Rare earth metals influence on morphology of non-metallic inclusions and mechanism of GP240GH and G17CrMo5-5 cast steel cracking

M. Gajewski*, J. Kasińska
Department of Metal Science and Materials Technology, Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25 – 314 Kielce, Poland
*Corresponding author. E-mail address: gajem@tu.kielce.pl

Received 02.07.2009; accepted in revised form 14.07.2009

Abstract

This paper presents results of research carried out in order to specify the influence of the rare earth metals on the morphology of the occurring non-metallic inclusions as well as on the cracking mechanism of GP240GH cast carbon steel and G17CrMo5-5 (0.18%C, 1.2%Cr, 0.53%Mo) high temperature cast steel. The tests have been performed on successive industrial melts adding rare earth metals to the ladle during tapping of heat melt from the furnace. It was found that ball-shaped non-metallic inclusions occurring as a result of the rare earth metals influence are heterogenic and they significantly influence the cracking mechanism of Charpy specimens and the impact strength. The morphology of the specimens fracture surface has been substantially changed as a result of the rare earth metals modification.

The impact strength of the tested cast carbon steel increased from 100 J/cm² to ca 155 J/cm², and the high-temperature cast steel from 30 J/cm² to ca 100 J/cm².

Keywords: Cast steel, Rare earth metals, Modification, Non-metallic inclusions, Fractography

1. Introduction

The disadvantageous influence of non-metallic inclusions on ferrous alloys properties makes the morphology occurrence be vitally important [1-5].

Authors of this paper have carried out research aiming to define was to define the rare earth metals influence on the change of the non-metallic inclusions morphology as well as on the mechanism of cracking of GP240GH cast carbon steel and G17CrMo5-5 high temperature cast steel in industrial conditions. It was noticed than putting REM (Ce, La, Nd, Pr and others) into the ladle during tapping of heat melt out of the furnace causes the changes of the mechanical features of cast steels and first of all it causes impact strength improvement. The impact strength tests were carried out on Charpy-V specimens taken from successive industrial melts made in electrical inductive furnace of 2000 kg capacity and the basic lining crucible. There was used heat treatment for GP240GH cast steel – normalizing (940 °C/1h/air), and for G17CrMo5-5 – normalizing (940 °C/1h/air) and tempering (710 °C/2h/air). After heat treatment the GP240GH cast steel had the ferritic-perlitic microstructure, and the G17CrMo5-5 had the sorbite microstructure (Fig. 1).
For the GP240GH cast steel the significant impact strength increase from 100.5 J/cm$^2$ to 150.5 J/cm$^2$ was noticed just after adding 0.8 kg REM/tone of liquid metal and for G17CrMo5-5 cast steel from 30 J/cm$^2$ to 99 J/cm$^2$ after adding 1.02 kg of REM/tone of liquid metal (Table 2). These changes were accompanied by changes of the morphology of Charpy specimens fracture surfaces and non-metallic inclusions.

![Fig. 1. Microstructure of GP240GH (a) and G17CrMo5-5 cast steel castings after heat treatment. Eaching 4% HNO$_3$ in C$_2$H$_5$OH. SEM](image)

Table 1.
Chemical composition of cast steels from successive industrial melts modified by REM

<table>
<thead>
<tr>
<th>The amount of REM addition kg/tone of liquid metal</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Al</th>
<th>O$_2$ ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without REM</td>
<td>0.21</td>
<td>0.40</td>
<td>0.71</td>
<td>0.020</td>
<td>0.015</td>
<td>0.20</td>
<td>0.035</td>
<td>0.088</td>
<td>0.049</td>
<td>64</td>
</tr>
<tr>
<td>0.27</td>
<td>0.20</td>
<td>0.39</td>
<td>0.63</td>
<td>0.018</td>
<td>0.012</td>
<td>0.14</td>
<td>0.037</td>
<td>0.054</td>
<td>0.076</td>
<td>—</td>
</tr>
<tr>
<td>0.80</td>
<td>0.21</td>
<td>0.39</td>
<td>0.64</td>
<td>0.015</td>
<td>0.010</td>
<td>0.13</td>
<td>0.043</td>
<td>0.084</td>
<td>0.055</td>
<td>—</td>
</tr>
<tr>
<td>1.25</td>
<td>0.21</td>
<td>0.43</td>
<td>0.69</td>
<td>0.022</td>
<td>0.013</td>
<td>0.20</td>
<td>0.034</td>
<td>0.077</td>
<td>0.037</td>
<td>—</td>
</tr>
<tr>
<td>1.48</td>
<td>0.20</td>
<td>0.41</td>
<td>0.75</td>
<td>0.023</td>
<td>0.013</td>
<td>0.18</td>
<td>0.040</td>
<td>0.076</td>
<td>0.037</td>
<td>65</td>
</tr>
<tr>
<td>G17CrMo5-5 alloy cast steel</td>
<td>0.18</td>
<td>0.40</td>
<td>0.90</td>
<td>0.022</td>
<td>0.015</td>
<td>1.20</td>
<td>0.53</td>
<td>0.070</td>
<td>0.041</td>
<td>63</td>
</tr>
<tr>
<td>1.02</td>
<td>0.16</td>
<td>0.37</td>
<td>0.62</td>
<td>0.022</td>
<td>0.013</td>
<td>1.22</td>
<td>0.53</td>
<td>0.120</td>
<td>0.050</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 2.
REM addition influence on impact strength of GP240GH and G17CrMo5-5 cast steels

