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## Si AND Mn EFFECT ON MECHANICAL PROPERTIES AND LINEAR SHRINKING OF NON-MAGNETIC Cu-Al SYSTEM CAST BRONZES

**Purpose.** To establish Si and Mn influence on mechanical properties level at 20 °C and aluminum bronzes structure with Al from 3 to 9 % mass content investigation.

**Methodology.** Cast bronzes mechanical properties have been determined based on their fracture results on FP-100/1 machine and PSW-30 pendulum impactor. Microstructure has been examined using Neophot-21 optical microscope. Bronzes linear shrinkage coefficients have been calculated based on results of determining cast cylindrical samples lengths changes. Si and Mn complex influence on bronzes properties has been determined by the results of simplex triangles according to H. Scheffer plan constructing. Temperature has been measured with chromel-alumel thermocouple completed with electronic potentiometer. Bronzes chemical composition has been determined on EXPERT 4L analyzer.

**Findings.** Silicon (up to 2 %) and manganese (up to 2 %) adding to Cu-Al system bronze, while aluminum content from 9 to 3 % reducing, leads to bronze ultimate tensile and yield strength decreasing during stretching and its plasticity increasing. At the same time, bronze structure, at any combination of Al, Si and Mn contents within their changes in studied limits, remains single-phase.

**Originality.** For the first time, comprehensive assessment of influence of Si and Mn with simultaneous decrease in Al content on mechanical properties and linear shrinkage of Cu-Al-Si-Mn system cast bronzes has been carried out. It has been established that all bronzes of studied compositions have a single-phase structure and mechanical properties level that is inherent for pressure-worked bronzes.

**Practical value.** The research results expand understanding about elemental and complex influence of Si and Mn on aluminum bronzes properties, provide an opportunity to choose a bronze with properties required level from its cast billet for deformation or to design castings taking into account the linear shrinkage values discovered in this work. The data obtained can also be the basis for new foundry, corrosion-resistant, non-magnetic bronzes, which have strength and density at the level of some carbon steel grades, development. Such materials have been used for parts that operate in chemically aggressive environments manufacturing, for control and measuring equipment and devices parts, for ship parts and naval devices, fittings, bushings, couplings, intrinsically safe tools, etc.

**Keywords:** *bronze, strength, shrinkage, mechanical properties, aluminum, silicon, manganese*

**Introduction.** Steady expansion of technique using areas, its operation heavy and diverse conditions, increasing requirements for durability, reliability and its exploitation safety are the main factors that determine new materials searching necessity. Among such materials are aluminum bronzes with new levels and complexes of desired properties.

Aluminum bronzes within each grade have unique properties combinations. Among them are high strength, plasticity, elasticity, corrosion, erosion, cavitation and abrasive resistance, resistance to corrosion fatigue, wear resistance to friction, operational properties high level at high and low temperatures, resistance to fatigue and creep, resistance to oxidation at elevated temperatures in oxidizing environments, good weldability, low magnetic susceptibility, good machinability with blade tool, high thermal and electrical conductivity, toxicity to marine organisms (algae, lichens, mussels, sea acorns), industrial parts manufacturability by deformation and

casting, etc. All this has determined aluminum bronzes applications wide scope. They are used to manufacture parts for sea and river vessels and ships, offshore platforms, marine equipment, seawater desalination systems, equipment for working in sour mines, drilling rigs, non-critical engine parts, heat exchangers, equipment for chemical and food industries, parts that work into contact with acidic and alkaline environments, variety of industrial technological fluids, gases for automotive and railway transport, mining equipment, metallurgical and construction industries, etc. [1, 2].

Today, among the most popular are aluminum bronzes with low magnetic permeability ( $m \leq 1.05$  H/m) [3]. Such bronzes are used to make parts for precision control-measuring devices, oil and gas exploration instruments, medical magnetic resonance imaging scanners, compasses, telescopes, displays, minesweepers, submarines, fasteners and fittings for different watercrafts. Non-magnetic aluminum bronzes are also used for coins manufacturing, tools and equipment for working with explosives, chemicals and fuels in mining in-

dustry, equipment parts for oil and gas rectification, aerospace technic elements, etc. [1, 3].

Among non-magnetic bronzes are tin, aluminum, silver, lead, and other bronzes that do not contain ferromagnetic chemical elements (iron, nickel, cobalt) or these components are minor admixture in bronzes, and bronzes structure does not contain or contains in small quantities electronic compounds which have ferromagnetic properties –  $\text{Cu}_2\text{MnAl}$ ,  $\text{Fe}_3\text{Al}$ ,  $\text{Ni}_3\text{Mn}$ ,  $\text{SmCo}_5$ , etc. [3, 4].

Today, among standardized corrosion-resistant non-magnetic or low-magnetic bronzes in the world, largest share is occupied by bronzes for pressure processing. In Ukraine, according to generally accepted marking, for such structural foundry bronzes are provided two grades (БрА9Мц2Л, БрА10Мц2Л) for castings manufacturing. There are 1 or 2 grades in Germany (DIN), France (AFNOR) and some other countries standards. At the same time, in, for example, United States of America and Japanese standards such foundry bronzes are absent. At the same time, non-magnetic aluminum (БрА5, БрА7), aluminum-nickel (БрА10Н) or aluminum-silicon (БрА7К2) bronze, which are designated in standards of these countries as bronzes intended for pressure processing, are also used to limited extent in foundry production [5, 6].

