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# Simulation of Stress Distribution in a Thick-Walled Bushing Produced by Die-Casting

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## Abstract

Metallographic investigations and a computer simulation of stresses in a gravity die-casting bushing were performed. Simulation of the casting process, solidification of the thick-walled bushing and calculations of the stress was performed using MAGMA5.3 software. The size variability of phases  $\kappa_{II}$  affecting the formation of phase stresses  $\sigma_f$ , depending on the location of the metallographic test area, was identified. The distribution of thermal  $\sigma_t$  and shrinkage stresses  $\sigma_s$ , depending on the location of the control point SC in the bushing's volume, was estimated. Probably the nature of these stresses will change slightly even after machining. This can cause variations in operating characteristics (friction coefficient, wear). Due to the strong inhomogeneity of the stress distribution in the bushing's casting, it is necessary to perform further tests of the possibility to conduct thermal treatment guaranteeing homogenization of the internal stresses in the casting, as well as to introduce changes in the bushing's construction and the casting technology. The paper presents the continuation of the results of research aimed at identifying the causes of defects in the thick-walled bushing, die-casting made of CuAl10Fe5Ni5Cr aluminium bronze.

**Keywords:** Mechanical properties, Metallography, Computer simulation, Residual stress, Complex aluminium bronze

## 1. Introduction

In order to optimize the construction of instrumentation and the technological processes, the casting industry applies numerical programs for the simulation of these processes and the prediction of e.g.: the casting's quality, the areas with the risk of casting defects, the areas of hot and cold cracking, etc. The most commonly used programs are simulation casting packages, such as: MAGMASOFT, FLOW-3D, ProCAST, WinCast [1]. For the simulation of the residual stresses occurring during the cooling process, the Flow3D packet is also applied [2]. In order to solve the issue of thermal stresses in the casting, the finite difference method [3,4] or the finite element method [4] are used. It is assumed that the internal (so-called, residual) stresses occurring during the casting process can be divided into macro-stresses (so-

called stresses of the first kind, formed within the casting) and microstresses (so-called stresses of the second kind, formed within the microstructure grains) [5]. In a raw casting, after its cooling to room temperature, a complex state of internal stresses is present – a state of casting stresses [6]. This state is the final effect of the momentary stress systems, which are formed during the crystallization (phase stresses) and cooling of the casting in the casting mould, as well as after its removal from the mould and cooling to room temperature and the temperature equalization in the whole casting volume (thermal stresses). In this way, the casting is led to the state of thermal equilibrium and it is not loaded by any external forces. It is the sum of the thermal stresses  $\sigma_t$ , phase stresses  $\sigma_p$ , and shrinkage stresses  $\sigma_s$  (caused by the mechanical inhibition of the shrinkage because of the resistance of a particular part of the casting mould, most of all, the cores) creates the residual casting stress  $\sigma_0$  (1).

$$\sigma_t + \sigma_p + \sigma_s = \sigma_o \quad (1)$$

The momentary stresses, which are formed at different stages of the formation from the liquid state of the microstructure of the casting can exceed the strength of the material at a given temperature, which causes hot cracking of the cast, or cold cracking, when the stresses are caused by the stress system in the cast, in the solid state [7]. The article presents a continuation of tests aiming at identifying the cause of the formation of defects in a thick-walled bushing casting made in the die casting technology from complex aluminium bronze CuAl10Fe5Ni5Cr.

## 2. Work methodology

The methodology of: melting bronze CuAl10Fe5Ni5Cr, casting, alloy's thermal parameters introduced as the input parameters for the simulation of die casting, solidification and cooling of the casting in the mould with the use of the MAGMA5.3 program, has been discussed in the paper [7].

Figure 1 shows a model of a die after the alloy is casting and the location of the stress control points (SC). Points 13, 15, 18 and 22 are located inside the bushing casting at the depth of 5 mm from the die's wall, whereas points 14, 17, 21 and 26 are located inside the bushing casting at the depth of 5 mm from the core surface.

