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Structure and properties of C92900 antifriction bronze produced by upward continuous casting

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Abstract: Antifriction tin bronzes are used in the aerospace industry to manufacture components that operate in friction assemblies at elevated temperatures. This is due to the alloy's favorable combination of antifriction, mechanical, and corrosion properties. In particular, tin bronze C92900 (alloy Cu–10Sn–3Ni–2Pb (wt. %)) is widely used in such applications. It is employed in the production of braking system components and plunger pump parts. Currently, these parts are manufactured by machining ingots produced through casting with directional solidification. However, this method has a low material utilization rate, typically between 5 % and 15 %. The most promising method for producing C92900 ingots is upward continuous casting technology, which allows the ingot dimensions to closely match those of the finished part. This significantly reduces machining effort and increases metal utilization to 95 %. This study presents the results of process development for the upward continuous casting technology of 15 mm diameter C92900 ingots. The structure and properties of the castings were also investigated. It was shown that as the casting speed increased from 90 to 360 mm/min, the volume fraction of the γ-Cu_3Sn intermetallic phase increased, while the amount of tin-based solid solution remained nearly unchanged. At the same time, the phase distribution became more refined. The macrostructure consisted of columnar and equiaxed grains. As the casting speed increased, the columnar grains became more tilted relative to the direction of heat removal. The hardness increased from 127 ± 2.73 to 136 ± 4.25 HB, and the tensile strength and elongation slightly increased up to 250 mm/min, then decreased at 360 mm/min, which was associated with the macrostructure approaching a transcrystalline form. The study also examined shrinkage cavities and segregation defects in ingots cast at 150 mm/min and analyzed their causes. Finally, the paper provides recommendations for optimal casting parameters for 15 mm diameter ingots produced by upward continuous casting technology.

Keywords: upward continuous casting technology, antifriction bronze, C92900, mechanical properties, ingot defects.

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Исследование влияния режимов получения слитков методом непрерывно-пошагового литья вверх на структуру и свойства антифрикционной бронзы БрО10С2Н3

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Аннотация: Антифрикционные оловянные бронзы используются в авиастроении для изготовления деталей, работающих в узлах трения при повышенных температурах. Это обусловлено хорошим сочетанием антифрикционных, механических и коррозионных свойств сплава. В частности, в таких изделиях широко используется оловянная бронза БрО10С2Н3. Из нее изготавливают узлы систем торможения и детали плунжерных насосов. В настоящее время детали из этой бронзы производят механической обработкой слитка, полученного наполнительным литьем с направленной кристаллизацией. Однако такой способ имеет низкий коэффициент использования материала, который составляет 5–15 %. Наиболее перспективным методом получения слитков из бронзы БрО10С2Н3 является непрерывно-пошаговое литье вверх, которое позволяет максимально приблизить размеры слитка к размеру детали, что значительно сокращает трудоемкость механической обработки и повышает коэффициент использования металла до 95 %. В настоящей работе приведены результаты отработки режимов литья слитков диаметром 15 мм из оловянной бронзы БрО10С2Н3 по этой технологии. Также исследованы их структура и свойства. Показано, что с увеличением скорости литья с 90 до 360 мм/мин в слитках возрастает объемная доля интерметаллидной фазы γ-Cu_3Sn, а количество твердого раствора на основе олова практически не изменяется. При этом распределение фаз в бронзе становится более дисперсным. Макроструктура бронзы состоит из столбчатых и равноосных кристаллов. С увеличением скорости литья столбчатые кристаллы меняют свой наклон относительно направления теплоотвода, твердость возрастает с 127 ± 2,73 до 136 ± 4,25 HB, а предел прочности и относительное удлинение незначительно повышаются при скорости литья до 250 мм/мин, а затем снижаются при 360 мм/мин, что связано с приближением макроструктуры к транскристаллитной форме. В работе также проанализированы дефекты (ужимины и ликваты) в слитках, полученных при скорости литья 150 мм/мин, и причины их возникновения. В заключение сформулированы рекомендации по режимам литья слитков диаметром 15 мм при непрерывно-пошаговом литье вверх.

