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Effect of Heat-treatment Parameters of Cast Iron GJS-X350NiMnCu7-3-2 on its Structure and Mechanical Properties

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Abstract

The paper presents influence of soaking parameters (temperature and time) on structure and mechanical properties of spheroidal graphite nickel-manganese-copper cast iron, containing: 7.2% Ni, 2.6% Mn and 2.4% Cu. Raw castings showed austenitic structure and relatively low hardness (150 HBW) guaranteeing their good machinability. Heat treatment consisted in soaking the castings within 400 to 600°C for 2 to 10 hours followed by air-cooling. In most cases, soaking caused changes in structure and, in consequence, an increase of hardness in comparison to raw castings. The highest hardness and tensile strength was obtained after soaking at 550°C for 6 hours. At the same time, decrease of the parameters related to plasticity of cast iron (elongation and impact strength) was observed. This resulted from the fact that, in these conditions, the largest fraction of fine-acicular ferrite with relatively high hardness (490 HV0.1) was created in the matrix. At lower temperatures and after shorter soaking times, hardness and tensile strength were lower because of smaller degree of austenite transformation. At higher temperatures and after longer soaking times, fine-dispersive ferrite was produced. That resulted in slightly lower material hardness.

Keywords: Mechanical properties, Heat treatment, Austenitic transformation, Austenitic cast iron, Cast iron Ni-Mn-Cu

1. Introduction

Spheroidal graphite nickel-manganese-copper cast iron with properly high content of nickel equivalent shows all the features characteristic for austenitic cast iron. These features include e.g. very good casting properties, high corrosion resistance, good machinability and also relatively low mechanical properties and low abrasive-wear resistance [1-5].

Increasing strength and abrasion resistance is only possible as a result of changing matrix structure of raw castings. This means, first of all, the necessity to introduce to cast iron a proper amount of the austenite-stabilizing elements (nickel, manganese and copper) [6-7] and to choose proper heat-treatment parameters of raw castings [8]. With regard to increasing hardness, heat treatment should be carried-out on the castings after their mechanical processing.

Selecting chemical composition of a cast iron is controlled by its nickel equivalent value Equ_{Ni} that decides thermodynamic stability of austenite [9-10]. Too small Equ_{Ni} value may lead to partial transformation of austenite to martensite. Even though this will cause a clear increase of abrasion resistance, strength of the castings will not be increased to an adequately high degree. In turn, too large Equ_{Ni} value results in so high stability of austenite in raw castings that their heat treatment is not able to create a structure resulting in clearly higher strength. When selecting a chemical composition, chilling action of manganese and limited solubility of copper in austenite should be also taken into account [9,11].

It seems that, with properly selected chemical composition of cast iron, structure of raw castings can be controlled by parameters of heat treatment (temperature and time). Like in the case of hardening with isothermal transformation, this should permit an assumed ratio between strength and plasticity of a casting to be obtained [12].

2. Purpose, scope and methodology

The research was aimed at determining the effect of heat treatment parameters on austenitic transformation degree and basic mechanical properties of examined cast iron.

Examinations were carried-out for spheroidal cast iron containing 3.4% C, 2.3% Si, 7.2% Ni, 2.6% Mn, 2.4% Cu, 0.11% Mg, 0,15% P and 0.04% S, on Y-block coupons. The wall thickness in the Y-shaped test block casting was 30 mm. Heat treatment consisted in soaking the specimens at temperatures between 400 and 600°C (in steps of 50°C) for 2, 4, 6, 8 and 10 hours (with air cooling).

Scope of the examinations included microscopic observations on a light microscope and a scanning electron microscope equipped with an energy dispersive X-ray spectroscopy EDX detector. Hardness was measured by Brinell method for castings and by Vickers method for structural phases. Mechanical testing was based on EN ISO 6892-1:2010 and PN-81/H-83108. Impact strength was measured on U-notch test specimens acc. to EN ISO 148-1:2010 and PN-79/H-04370.

3. Results and discussion

3.1. Microscopic examinations

Because of copper content that can hamper spheroidization of graphite, magnesium content in the examined cast iron was increased to 0.11% [11]. This made it possible to obtain fine, regular nodular graphite, see Fig. 1.