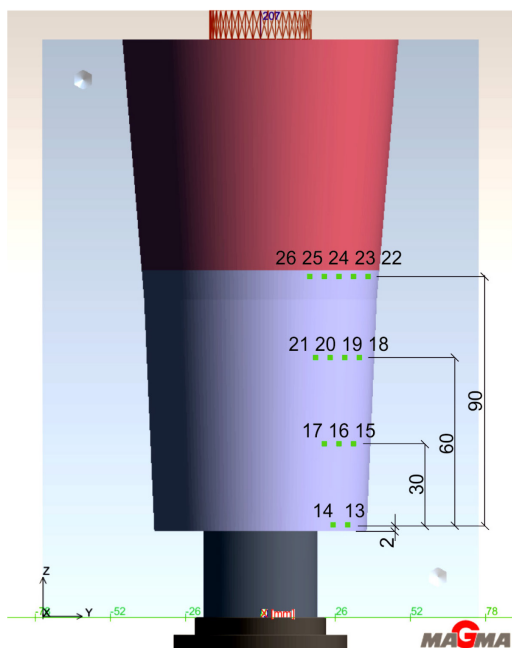


Fig. 1. Model of a die after the alloy is cast; location of stress control points (SC)

In order to identify the changes in the alloy's microstructure in a thick-walled bushing cast, microsections were made on samples cut out of the bushing, which revealed the microstructure of the alloy at the bushing's height  $h = \{2, 30, 60, 90\}$  mm. The microsections were etched with the Klemm II reagent. Digital microstructure images were made by means of the metallographic

microscope Nikon Eclipse MA200 (brightfield illumination, Nomarski contrast – DIC).

The article presents the results of a simulation of the main maximal stresses  $\sigma_{max}$  and minimal stresses  $\sigma_{min}$ , as well as Von Mises stresses calculated for the beginning of their formation  $\tau = 11.857$  s (with 16% content of the solid phase in the cast's volume), after the alloy's solidification in the casting  $\tau = 1$  min 21 s and after the cast's cooling to 30 °C, after the time  $\tau = 3$  h 33 min 36 s.

## 3. Description of achieved results of own researches

### 3.1. Temperature field and microstructure

The course of the crystallization process in reference to the amount and size of the phases crystallizing in the alloy's microstructure is mostly affected by the varying temperature field in the alloy and thus also the different values of the alloy's supercooling in different areas of the cast. Figure 2 (a,b) shows the temperature field in the casting after the time  $\tau = 11.857$  s (a) and after the alloy's solidification in the casting  $\tau = 1$  min 21 s (b).

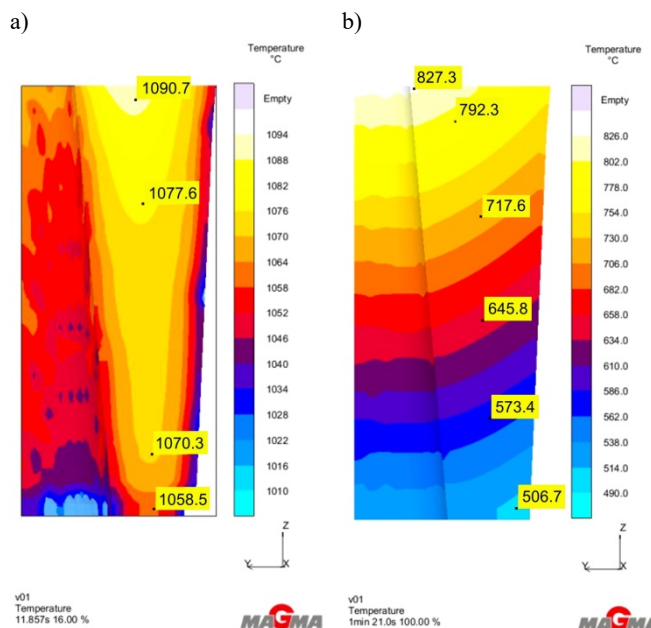


Fig. 2. Temperature field on the bushing's wall cross-section after the time: a)  $\tau = 11.857$  s, b)  $\tau = 1$  min 21 s

The microstructure of the examined bronze in the casting of a thick-walled bushing at the selected height  $h$  and the locations in respect of a particular part of the mould are presented in Figure 2. The bronze microstructure is composed of the following phases or their systems:  $\alpha_{Cu}$ ,  $\kappa_{II}$ ,  $\kappa_{III}$ ,  $\alpha_{Cu} + \gamma_2$ . The Cr addition dissolved mainly in phases  $\kappa$ , and, to a lesser extent, in solutions  $\alpha_{Cu}$  and  $\gamma_2$ .

