Effect of alloying elements on branching of primary austenite dendrites in Ni-Mn-Cu cast iron

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Abstract

Within the research, determined were direction and intensity of influence of individual alloying elements on branching degree of primary austenite dendrites in austenitic cast iron Ni-Mn-Cu. 30 cast shafts dia. 20 mm were analysed. Chemical composition of the alloy was as follows: 2.0 to 3.3 % C, 1.4 to 3.1 % Si, 2.8 to 9.5 % Ni, 0.4 to 7.7 % Mn, 0 to 4.6 % Cu, 0.14 to 0.16 % P and 0.03 to 0.04 % S. Analysis was performed separately for the dendrites solidifying in directional and volumetric way. The average distance "x" between the 2nd order arms was accepted as the criterion of branching degree. It was found that influence of C, Si, Ni, Mn and Cu on the parameter "x" is statistically significant. Intensity of carbon influence is decidedly higher than that of other elements, and the influence is more intensive in the directionally solidifying dendrites. However, in the case of the alloyed cast iron Ni-Mn-Cu, combined influence of the alloying elements on solidification course of primary austenite can be significant.

Key words: primary austenite, solidification, austenitic cast iron, Ni-Mn-Cu cast iron

1. Introduction

Features of primary austenite dendrites, i.e. their quantity, size and branching degree, significantly influence properties of a hypoeutectic cast iron. They form the casting structure not only directly, but also indirectly, determining the space in that the eutectic mixture solidifies. This is especially important in the case of an austenitic cast iron in that the austenite transformation process does not occur, as opposed to the unalloyed cast iron [xx].

The features of austenite dendrites, mainly their branching degree, are in large measure decided by the overcooling degree, both the kinetic overcooling connected with cooling rate, and the concentration overcooling related to average concentration of individual elements in the alloy and their segregation degree [1], [2], [4]. Effect of the kinetic overcooling degree on the solidification process of austenite dendrites is relatively well known. The dendrite branching degree is strictly related to the overcooling degree of the liquid alloy. This results from positive influence of overcooling on nucleation rate. In practice, this means that all the factors increasing solidification rate of a cast iron, at the same time increase the dendrite branching degree [8], [9].

A much smaller number of data is available on influence of chemical composition on the solidification process of austenite dendrites. The element known to affect shape of dendrites significantly is carbon. This is described by the empirical relationship (1) describing influence of carbon concentration and cooling rate of a cast iron on average distance between the 2nd order dendrite arms [3], [7]:

...
\[ x_H = 340 \cdot v_s^{-0.27} \left( \frac{1}{5.4C} + \frac{1}{4.3} \right)^{0.35} \]  

where:
- \( x_H \) – average distance between 2nd order dendrite arms [\( \mu m \)],
- \( v_s \) – cooling rate [K/min],
- \( \% C \) – carbon concentration [%].

2. Purpose and scope of the research

The research was aimed at determining the extent to that alloying elements in the cast iron Ni-Mn-Cu influence branching degree of primary austenite dendrites. The examinations were performed on 30 shell-cast shafts dia. 20 mm. Chemical composition of the examined material is given in Table 1. Determined was influence of chemical composition on the distances between 2nd order arms. Because of various solidification way, the analysis was performed separately for columnar dendrites, the ones solidifying directionally and those solidifying volumetrically [5], [6].

Table 1. Chemical composition of the examined cast iron

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration [%]</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td></td>
<td>2.0</td>
<td>3.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Si</td>
<td></td>
<td>1.4</td>
<td>3.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Ni</td>
<td></td>
<td>2.8</td>
<td>9.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Mn</td>
<td></td>
<td>0.4</td>
<td>7.7</td>
<td>3.1</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>0.0</td>
<td>4.6</td>
<td>2.8</td>
</tr>
<tr>
<td>P</td>
<td></td>
<td>0.14</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>S</td>
<td></td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Sc</td>
<td></td>
<td>0.64</td>
<td>1.02</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Among the examined alloys, present were also those with the eutectic saturation coefficient over 1.00, as calculated acc. to the commonly used relationship [5]. However, analysis of their structures indicated the presence of the primary austenite dendrites. This results from non-equilibrium solidification of castings.

3. Own examinations

For columnar dendrites, the linear regression equation combining the distance "x" between 2nd order arms and concentrations of individual elements has the following form:

\[ x = 85.4 - 16.3C - 2.2Si - 1.6Ni + Mn - 0.33Cu \ [\mu m] \]  

(2)

Statistical parameters of the equation:
- standard deviation: \( \sigma = 8 \mu m \)
- coefficient of determination: \( R^2 = 0.84 \)
- Fisher’s test: \( F_{(5,25)} = 74.9 \)
- significance level: \( p < 0.01 \)

Low values of statistical parameters of this equation result, among others, from relatively large differences of the "x" values measured for one specimen. The scatter was large, even though the measurements were taken at the same distance from the casting surface (ca. 2 mm). However, the equation (2) can be used for qualitative evaluation of influence of the analysed elements on the average "x" value.

The element influencing the distance "x" most intensively is carbon. Increase of its concentration by 0.1 % reduces the "x" value by 1.6 \( \mu m \), in average. This relation was determined for a cast iron containing 2.0 to 3.5 % C. Influence of the other elements is much weaker and can be probably reduced to a change of the equilibrium liquidus temperature of austenite.

The diagram in Fig. 1 shows average distances between 2nd order dendrite arms of primary austenite as a function of equivalent carbon content \( C_{Ekx} \) calculated from the equation (2). The solid line represents a graphic interpretation of the equation (4), and the dotted line – of the equation (1), calculated for the cooling rate of 300 K/min. This is approximately the cooling rate of near-surface areas of the examined castings.