Nickel equivalent value in the examined cast iron, calculated according to the relationship (1) [10], was 16.1% and, as expected, raw castings showed austenitic matrix structure (Fig. 2) with its hardness ca. 200 HV0.01. In consequence, hardness of raw castings was also low, amounting to ca. 150 HBW.

$$\mathrm{Equ}_{Ni} = 0.32\cdot \mathrm{C} + 0.13\cdot \mathrm{Si} + \mathrm{Ni} + 2.48\cdot \mathrm{Mn} + 0.53\cdot \mathrm{Cu}\ [\%] \qquad (1)$$

where:

Equ_{Ni} – nickel equivalent [%],

C, Si, Ni, Mn, Cu, Mg – concentration of elements [%].

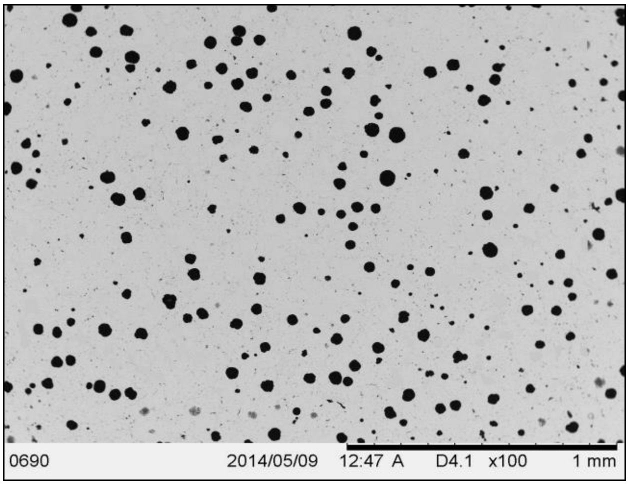

Fig. 1. Regular nodular graphite VIA5 (acc. to EN ISO 945-1:2009). Unetched

Fig. 2. Austenitic matrix structure with spheroidal graphite of raw casting. Etched with Mi1Fe

Heat treatment resulted in strong diversification of matrix structure of the examined specimens. In most cases, soaking of a casting caused partial transformation of austenite. Its way and ratio were strictly dependent on parameters of heat treatment. The austenite transformation degree increased along with increasing temperature and extending time of soaking; nature of the transformation changed as well.

Soaking a casting at 400°C irrespective of time and soaking at 450°C for 2 and 4 hours did not cause any change in matrix structure. Increasing temperature and extending the soaking time led to creation, in the vicinity of nodular graphite particles, of single martensite needle-like plates (see Fig. 3) with hardness of ca. 520 HV0.1. Average carbon concentration in this phase was 0.32%.

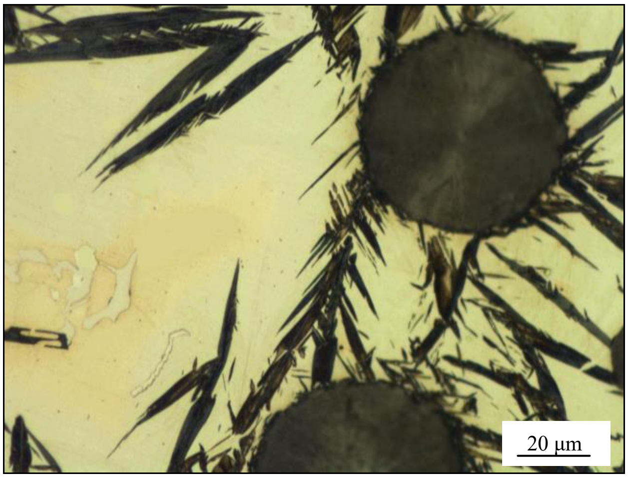

Fig. 3. Structure of a casting soaked at 450°C for 6 h and air-cooled: needle-like martensite plates in vicinity of nodular graphite particles. Etched with Mi1Fe

For higher temperature and longer soaking time, austenite transformation degree was higher, as well as morphological structure and hardness of the created phase changed. It became more and more similar to supersaturated with carbon fine-acicular ferrite present in bainite or ausferrite, see Fig. 4. Hardness of the created phase was in average 490 HV0.1, lower than hardness of martensite. This slightly lower hardness resulted from lower supersaturation degree of the phase, being ca. 30%.

