% Ca, 2,2 wt.% Ba) in an amount of 0,6 wt. %. Altogether, 6 ductile iron melts was made with the following targeted silicon contents: 3,1 wt. %, 3,5 wt. %, 3,8 wt. %, 4,2 wt. %, 4,7 wt. % and 5,4 wt. %.

Y-blocks (type II in accordance with EN 1563:2012) were cast in green sand moulds. Late inoculation (instream) was carried out by adding 0,15 wt. % of commercial inoculant (70 – 76 wt. % Si, 0,75 – 1,25 wt. % Al, 0,75 – 1,25 wt. % Ca, 1,5 - 2 wt. % Ce). The tensile test pieces of 14 mm in diameter were machined from Y-blocks. The dimensions and the shape of the test pieces are in accordance with EN 1563:2012. The tensile test was carried out in accordance with EN ISO 6892-1:2009. Un-notched impact test pieces were machined from Y-blocks and pre-

_____
A. Strkalj, Z. Glavas, A. Stojakovic, University of Zagreb, Faculty of Metallurgy, Sisak, Croatia

pared according to the dimensions specified in EN 1563:2012. The Charpy impact test was carried out at room temperature in accordance with EN ISO 148-1:2010 and EN 1563:2012 using testing machine with maximum energy of 150 J. After impact test, fracture surfaces of test pieces were observed under scanning electron microscope (SEM). Vickers's hardness was determined in accordance with EN ISO 6507-1 on the test pieces taken from the tensile test pieces after the tensile test. Test pieces for the metallographic examinations were taken from the tensile test pieces after the tensile test. Microstructure features (nodularity, nodule count (expressed as number of graphite nodules/mm^2), ferrite content and pearlite content) were determined using a light metallographic microscope with a digital camera and the image analysis system. Determination of nodularity and nodule count was carried out in accordance with ASTM E2567-14. Graphite particle was considered as a nodule if the value of its roundness-shape factor exceeds 0,725.

RESULTS AND DISCUSSION

The chemical compositions of ductile irons are given in Table 1. It can be observed from Table 1 that the targeted silicon contents were achieved. The high silicon contents and low contents of pearlite promoting elements (Cu, Sn, Mn) and carbide forming elements (Cr, V, Mo, Mn) allowed the formation of a fully ferritic metal matrix in the as-cast condition.

Table 2 and Figure 1 show that the silicon content significantly affects the microstructure of ductile irons. Increasing silicon content resulted in an increase of ferrite content in the metal matrix because silicon promotes ferrite. Fully ferritic metal matrix was obtained at the silicon contents from 3,8 wt. % to 5,42 wt. %. Duc-
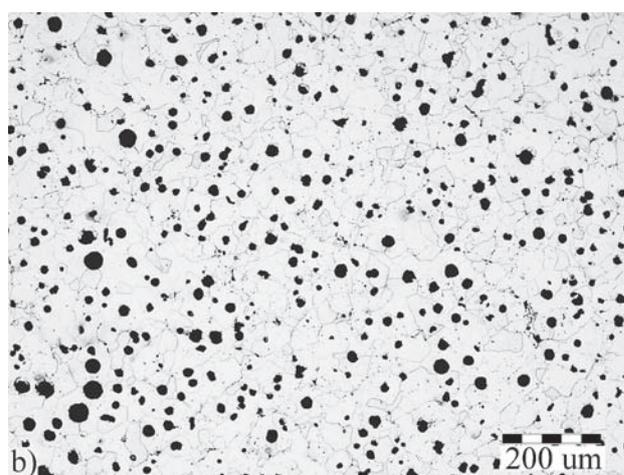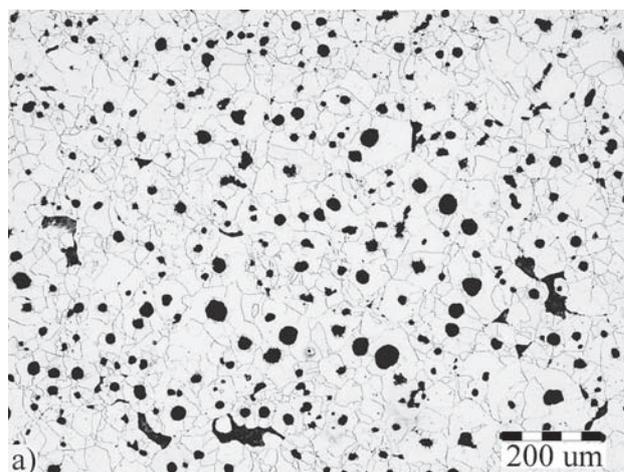
Figure 1 Optical micrographs of the microstructure of ductile iron No. 1 (a) and ductile iron No. 4 (b), etched

