

# Effect of alloying elements on solidification of primary austenite in Ni-Mn-Cu cast iron

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## Abstract

Within the research, determined were direction and intensity of alloying elements influence on solidification way (directional or volumetric) of primary austenite dendrites in hypoeutectic austenitic cast iron Ni-Mn-Cu. 50 cast shafts dia. 20 mm were analysed. Chemical composition of the alloy was as follows: 1.7 to 3.3 % C, 1.4 to 3.1 % Si, 2.8 to 9.9 % 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. The discriminant analysis revealed that carbon influences solidification of primary austenite dendrites most intensively. It clearly increases the tendency to volumetric solidification. Influence of the other elements is much weaker. This means that the solidification way of primary austenite dendrites in hypoeutectic austenitic cast iron Ni-Mn-Cu does not differ from that in an unalloyed cast iron.

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

## 1. Introduction

In a hypoeutectic cast iron, the solidification process of castings begins from crystallisation of primary austenite dendrites. The way of crystallisation significantly affects structure and properties of cast iron. It determines not only features of the created austenite dendrites but also indirectly decides the nature of eutectic colonies created in the austenite interdendritic spaces [xx].

Course of primary austenite crystallisation is strictly connected with overcooling of liquid alloy. The overcooling degree is usually related to cooling rate of the castings (and thus to the real liquidus temperature). According to the commonly

recognised theory, as the cooling speed rises (kinetic overcooling rises), volumetric solidification changes to directional solidification with a dendritic, cellular crystallisation front or with a flat front at the smallest overcooling degree [1÷4].

The overcooling degree is also influenced by chemical composition of the alloy (changed equilibrium transformation point). This refers to both average concentrations of the alloying elements and their local microsegregation (concentration overcooling).

Influence of solidification rate on the course of primary austenite crystallisation is relatively well known. Much less information refers to influence of chemical composition. It is known that increased carbon composition is conducive to changing the austenite crystallisation way from directional

(exogenous) to volumetric (endogenous). The presence of silicon, manganese and phosphorus (in concentrations usually applied in unalloyed cast irons) does not change this relationship. However, no unambiguous information is available on influence of individual elements on solidification way of primary austenite in alloyed cast irons [5].

From the methodological point of view, description of this process can be reduced mainly to determining the way of austenite solidification (directional or volumetric). An attempt to classify the ways of primary austenite solidification is presented in [6], see Fig. 1. The following solidification ways were distinguished:

- I** – purely directional solidification (bundles of dendrites reach the casting axis),
- II to IV** – mixed directional and volumetric solidification (bundles of dendrites do not reach the casting axis),
- V** – purely volumetric solidification (bundles of dendrites on the entire casting cross-section),
- VI** – purely volumetric solidification (individual dendrites are randomly distributed on the entire casting cross-section).

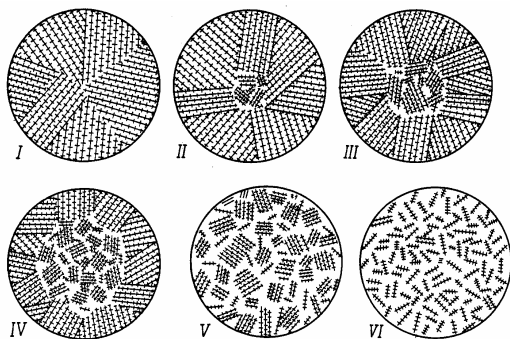


Fig. 1. Solidification ways of primary austenite in white cast iron [x]

## 2. Purpose and scope of the research

The research was aimed at determining the way how the alloying elements in the cast iron Ni-Mn-Cu influence solidification of primary austenite dendrites. The examinations were performed on 50 shell-cast shafts dia. 20 mm. Chemical composition limits of the examined material are given in Table 1.

Table 1. Chemical composition of the examined cast iron

Element	Concentration [%]		
	Minimum	Maximum	Average
C	1.7	3.3	2.6
Si	1.4	3.1	2.3
Ni	2.8	9.9	6.8
Mn	0.4	7.7	3.6
Cu	0.0	4.6	2.8

P	0.14	0.16	0.14
S	0.03	0.04	0.04
<b>S<sub>C</sub></b>	<b>0.64</b>	<b>1.03</b>	<b>0.88</b>

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

## 3. Own examinations

Microscopic observations indicate various solidification ways of primary austenite dendrites. Depending on chemical composition, the castings solidified in exclusively directional way (pattern I in Fig. 1) or directionally at the surface and volumetrically next to the axis (patterns II to IV in Fig. 1). Because of relatively large kinetic overcooling, the purely volumetric solidification (patterns V and VI in Fig. 1) was not found in any of the examined castings. Exemplary structures of the castings are shown in Figs. 2 and 3.

