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Feeding and Cooling and Time of Thermal Treatment of a Massive Bush Made of the Complex Aluminum Bronze Cast by the Lost Foam

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Abstract

Small additions of Cr, Mo and W to aluminium-iron-nickel bronze are mostly located in phases κ_i ($i=II; III; IV$), and next in phase α (in the matrix) and phase γ_2 . They raise the temperature of the phase transformations in aluminium bronzes as well as the casts' abrasive and adhesive wear resistance. The paper presents a selection of feeding elements and thermal treatment times which guarantees structure stability, for a cast of a massive bush working at an elevated temperature (650–750°C) made by means of the lost foam technology out of composite aluminium bronze. So far, there have been no analyses of the phenomena characteristic to the examined bronze which accompany the process of its solidification during gasification of the EPS pattern. There are also no guidelines for designing risers and steel internal chill for casts made of this bronze. The work identifies the type and location of the existing defects in the mould's cast. It also proposes a solution to the manner of its feeding and cooling which compensates the significant volume contraction of bronze and effectively removes the formed gases from the area of mould solidification. Another important aspect of the performed research was establishing the duration time of bronze annealing at the temperature of 750°C which guarantees stabilization of the changes in the bronze microstructure – stabilization of the changes in the bronze HB hardness.

Keywords: Innovative materials and casting technologies, Lost foam, Aluminium bronze, Casting properties, Riser heads, Steel internal chill, Thermal treatment

1. Introduction

Composite aluminium bronzes with additions of Cr, Mo and W characterize in a high abrasive wear resistance in the state as-cast as well as high mechanical properties both in the state as-cast and after the thermal treatment [1,2]. These bronzes characterize in the volume contraction of the order of 4–7% and the linear contraction of around 1.3–2%. That is why, in order to obtain

a cast without defects caused by a high volume contraction, it is necessary to use risers [3,4]. So far, the casting process of such bronzes by the lost foam method has not been studied. The presence of the pressure of the formed gas over the mirror of the metal filling the mould cavity during gasification of the EPS pattern [5,6] will have a positive effect on the work of the risers. This impact will probably be close to the work of pressure risers. For composite aluminium bronzes with additions of Cr, Mo and

W, clear guidelines have been elaborated for the riser design. For aluminium, risers of the following modules are used $\Omega = M_R/M_C = 1.2-1.6$ (M_R – riser module, M_C – cast module) [3,7]. That is why the work undertakes the challenge of selecting the elements of feeding (risers) and cooling (moulds) of a massive bush made of the examined bronze cast by the lost foam technology. Using this method for alloy casting guarantees relatively high measurement accuracy [8,9] on the condition of a proper consideration of the following in the pattern design: the volume contraction (risers) and the linear contraction (contraction allowances). Also performed are simulation tests of the conditions under which the mould cavity is filled with liquid metal in the lost foam technology [10,11]. However, there is no sufficient data necessary for the simulation of the process of filling the mould cavity with liquid composite bronze with Cr, Mo and W additions. That is why the test results constitute the output (validating) data for the future computer simulation of this process. Due to the fact that the bush would work at a high temperature within the range of 650–750°C, it was also annealed at 750°C in order to determine the tendency for microstructure changes and its HB hardness.

2. Test methodology

2.1. Alloy preparation

The chemical composition of composite aluminium bronze CuAl10Fe5Ni5-CrMoW is shown in Table 1.

Table 1.
Bronze chemical composition

Chemical composition, %							
Al	Fe	Ni	Cr	Mo	W	Cu	other
10.1	4.6	4.7	0.2	0.1	0.1	79.2	balance

The bronze was cast in a crucible induction furnace of the frequency of 3.5kHz in an AC20 silicon carbide crucible. A liquid alloy of the temperature of 1250±10°C was cast into EPS patterns imaging the casts for the technological studies: the volume contraction, the linear contraction mechanically impeded, as well as massive bush casts.