Ключевые слова: непрерывно-пошаговое литье вверх, антифрикционная бронза, БрО10С2Н3, механические свойства, дефекты в слитках.

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Introduction

Tin bronze C92900 is widely used in the aerospace industry due to its advantageous combination of strength, corrosion resistance, and antifriction properties [1; 2]. It is most commonly used for manufacturing components that operate in friction assemblies under elevated temperatures [3; 4]. These parts are typically produced by machining ingots obtained through gravity casting with directional solidification of the alloy. However, this casting method has a low material utilization rate and requires the use of a large feeder head to compensate for solidification shrinkage [5]. This is due to the alloy's tendency to form shrinkage porosity, which results from the wide solidification temperature range of the alloy (70 to 200 °C) [6]. To reduce porosity, special water-cooled molds are used. These ensure a high cooling rate and create favourable conditions for directional solidification of the alloy [5].

The most promising and cost-effective method for producing C92900 blanks is upward continuous casting technology [5; 7]. This method enables the production of ingots with diameters ranging from 15 to 55 mm with minimal shrinkage porosity. This is achieved by promoting directional solidification and ensuring a high cooling rate during solidification. In addition, this casting method reduces the labour intensity of machining and increases material utilization to up to 95 % [8; 9].

It is known [8; 10] that the ingot casting speed during upward continuous casting significantly affects the alloy's micro- and macrostructure. This is due to the increasing intensity of heat removal through the lateral walls of the graphite sleeve of the mold. As shown in [5] for ingots produced by gravity casting, the cooling conditions during solidification influence the quantity, distribution, and size of the structural constituents in C92900 bronze, which in turn affects the mechanical properties of the ingots. However, no such data are available for C92900 ingots produced by upward continuous casting.

The aim of this study was to investigate the effect of casting speed on the structure and properties of C92900 bronze in 15 mm diameter ingots produced by upward continuous casting.

Experimental

To prepare the C92900 bronze samples, primary metals of industrial purity were used: copper grade M1, tin grade O1, nickel grade N-1, and lead grade S1. The alloy was melted in a high-frequency induction crucible furnace (RELTEK, Russia) with a 50 kg capacity, using a graphite-chamotte crucible. To protect the melt from oxidation and hydrogen absorption, the smelting process was carried out under a charcoal cover pre-dried at 120—150 °C. The full charge of nickel and copper was first placed into the crucible. The melt was then heated to 1150—1200 °C and held at this temperature to ensure complete dissolution of nickel. Deoxidation was performed using a copper—phosphorus master alloy (MF10). Tin and lead were introduced at 1150 °C, with the melt held for 3—5 min after each addition. Degassing and removal of non-metallic inclusions were per-

Table 1. Chemical composition of C92900 bronze

Таблица 1. Химический состав бронзы БрО10С2Н3

Composition	Elements, wt. %				Impurities, max wt. %						
	Cu	Ni	Sn	Pb	Fe	Zn	P	Si	Al	Sb	Bi
As per OST 1 90054-72	Balance	3–4	9–11	2–3.25	≤0.3	≤0.5	≤0.1	≤0.02	≤0.02	≤0.3	≤0.02
Actual	Balance	3.46	10.81	2.37	<0.01	<0.01	0.019	<0.005	<0.003	<0.01	<0.003

formed by argon purging (grade 5.6, high purity) for 5—7 min. The chemical composition of the C92900 alloy was determined using a Q4 Tasman optical emission spectrometer (Bruker Quantson, USA) and is presented in Table 1.

The casting process was carried out using the PUVL-450.PS portal-type upward continuous casting unit (NL-Engineering LLC, Belarus), which operates in a cycle of forward stroke — pause — reverse stroke. The working part of the mold (sleeve) was made of graphite grade MPG7. Before casting, the mold was immersed into the melt (temperature: 1100 ± 10 °C) to a depth of 115 ± 5 mm. The experiments were conducted by varying the forward stroke length and pause durations. The casting parameters are presented in Table 2.