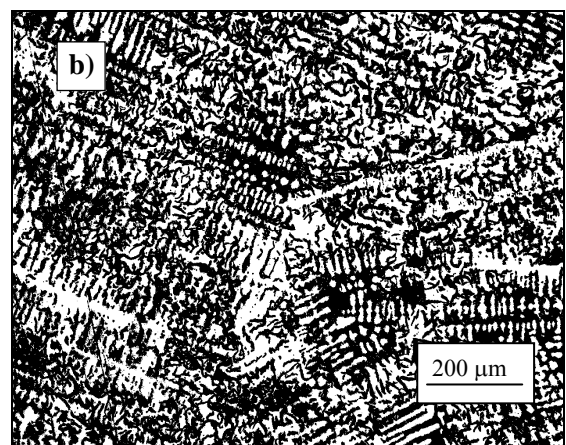
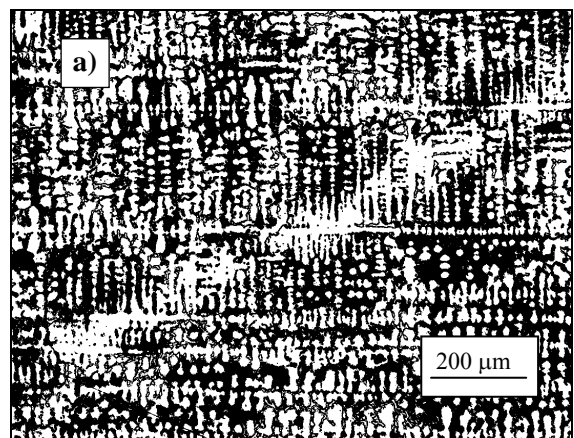


Fig. 2. Directional solidification – dendrite bundles of primary austenite in the casting containing 2.63 % C, 1.8 % Si, 9.8 % Ni, 5.8 % Mn and 2.7 % Cu: a) near-surface area, b) axis area

Figure 2 shows the structure observed in the casting containing 2.63 % C, 1.8 % Si, 9.8 % Ni, 5.8 % Mn and 2.7 % Cu. At the casting surface, bundles of equiaxial dendrites are visible. They are oriented perpendicularly to the casting surface, in the way typical for directional solidification, see Fig. 2a. These bundles converge at the casting axis, see Fig. 2b.

In turn, Fig. 3 shows a structure of the casting containing 3.60 % C, 1.4 % Si, 7.8 % Ni, 3.8 % Mn and 1.4 % Cu. At ca. 5 mm from the casting surface (Fig. 3a), a clear boundary visible is between the dendrites solidified directionally (left side of the photograph) and those solidified volumetrically (right side of the photograph). A characteristic feature of the volumetrically solidifying dendrites is random space orientation of their main axes, see Fig. 3b.

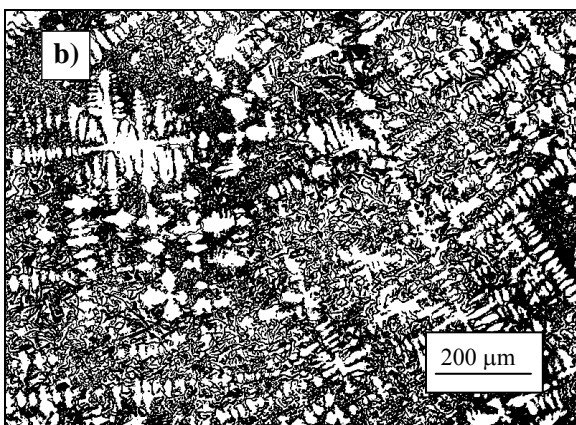
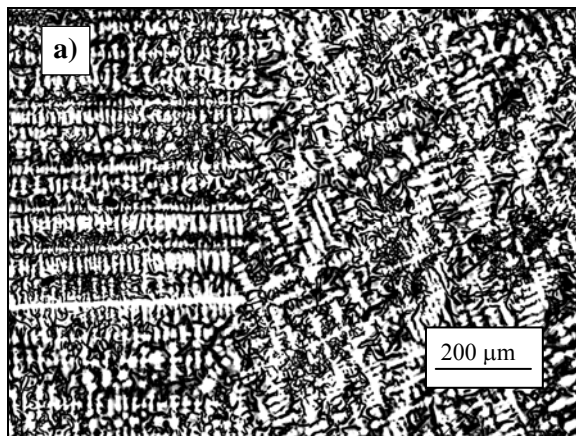