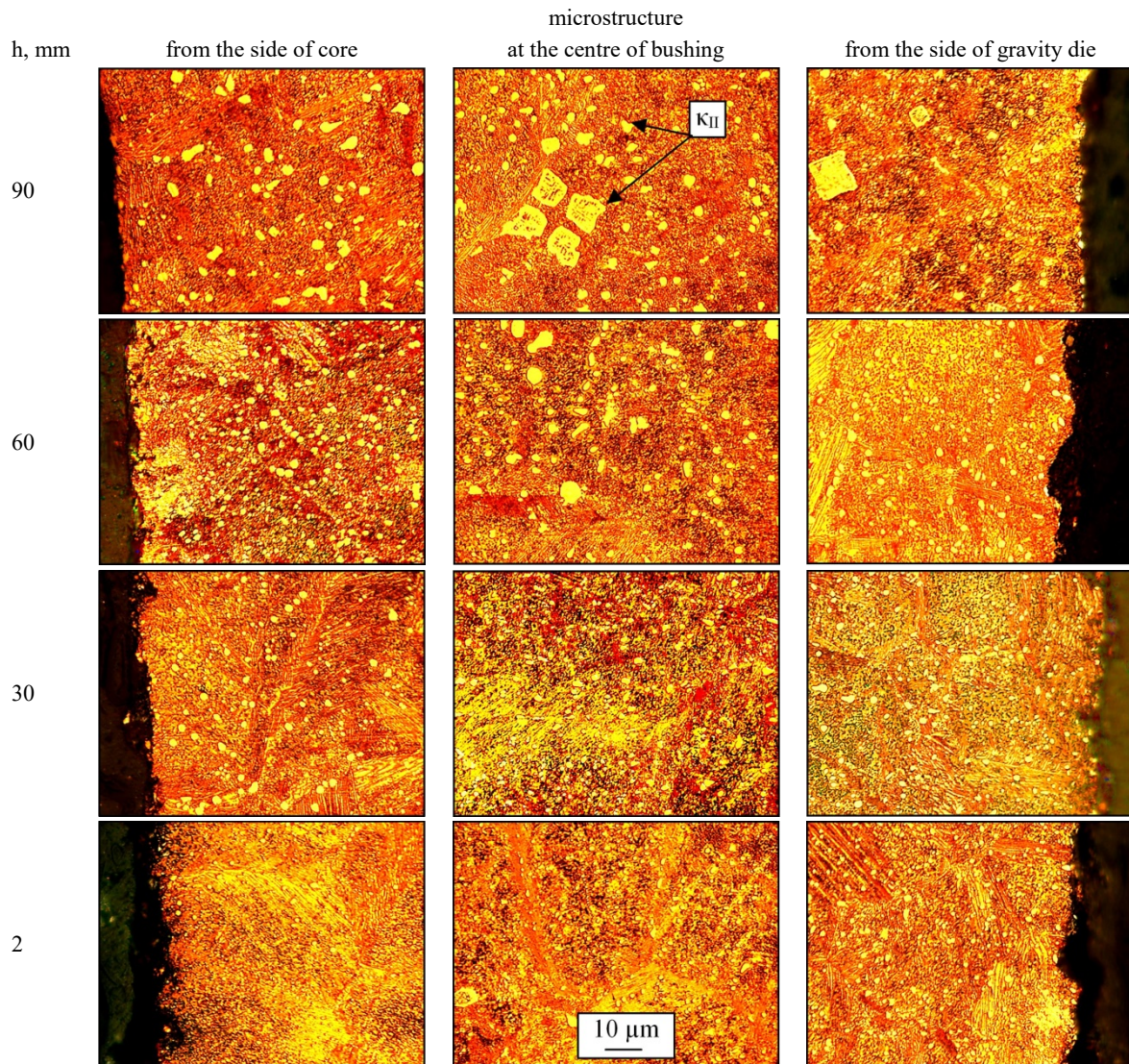


Fig. 3. Microstructure of CuAl10Fe5Ni5Cr in function of location in bush

It can be inferred from the presented data (Fig. 2 and 3) that the temperature gradient existing on the cross-section of the cast's wall decreases the alloy's cooling rate, and this, mostly, increased the size of phase  $\kappa_{II}$  precipitates in the upper part of the bushing, which causes changes of the phase stresses  $\sigma_f$ .