To reveal the alloy's macrostructure, an etchant with the composition 5 g $FeCl_3$ + 15 mL HCl + 50 mL H_2O was used. The microstructure of the bronze was examined using a Vega SBH3 scanning electron microscope (Tescan, Czech Republic) equipped with an Oxford energy-dispersive spectroscopy (EDS) system. The phase fractions in the structure were determined using ImageJ 1.52a image analysis software (National Institutes of Health, USA).

Brinell hardness was measured using a NEMESIS 9001 universal hardness tester (INNOVATEST, Netherlands) under the following test parameters: 2.5 mm diameter steel ball, 187.5 kgf (≈1839 N) load, and a 10 s dwell time.

Table. 2. Casting modes of 15 mm diameter C92900 ingots produced by upward continuous casting

Таблица 2. Режимы литья слитков диаметром 15 мм из бронзы БрО10С2Н3 методом непрерывно-пошагового литья вверх

Mode No.	Forward stroke, mm	Pause duration, s	Reverse stroke, mm	Casting speed, mm/min
1	4	2	1	90
2	5	1	1	240
3	7	1	1	360

Tensile tests were performed using a 5569 universal testing machine (Instron, USA). The specimens were machined from the ingots with a gauge section diameter of 5 mm (specimen type Sh No. 7, in accordance with GOST 1497-84).

Phase composition calculations were carried out using the FactSage 8.0 thermochemical software package (Canada).

Results and discussion

The microstructure of C92900 bronze ingots produced by upward continuous casting is shown in Fig. 1. It consists of a copper-based solid solution, eutectic γ-Cu_3Sn intermetallic phase, and a lead-based solid solution [11; 12]. In addition, zonal segregation was observed, resulting in the formation of light regions of the copper-based solid solution with reduced nickel content (down to 2—3 %) and elevated tin content (up to 16.5 %), as well as dark regions containing up to 4 % of both Ni and Sn. The extent of dendritic segregation decreases as the ingot casting speed increases [13; 14]. This is due to enhanced heat removal from the ingot surface during solidification, which correlates with previously reported findings [15; 16]. As a result, the tin content dissolved in the copper-based solid solution in the light regions decreases to 12—14 %, while in the dark regions it remains unchanged at 4 %.

Fig. 2 presents an isothermal section of the Cu—2.5Pb—(9—11)Sn—(3—4)Ni system at 20 °C, constructed using the FactSage software package. It can be seen that in the region corresponding to the alloy's chemical composition (marked as a point on the diagram), in addition to the phases mentioned above, the Sn_4Ni_3Cu phase is also present. However, this phase could not be identified in the microstructure. It is likely that it forms as a result of eutectoid decomposition and occurs only in minor quantities at the examined casting speeds. Further studies are required to confirm this assumption.

[1] Unless otherwise stated, all compositions are given in wt. %.