Binary Cu-Al alloys with Al content of up to 8 % (by weight) are plastic single-phase bronzes that are suitable for pressure processing at any temperature. Binary bronzes with 8–10 % Al are two-phase alloys with increased strength and hardness levels. Such bronzes pressure treatment is carried out exclusively in hot state.

Binary Cu-Al casting bronzes absence in some countries standards is probably due to the fact that, when alloy contains 8–10 % Al, bronzes become two-phase and, as a result, quite brittle, which is due to body-centered cubic beta-phase (chemical compound) in their structure appearance.

Cu-Al-Si system bronzes are single-phase alloys with fairly high strength and ductility, which they acquire after deformation treatment. Among such bronzes is C64200 bronze (AMS 4634) or C95600 bronze with ~2 % silicon, ~7 % aluminum and up to 0.25 % [7] nickel content. It is included in United States standard as material with low magnetic permeability, high corrosion resistance and resistance against shock loads. The same bronze is also used for castings, which strength indicators level is somewhat lower than have the products made of deformed bronze with same composition.

Cu-Al-Mn system bronzes, containing 8–9 % Al and 13–15 % Mn, are magnetic (for example, БрА7Мц15Ж3Н2Ц2), strong and have good casting properties and weldability. Cast products made from such bronzes are resistant to shock and cavitation, which is why they are widely used, in particular, for marine propellers manufacturing. In order to magnetic permeability level somewhat (by ~0.1 H/m) reducing, products made of such bronzes have to be heat treated [3, 8].

Bronzes БрА9Мц2Л, БрА10Мц2Л and БрА9Н1, which are standardized as foundry, are two-phase, non-magnetic or low-magnetic alloys with high corrosion resistance in seawater. These bronzes are used to make marine propellers, valves, antifriction cast parts, fittings that operate in fresh water, liquid fuel or steam at tem-

peratures up to 250 °C, etc. [3, 9]. Foundry non-magnetic corrosion-resistant bronzes have mechanical properties satisfactory level in cast state and their increasing possibility by carrying out appropriate heat treatment.

Naturally, by two-phase bronzes heat treating it is possible to significantly change their mechanical properties level, but, at the same time, not significantly effect, for example, their exploitation properties (hermetic, corrosion resistance in sea water and salt fog, etc.), which level is largely determined by any alloy genesis (chemical composition, microstructure). That is, standardized foundry non-magnetic corrosion-resistant bronzes small number, in modern technology dynamic development conditions, not only limits the choice and scope of these materials application, but also makes it necessary to use substitute materials that are not always suitable or economically reasonable for such cases. This increases the risk of unplanned delays appearance due to equipment laborious losing.

It follows from above that work aimed at non-magnetic or low-magnetic corrosion-resistant bronzes new grades researching and developing is relevant.

**Literature review.** Today, non-magnetic corrosion-resistant bronzes properties improvement has been achieved by using the multicomponent principle for their compositions. In particular, in order to ensure non-magnetic and corrosion resistance, the Vulcan's copper alloy contains the following chemical elements, % (by weight): 0.05–2.00 Ni, 8–15 Al, 0.5–8.0 Zn, 1–10 Sn, the rest – Cu (CN100447267C, China. December 31, 2008). Changes significant range in alloying elements content in Vulcan's alloy allows products with different properties levels to be manufactured from it by both: billets at 720 °C hot forging and casting. At the same time, while retaining its non-magnetism after forging, according to authors (CN100447267C, China. December 31, 2008), the Vulcan's alloy, in terms of corrosion resistance in seawater, has better corrosion resistance than red copper, but worse than silicon bronze.

In other cases, for corrosion resistance increasing, for example, in nickel-aluminum bronze Ni content in composition increases [10]. To cast parts surface protective coating by thermal spraying has been applied, according to R. C. Barik, et al. (2005). Cast parts surfaces have been treated by friction with stirring [11]. Castings complete heat treatment has been carried out [12]. Bronze rapidly solidified thin layer has been formed on cast parts surface with laser beam [13]. Cast parts surface layer has been alloyed with chromium by ion implantation [14], etc.