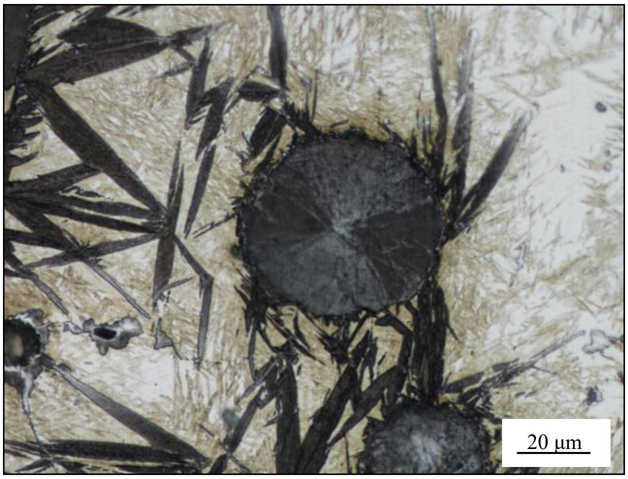

Fig. 4. Structure of a casting soaked at 550°C for 6 h and air-cooled: martensite and fine-acicular phase similar to ferrite in bainite or ausferrite. Etched with Mi1Fe

Soaking at 550°C for 6 h resulted in the largest degree of austenite transformation to fine-acicular phase, see Fig. 5.

Extension of soaking time to 8 hours led to creation, except the fine-acicular phase, of dispersive pearlite areas, with average hardness of 330 HV0.1. Further extension of soaking time resulted in larger fraction of pearlite at the expense of fine-acicular ferrite.

Fig. 5. Structure of a casting soaked at 550°C for 6 h and air-cooled: the largest degree of austenite transformation to fine-acicular ferrite. Etched with Mi1Fe

When soaking at higher temperature of 600°C, pearlite areas appeared after 6 hours, see Fig. 6.

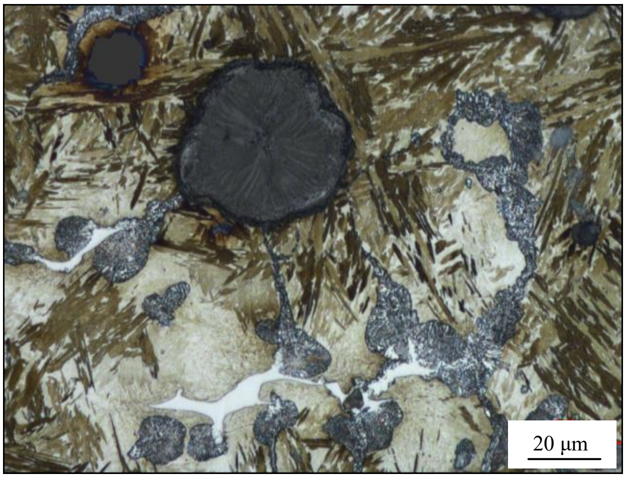

Fig. 6. Structure of a casting soaked at 600°C for 6 h and air-cooled: fine ferrite needles, dispersive pearlite areas and cementite phase. Etched with Mi1Fe

3.2. Measurements of mechanical properties

Structural changes activated by soaking resulted in changed hardness of castings, depending on the way and degree of austenite transformation. Results of hardness measurements are given in Table 1 and presented graphically in Fig. 7.

Soaking the castings at 400°C irrespective of time and soaking at 450°C for 2 and 4 hours did not cause any change of hardness.

Table 1.
Structure and HBW hardness of castings depending on temperature and time of soaking

Soaking time [h]	Soaking temperature [°C]									
	400		450		500		550		600	
	Fe_γ-$Fe_{\alpha'}$-P [%-%-%]	HBW [/]	Fe_γ-$Fe_{\alpha'}$-P [%-%-%]	HBW [/]	Fe_γ-$Fe_{\alpha'}$-P [%-%-%]	HBW [/]	Fe_γ-$Fe_{\alpha'}$-P [%-%-%-%]	HBW [/]	Fe_γ-$Fe_{\alpha'}$-P [%-%-%-%]	HBW [/]
2	100-0-0	158	100-0-0	155	94-6-0	245	91-9-0	269	68-32-0	331
4	100-0-0	162	100-0-0	159	88-12-0	271	64-36-0	349	49-51-0	371
6	100-0-0	159	91-2-0	187	70-30-0	325	6-94-0	464	7-89-4	458
8	100-0-0	160	96-4-0	210	63-37-0	350	8-87-5	452	6-86-8	440
10	100-0-0	164	94-8-0	250	45-55-0	390	7-84-9	444	7-79-14	421