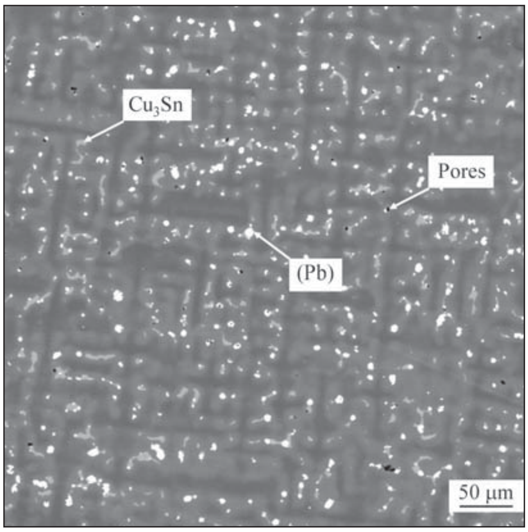

Fig. 1. Microstructure of C92900 bronze in ingots

Рис. 1. Микроструктура бронзы БрО10С2Н3 в слитках

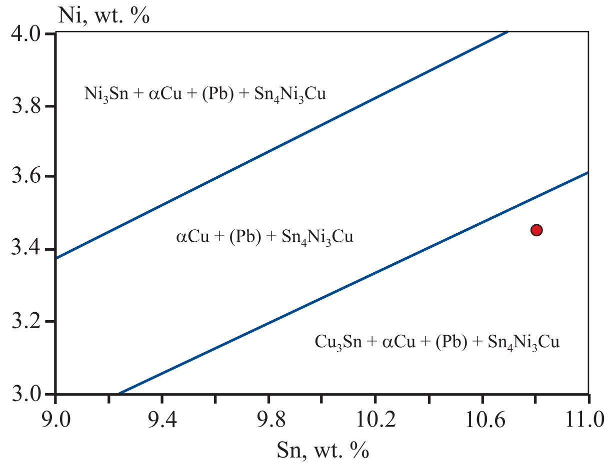

Fig. 2. Isothermal section of Cu–Ni–Sn–Pb phase diagram at 20 °C

Рис. 2. Изотермический разрез диаграммы Cu–Ni–Sn–Pb при t = 20 °C

Fig. 3 shows the dependence of the volume fraction and average size (d) of the structural components — lead phase (a) and γ-Cu_3Sn intermetallic phase (b) — on the литье (ν) of the ingots. It can be seen that as the casting speed increases, the volume fraction of the γ-Cu_3Sn phase rises from 3.5 ± 0.83 % to 4.7 ± 0.70 %, while the average grain size remains virtually unchanged. This is likely due to the increased cooling rate during solidification, which promotes the formation of more intermetallics in the alloy structure [7]. The volume fraction of the lead phase increases only slightly — up to 2.5 ± 0.19 %, and its average grain size remains stable. However, the lead inclusions become finer in shape, and their distribution becomes more dispersed. This can be attributed to the fact that lead crystallizes last, forming small globules in the interdendritic spaces [17; 18].

The macrostructure of C92900 bronze in the cross-section of ingots cast at different speeds is shown in Fig. 4. It can be observed that with increasing casting speed d, the columnar crystal zone becomes wider, and the inclination angle (α) of their growth relative to the direction of heat removal decreases. At a casting speed of 90 mm/min, the inclination angle is 52.86 ± ± 8.80° (Fig. 4, a), whereas at 360 mm/min the structure becomes close to transcrystalline, with an angle of α = 25.10 ± 5.16° (Fig. 4, c). This is due to the increase in the temperature gradient along the graphite mold sleeve