tile irons No. 1 and No. 2, which contain less than 3,8 wt. % Si, have negligible proportion of pearlite in the metal matrix (< 2 %).

Table 1 **Chemical composition of ductile irons / wt. %**

Element	Number of melt					
	1	2	3	4	5	6
C	3,35	3,21	3,19	3,04	2,95	2,86
Si	3,11	3,55	3,8	4,22	4,71	5,42
Mn	0,128	0,104	0,104	0,129	0,194	0,226
P	0,03	0,032	0,031	0,028	0,026	0,024
S	0,009	0,012	0,01	0,013	0,011	0,007
Mg	0,037	0,038	0,039	0,059	0,04	0,041
Cu	0,023	0,019	0,016	0,019	0,022	0,032
Sn	0,005	0,006	0,006	0,006	0,008	0,007
Cr	0,028	0,027	0,026	0,026	0,027	0,024
Mo	0,002	0,001	0,001	0,001	0,001	0,002
V	0,011	0,009	0,009	0,01	0,009	0,008

Table 2 **Microstructural features of ductile irons**

Ductile iron	Si content / wt. %	Nodularity / %	Nodule count	Ferrite content / %	Pearlite content / %
1	3,11	83,1	177	98,1	1,9
2	3,55	84,6	198	98,6	1,4
3	3,80	87,1	249	100	0
4	4,22	87,6	305	100	0
5	4,71	87,4	301	100	0
6	5,42	86,1	304	100	0

Table 3 **Tensile properties, hardness and un-notched impact energy of ductile irons**

Ductile iron	Si content / wt. %	$R_{p0,2}$ / N/mm²	R_m / N/mm²	$R_{p0,2}/R_m$	A / %	Hardness / HV20	Impact energy / J
1	3,11	356	487	0,73	18,5	206	106
2	3,55	410	509	0,81	17,4	212	81
3	3,80	468	551	0,85	17,0	226	63
4	4,22	553	637	0,87	10,5	251	45
5	4,71	538	592	0,91	3,3	282	19
6	5,42	531	531	1	-	322	10

Nodule count is high in all ductile irons and increases with increasing silicon content because it promotes graphite. Very important parameters for obtaining a high nodule count were the high metallurgical quality and high nucleation potential of melt, which come from the high content of pig iron, preconditioning and powerful inoculation in the ladle and in the metal stream during the casting in the moulds. The high nodule count is favourable for obtaining high nodularity and high ferrite content in the metal matrix. Acceptable nodularity (over 80 %) was achieved in all ductile irons.

Silicon content affects the tensile properties, hardness and impact energy of analysed ductile irons (Table 3).

Tensile strength and yield strength increased with increasing silicon content up to 4,22 wt. % due to increases in the intensity of strengthening of the ferrite by silicon. Thereafter, further increase in silicon content decreases the tensile strength and yield strength since high silicon content increases the embrittlement of ferrite. Data analysis shows that the ductile irons strengthened by silicon have a higher $R_{p0,2}/R_m$ ratio than conventional ferritic, ferritic/pearlitic and pearlitic ductile irons ($R_{p0,2}/R_m$ = 0,55 to 0,65). This indicates that the strengthening of the ferrite by silicon has a greater effect on the yield strength than the tensile strength.