### 3.2. Residual stress in the thick-walled bushing

Figure 4 (a-f) shows, on the bushing's wall, the main, maximal and minimal, thermal and shrinkage stress fields, as well as reduced, Von Mises stresses after the time  $\tau=11.857$  s (a) and after the alloy's solidification in the casting  $\tau=1$  min 21 s (b). It can be inferred from the performed simulation that after the solidification of about 16% of the liquid bronze, solid phase areas

are appear in which the first internal stresses on the casting are formed ( $\tau=11.857$  s). Until the metal core is removed from the cast, i.e. up to 625 °C, the forming stresses are thermal  $\sigma_t$  and shrinkage  $\sigma_s$  stresses, and below this temperature – mainly thermal  $\sigma_s$  stresses. After the solidification of the bushing ( $\tau=1$  min. 21 s), the maximal tensile stresses occur on the side of the core, whereas, compressive stresses are formed on the external surface of the bushing, on the side of the die and at the base of the bushing, on the side of the core. Such a system of stresses is related to the temperature field during the alloy's solidification and the inhibition of the casting shrinkage of the bronze through the presence of a non-deformable core inside the bushing.

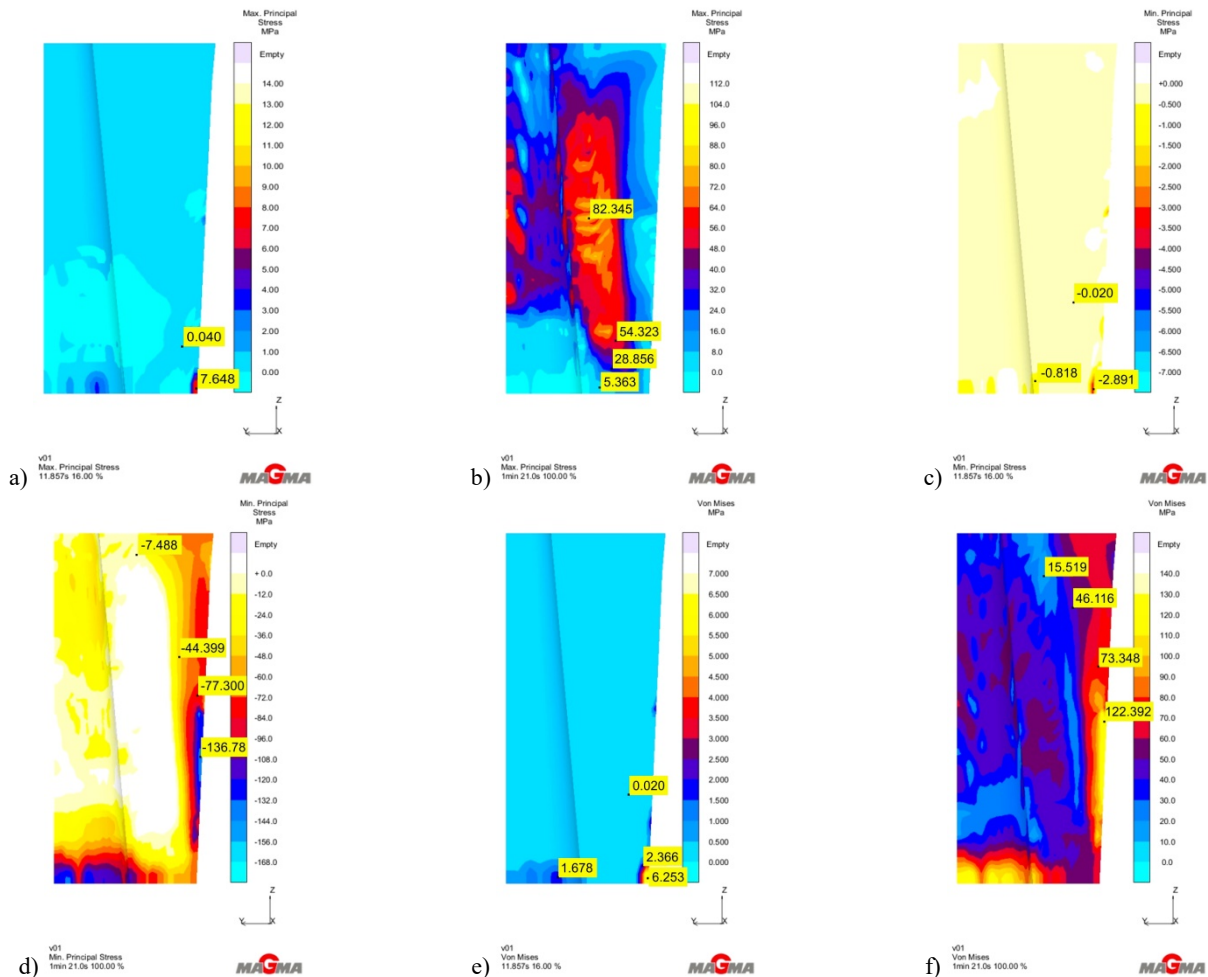


Fig. 4. Stress field: a-b) main maximal stresses, c-d) main minimal stresses, e-f) reduced Von Mises stresses; a,c,e –  $\tau=11.857$  s; b,d,f, –  $\tau=1$  min 21 s

Table 1 shows the values of the main maximal and minimal thermal stresses  $\sigma_t$ , calculated based on the simulation, as well as Von Mises stresses, calculated from the simulation for the time  $\tau=3$  h 33 min 36 s – bushing's solidification to 30 °C – for characteristic points SC.