Fig. 3. Transition zone between directional and volumetric solidification areas of primary austenite dendrites in the casting containing 3.60 % C, 1.4 % Si, 7.8 % Ni, 3.8 % Mn and 1.4 % Cu: a) area ca. 5 mm from the casting surface, b) axis area

In order to determine the degree to that chemical composition of the cast iron influences the way of primary austenite

solidification, the discriminant statistical analysis was performed. The castings were divided into two groups (classes). The first class included the castings where the dendrite bundles reached the casting axes (purely directional solidification). The second class included the other castings, where admittedly dendrite bundles occurred, but with central castings areas solidifying volumetrically. It can be assumed that the first group represents cast irons with higher inclination to directional solidification than the second group. Generally, of the analysed 50 castings, 18 ones were counted to the first group and 32 ones to the second group. A system of two equations was obtained:

- 1<sup>st</sup> class (castings solidifying directionally only):

$$S_{cl1} = -76.711 + 19.233 \cdot C + 26.568 \cdot Si + 5.965 \cdot Ni + -2.584 \cdot Mn + 2.432 \cdot Cu \quad [\%] \quad (1)$$

- 2<sup>nd</sup> class (dendrite bundles not reaching the casting axis):

$$S_{cl2} = -84.448 + 21.894 \cdot C + 27.176 \cdot Si + 6.420 \cdot Ni + -2.284 \cdot Mn + 2.884 \cdot Cu \quad [\%] \quad (2)$$

Statistical parameters of the equation:

Wilks' lambda:  $\lambda = 0.827$   
 Fisher's test:  $F_{(5,44)} = 32.78$   
 significance level:  $p < 0.05$

Affiliation of the cast iron to a specific class is determined by the larger value of total concentration  $S_{cl1}$  or  $S_{cl2}$  calculated from the equations (1) and (2). Conformity of the specimens' structure with the classification based on their chemical analyses is illustrated by the classification matrix given in Table 2. It results from the table that 10 alloys from among 50 examined alloys (20 %) were classified incorrectly. In three cases it was related to the cast iron with a distinct tendency to directional solidification, and in seven cases – to the cast iron more inclined to volumetric solidification.

Table 2. Classification matrix of the equations (1) and (2)

	Correct classification [%]	Number of observations	
		Class 1	Class 2
Class 1	73	13	7
Class 2	84	3	25
Total		18	32

The relatively large number of incorrectly classified castings results probably from uncontrolled differences in kinetic overcooling that could happen during solidification of the castings. However, the obtained relationships permit determining the ways how individual elements act and comparing intensities of their actions. By deducting the equation (1) from (2) and reducing the absolute term to unity one obtain the condition that must be met to ensure volumetric solidification of primary austenite dendrites at least in central areas of the castings dia. 20 mm. This condition has the form:

$$-1.00 + 0.34 \cdot C + 0.08 \cdot Si + 0.06 \cdot Ni + 0.04 \cdot Mn + 0.06 \cdot Cu > 0 \quad (3)$$

## 4. Summary

It results from (3) that all the analysed elements are conducive for volumetric solidification of primary austenite dendrites, but with various intensities. It is carbon that acts most intensively. Presumably, concentration overcooling at the crystallisation front rises with increasing average carbon concentration in the cast iron, changing the solidification way from directional to volumetric [x].

Intensity of influence of the other elements is many times weaker. Even though each of them shows statistical significance of its effect, silicon concentration only can influence the primary austenite solidification process to a practically important extent, as demonstrated by the performed tests. This means that solidification of primary austenite dendrites in the hypoeutectic austenitic cast iron Ni-Mn-Cu does not differ significantly from solidification of austenite in unalloyed cast irons.

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