Elongation decreases with increasing silicon content due to a decrease in ductility of the ferrite. However, the reduction in elongation with increasing yield strength and tensile strength by adding up to 4,22 wt. % Si is significantly smaller compared to conventional ferritic, ferritic/pearlitic and pearlitic ductile irons. Elongation not measurable at 5,42 wt. % Si, since the values of tensile strength and yield strength coincide due to the excessive embrittlement of ferrite.

The hardness continuously increases with increasing silicon content because of the increasing strengthening of ferrite.

Increasing silicon content significantly reduces the un-notched impact energy due to increase in embrittlement of ferrite. Analysis of the fracture surface of ductile iron No. 1 containing 3,11 wt. % Si by scanning electron microscope (SEM) showed a significant plastic deformation of ferrite before fracture (Figure 2a). This is a typical dimpled model of fracture which indicates the increased plasticity of ferrite and its ability to absorb impact energy. SEM micrograph of fracture surface of ductile iron No. 2 containing 4,22 wt. % Si shows a

SEM HV: 20 kV
SEM MAG: 1.00 kx
100 um
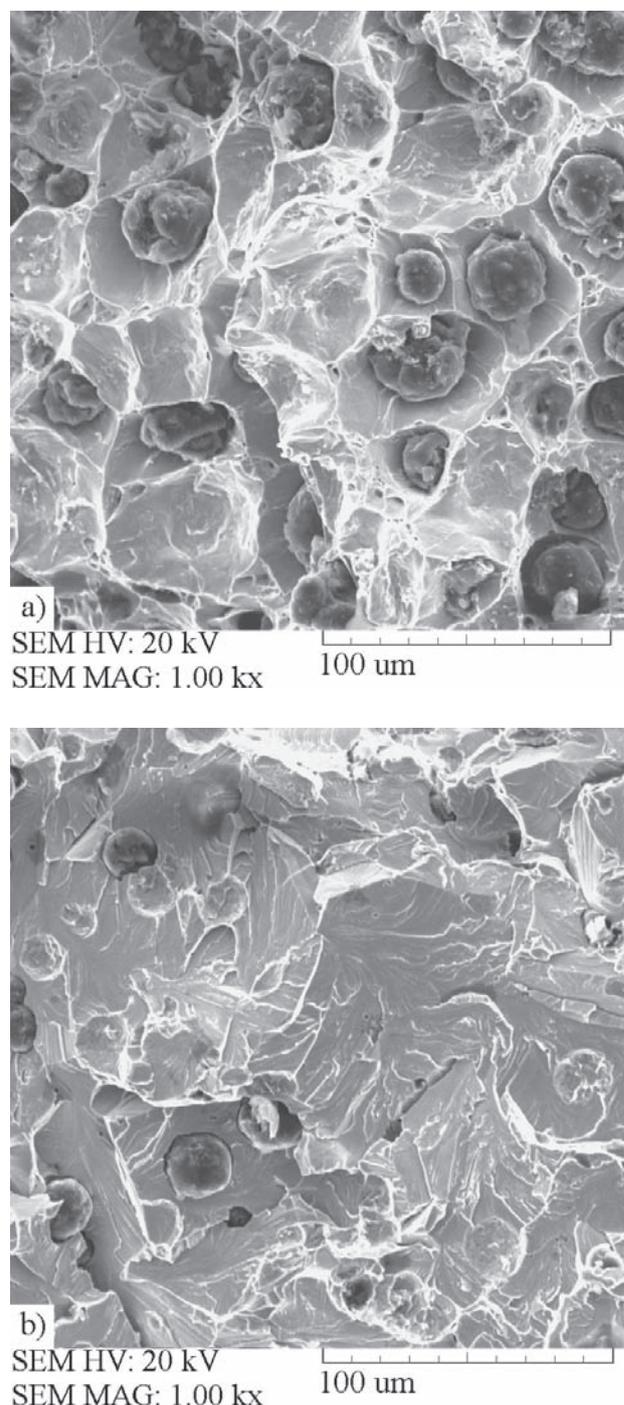
Figure 2 Fracture surfaces of ductile iron No. 1 and ductile iron No. 4

typical example of brittle fracture due to low plasticity and high embrittlement of ferrite strengthened by silicon (Figure 2b).

