Austenitic ductile iron for low temperature applications

A. Tabor a,*, P. Putyra b, K. Zarębski c, T. Maguda d

a Training and Organisation Centre of Quality System s, Cracow University of Technology, al. Jana Pawła II nr 37, 31-864 Kraków, Poland, Chair of Materials Technology, Cracow University of Technology, al. Jana Pawła II nr 37, 31-864 Kraków, Poland

b Department of Materials Engineering, Institute of Advanced Manufacturing Technologies, ul. Wrocławska 37a, 30-011 Kraków, Poland
c Institute of Materials Engineering, Cracow University of Technology, al. Jana Pawła II nr 37, 31-864 Cracow, Poland

d General Electric Company Poland, ul. Hanasiewicza 19, 35-103 Rzeszów, Poland

* Contact for correspondence: e-mail: atabor@mech.pk.edu.pl

Received 26.02.2009; accepted in revised form: 30.03.2009

Abstract
The study presents the results of mechanical tests carried out on austenitic ductile iron with varied nickel content and additions of chromium and vanadium. The tests and investigations were carried out over a wide range of temperatures, i.e. from -196°C to +20°C, and included determination of the yield strength, tensile strength, reduction of area and elongation. Additionally, the microstructure of different cast iron types was examined, along with the factographic examinations of specimens subjected to the tensile test. In final part of the study, the obtained results were discussed and relevant conclusions were drawn.

Keywords: mechanical properties, ductile iron, austenite

1. Introduction
The correct choice of cast iron grade for low temperature applications has recently gained importance due to rapid development of cryotechnique. Stringent requirements concerning mechanical properties at low temperatures are satisfied, first and foremost, by the high-nickel cast iron of austenite matrix, containing nodular graphite and included in the family of Ni-Resist cast irons. Owing to its high castability, this cast iron is used, among others, for valves, pipe fittings, pumps, compressors and expanders. It is also the material of choice for intricate parts of equipment operating under loads and in contact with liquid oxygen or nitrogen. The main aim of adding nickel to the cast iron for low temperature applications is to retain austenite in the cast iron matrix. To make the austenitic matrix stable at low temperatures requires raising the nickel content in cast iron to a level of 30-35%. When this content is lower, the structure of the cast iron runs the risk of having some detrimental precipitates of martensite [1,2,3,4].

Austenitic ductile iron is the material indispensable in all those cases when the elements of structures operating at low temperatures are characterised by intricate shapes and would otherwise require the difficult and time-consuming machining. In low-temperature technology, cast iron can be a full-value structural material, often irreplaceable even by steel [5].

The wide range of applications, the high-nickel austenitic cast iron owes to its specific chemical and physical properties. It is also characterised by good resistance to gas-induced and chemical corrosion, combined with satisfactory resistance to the effect of both high and low temperatures. The nodular shape of graphite improves the resistance in corrosive media, allowing also
the austenitic cast iron to preserve its high mechanical properties over a wide range of temperatures [6,7,8]. Its high corrosion resistance, the austenitic ductile cast iron owes not only to the beneficial shape of graphite but also to the reduced content of non-metallic inclusions present during nodularising treatment, and hence to less possibilities of the formation of microcells that increase the risk of casting failure [6]. The high-nickel, acid-resistant, austenitic cast iron can also find numerous applications in all those cases when the material should offer a high heat resistance. The chromium-free cast iron is characterised by sufficiently good corrosion resistance in oxidising gaseous media at temperatures of up to 700°C, and as such is used for parts of chemical apparatus [1].

The aim of the present investigations was to determine the effect of nickel content in austenitic ductile iron on the mechanical and plastic properties obtained over a wide range of temperatures. The scope of the investigations included the determination of tensile strength (Rm), yield strength (Rp0.2), elongation (As), and reduction of area (Z) in the range from (-196°C) to (+20°C).

2. Methods of investigations

Studies were made on austenitic ductile iron with nickel content from 17% to 25%. The carbon content in individual melts was comprised in a range from 2.40% to 3.00%, the content of silicon from 2.30% to 2.90%, and of manganese from 3.70% to 4.15%. In all melts, the sulphur content never exceeded the level of 0.020%, while that of magnesium was comprised in a range from 0.05% to 0.13%. Additionally, the melts of the highest nickel content also contained some carbide-forming elements, like chromium or vanadium. Table 1 gives chemical composition of the examined materials.