Various systems bronzes research results significant number today allow assessing the overall influence of chemical elements that make up their composition on their mechanical and operational properties level. In particular, it has been established that [1, 3]:

**Al** – increases mechanical, anti-corrosion and anti-friction properties, wear resistance, fluidity and hermetic. With Al content of up to 7 %, bronze is poorly machined by cutting;

**Fe** – refines cast bronze structure, increases strength and hardness, increases antifriction properties, reduces tendency to brittleness in two-phase bronzes, reduces

corrosion resistance and hot brittleness, worsens machinability by cutting with blade tool, gives bronze magnetic properties;

**Ni** – in aluminum and aluminum-iron bronzes increases corrosion resistance, technological and mechanical properties both at normal and elevated temperatures [9];

**Mn** – deoxidizer, increases strength, plasticity, yield strength, hardness and corrosion resistance [8, 15];

**Si** – deoxidizer, increases casting properties, strength, plasticity, elasticity, antifriction properties and corrosion resistance. Si provides good weldability, soldering and machinability by cutting. Currently, springs, membranes and other devices parts that operate in fresh or sea water at temperatures up to 250 °C have been made from bronzes grades БрКН 1-3, БрКМц 3-1 instead of beryllium bronzes;

**P** – deoxidizer, increases hardness, corrosion resistance in domestic environments, fluidity, prevents oxides formation. With P content of < 0.1 % increases hot brittleness, with P content of ≥ 0.1 % reduces bronzes hot brittleness. Improves weldability and machinability with blade tools;

**Sn** – increases bronzes crystallization temperature range, reduces fluidity, linear shrinkage, melt saturation with gas. Sn increases corrosion resistance, hardness, strength, but reduces elongation and impact toughness [15];

**Zn** – deoxidizer, increases casting properties and castings density, reduces hydrogen content in bronzes, reduces bronzes tendency to liquation. In aluminum bronzes undesirable impurity that reduces plastic, antifriction, and technological properties. In tin bronzes reduces crystallization interval, reduces linear shrinkage, hot brittleness, and melt gas saturation. Reduces corrosion resistance, increases castings density [15];

**Pb** – increases antifriction properties and machinability by cutting, reduces mechanical properties and hardness. Pb content more than 1 % reduces fluidity and leads to melt lamination and castings density liquation;

**Be** – improves corrosion resistance, electrical conductivity, non-magnetism, manufacturability and ensures bronze developing ability by heat treatment. Promotes sharp increasing in strength and elastic properties, yield strength at low elastic modulus;

**Cr** – in small amount increases strength, wear resistance, increases stability to high temperatures;

**Ti** – in small amount titanium in bronze is its deoxidizer, modifier and degasser, lowering cast grain size in castings, increases density, heat resistance and strength;

**B, V, Nb** – modifying micro impurities that reducing cast structure grains.

It should be noted that description above concerning influence of chemical elements increasing in each bronze grade on bronzes properties will be individual both in terms of influence level and in nature. At the same time, not all mentioned above chemical elements are technological in terms of their using for bronzes melting and subsequent pouring into foundry molds. In particular, among the elements that complicate melting and pouring process are Ti, Cr, Zn. This is due to their high reactivity at high temperatures. Beryllium is scarce and expensive metal. Phosphorus does not provide bronze with corrosion resistance necessary level, in particular, in seawater

and salt fog. According to European Union recommendations, lead should be completely excluded from any alloys composition due to its toxicity. From ensuring non-magnetism or low magnetism point of view, bronze should not contain Fe, Ni or Co and have multiphase microstructure in which ferromagnetic electronic compounds should be absent, for example, Cu<sub>2</sub>MnAl.

In addition, as noted above, it should also be taken into account that foundry bronze, unlike bronze intended for pressure processing, should not be, first of all, single-phase. Today, W. Hume-Rothery (1959) rules are generally accepted for obtaining single-phase alloys. That is, using Hume-Rothery rules, obtaining alloys with single-phase structure possibility in substitutional or interstitial solid solutions form has been assessed.

In particular, substitutional solid solution occurrence in alloy is possible if:

1 – solvent and soluble component crystal structures are the same;

2 – solvent and soluble component atoms radii should be different by no more than 15 %;

3 – solvent and soluble component should have the same valence;

4 – solvent and soluble component difference in electronegativity, according to Darken L. S. (1953) and Waber J. T. (1961) works, should not exceed 0.2–0.4.

Interstitial solid solution occurrence is possible if:

5 – soluble component ( $R_x$ ) atoms radius is not more than 59 % of solvent ( $R_{me}$ ) atoms radius, but larger than solvent crystal lattice possible smallest pore size, that is, when Hegg's rule is fulfilled;

6 – solvent and solute component have similar electronegativities.

Based on above, among chemical elements that provide bronze with non-magnetic properties and high corrosion resistance in seawater are Al, Si and Mn. For preliminary theoretical assessment of two-phase alloy obtaining from given metals set possibility, according to W. Hume-Rothery rule, data on their indicators have been used and given in Table 1.

From W. Hume-Rothery rules feasibility point of view, Cu-Al-Si-Mn system bronzes must be two-phase, since rules Nos. 1 and 2 for silicon and rule No. 1 for manganese are not fulfilled in the system. It should be noted that Cu-Al-Mn system alloys are classified as alloys with limited mutual solubility. In their structure, according to S. V. Shukhardin and colleagues (1979), with aluminum content of up to 14 % by mass and 15 % manganese there are: Al and Mn in copper  $\alpha$ -solid solution,  $\beta$ -solid solution based on binary Cu-Al system  $\beta$ -phase, and  $\gamma$ -solid solution based on binary Cu-Al system  $\gamma$ -phase (Cu<sub>9</sub>Al<sub>4</sub>). At the same time, according to S. Konoplyuk, et al. (2010), when manganese content in Cu-Al-Mn system bronze is up to 12 %, non-magnetic phase Cu<sub>3</sub>Al and ferromagnetic phase Cu<sub>2</sub>MnAl coexist in so-called temperature-concentration interval "miscibility gap".