Fe_γ – austenite
$Fe_{\alpha'}$ – martensite and fine-acicular ferrite
P – pearlite

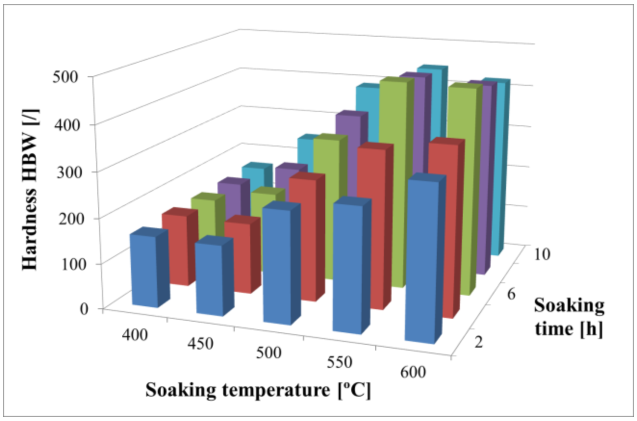

Fig. 7. Effect of soaking temperature and time on hardness HBW of castings

Soaking at 450°C for 6 hours resulted in increased hardness of the castings.

Generally, soaking at higher temperatures resulted in clearly higher hardness of castings, especially after longer soaking times.

The highest hardness of 464 HBW was obtained after soaking at 550°C for 6 hours. The matrix contained then the largest fraction of fine-acicular ferrite, see Fig. 5.

In as-cast condition, tensile strength (R_m) of the castings was nearly 360 MPa and elongation (A) was ca. 2.22%. Results of static tensile tests are shown in Figs. 8, 9, 10 and 11.

Soaking the specimens at 400 and 450°C for 2 and 4 hours did not cause any significant changes of tensile strength and elongation in comparison to those of raw castings.