For the characteristic points SC, located on the cross-section described by the height  $h$ , the calculated stress values are presented in Figure 5 (a-d).

Figure 6 (a-d) shows a compilation of these stresses, depending on the location in respect of the particular elements of the metal mould.

Table 1. Characteristic points SC and value of thermal stress  $\sigma_t$ :  $\sigma$  max,  $\sigma$  min, von Mises

SC	$\sigma$ max, MPa	$\sigma$ min, MPa	von Mises, MPa
13	16.5	-133	134
14	8.68	-137	127
15	168	14.5	141
16	136	27.5	99.5
17	51.2	-84.6	119
18	236	28.1	182
19	184	70.5	105
20	81.2	-23.7	92.2
21	34.9	-177	196
22	34.1	-28.8	54.6
23	20.6	-90.7	99.5
24	24.7	-169	184
25	35.9	-194	211
26	31.7	-194	210

It can be inferred from the presented stress simulation results (Fig. 5 and 6) that the change in the location of the control point SC in the bushing's volume is accompanied by a significant diversification of the thermal stresses. The distribution of the main maximal and minimal stresses, as well as von Mises stresses, changes depending on both the distance from the feeder (Fig. 5) and the distance from a particular part of the metal mould

– the die or the core (Fig. 6). In the vicinity of the feeder, at the height  $h=90$  mm, and at the base of the bushing,  $h=2$  mm, compressive stresses are dominant (Fig. 5d). The central part of the bushing,  $h=\{60,30\}$ , is dominated by tensile stresses. The external surface of the bushing – from the contact side of with the metal mould – is mainly subjected to tensile stresses (Fig. 6a), whereas on the side of the core – to shrinkage stresses (Fig. 6b).