From the above it follows that it is advisable to create cast non-magnetic corrosion-resistant bronze from alloys based on Cu-Al-Si-Mn system with mass content of 3–9 % Al and Si, Mn up to 2 % each. For these alloys there is currently no data on alloying elements influence on its mechanical properties and linear shrinkage.

**Purpose.** Investigation of Al, Si and Mn complex influence on bronzes', which contented 3–9 % Al up to

Metals indicators

| Metals | Metals crystal lattice type | Metals atomic radii, nm | <sup>1</sup> SV [20] | <sup>2</sup> EN [21] | <sup>3</sup> LS | <sup>4</sup> DR | <sup>5</sup> $\Delta_{EN}$ |
|--------|-----------------------------|-------------------------|----------------------|----------------------|-----------------|-----------------|----------------------------|
| Cu     | FCC [16]                    | 0.12773 [16]            | 1, 2, 3              | 1.90                 | 100             | 0               | 0                          |
| Al     | FCC [17]                    | 0.143 [17]              | 3                    | 1.61                 | 9.4             | 12              | -0.29                      |
| Si     | FCC diamond type [18]       | 0.111 [18]              | 2, 4                 | 1.90                 | 3.2             | -22             | 0                          |
| Mn     | BCC [19]                    | 0.127–0.135 [19]        | 2, 3, 4, 6, 7        | 1.55                 | 26              | 14–6            | -0.35                      |

Notes: <sup>1</sup> – stoichiometric valence; <sup>2</sup> – electronegativity according to Pauling scale; <sup>3</sup> – soluble component limited solubility in Cu at 400 °C, % (by mass); <sup>4</sup> – soluble component and Cu atoms radii size difference, %; <sup>5</sup> – soluble component and Cu electronegativities difference

2 % Si and Mn each, mechanical properties level and structure at 20 °C.

**Methodology.** Mechanical properties study at normal temperature has been carried out on cast bronze samples without heat treatment, which have been manufactured by mechanical processing from cast blanks (20 × 20 × 120 mm) obtained by pouring molten bronze into sand-sodium-silicate casting molds.

In static uniaxial tension studies, samples with working part dimensions of  $\varnothing 8 \times 40$  mm have been used. For impact energy determination, dimensions of 10 × 10 × 55 mm samples with a U-shaped notch 2 mm deep have been used. Tests have been performed on universal testing machine FP-100/1 at stretching speed of 1 mm/min.

Impact bending has been investigated on PSW-30 pendulum impactor with maximum impact energy of 300 J.

Electronic caliper has been used for samples dimensions determination with an accuracy of 0.01 mm.

Microstructural studies have been performed on metallographic micro specimens prepared using standard techniques on Neophot-21 optical microscope.

Free and absolutely hindered linear shrinkage has been calculated based on results of cast cylindrical blanks change in length measuring. These samples have been cast in molds of various designs, which provided different types of their linear shrinkage inhibition.

For bronzes pressure processing or casting suitability determination, dimensionless parametric criterion *A* has been used

$$A = \frac{\alpha_{AH}}{\alpha_F},$$

where  $\alpha_{AH}$ ,  $\alpha_F$  – accordingly, absolutely hindered and free cast metal (alloy) linear shrinkage, %.

And dimensionless parametric criterion *B*

$$B = \frac{\delta_5}{100} \cdot \frac{\sigma_B}{\sigma_{0.2}},$$

where  $\delta_5$  – relative elongation, %;  $\sigma_B$ ,  $\sigma_{0.2}$  – accordingly, metal (alloy) samples tensile strength and yield strength in cast state at temperature of  $20 \pm 1$  °C, MPa; 100 – balance constant, %.

In research, it is accepted that any alloy is suitable for pressure processing within conditions:  $1.0 \geq A \geq 0.7$  and  $B \geq 0.9$ . At the same time, alloys with  $B \geq 1.8$  are suitable for cold pressure processing by any method.

To identify Al, Si and Mn influence on bronzes', containing 3–9 % Al, up to 2 % Si and up to 2 % Mn at 20 °C, mechanical properties level, samples have been manufactured according to plan-matrix of incomplete cube in H. Scheffer's active experiments ternary system, which is given in Table 2.

Incomplete cube mathematical model in ternary system according to H. Scheffer's plan looks like

$$Y = \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \beta_3 \cdot x_3 + \beta_{12} \cdot x_1 \cdot x_2 + \beta_{13} \cdot x_1 \cdot x_3 + \beta_{23} \cdot x_2 \cdot x_3 + \beta_{123} \cdot x_1 \cdot x_2 \cdot x_3, \quad (1)$$

where *Y* – materials property;  $\beta$  – regression coefficient; *x* – weight chemical element content in alloy, mass. %.