<table>
<thead>
<tr>
<th>Amount of REM addition kg/tone of liquid metal</th>
<th>impact strength KV J/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without REM addition</td>
<td>100.5</td>
</tr>
<tr>
<td>0.27</td>
<td>112.0</td>
</tr>
<tr>
<td>0.80</td>
<td>150.5</td>
</tr>
<tr>
<td>1.25</td>
<td>153.5</td>
</tr>
<tr>
<td>1.48</td>
<td>158.6</td>
</tr>
<tr>
<td>G17CrMo5-5 alloy cast steel</td>
<td>30.0</td>
</tr>
<tr>
<td>1.02</td>
<td>99.0</td>
</tr>
</tbody>
</table>

2. Fractography tests of Charpy specimens fracture surfaces

GP240GH cast carbon steel

There occur two areas of cracking in the specimens fracture surfaces i.e. the area of ductile fracture and the area of cleavage fracture.

In non-modified cast iron specimens each area covered ca 50% of the fracture surface. After the modification by means of REM the ductile fracture area was increasing and in the area of cleavage fracture locally occurred the areas of ductile fracture. At the same time, the impact strength was increasing (Table 2), as well as the “b” crosswise shortening of specimens measured at the bottom of the notch (Fig. 2) from 2.0% for non-modified cast steel to 9.85% for cast steel modified by REM in the amount of 1.48 kg/tone of liquid metal.
In the areas of ductile cracking the cracking initiation was forced by the occurrence of microvoids at the boundaries of non-metallic inclusions and the metallic matrix in the process of specimens breaking. The shape and size of non-metallic inclusions were responsible for the dimples occurring around them. In the non-modified cast steel the size and shape of the occurring dimples depended on non-metallic inclusions shaped irregularly and unevenly arranged, which made the surrounding dimples big and irregular (Fig. 3a,b). In the ductile fracture areas cracks were initiated mainly at the grain boundary (Fig. 4a). The occurrence of brittle fracture was due to the movement of the cracking front reaching the non-metallic inclusions (Fig. 4b).

These inclusions cause momentary retain of cracking inside the grains and they are also the reason of new series of steps called ‘river patterns’ [6,7] (Fig.4d,e). Around the inclusions small plastic strain was noticed. The significantly bigger number of microcracks (dimples) at the ductile fracture area and changes of the cracking directions as well as the steps at the cleavage fracture area of the modified cast steel specimens cause more energy consumption in the process of cracking and at the same time – the increase of fracture toughness. Putting REM into the liquid metal caused the significant change of the shape and size of non-metallic inclusions. They mostly assumed the spherical shape, had significantly bigger and more differentiated dispersion in comparison with non-modified cast steel and also they were more evenly arranged in the metallic
matrix. It made the amount of occurring dimples in the metallic matrix be significantly bigger as well. Their sizes were smaller and shapes more regular (Fig. 3c,d). In the areas of cleavage fractures the fracture surfaces were much bigger (Fig. 4c) due to a bigger amount of changes of cracking directions and steps at cleavage surfaces in comparison with non-modified cast steel (Fig. 4a). The increase of the amount of cracking direction changes appearing due to different crystallographic orientation of the grain proves the smaller sizes. The increase of the amount of steps inside the grains is caused by the spherical inclusions occurrence.

![Fig. 4 Morphology of fracture surfaces of GP240GH cast steel charpy specimens at the cleavage fracture areas; a,b – no-modified; c,d,e modified by REM. SEM](image)

**G17CrMo5-5 high temperature cast steel**

At non-modified cast steel fracture surface of the charpy specimens (Fig. 5a) the area of ductile fracture is limited to a narrow (ca 0.1 – 0.2mm) strip directly under the bottom of the noth of the specimens. The shape and size of non-metallic inclusions as well as numerous evolvings of a large dispersion carbides have a great influence on the mechanism of cracking in this area. At the other part of the fracture surface there occur
cleavage fracture with ductile fracture marks mainly at the grain boundaries (Fig. 6a). Irregularly shaped non-metallic inclusions cause brittle fracture (Fig. 6b).