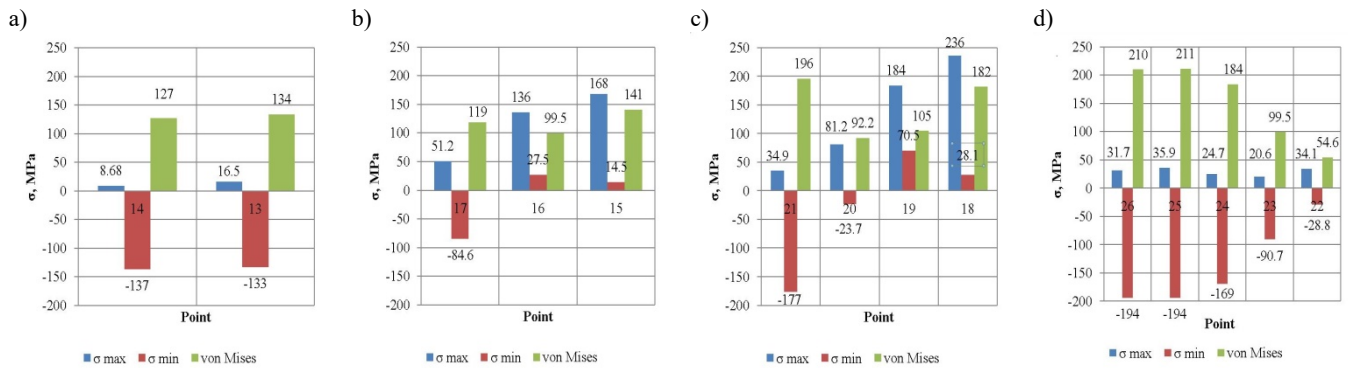


Fig. 5. Calculated stress values for characteristic points SC located on the cross-section described by the height  $h$ : a)  $h=2$  mm (SC13 and SC14), b)  $h=30$  mm (SC15–SC17), c)  $h=60$  mm (SC18–SC21), d)  $h=90$  mm (SC22–SC26)

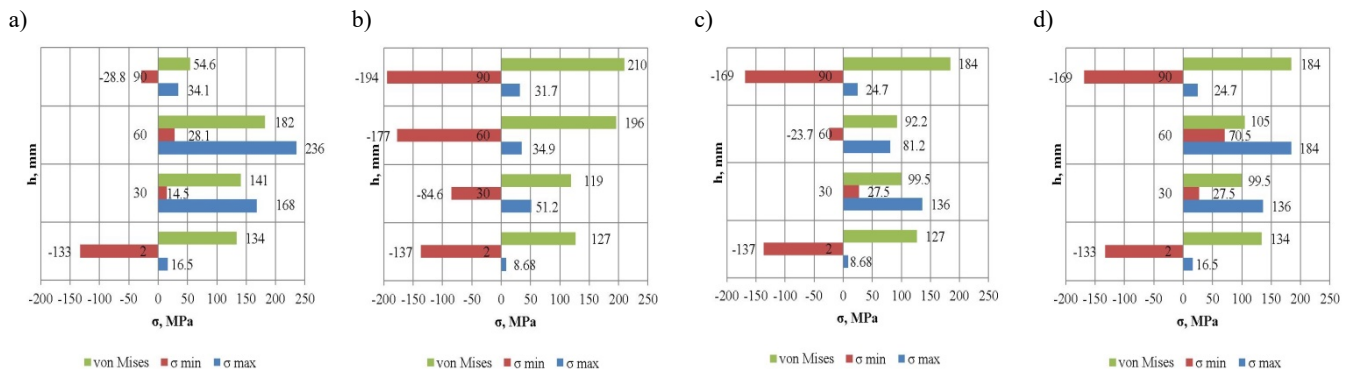


Fig. 6. Calculated stress values for characteristic points SC depending on the location in respect of the elements of the metal mould: a) 5 mm from the die's surface (SC{13,15,18,22}), b) 5 mm from the core (SC{14,17,21,26}), c) centre of the bushing's wall on the side of the die (SC{13,16,19,24}), d) centre of the bushing's wall on the side of the core (SC{14,16,20,24})

## 4. Conclusions

The die casting of a thick-walled bushing made of bronze CuAl10Fe5Ni5Cr is characterized in a strongly inhomogeneous distribution of residual stresses. It can be inferred from the performed investigations of the bushing's microstructure that relatively the highest phase stresses  $\sigma_f$  are present in the upper part of the bushing, especially in the central part of its wall, due to the significant difference in the size and amount of phase  $\kappa_{II}$ . The analysis of the performed simulation of the main, maximal and minimal, thermal and shrinkage stresses, as well as Von Mises stresses, in the bushing's casting show a high diversification of these stresses depending on the location of the control point SC in the volume of the bushing. The character of these stresses will probably slightly change even after the treatment forming the ready product. This can be the cause of the diversification of the

operation properties (friction coefficient, wear). Due to the above, it is necessary to analyze the possibilities to perform thermal treatment guaranteeing homogenization of the internal stresses in the cast, as well as to introduce changes in the construction and the casting technology.

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