Regression coefficients calculation in formula (1) has been carried out using following equations

$$\beta_1 = \xi_{11}; \quad \beta_{ij} = 4 \cdot \xi_{ij} - 2 \cdot \xi_{i1} - 2 \cdot \xi_{j1}; \quad \beta_{123} = 27 \cdot \xi_{123} - 12 \cdot (\xi_{12} + \xi_{13} + \xi_{23}) + 3 \cdot (\xi_1 + \xi_2 + \xi_3),$$

where  $\xi_i$ ,  $\xi_j$ ,  $\xi_{123}$  – experiments' results at simplex lattices (Fig. 5) points.

Bronzes' components content complex influence analysis on tensile strength and yield strength, relative elongation, impact toughness values, linear absolutely hindered and free linear shrinkage values, criteria "A" and "B" values has been carried out based on studied parameters in simplex triangles isolines constructing results. Simplex triangle form with "key" (red arrows) and reference points is presented in Fig. 1

Bronzes have been melted in graphite crucible with metal capacity of 5 kg (in copper terms) under charcoal

Table 2

Plan-matrix of active experiments for system Cu-Al-Si-Mn bronzes

| Chemical element | Chemical elements content in lattice points, mass % |    |    |    |    |    |      |      |      |      |
|------------------|---|----|----|----|----|----|------|------|------|------|
|                  | X1  | X2 | X3 | X4 | X5 | X6 | X7   | X145 | X246 | X356 |
| Al               | 9   | 3  | 3  | 6  | 6  | 3  | 5    | 7    | 4    | 4    |
| Si               | 0   | 2  | 0  | 1  | 0  | 1  | 0.67 | 0.33 | 1.33 | 0.33 |
| Mn               | 0   | 0  | 2  | 0  | 1  | 1  | 0.67 | 0.33 | 0.33 | 1.33 |

layer. As charge copper, aluminum, silicon and manganese of technical purity have been used. Casting molds pouring has been carried out from crucible at bronzes melt temperature of 1.170–1.190 °C. Melt temperature has been measured with chromel-alumel thermocouple completed with electronic digital potentiometer.

Alloys chemical composition has been determined on EXPERT 4L precision analyzer using bronze samples cut from cast blanks. Three to five measurements series have been made for each sample. Alloys chemical composition has been determined by results average value.

**Findings.** Active testing results of experimentally implemented plan-matrix, as 5 cast bronze samples investigations data average values with main alloying elements content up to 0.02 % absolute error, for each indicator are given in Table 3.

Implemented plan-matrix active experiments correlation coefficients, calculated according to H. Scheffer's plan are presented in Table 4.

Experimental (exp.) and calculated (calc.) according to formula (1) indicators values at control points on simplex lattice are given in Table 5.

Studied bronzes parameters experimental and calculated values at control points comparison showed their coincidence relatively high level (largest relative error is less than 7 %), which is a reason to believe that simplex triangle model adopted in this study has been chosen

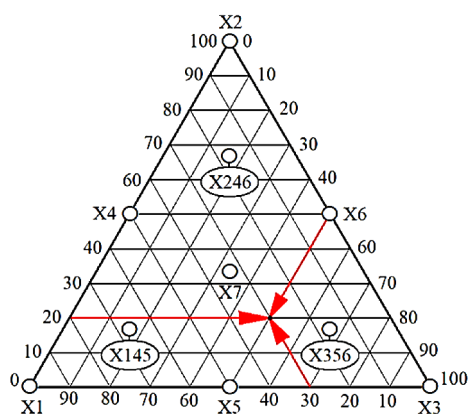


Fig. 1. Incomplete third degree polynomial simplex triangle with "key" (red arrows) and reference points

Table 3

Implemented plan-matrix active experiments results

| Indicator              | Indicator values in lattice points |      |      |      |      |      |      |
|------------------------|------------------------------------|------|------|------|------|------|------|
|                        | X1                                 | X2   | X3   | X4   | X5   | X6   | X7   |
| $\sigma_B$ , MPa       | 448                                | 315  | 249  | 342  | 286  | 276  | 309  |
| $\sigma_{0.2}$ , MPa   | 157                                | 61   | 88   | 88   | 71   | 70   | 63   |
| $\delta_5$ , %         | 35                                 | 53   | 48   | 52   | 42   | 61   | 55   |
| KCU, J/cm <sup>2</sup> | 135                                | 272  | 160  | 290  | 210  | 246  | 256  |
| $\alpha_{AH}$ , %      | 1.66                               | 1.42 | 1.67 | 0.74 | 0.9  | 1.07 | 1.14 |
| $\alpha_F$ , %         | 2.18                               | 1.62 | 1.88 | 1.05 | 1.29 | 1.57 | 1.66 |
| HB                     | 70                                 | 68   | 58   | 74   | 60   | 59   | 57   |
| Criterion A            | 0.76                               | 0.88 | 0.89 | 0.70 | 0.70 | 0.68 | 0.69 |
| Criterion B            | 1.00                               | 2.74 | 1.36 | 2.02 | 1.69 | 2.41 | 2.70 |

correctly, and obtained results, accordingly, are reliable.