In order to isolate the melted metal from the atmosphere of the furnace, synthetic coating-refining slag BA-1 was used (mixture of sodium fluoride and sodium fluorosilicate by PEDMO S.A.) by way of introducing a half of it on the, so-called, cold charge and the other half on the metallic mirror. With the purpose to create an inert atmosphere over the metallic mirror, charcoal was additionally applied onto the surface of the metal charge.

2.2. Technological trial pattern equipment and a massive bush cast

A scheme of the station for alloy casting by the lost foam method is presented in Figure 1.

In order to determine the linear contraction and the volume contraction, for patterns of the examined composite aluminium bronze (Tab. 1) obtained by the lost foam method, pattern equipment was designed and produced, which consisted of a cuboidal pouring gate, an ingate, a frame for evaluating the mechanically impeded linear contraction and a cylindrical trial cast for the determination of the volume contraction.

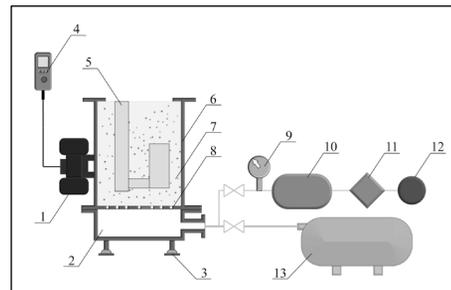


Fig. 1. Scheme of the station for lost foam alloy casting
1 – electrovibrator, 2 – air chamber, 3 – elastic supports (vibroisolators), 4 – inverter, 5 – EPS pattern with fireproof coating, 6 – moulding flask, 7 – quartz sand without binder, 8 – perforated bottom, 9 – vacuumometer, 10 – accumulating tank, 11 – air filter, 12 – vacuum pump, 13 – compressed air installation

The pattern equipment for the technological studies of the casting contraction – linear and volume – is presented in Figure 2.

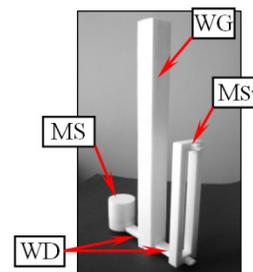


Fig. 2. EPS equipment pattern for evaluating the volume contraction and the impeded linear contraction of composite aluminium bronze cast by lost foam method, WG – pouring gate, WD – ingate, MSv – pattern for volume contraction evaluation, MS – pattern for impeded linear contraction evaluation

The volume contraction S_v in % was determined from equation (1), by way of calculating the theoretical volume V_o of the examined sample – the volume of the EPS pattern – and the actual volume V determined experimentally by the Archimedes method.

$$S_v = ((V_o - V)/V_o) \cdot 100\% \quad (1)$$

The linear contraction was determined from equation (2):
 $s = ((L_o - L)/L_o) \cdot 100\%$ (2)
 where:

L_o – distance between markers for contraction frame pattern, cm;
 L – distance between markers for contraction frame cast, cm.

The tests were performed for a massive bush of the size presented in Figure 3.

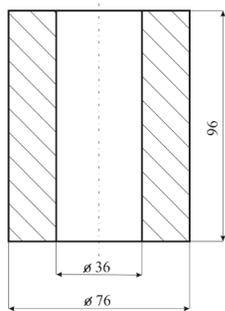


Fig. 3. Massive bush

Figure 4 shows the construction of the EPS pattern of the cast and the pattern equipment. The elements of the gating system and the pattern of the bush were cut out of a high-molecular material on a thermal plotter, P60S Megaplot. The examinations involved the use of two types of material for the patterns: foamed polystyrene, density 17kg/m^3 , and extruded polystyrene, density 40kg/m^3 .

The foamed polystyrene was applied for the elements of the gating and the feeding system. The extruded polystyrene was used for those parts of the patterns for which correct imaging of the surface roughness was significant. Polystyrene of a lower density was used for the inner part of the pattern and next, it was covered with a thin sheet of polystyrene of a high density (styrodur) in order to assure a lower roughness of the cast. With the purpose to identify the potential defects of the cast made of the examined bronze by the lost foam method, tests were performed of the pattern equipment without risers necessary for massive casts made of an alloy characterizing in a high volume contraction, such as the composite aluminium bronze.