The cast iron nodularising treatment was carried out with an FeNiMg1 master alloy; for inoculation the Si75A ferrosilicon, added in an amount of 0.5-0.7% in respect of the molten cast iron weight, was used. The test pieces of YII type were cast in bentonite-bonded sand moulds according to PN-EN 1563:2000. The cast iron was melted in a medium-frequency, induction furnace with crucible of 60 kg capacity. The melt temperature was 1490°C. The nodularising treatment was carried out in a foundry ladle at a temperature of 1430°C. Moulds for the test pieces were poured when the melt temperature was 1390°C.

The mechanical properties were determined from the results of static tensile test. The test was carried out on an INSTRON 1273 machine of 100kN maximum load, using five-fold specimens of d0=5mm diameter with the threaded grips. Specimens were prepared according to EN-1563:2000. Trials were carried out at the following temperatures: (+20°C), (-20°C), (-40°C), (-60°C) and (-196°C), testing three specimens for each temperature level. The measuring range of the machine was 10, 20 and 25kN. The tensile tests at the temperatures of (+20°C), (-20°C) and (-40°C) were carried out in a climatic chamber of the INSTRON 3110 machine, using dry ice. The test temperature (-196°C) was obtained using liquid nitrogen. The static tensile test was carried out according to EN-10002-5:1991 and EN-10002-1:2001.

Table 1.
Chemical composition of the examined materials

<table>
<thead>
<tr>
<th>Melt</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Mg</th>
<th>Ni</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.80</td>
<td>2.30</td>
<td>3.70</td>
<td>0.035</td>
<td>0.02</td>
<td>0.13</td>
<td>17</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2.80</td>
<td>2.90</td>
<td>4.10</td>
<td>0.035</td>
<td>0.02</td>
<td>0.13</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>2.40</td>
<td>2.25</td>
<td>3.75</td>
<td>0.035</td>
<td>0.02</td>
<td>0.12</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>2.90</td>
<td>2.60</td>
<td>4.10</td>
<td>0.04</td>
<td>0.015</td>
<td>0.06</td>
<td>24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>3.00</td>
<td>2.30</td>
<td>4.10</td>
<td>0.04</td>
<td>0.010</td>
<td>0.05</td>
<td>24</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>2.90</td>
<td>2.70</td>
<td>4.15</td>
<td>0.03</td>
<td>0.016</td>
<td>0.06</td>
<td>25</td>
<td>1.15</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>2.50</td>
<td>2.70</td>
<td>4.00</td>
<td>0.04</td>
<td>0.018</td>
<td>0.08</td>
<td>25</td>
<td>-</td>
<td>0.60</td>
</tr>
</tbody>
</table>

3. Results and discussion

The results of the static tensile test were represented in a graphic form. Figure 1 shows the effect of temperature on the tensile strength (Rm) of the examined materials. Figure 2 shows the yield strength values obtained in the examined types of cast iron, plotted in function of temperature. The plastic properties, i.e. the elongation (As) and reduction of area (Z), are shown in Figures 3 and 4, respectively.

Microstructural examinations and observations of cast iron fractures were carried out under a JSM 6460LV scanning electron microscope made by JEOL, equipped with EDS spectrometer. The examined materials were characterised by a mildly heterogeneous distribution of graphite in matrix, with prevalence of the nodular forms of the precipitates. The matrix was formed of austenitic; no precipitates of martensite were observed even in material of the lowest nickel content (17%). The structure typical of austenitic ductile iron is shown in Figure 5 (melt 2).
The analysis of microstructure present in each cast iron type has revealed the degenerated forms of graphite, defined as spiky (Fig. 6). As mentioned in [9], this name refers to one of the several different types of the degenerated graphite present in cast iron; the degree to which the graphite is degenerated is determined from appropriate reference standards (vermicular, spiky, coral, exploded).

In general terminology, the heavily degenerated form of graphite precipitates, deviating much from the expected nodular form, is called chunky graphite. The precipitates of chunky graphite start growing as regular spheroids to undergo later a deformation and form the most scattered type of precipitates. This form of graphite has a detrimental effect on both mechanical and plastic properties of cast iron, as proved in [10,11,12].