Simplex triangles constructing results regarding bronzes' properties are presented in Figs. 2–4.

From alloys mechanical properties and linear shrinkage isolines course analysis in simplex triangles, it follows that all the studied bronzes are single-phase alloys. This is evidenced, in particular, by bronze microstructure in Fig. 5, which has chemical composition corresponding to point X7 on simplex triangle (Fig. 1).

At the same time, according to criteria A and B values, bronzes in studied alloying element content range can be characterized as alloys poorly suitable for cast parts (ingots) manufacturing, but which can be pressure-processed in cold and hot state.

It should be noted that W. Hume-Rothery's rules are largely valid for binary alloys, but require additions for multicomponent systems. In particular, according to present work authors opinion, all interatomic interactions in multicomponent bronzes possible types could be divided into four types ("rule of four"). Their schemes are presented in Fig. 6.

In "K" type alloys (Fig. 6, a), all components (Cu, E, D) dissolve in each other in large amount. As a result, at normal (20 °C) temperature, such bronze will have single-phase structure. Such bronze example is single-phase bronze brand БрА7К2 or БрКМц3-1 bronze.

In the case (Fig. 6, b) when all alloying components of bronze (E, D) dissolve in large quantities in copper but are not soluble in any significant quantity in each other – this bronze (type "N") at normal temperature will have multiphase structure. Such bronze example is two-phase bronze grade БрО3А3 [22] or БрК5О3 [23] bronze.

Bronze type "M" will also have multiphase structure, in which alloying components E and D dissolve well in each other, but one of them does not dissolve or dissolves to limited extent in copper, and other one dissolves in copper in large amount (Fig. 6, c). Such bronze example is two-phase bronze brand БрО10С10 or БрА11Ж6Н6 bronze.

"F" type (Fig. 6, d) bronzes are also multiphase. In these alloys one of alloying components practically does not dissolve in either copper or its other alloying element (elements). Such bronzes examples are two-phase

Table 4

Implemented plan-matrix active experiments correlation coefficients

| Indicator                | Implemented plan-matrix active experiments correlation coefficients |           |           |              |              |              |               |
|--------------------------|---|-----------|-----------|--------------|--------------|--------------|---------------|
|                          | $\beta_1$   | $\beta_2$ | $\beta_3$ | $\beta_{12}$ | $\beta_{13}$ | $\beta_{23}$ | $\beta_{123}$ |
| $\sigma_B$               | 448   | 315       | 249       | -158         | -250         | -24          | 531           |
| $\sigma_{0.2}$           | 157   | 61        | 88        | -84          | -206         | -18          | -129          |
| $\delta_5$               | 35  | 53        | 48        | 32           | 2            | 42           | 33            |
| KCU                      | 135   | 272       | 160       | 346          | 250          | 120          | -339          |
| $\alpha_{AH}$            | 1.66  | 1.42      | 1.67      | -3.2         | -3.06        | 0.50         | 5.31          |
| $\alpha_F$               | 2.18  | 1.62      | 1.88      | -3.4         | -2.96        | -0.72        | 14.94         |
| HB                       | 70  | 68        | 58        | 20           | -16          | -16          | -189          |
| Criterion A <sub>F</sub> | 0.76  | 0.88      | 0.89      | -0.46        | -0.51        | -0.80        | 3.10          |
| Criterion B              | 1.00  | 2.74      | 1.36      | 0.6          | 2.04         | 1.44         | 14.76         |

Experimental (exp.) and calculated (calc.) according to formula (1) indicators values at control points on simplex lattice

| Indicator              | Indicators values at points on simplex lattice |       |                 |       |                 |       |
|------------------------|--|-------|-----------------|-------|-----------------|-------|
|                        | X145   |       | X246            |       | X356            |       |
|                        | exp.   | calc. | exp.            | calc. | exp.            | calc. |
| $\sigma_B$ , MPa       | $328 \pm 11$                                   | 333   | $327 \pm 14$    | 324   | $274 \pm 9$     | 269   |
| $\sigma_{0,2}$ , MPa   | $90 \pm 5$                                     | 95    | $64 \pm 3$      | 61    | $63 \pm 4$      | 66    |
| $\delta_5$ , %         | $48 \pm 1$                                     | 47    | $55 \pm 2$      | 55    | $53 \pm 3$      | 54    |
| KCU, J/cm <sup>2</sup> | $232 \pm 11$                                   | 227   | $286 \pm 9$     | 283   | $224 \pm 7$     | 219   |
| $\alpha_{AH}$ , %      | $1.17 \pm 0.04$                                | 1.09  | $1.02 \pm 0.03$ | 1.08  | $1.18 \pm 0.6$  | 1.22  |
| $\alpha_F$ , %         | $1.60 \pm 0.04$                                | 1.58  | $1.48 \pm 0.04$ | 1.49  | $1.64 \pm 0.03$ | 1.66  |