The pattern equipment consisted of a cuboidal upper gate (WG – size $25 \times 25 \times 300\text{mm}$), an ingate (WD – size $15 \times 16 \times 35\text{mm}$) and a bush pattern (MO).

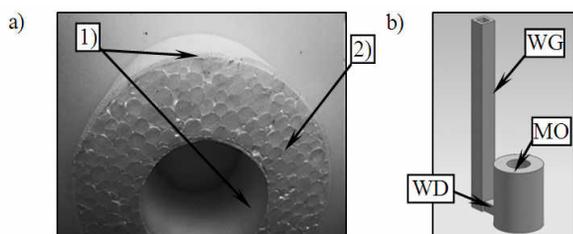


Fig. 4. EPS bush pattern (a) 1 styrodur, 2 low-density polystyrene (b) WG – sprue, WD – ingate, MO – bush pattern

The patterns were covered with a fireproof coating, Disopast 7805/3 by Huttenes-Albertus. The coating was applied by means of a brush. Each element of the pattern equipment was covered with two layers of the coating.

2.3. Cast feeding system design

Due to the fact that the process of filling the mould cavity with composite aluminium bronze has not been studied before, the

Nielsen gate was not applied, as is the case of the traditional sand moulds [3]. Instead, a straight gate was used, which guarantees a wider stream of the metal in the gating system and a more rapid gasification of the EPS pattern. For the same reason, a swirler was not used either.

With the aim of the proper feeding of the bush, a feeding system was designed and produced. In the first approach to the problem, the guidelines for designing steel cast risers were used [12] with a volume contraction similar to that of the examined aluminium bronze. In the design, the following proportions were applied (3) between the casting modules of: the thermal centre M_W , the riser neck M_{SZ} and the riser M_R .

$$M_W : M_{SZ} : M_R = 1 : 1,1 : 1,2 \quad (3)$$

For aluminium bronzes, the mass of the riser head can be approximately determined from equation (4) [4]:

$$m_R = \sqrt{m_C} \cdot \sqrt[3]{w_C} - \frac{w_C}{10} \quad (4)$$

where:

m_R – riser mass in kg,

m_C – cast mass in kg,

w_C – cast wall thickness in mm.

2.4. Thermal treatment

The bronze samples cut out of the bush underwent the process of thermal treatment. According to its scheme presented in Figure 5, the samples were placed in the furnace and next heated together with the furnace from the ambient temperature (20°C) to the temperature of 750°C . The first sample was removed from the furnace after 1h, and each of the remaining samples – after the period of another hour. The samples underwent free cooling at 25°C .

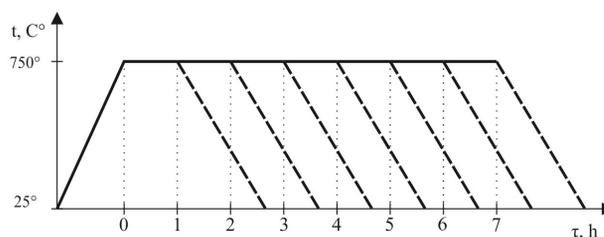


Fig. 5. Scheme of thermal treatment process

2.5. HB hardness measurement

The measurement of the hardness of bronze in the state as-cast and after the thermal treatment was performed according to the standard PN-EN ISO 6506-1:2008 (Metals – Hardness measurement by Brinell method - Part 1: Test methodology).

3. Test results

3.1. Casting contraction determination

Table 2 presents the measurements of the volume V and the length L of the test casts (Fig. 2) for the evaluation of the volume contraction S_V and the linear contraction s of the examined bronze.

Table 2.