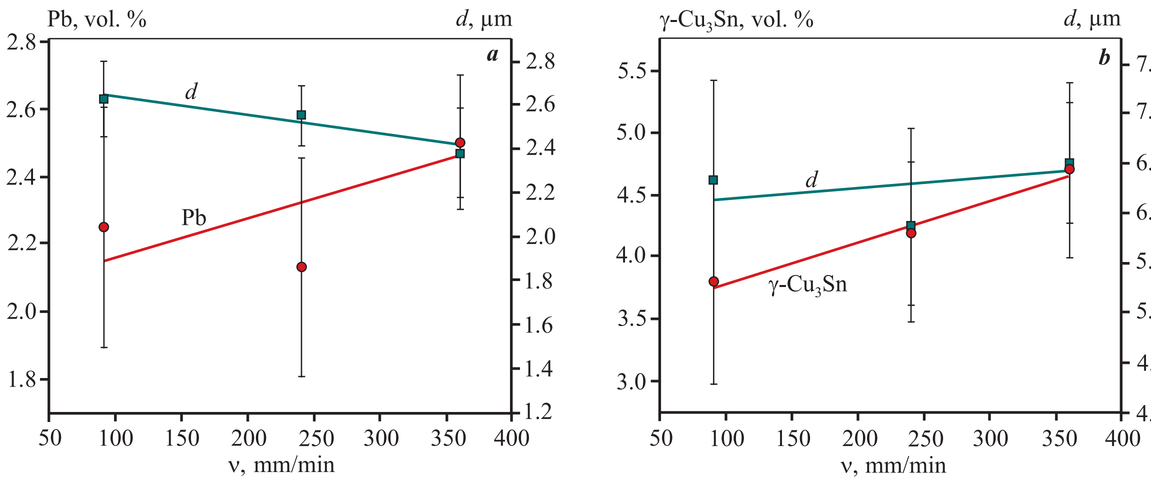

Fig. 3. Effect of casting speed on the phase fractions in the structure of 15 mm C92900 bronze ingots: lead phase (***a***), γ-Cu_3Sn phase (***b***)

Рис. 3. Влияние скорости литья слитков Ж15 мм из бронзы БрО10С2Н3 на долю фаз в структуре сплава: свинцовой (***a***) и γ-Cu_3Sn (***b***) and enhanced heat removal from the ingot surface. A similar pattern was reported by the authors of [8; 19] for C92900 bronze ingots with a diameter of 25 mm.

The effect of ingot casting speed on the mechanical properties of C92900 bronze is shown in Fig. 5. As previously established, an increase in casting speed (ν) leads to a higher volume fraction of the intermetallic phase in the bronze structure, which in turn causes an increase in hardness from 127 ± 2.73 to 136 ± 4.25 HB. At the same time, both ultimate tensile strength (σ_u)and elongation (δ) decrease. The increase in tensile strength at ν = = 240 mm/min is associated with refinement of the macrostructure, while the subsequent decline is attributed to changes in the growth direction of columnar crystals. As the macrostructure of the bronze approaches a transcrystalline form, the alloy strength decreases further due to the accumulation of insoluble impurities in the central part of the ingot [20].

During the development of casting parameters for 15 mm ingots, surface defects were observed on the outer surfaces of the ingots. These included uzhimina defects and segregation defects, as shown in Fig. 6. Uzhimina defects may appear as isolated features or form a ring-shaped pattern on the ingot surface.

Fig. 7 shows the macrostructure and microstructure of the alloy in the area of an uzhimina defect. For clarity, grain boundaries in the macrostructure image of the transverse section are outlined in yellow. Two distinct regions can be identified within the defect: the upper region, containing interdendritic porosity, and the

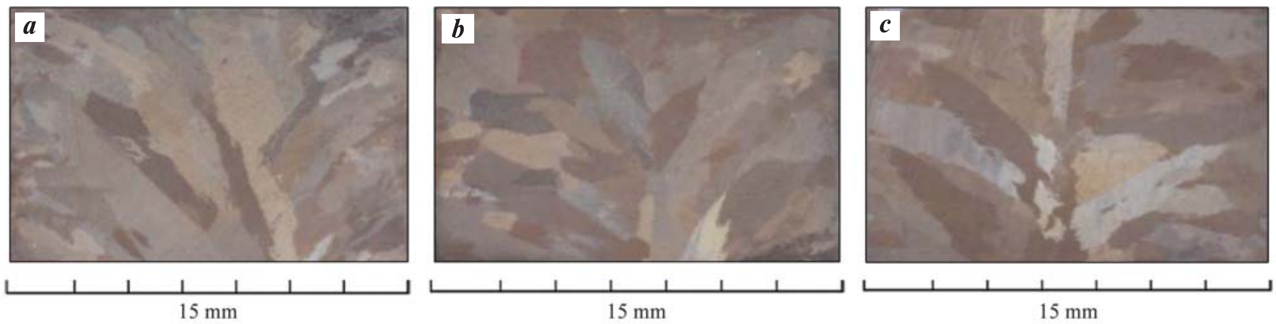

Fig. 4. Macrostructure of C92900 bronze in samples from 15 mm diameter ingots
a – ν = 90 mm/min, inclination angle α = 52.86° ± 8.80°; ***b*** – 240 mm/min, α = 43.71° ± 11.96°; ***c*** – 360 mm/min, α = 25.10° ± 5.16°