Fig. 5. Morphology of the fracture surfaces of G17CrMo5-5 cast steel Charpy specimens at the area of ductile fracture; a – non-modified; b – REM modified. SEM

Fig. 6. Morphology of fractures of G17CrMo5-5 Charpy specimens at the cleavage fracture area; a,b – non-modified; c,d – REM modified. SEM

REM cast steel modification causes the increase (to ca 1mm) of the ductile fracture area under the specimens noth bottom (Fig. 5b). At the areas of cleavage fracture there occurred significant increase of the changes of cracking directions due to smaller grain sizes (Fig. 6c). The share of ductile fracture at these areas was also increased. Spherical evolwins of non-metallic inclusions influence the cracking process similarly to those incast carbon steel. The difference lies in the fact that after a momentary halt of cracking the number of new steps increases significantly and the non-metallic inclusions are quite often the ductile crackin
initiators (Fig. 6d). The carbides occurrence of large dispersion influence the cracking mechanism of the specimens which is identical as in the case of non-modified cast steel. The presented change of the morphology of fracture surfaces of charpy specimens due to REM modification was accompanied by impact strength increase (Table 2) as well as by crosswise shortening from 1.5% to 4% measured next to the notch bottom.

3. Non-metallic inclusions morphology tests

Non-metallic inclusions occurring at the non-modified cast steel fractures are mostly heterogeneous. It is proved not only by observations done by means of the scanning electron microscope on the non-etched metallographic specimen but also by microanalysis of chemical composition. \((\text{Mn,Fe})_2\text{S}\) sulfides crystallize on pads which are most often the \(\text{Al}_2\text{O}_3\) particles of a large dispersion (Fig. 7a). \(\text{Al}_2\text{O}_3\) oxides in turn occur in the \(\text{CaO}\) border, and in larger clusters they are accompanied by \((\text{Mn,Fe})_2\text{S}\) sulfides (Fig. 7b).

The structure and kinds of non-metallic inclusions occurring in REM modified cast steels depend not only on the amount of REM addition but also on the way of their putting into the liquid metal. The way of putting them in influences the amount of REM melting loss and at the same time – the amount of REM which really participates in the process of non-metallic inclusion formation.

REM effectiveness increases when the initial alluminium deoxidation is used and also when the way of REM putting in ensures the smallest oxidation loses which appear due to REM reaction with air, slug and refractories. Meeting these requirements makes the ball-shaped non-metallic inclusions of large dispersion dominate at the cast steel structure.

At the X-ray spectrum emitted by spherical non-metallic inclusions occurring on the charpy specimens fractures surfaces of modified cast steels there appear not only the sulphur and REM peaks but oxygen, alluminium, manganese and iron peaks of various intensity as well (Fig. 8). The particles of spherical non-metallic inclusions observed at the charpy specimen fractures crack brittlely (Fig. 9a). At the metallographic specimens etched by 4%\(\text{HNO}_3\) in \(\text{C}_2\text{H}_5\text{OH}\) some areas of inclusions are etched while others remain untouched (Fig. 9b). By means of the scanning electron microscope it can be seen that on the non-etched metallographic specimens there appears a strong composition contrast inside these inclusions (Fig. 9c,d).

All these tests results prove explicitly that spherical non-metallic inclusions occurring in the structure of REM modified cast steels are heterogeneous and of a very complex inner structure. Microanalysis and linescans results of selected elements (Fig. 10) reveal that REM sulfides crystallize on the pads which are usually \(\text{Al}_2\text{O}_3\) oxides and \((\text{Mn,Fe})_2\text{S}\) sulfides slightly modified by REM. The lack of a solid connection of the pads with REM sulfides is the reason of brittleness of these non-metallic inclusions.

Fig. 7. Non-metallic inclusions in non-modified cast steels. Non-etched. SEM. Composition contrast
Fig. 8. X-ray spectrum emitted by spherical non-metallic inclusions occurring at charpy specimens fracture surfaces from modified cast steels. EDS

Fig. 9. Spherical non-metallic inclusions in REM modified cast steels; a – at the charpy specimen fracture surface; b – at the metallographic specimen after etching by 4%HNO₃ in C₂H₅OH; c,d – at the metallographic specimen non-etched (SEM, composition contrast)
4. Conclusions

The carried out tests proved that rare earth metals (Ce, La, Nd, Pr) are very effective when increasing toughness of cast steels used for fittings production in power industry. It is essential for increasing life and reliability of these systems.

The influence of REM consists in the morphology change of non-metallic inclusions, decrease of the casting grain and cracking inhibition. The significant factors, which determine the effectiveness of REM influence, are their form, amount and method of putting them into the liquid metal.

References