Measurements of volume V and length L of test casts for the evaluation of volume contraction S_V according to equation (1) and linear contraction S according to equation (2)

Lp	V_3 , cm ³	V_{O_3} , cm ³	S_V , %	L , mm	L_0 , mm	s , %
1	48.0		5.9	153.0		1.9
2	47.5		6.9	153.4		1.7
3	47.8	51.0	6.3	153.9	156.0	1.3
4	48.5		4.9	153.0		1.9
5	48.0		5.9	153.5		1.6
Average			6.0	Average		1.7
Stand. Deviation σ			0.72	Stand. Deviation σ		0.24

3.2. Preliminary tests

The first cast was made according to the basic variant of pattern equipment (Fig. 4b). Figure 6 a–c shows the following: a photograph of the bush cast (a), a photograph of the surface inside the bush (b), a section along its wall (c) and the identified cast defects.

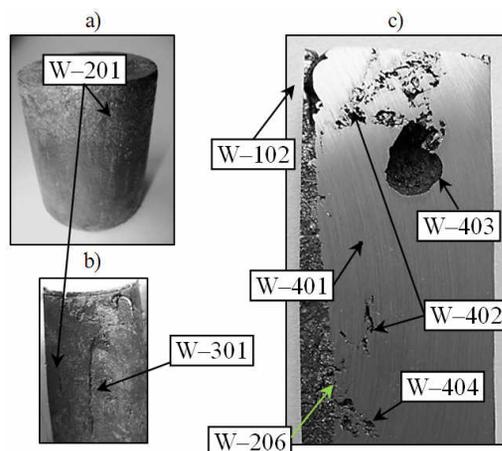


Fig. 6. Photograph of bush cast: a) inner surface, b) outer surface, c) section along bush wall

Table 3 presents the defects of the bush cast. The source of those defects is mostly the non-compensated volume contraction of the examined bronze (defects: 102; 206; 301; 401–404) as well as the lost foam technology itself (a significant amount of gases released during the pattern gasification; defects: 201; 401; 402).

Table 3.

Bush cast defects

Group	Name	Marking [13]
Shape defects	Short casting	W – 102
	Roughness	W – 201
Raw surface defects	Shrinkage depressions	W – 206
	Discontinuities	Hot cracking
Inner defects	Gas cavity	W – 401
	Porosity	W – 402
	Contraction cavity	W – 403
	Micro-shrinkage	W – 404

The produced cast, as well as its identified defects and their distribution constituted the basis for the selection of the feeding and the cooling system which would eliminate those defects.

3.3. Cast feeding analysis

Figure 7 a–e presents the variants of feeding and cooling of the massive bush cast. Five feeding variants were used to perform the tests with the use of the following risers: side cylindrical risers (a), upper cylindrical riser (b), shape risers without a cooling mould (c) and with a perforated cylindrical mould placed inside the cast (d) or with a perforated cylindrical mould with a lowered surface of openings (e).

On the basis of the defects in the cast (Fig. 6), the thermal centre area was determined, which covered the upper part of the bush at the height of 25 mm, with the volume of about $V_W=88$ cm³. The module of the thermal centre was determined to be $M_W=0.71$ cm. For side cylindrical risers (a), in order to increase their range, two risers were used with the module $M_R=0.85$ cm determined from relation (3). The size of a riser was selected for the feeding of at least half of the thermal centre volume and the volume contraction of the order of 6% [12].

The side cylindrical risers (Fig. 7a) did not fulfil their role; they only reduced the defects of the raw surface shape, the discontinuities and the inner defects (Table 3, Fig. 6). In the upper part of the cast, short casts were still present. This was probably caused by the fact that, for the assumed sizes of the pouring gate and the ingate as well as the side risers, the generated metallostatic pressure and the rate of transporting the liquid bronze to the gasified pattern were not sufficient to push out the whole of the gas formed during the pattern gasification before the inner surface of the bush solidified.