Рис. 4. Макроструктура бронзы БрО10С2Н3 в образцах из слитков диаметром 15 мм
a – ν = 90 мм/мин и угол α = 52,86° ± 8,80°; ***b*** – 240 мм/мин и α = 43,71° ± 11,96°; ***c*** – 360 мм/мин и α = 25,10° ± 5,16°

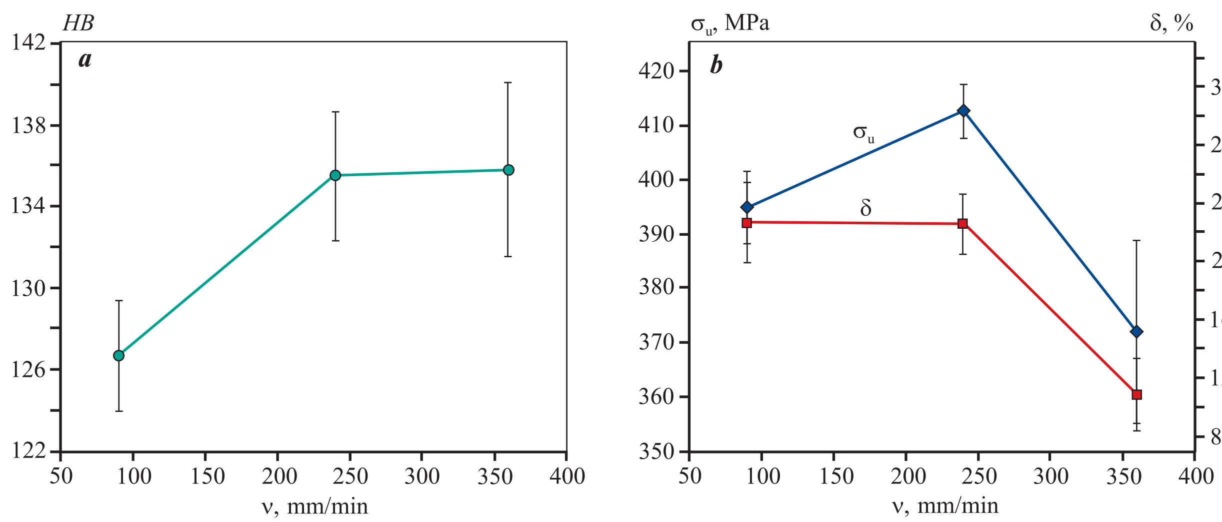

Fig. 5. Effect of ingot casting speed on the mechanical properties of C92900 bronze
a – hardness, ***b*** – ultimate tensile strength and elongation

Рис. 5. Влияние скорости литья слитков на механические свойства бронзы БрО10С2Н3
a – твердость, ***b*** – предел прочности и относительное удлинение