The structure of cast iron with the precipitates of degenerated graphite may occur in heavy-walled castings, also as a result of the use of inoculants containing Ce, Ca or Al [4,11,13]. On one hand, the use of aluminium-containing inoculants reduces the size of graphite spheroids and increases their number, while – on the other – as disclosed in [9], it favours the precipitation of the degenerated (chunky) graphite.
Additionally, the analysis of cast iron microstructure revealed the presence of complex intermetallic phases. The precipitated phases of rather irregular shape were distributed mainly along the austenite grain boundaries. A characteristic feature of the examined materials was the presence of the precipitates of intermetallic phases forming a network of rings with graphite located inside the rings. The results discussed in [14] have proved that with the sulphur content kept at a level of 0.02%, the interior part of the graphite precipitates might contain magnesium sulphide. The chemical composition and the shape of these phases depended not only on the type of the applied inoculant, but also on the content of sulphur in cast iron. The analysis of microstructure carried out by the backscattered electron analysis revealed the presence of some phases inside the graphite precipitates, but because of the very small size, the results of the chemical analysis made on an EDS spectrometer were burdened with an error definitely too large.

Examined at large magnifications of 1000x and more, the precipitates of intermetallic phases have proved to be of highly non-homogeneous character. In the central part of the precipitates, defined as "complex intermetallic phases", the microregions rich in nickel, manganese and magnesium were prevailing, accompanied by the regions where the main element was aluminium. Between the central part and austenite grains, the regions of lower magnesium content and higher, compared to the central part, iron content occurred (Fig. 7). The intermetallic phases were also present as envelopes around the graphite precipitates, while the detected precipitates rich in aluminium were rather located at the graphite-austenite phase boundary.

The complex character of the examined phases was confirmed by analysis of the distribution of elements and by the chemical analysis in microregions (Fig. 8, Table 2). Yet, the applied method did not enable a consistent determination of the type of the detected intermetallic phases. The precipitates of phases rich in alloying elements were characterised by relatively high brittleness, promoting the propagation of brittle fractures. Cracks on the whole length of the precipitated phases were typical of the examined materials.

The microstructural analysis of the examined materials carried out at lower magnifications has proved that the regions most adjacent to graphite nodules were free from the precipitates of intermetallic phases.
examination of fractures at lower magnifications has revealed that the regions directly adjacent to graphite nodules included only the fractures of ductile character. It is supposed that the formation of brittle intercrystalline fractures was preceded by the formation of transcrystalline fractures of an intermetallic phase precipitating in a rather irregular mode along the austenite grain boundaries and forming a network there.

Table 2.
Chemical analysis in microregions designated as in Fig. 8 (the cast iron with 17%Ni – melt 1)

<table>
<thead>
<tr>
<th>Elt.</th>
<th>Conc wt.%</th>
<th>Error 2-sig</th>
<th>Conc wt.%</th>
<th>Error 2-sig</th>
<th>Conc wt.%</th>
<th>Error 2-sig</th>
<th>Conc wt.%</th>
<th>Error 2-sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>15,84</td>
<td>0.76</td>
<td>11,30</td>
<td>0.75</td>
<td>17,80</td>
<td>0.77</td>
<td>6,54</td>
<td>0.49</td>
</tr>
<tr>
<td>O</td>
<td>0.80</td>
<td>0.10</td>
<td>0.13</td>
<td>0.04</td>
<td>2.55</td>
<td>0.19</td>
<td>5.86</td>
<td>0.26</td>
</tr>
<tr>
<td>Mg</td>
<td>8.67</td>
<td>0.23</td>
<td>16.50</td>
<td>0.29</td>
<td>0.24</td>
<td>0.03</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>Al</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.007</td>
<td>0.06</td>
<td>0.01</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>Si</td>
<td>0.12</td>
<td>0.02</td>
<td>6.81</td>
<td>0.16</td>
<td>1.05</td>
<td>0.06</td>
<td>2.98</td>
<td>0.11</td>
</tr>
<tr>
<td>P</td>
<td>0.08</td>
<td>0.01</td>
<td>4.28</td>
<td>0.13</td>
<td>0.18</td>
<td>0.02</td>
<td>0.22</td>
<td>0.03</td>
</tr>
<tr>
<td>S</td>
<td>0.09</td>
<td>0.01</td>
<td>0.02</td>
<td>0.008</td>
<td>0.08</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Cr</td>
<td>0.15</td>
<td>0.03</td>
<td>0.11</td>
<td>0.02</td>
<td>0.23</td>
<td>0.03</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>Mn</td>
<td>10.27</td>
<td>0.30</td>
<td>4.70</td>
<td>0.19</td>
<td>8.94</td>
<td>0.29</td>
<td>6.66</td>
<td>0.24</td>
</tr>
<tr>
<td>Fe</td>
<td>43.55</td>
<td>0.69</td>
<td>5.62</td>
<td>0.22</td>
<td>62.63</td>
<td>0.85</td>
<td>61.57</td>
<td>0.82</td>
</tr>
<tr>
<td>Ni</td>
<td>19.98</td>
<td>0.60</td>
<td>49.85</td>
<td>0.91</td>
<td>5.79</td>
<td>0.33</td>
<td>15.21</td>
<td>0.52</td>
</tr>
<tr>
<td>Cu</td>
<td>0.40</td>
<td>0.09</td>
<td>0.66</td>
<td>0.12</td>
<td>0.40</td>
<td>0.10</td>
<td>0.60</td>
<td>0.12</td>
</tr>
</tbody>
</table>