The equation for the carbon equivalent, obtained on the grounds of (2), is as follows:

\[ C_{Ekx} = C + 0.13Si + 0.10Ni - 0.06Mn + 0.02Cu \ [%] \]  

(3)

Thus, the equation (2) can be presented in form:

\[ x = 85.4 - 16.3C_{Ekx} \ [\mu m] \]  

(4)

Fig. 1. Effect of carbon equivalent (3) on average distance between 2nd order arms of primary austenite dendrites solidifying directionally. Solid line represents equation (4) and dotted line – equation (1) calculated for \( v = 300 \text{ K/min} \).

The exemplary photographs in Fig. 2 show directionally solidified dendrites in the near-surface layer of a dia. 20 mm casting with chemical composition: 2.63 % C, 1.8 % Si, 6.8 % Ni, 2.0 % Mn and 3.4 % Cu. The carbon equivalent value \( C_{Ekx} \) calculated from (3) for this cast iron is 3.49 %. According to (4), the average distance between 2nd order dendrite arms should be ca. 30 \( \mu m \). In reality, this value is slightly smaller, amounting to ca. 25 \( \mu m \).

Similarly as in the case of the dendrites solidifying directionally, the analysis was performed for those solidifying volumetrically. The respective regression equation is as follows:

\[ x = 120.4 - 21.8C - 3.2Si - 1.2Ni + 0.83Mn + 0.42Cu \ [\mu m] \]  

(5)
Statistical parameters of the equation:

- standard deviation: $\sigma = 6 \, \mu m$
- coefficient of determination: $R^2 = 0.63$
- Fisher's test: $F_{(5,20)} = 44.9$
- significance level: $p < 0.05$

Like in the case of columnar dendrites, carbon is the element that changes geometry of volumetrically solidifying dendrites to the highest degree. Increase of carbon concentration by 0.1% results in reducing the distance between 2nd order dendrite arms by 2.2 mm, on average. This relationship is valid for the alloys containing 2.5 to 4.0% C.

In comparison to carbon, silicon increases the dendrite branching degree many times weaker. It results from the equation (5) that this influence is six times weaker. Influence of the other elements can be considered negligible from the practical point of view, even though statistically significant.

The carbon equivalent obtained on the grounds of (2) is as follows:

$$C_{\text{Ekx}} = C + 0.15 \cdot \text{Si} + 0.06 \cdot \text{Ni} - 0.04 \cdot \text{Mn} + 0.02 \cdot \text{Cu}$$

(6)

and thus the equation (5) is:

$$x = 120.4 - 21.8 \cdot C_{\text{Ekx}}$$

(7)

A graphic interpretation of this equation is shown in Fig. 3 (solid line). In addition, a diagram of the relationship (1) is also shown with dotted line. Considering that the measurements of "x" were taken in the central areas of the castings that cooled down more slowly than the near-surface areas, the cooling rate in the equation was reduced to 250 K/min.

4. Summary

The performed analysis of 30 shafts dia. 20 mm of austenitic cast iron Ni-Mn-Cu revealed variable branching degree of the
present primary austenite dendrites. This concerns both the directionally solidifying dendrites (mainly in near-surface layers) and the volumetrically solidifying ones (close to the casting centre).

The average distance between 2nd order dendrite arms was accepted as the measure of the dendrite branching. It was assumed that reduction of this distance is equivalent to increase of the dendrite branching degree.

The directionally solidifying columnar dendrites are characterised by higher branching degree than those solidifying volumetrically. In the former ones, the distance "x" ranges from 25 to 80 μm and its average value for all the castings is ca. 55 μm. For the latter ones, the distances are smaller. The value "x" ranges from 25 to 80 μm, with the average of ca. 40 μm. This difference can be explained, first of all, by higher cooling rate at the casting surface and thus larger kinetic overcooling of the transformation than in the central area.

An additional cause can be also different concentration overcooling, related to changing equilibrium transformation temperature and thus to chemical composition of the alloy. Rightness of this conclusion is evidenced by the performed analysis that demonstrated statistically significant influence of chemical composition on the average distance "x" for the dendrites solidifying both directionally and volumetrically.

The following conclusions can be drawn from the equations (2) and (5) describing this relationship:

1. Carbon is the element that reduces the distances between dendrite arms (increases their branching degree) to the largest extent.
2. The influence of carbon is stronger in the dendrites solidifying volumetrically. Increase of carbon content by 0.1% results in reducing the average distance "x" by 1.6 μm in directionally solidifying austenite dendrites and by 2.2 μm in those solidifying volumetrically. This difference can be explained by segregation of carbon during non-equilibrium solidification of castings. Carbon concentration in central areas can be higher than that near the casting surface (inverse macrosegregation).
3. The effect of the other elements is many times weaker. Silicon, nickel and copper increase the dendrite branching degree, but manganese reduces it slightly. Direction and intensity of influence of individual elements is basically consistent with their influence on carbon activity in liquid cast iron. Some differences in intensity of this action can result from the phenomenon of segregation of alloying elements.
4. Because of relatively low influence of the alloying elements on the distance "x", they can be omitted when analysing the process of primary austenite solidifying in low-alloyed cast irons. However, their presence should be considered in medium- and high-alloyed cast irons, as e.g. the Ni-Mn-Cu alloy. This is evidenced by the difference between carbon content and the carbon equivalent value C_{eq} calculated from the equations (3) and (6) in the exemplary alloys, see Figs. 2 and 4. It should be assumed that higher dendrite branching degree in the examined alloys in relation to the distance "x" calculated from the relationship (1) results from the presence of alloying elements, see Figs. 1 and 3.

References