CONCLUSIONS

Obtained results show that silicon strengthens ferrite. Tensile strength and yield strength of ductile iron increase with increasing silicon content up to 4,22 wt. %, and then decrease with the further increase of the silicon due to a significant increase in embrittlement. Elongation and impact energy continuously decrease with an increase in silicon content from 3,11 to 5,42 wt. % due to decrease in plasticity and increase in embrittlement of ferrite. However, ferritic ductile irons strengthened by silicon have a higher $R_{p0,2}/R_m$ ratio and a higher elongation than conventional ferritic, ferritic/pearlitic and pearlitic ductile irons at the same level of tensile strength, which are very important properties. Higher yield strength enables reducing the wall thickness of the casting. Increase in silicon content results in a continuous increase in hardness due to the increasing intensity of strengthening of ferrite by silicon.

It is obvious that ferritic ductile irons strengthened by silicon exhibit very small hardness variation due to their single-phase metal matrix. This uniform hardness results in improved machinability.

Analysed silicon alloyed ductile irons belong to the group of solid solution strengthened ferritic ductile irons in accordance with EN 1563:2012, which are the new materials in ductile iron family. Ferritic ductile iron containing 3,11 wt. % Si can replace conventional ductile iron grades EN-GJS-400-15 and EN-GJS-450-10 because it has a better tensile properties. It fulfills the requirements of the new grade EN-GJS-450-18. Ferritic ductile irons containing 3,55 and 3,8 wt. % Si, in addition to the aforementioned grades, can replace conventional ductile iron grade EN-GJS-500-7 and fulfill the requirements of the new grade EN-GJS-500-14.

Ferritic ductile iron containing 4,22 wt. % Si has significantly better tensile properties than conventional ductile iron grade EN-GJS-600-3 and fulfills the requirements of the new grade EN-GJS-600-10.

Ferritic ductile irons strengthened by silicon have a unique combination of properties, i.e. high tensile strength, high yield strength, high elongation, uniform hardness and good machinability. Therefore, we can expect an increase in demand of these materials for applications where impact load and low temperature impact properties are not involved.

REFERENCES

[1]   M. Gagné, The Sorelmetal Book of Ductile Iron, Rio Tinto Iron & Titanium, Montreal, 2004. pp. 3-38
[2]   R. A. Gonzaga, P. Martínez Landa, A. Perez, P. Villanueva, Journal of Achievements in Materials and Manufacturing Engineering 33 (2009) 2, 150-158.
[3]   J. Sertucha, J. Lacaze, J. Serrallach, R. Suarez, F. Osuna, Materials Science and Technology 28 (2012) 2, 184-191.
[4]   A. M. Omran, G. T. Abdel-Jaber, M. M. Ali, International Journal of Engineering Research and Applications 4 (2014) 6, 90-96.
[5]   J. Zhou, China Foundry 7 (2010) 1, 76-88.
[6]   J. Zhou, China Foundry 7 (2010) 2, 183-198.
[7]   J. Zhou, China Foundry 7 (2010) 3, 292-307.
[8]   J. Zhou, China Foundry 7 (2010) 4, 470-478.
[9]   K. Röhring, Ljevarstvo 31 (1984) 2, 25-41.
[10] R. Larker, China Foundry 6 (2009) 4, 343-351.
[11] W. Stets, H. Löblich, G. Gassner, P. Schumacher, International Journal of Metalcasting 8 (2014) 2, 35-40.
[12] A. K. Sinha, Physical Metallurgy Handbook, Chapter One, Iron-Carbon Alloys, McGraw-Hill, New York, 2003., pp. 1.14-1.17
[13] W. D. Callister, Jr., Fundamentals of Materials Science and Engineering, John Wiley & Sons, New York, 2001., pp. 206-210.
[14] R. Abbaschian, L. Abbaschian, R. E. Reed-Hill, Physical Metallurgy Principles, CENGAGE Learning, Stamford, 2009., pp. 267-271.