From the conducted investigations it follows that the highest mechanical properties offered the specimens from melts 2 and 3, and within the temperature range from -60°C to -196°C, the specimens from melt 7 containing nickel in amounts of 20%, 23% and 25%. The highest value of the yield strength at a temperature of -196°C was reported for melt 1 with the nickel content kept at a level of 17%. At the remaining temperatures, the yield strength equally high as that of the cast iron from melt 1 was obtained only in the cast iron from melt 7, containing 25% nickel. As regards plastic properties, in the range from -60°C to -196°C, the highest values of the tension set and reduction of area were detected in the cast iron from melt 3 containing nickel in an amount of 23%.

At a temperature of -196°C, the materials with the highest nickel content (i.e. 24% and 25%), as well as those containing an addition of chromium were characterised by the lowest elongation and reduction of area, i.e. never exceeding 10% in either of the cases. Under the same temperature regime, the cast iron with similar nickel content but without the addition of chromium was characterised by the reduction of area and uniform elongation twice as high.

The results presented in this study confirm once again that austenitic ductile iron can be used for castings operating at low temperatures.

4. Summary

With increasing nickel content, the cast iron reveals a strong tendency to the formation of austenitic matrix, while the boundary nickel concentration value, necessary to make this matrix stable, depends on the casting wall thickness and on the content of other alloying elements, like Cu, Cr, Mn, Si. Because of the increasing carbon activity in molten cast iron and further extension of the range of eutectic temperature, nickel promotes graphitisation during solidification. Yet, the beneficial effect regarding the elimination of hard spots in iron castings decreases with the increasing nickel content in cast iron, and this is the reason why high-nickel austenitic cast irons should contain a predetermined amount of silicon. This enables obtaining in castings the structure free from any hard spots (the precipitates of cementite eutectic). Introduced to high-nickel cast iron, manganese causes the decay of martensite precipitates in the cast iron matrix and greatly improves the impact resistance at low temperatures.

As follows from the conducted investigations, to produce high quality austenitic ductile iron, the chemical composition of this cast iron before the nodularising treatment should be comprised in the following range of values: 3.0-3.5%C; 1.8-2.0%Si; 3.5-4.0%Mn; 0.04%P; 0.02%S; 20-24%Ni. To obtain in the cast iron the above mentioned chemical composition and minimum content of other elements, the metallic charge should preferably be composed of the LS pig iron, soft steel scrap, process scrap of austenitic ductile iron, pure ferroalloys of FeSi, FeMn, electrobriqettes, etc. Before the nodularising treatment, the cast iron should be preheated to a temperature of about 1480°C. Considering the beneficial effect of nickel on the cast iron structure formation, it is recommended to use for the nodularising treatment a magnesium-nickel master alloy (17%Mg) in the amount of 1.8-2.0% respective of the metal.
weight. Due to this, it should be possible to obtain in cast iron the content of magnesium in a range from 0.03-0.05%. The best inoculant ensuring the formation of graphite nodules of the proper shape and in proper number as well as the required type of the metallic matrix has proved to be the technically pure ferrosilicon FeSi75T. An important effect on the formation of proper cast iron structure has the cast iron pouring temperature. It should be kept in the range of 1380-1400°C. Observing the above described process conditions during manufacture of castings from the ductile iron of an austenitic matrix should ensure the fabrication of products characterised by optimum mechanical properties.

References