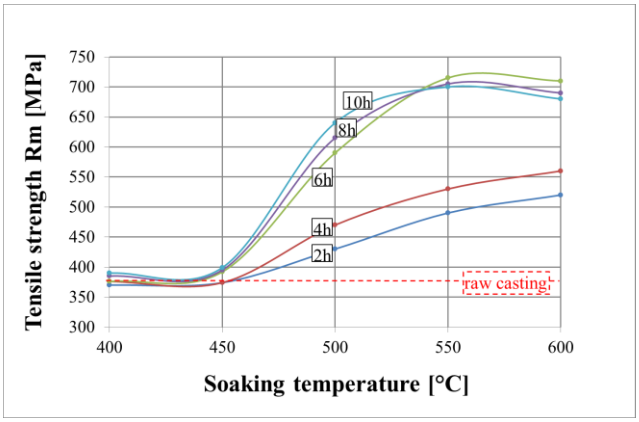

Fig. 8. Effect of soaking temperature on tensile strength R_m of castings

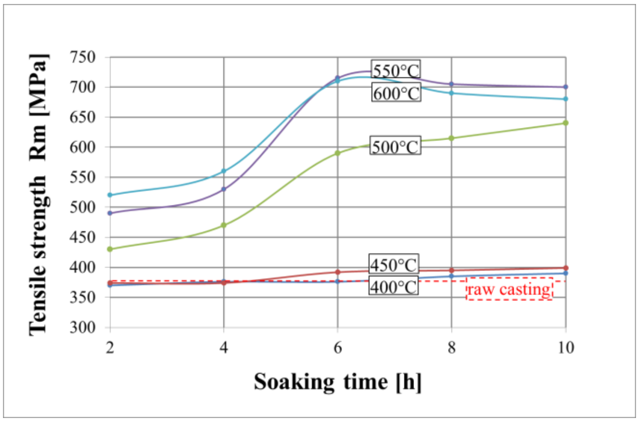

Fig. 9. Effect of soaking time on tensile strength R_m of castings

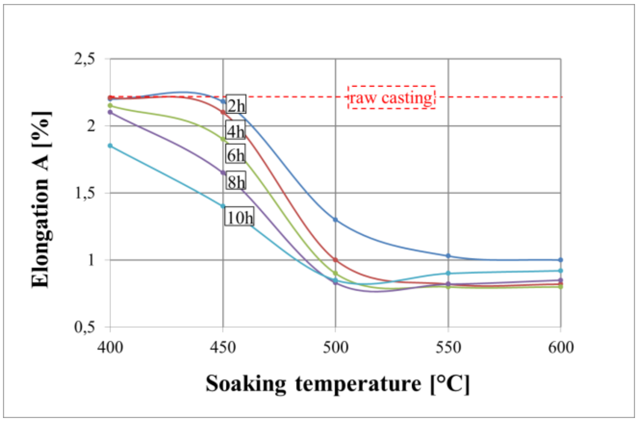

Fig. 10. Effect of soaking temperature on elongation A of castings

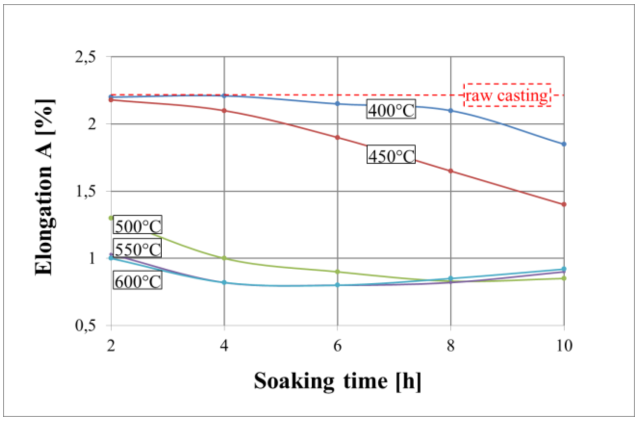

Fig. 11. Effect of soaking time on elongation A of castings

Soaking at higher temperatures resulted in clear increase of tensile strength R_m accompanied by decreased elongation, approximately proportional to increased hardness of the castings, see Figs. 8 to 11 and Table 1. Intensity of these changes increased with extension of soaking time.

Soaking at 550°C for 6 hours led to the highest tensile strength. It was 720 MPa, 359 MPa higher than that of raw castings (Figs. 8 and 9). Elongation was reduced approximately by half (Figs. 10 to 11), which resulted from maximum transformation degree of austenite to fine-acicular ferrite.

Further increasing of soaking temperature resulted in slight reduction of tensile strength and increase of elongation, especially for longer soaking times. This was caused by dispersive pearlite areas that appeared in the matrix.

Impact strength of raw castings was 52 J/cm^2. Soaking the specimens at 400 and 450°C did not cause significant changes of impact strength.

Soaking at higher temperatures and for longer times resulted in a decrease of impact strength to the extent depending mainly on temperature, see Fig. 12.

Soaking at 500°C resulted in reduction of impact strength by ca. 30% after 2 hours and by nearly 50% after 10 hours of soaking.

Increasing the temperature to 550°C caused a slight reduction of impact strength. Further increase of soaking temperature and extension of soaking time did not cause any significant changes of impact strength of the castings.

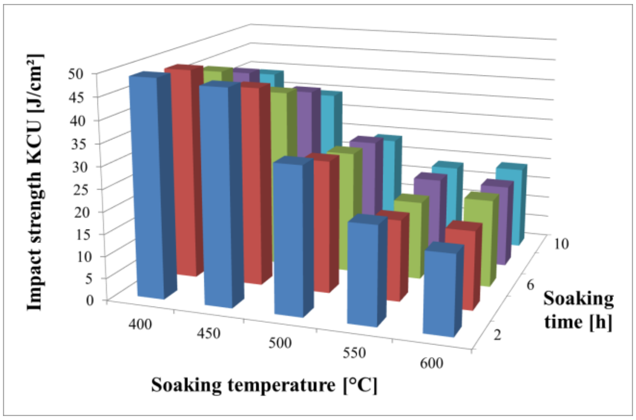

Fig. 12. Effect of soaking temperature and time on impact strength of castings

To illustrate differences in deformations after transverse breaking test, photographs of broken specimens of a raw casting as well as of the castings soaked at 450°C for 4 hours and at 550°C for 6 hours are shown in Fig. 13. Deformation of the specimen soaked at lower temperature was comparable to that from the raw casting. The specimen soaked at higher temperature showed clearly smaller deformation.

Figure 14 shows surfaces of brittle fractures of a raw casting and of a casting soaked at 550°C for 6 hours. Slight differences between fracture surfaces can be seen.