The feeding of the cast from the top while maintaining the same geometry of the risers (Fig. 7b) limited the presence of the mentioned defects even more; however, it did not eliminate them completely. An improvement of the cast quality, in this case (as compared with the solution presented in Fig. 7a), was mostly caused by the increase of the metallostatic pressure of the column of metal in the risers, which were gravitationally transporting the liquid bronze to the crystallization front in the bush, and that favoured a stronger removal of the gases through the ceramic coating of the pattern.

As the obtained cast was not satisfactory, the shape of the risers was modified and a module assumed for their construction was the same as that for cylindrical risers $\Omega=M_R/M_C=1.2$, yet of a much increased height, which guaranteed an increase of the metalostatic pressure in the cast and facilitated the risers being shut off the bush. The use of shape risers (Fig. 7c) allowed for the removal of all the, so far, identified defects, except for the hot cracks. This was probably caused by the fact that the heat was too slowly transported through the cast to the inside of the bush. In consequence, the bush solidified more slowly from the side of the inner surface than from the side of the outer one.

In order not to increase the volume of the risers, a steel internal chill was used in the shape of a massive bush (Fig. 7d). In order to make possible the gas offtake in the direction of the inner surface of the bush in the chill, cross-drillings, of a diameter higher than the quartz sand grains, were made on the contact surface with the pattern ceramics. In this way, all the defects of the cast were eliminated; however as a result of the low strength of the ceramic coating, cracks were observed on the latter, which made the metal flow into the chill's openings. This disadvantage was removed by way of lowering the surface of the openings (longitudinal canals) in relation to the surface of the ceramic coating as much so as the remaining space could be easily filled with a layer of sand (Fig. 7e).

The mass of the riser calculated from equation (4) equals about 2.5kg. As a result of the use of a bush, the mass of the designed shape riser is much lower than the calculated one, and it equals about 1.3 kg.

3.4. Thermal treatment

In the state as-cast, the microstructure of the bronze is composed of phases κ_{II} rich in Fe, Al, Cr, Mo and W, as well as phase systems $\alpha+\kappa_{III}$, $\alpha+\kappa_{IV}$ and $\alpha+\gamma_2$. As a result of the thermal treatment consisting in annealing the bronze at 750°C for the time period of 1 to 7 hours, we obtained a comparable microstructure

Table 4.

HB hardness and standard deviation σ of bronze CuAl10Fe5Ni5CrMoW in state as-cast and after thermal treatment

State as-cast		Annealing time τ , h													
		1		2		3		4		5		6		7	
HB	σ	HB	σ	HB	σ	HB	σ	HB	σ	HB	σ	HB	σ	HB	σ
270.3	2.2	273.4	3.8	274.9	1.1	275.7	1.0	285.2	2.3	285.0	2.3	285.5	1.9	285.1	0.9

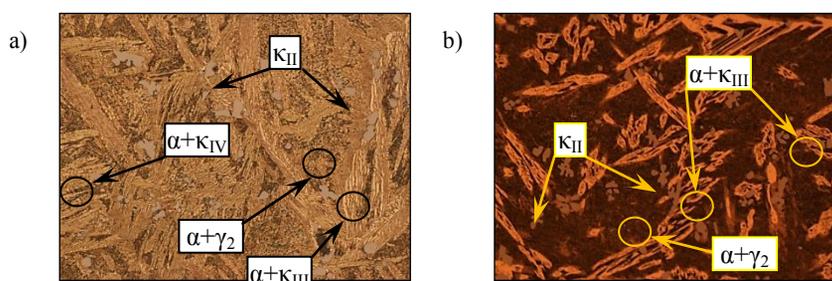


Fig. 8. Microstructure of bronze CuAl10Fe5Ni5CrMoW in state as-cast (a) and after thermal treatment (b)

consisting of phases κ_{II} rich in Fe, Al, Cr, Mo and W, which coagulated together with the increased annealing time, the increased amount of eutectoid $\alpha+\gamma_2$, as well as the phase systems $\alpha+\kappa_{III}$ in which, by way diffusion, we observed an increase of the thickness of the plates of phase κ_{III} , followed by their coagulation. Figure 8 shows a representative microstructure of bronze CuAl10Fe5Ni5CrMo in the state as-cast (a) and after the thermal treatment (b).