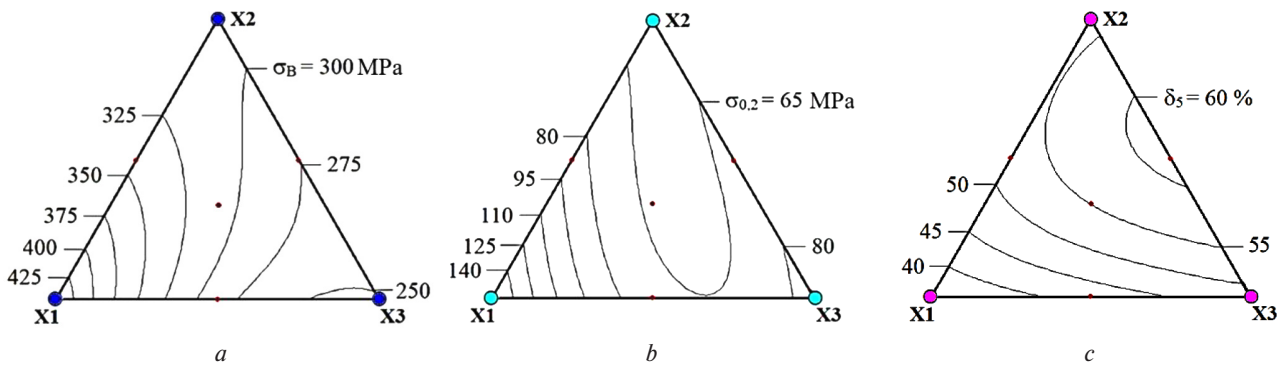


Fig. 2. Ultimate tensile strength  $\sigma_B$  (a), yield strength  $\sigma_{0,2}$  (b) and relative elongation  $d$  (c) at stretching

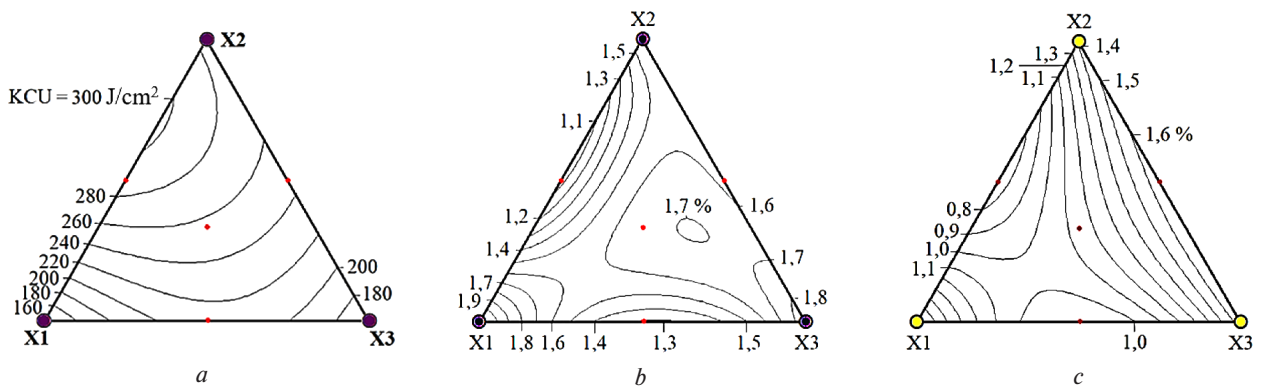


Fig. 3. Impact toughness KCU (a), free  $\alpha_F$  (b) and absolutely hindered  $\alpha_{AH}$  linear shrinkage (c)

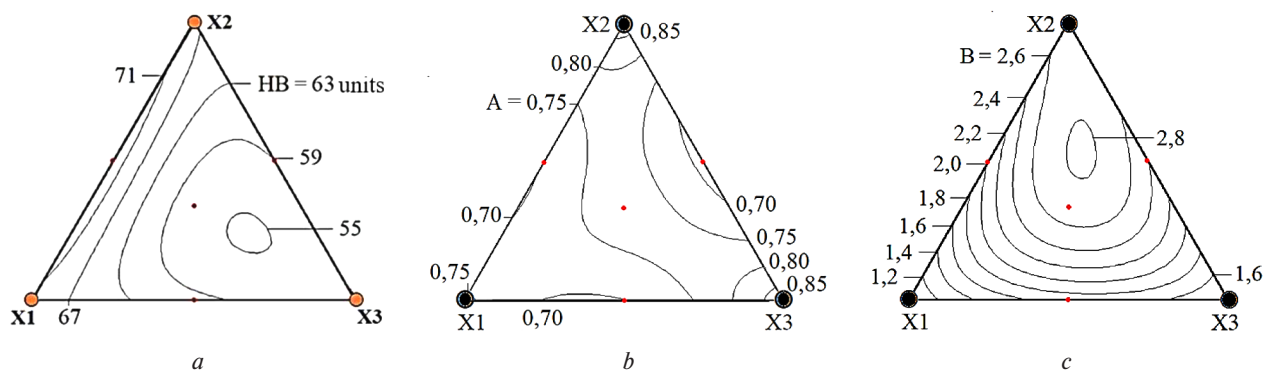


Fig. 4. Hardness HB (a), criterion A (b) and criterion B (c) for system's Cu-Al-Si-Mn bronzes