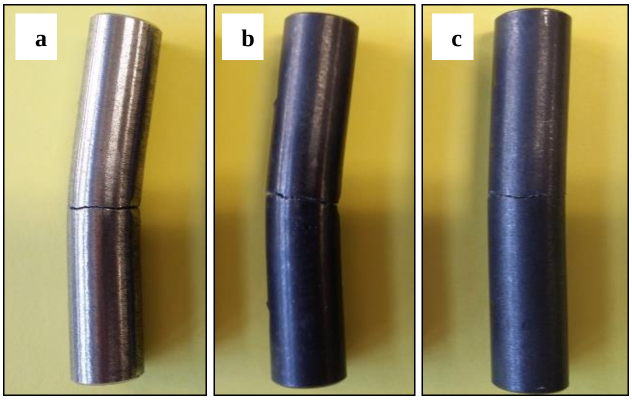

Fig. 13. Specimens dia. 15 mm after transverse breaking tests: a) raw casting; b) soaked at 450°C for 4 h; c) soaked at 550°C for 6 h

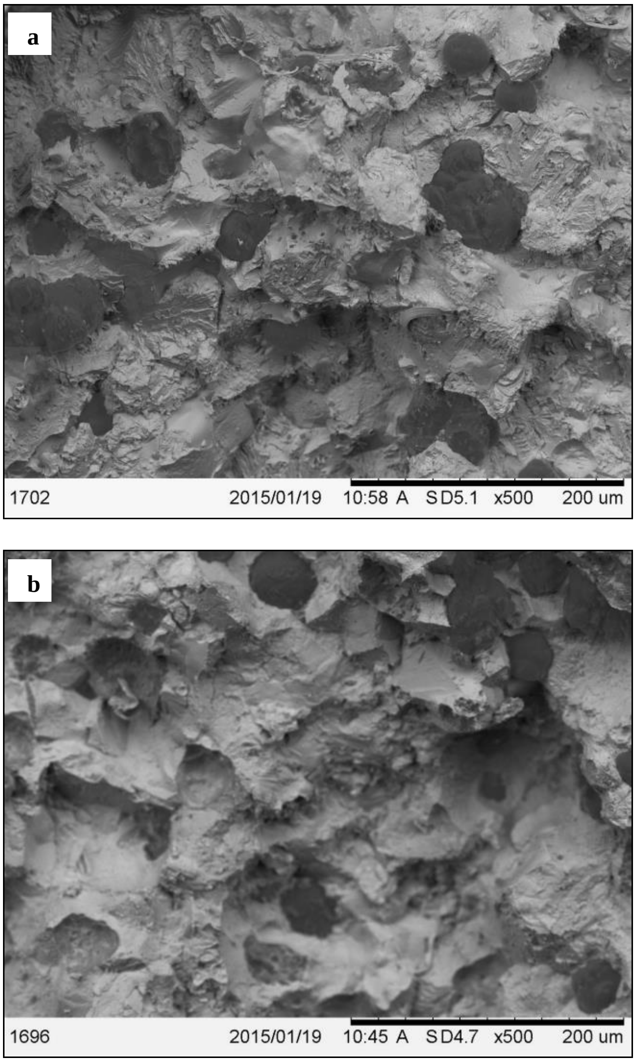

Fig. 14. SEM images of fracture surfaces: a) raw casting, b) soaked at 550°C for 6 h

4. Summary

Soaking of raw castings resulted in partial austenite transformation. Depending on soaking temperature and time, both degree and way of the transformation were changed, from diffusionless (martensite) through partially diffusive (fine-acicular ferrite) to diffusive (pearlite) transformation.

As a result of soaking raw castings at 450°C for 6 to 10 hours, martensite appeared in their structures. That resulted in, approximately proportional to martensite fraction, increase of hardness and tensile strength, as well as in slight reduction of elongation and impact strength.

Increase of soaking temperature to 500 and 550°C resulted in a change of morphology of the created phase (fine-acicular ferrite). Even though HV hardness of ferrite is lower than that of martensite, hardness and tensile strength of castings increased and elongation and impact strength decreased as a result of clearly increasing degree of austenite transformation.

After soaking at 550 and 600°C for 8 and 10 hours, pearlite appeared in the structure, which resulted in slight reduction of hardness of the castings, but did not significantly affect the other mechanical properties.

Results of the presented examinations indicate that it is possible to control the way and degree of austenite transformation in castings of the cast iron under consideration by changing parameters (temperature and time) of soaking. This makes it possible to choose (within some limits) between higher strength and better plasticity of the Ni-Mn-Cu cast iron.

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