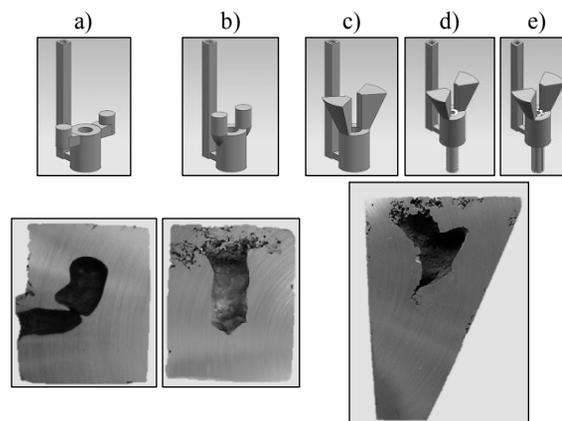


Fig. 7. Variants of the feeding and cooling system of the inner surface of the massive bush cast and sections of the risers:

- a) side cylindrical risers, b) upper cylindrical risers,
- c) upper shape risers, d) upper cylindrical risers with a steel internal chill, e) upper shape risers with a perforated steel internal chill of a lowered surface of openings

Table 4 and Figure 9 compile the results of the HB hardness measurement for the bronze in the state as-cast and after the thermal treatment. The presented data suggests that, after the annealing time of 4 hours, we observe stabilization of the bronze hardness changes at the level of about 285 HB.

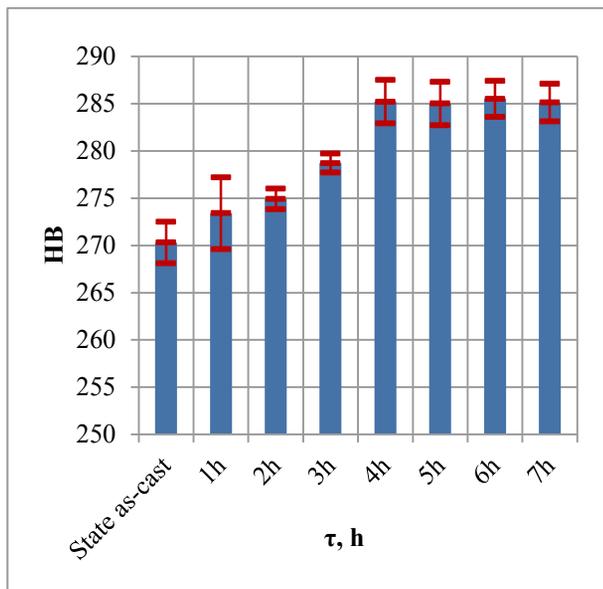


Fig. 9. HB hardness and standard deviation of bronze CuAl10Fe5Ni5CrMoW in state as-cast and after thermal treatment for 1h to 7h

4. Conclusions

The performed research suggests that:

- In reference to the selection of the elements of feeding and cooling of a massive bush made of bronze CuAl10Fe5Ni5CrMoW, cast by the lost foam method:
 - The lack of a properly designed feeding system of the cast causes the formation of: shape defects, raw surface defects, discontinuities, inner defects,
 - The source of these defects is mostly the non-compensated contraction volume of the examined bronze,
 - The source of these defects is also the lost foam technology itself, in which a significant amount of gases is released during the pattern gasification,
 - The use of high upper shape risers, increasing the metalostatic pressure of the alloy in the areas shaping the cast of the bush and the inner steel internal chill, eliminates the defects;
- In reference to the selection of the annealing time of the bush at 50°C:

- Annealing the bush for the time of 4h guarantees stabilization of the microstructure which characterizes in the hardness at the level of about 285HB.

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