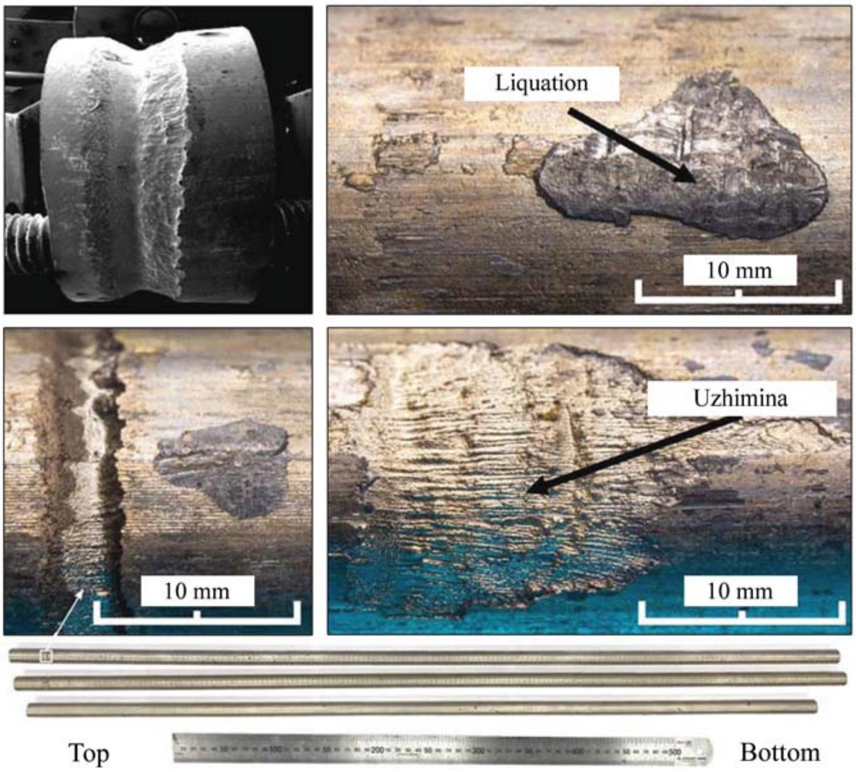

Fig. 6. Surface defects on C92900 bronze ingots

Рис. 6. Дефекты на поверхности слитков из бронзы БрО10С2Н3

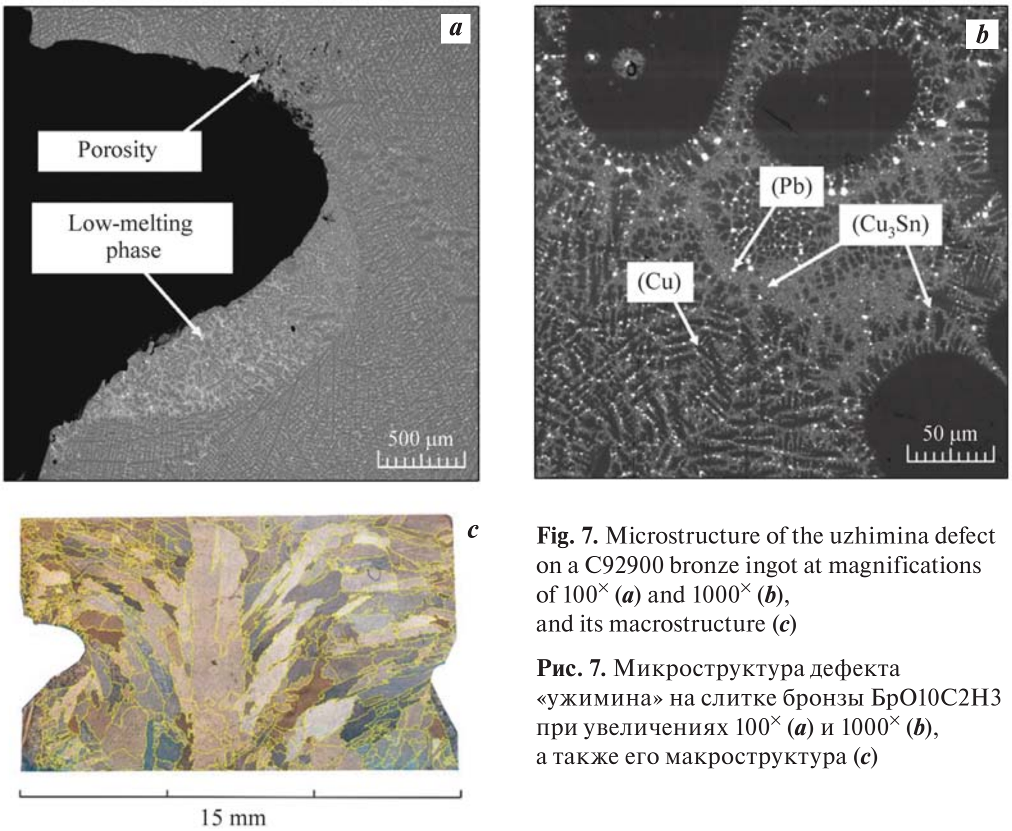

Fig. 7. Microstructure of the uzhimina defect on a C92900 bronze ingot at magnifications of $100^{\times}$ (***a***) and $1000^{\times}$ (***b***), and its macrostructure (***c***)