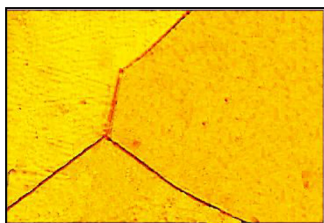


Fig. 5. Bronze microstructure ( $\times 400$ )

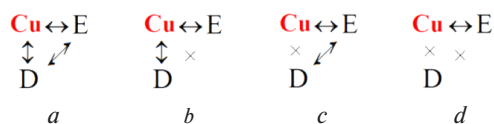


Fig. 6. Schemes of structures formation conditions in bronzes:

type “K” (a), type “N” (b), type “M” (c) and type “F” (d) (E and D – are symbolic alloying elements of bronze)

brands БрС60Н2.5, БрА9Ж3Л, БрА5С3.

As results obtained evidence, studied in this work Cu-Al-Si-Mn system, within alloying elements changes in its content accepted limits, according to proposed classification, belongs to type “K”. That is, these bronzes are most suitable for products manufacturing by cast billet deforming. To give these bronzes casting properties, it is necessary to add into Cu-Al-Si-Mn system metal whose solubility will correspond to “N” or “M” type schemes (Figs. 6, b, c).

Based on analysis obtained results, from studied alloys linear shrinkage, hardness and impact toughness values point of view, basis for cast non-magnetic corrosion-resistant bronze elaboration can be, in particular, Cu-Al system alloy with 6–7.5 % Al (by mass) content, which is additionally alloyed with 1–2.5 % Si, with small manganese amount (as deoxidizer) and certain metal, which presence will ensure the emergence type “N” or type “M” multiphase microstructure in bronze.

### Conclusions.

1. All bronzes in studied concentrations changes range of aluminum, silicon and manganese have a single-phase structure, relatively low strength and typical for single-phase structure high levels of relative elongation and impact toughness.

2. Studied bronzes can be characterized as materials not suitable for cast parts manufacturing, but they can be recommended for products processed by cold and/or hot deformation methods.

3. Further investigation should be aimed at metallic component searching whose presence in these bronzes will provide them with rational two-phase state and, accordingly, casting and mechanical properties high level, which inherent, in particular, to БрА9Ж3Л bronze brand.

4. As a basis for cast non-magnetic corrosion-resistant bronze development, it is advisable to use Cu-Al system bronze with aluminum content of 6–7.5 % (by mass), which is additionally alloyed with silicon and slight manganese amount.

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## Вплив Si та Mn на механічні властивості та лінійну усадку немагнітних литих бронз системи Cu-Al

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**Мета.** Встановити закономірності впливу Si та Mn на рівень механічних властивостей при 20 °С і структуру алюмінієвих бронз з масовим вмістом Al від 3 до 9 %.

**Методика.** Механічні властивості бронз у литому стані визначали за результатами їх руйнування на машині FP-100/1 і маятниковому копрі PSW-30. Мікроструктуру досліджували на оптичному мікроскопі Neophot-21. Коефіцієнти лінійної усадки бронз розраховували за результатами визначення зміни довжин литих циліндричних зразків. Комплексний вплив Si та Mn на властивості бронз визначали за результатами побудови симплекс-трикутників за планом Г. Шеффе. Температуру вимірювали хромель-алюмелевою термопарою у комплекті з електронним потенціометром. Хімічний склад бронз визначали на аналізаторі EXPERT 4L.

**Результати.** Додавання до бронзи системи Cu-Al кремнію (до 2 %) і марганцю (до 2 %) при зни-

женні вмісту алюмінію з 9 до 3 % приводить до зменшення міцності та плинності при розтягуванні бронзи й підвищує її пластичність. При цьому структура бронзи у будь якій комбінації вмісту Al, Si та Mn у досліджених межах їх змін залишається однофазною.

**Наукова новизна.** Уперше проведено комплексне оцінювання впливу Si та Mn з одночасним зниженням вмісту Al на механічні властивості та лінійну усадку литих бронз системи Cu-Al-Si-Mn. Встановлено, що всі бронзи досліджених складів мають однофазну структуру та рівень механічних властивостей, що притаманний бронзам для деформування.

**Практична значимість.** Результати досліджень розширюють уявлення щодо поелементного й комплексного впливу Si та Mn на властивості алюмінієвих бронз, надають можливість обрати бронзу із потрібним для деформації рівнем властивостей її литої заготовки або проектувати виливки з урахуванням встановлених у роботі величин лінійної усадки. Отримані дані також можуть бути базовими для розробки нових ливарних, корозійностійких немагнітних бронз, що мають міцність і щільність на рівні деяких марок вуглецевих сталей. Із таких матеріалів виготовляють деталі що працюють у хімічно-агресивних середовищах, у складі контрольно-вимірювальної апаратури та приладів, у складі суднових і корабельних пристроїв, арматури, втулки, муфти, іскро-безпечних інструментів, тощо.

**Ключові слова:** бронза, міцність, усадка, механічні властивості, алюміній, кремній, марганець

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