Рис. 7. Микроструктура дефекта «ужимина» на слитке бронзы БрО10С2Н3 при увеличениях $100^{\times}$ (***a***) и $1000^{\times}$ (***b***), а также его макроструктура (***c***) lower region, consisting mainly of eutectic phase, fine copper-based solid solution grains, and lead inclusions (Fig. 7). This structural pattern is typical for bronze quenched from a temperature within its solidification range. Additionally, traces of a phase enriched in low-melting components can be observed along the surface of the defect, in the direction opposite to the ingot's casting direction (see Fig. 7, *a*). The formation of uzhimina defects is likely associated with increased friction between the surface of the solidifying ingot and the graphite mold sleeve — a common cause of strand breakage and shell sticking during upward continuous casting [18; 21; 22].

As the graphite sleeve undergoes natural wear during operation, microroughness develops on its surface. This roughness becomes filled with molten bronze under static pressure. During the next stage of the casting cycle (forward or reverse stroke), the increased friction causes tearing of the solidifying surface layer, resulting in the formation of a uzhimina defect, which then solidifies without additional melt feeding. As the ingot shrinks, an air gap forms between the ingot surface and the graphite mold sleeve, significantly reducing heat extraction in that area. Under the combined effects of solidification shrinkage and capillary forces, low-melting phases (Pb and Cu3Sn) are squeezed out and accumulate at the base of the defect. As casting proceeds, lead is smeared along the ingot surface during its movement along the mold sleeve, forming segregation defects in the form of lead-enriched surface films. Meanwhile, the microroughness of the graphite surface is gradually polished by contact with the moving ingot. This mechanism accounts for the irregular appearance of such defects on the surface of 15 mm diameter C92900 bronze ingots during upward continuous casting.

Conclusions

1. With an increase in the casting speed of 15 mm diameter C92900 ingots by upward continuous casting from 90 to 240 mm/min, the inclination angle of columnar crystal growth relative to the direction of heat removal decreases from 52.86° ± 8.80° to 43.71° ± 11.96°, which leads to an increase in the alloy's strength to 412 ± 4.91 MPa. The elongation remains unchanged at 22 ± 2.07 %. Further increasing the casting speed to 360 mm/min reduces the inclination angle to 25.10° ± 5.16°, resulting in a decrease in strength and elongation to 372 ± 16.81 MPa and 11 ± 2.47 %, respectively.

2. The macrostructure of C92900 bronze in ingots cast at 360 mm/min approaches a transcrystalline form. It is likely that further increases in casting speed would lead to the formation of a fully transcrystalline structure and, consequently, a decline in both strength and elongation.

3. Increasing the casting speed of 15 mm C92900 ingots to 360 mm/min leads to an increase in the γ-Cu_3Sn phase fraction in the alloy structure from 3.5 ± 0.83 % to 4.7 ± 0.70 %, and in the lead phase fraction to 2.5 ± 0.19 %. The average particle size of γ-Cu_3Sn remains unchanged, while the lead inclusions become smaller and more finely dispersed. This is associated with the higher cooling rate during solidification.

4. The hardness of C92900 bronze ingots produced by upward continuous casting increases from 127 ± 2.73 to 135 ± 3.14 HB as the casting speed rises from 90 to 240 mm/min. This is likely due to the increase in γ-Cu_3Sn phase content in the alloy. Further increases in casting speed do not affect the hardness.

5. Surface defects such as uzhimina and liquation may form on 15 mm diameter C92900 bronze ingots. Their formation is associated with the natural cyclic variation in the surface roughness of the graphite mold sleeve during continuous casting.

6. The recommended casting speed for upward continuous casting of 15 mm C92900 bronze ingots is 240 mm/min. Ingots produced under these conditions exhibit high mechanical properties: ultimate tensile strength σ_u = 412 ± 4.91 MPa, elongation δ = = 22 ± 2.07 %.

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