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STUDY OF THE PROCESSES OF SHAPING THE HOLLOW BILLETS FROM ANTIFRICTION ALLOYS BY THE CENTRIFUGAL AND CONTINUOUS CASTING METHODS

The focus of this work is a comparative analysis of the mechanisms of shaping of the hollow billets, which affect the yield of the centrifugal and continuous casting of БрО8Н4Ц2 (Cu–8% Sn–4% Ni–2% Zn)- and БрО5Ц5С5 (Cu–5% Sn–5% Zn–5% Pb)-type bronzes. As revealed, the action of centrifugal forces causes the segregation of chemical elements of the alloys, depending on their density. The alloying elements of the alloy, Sn and Pb, which have an increased density, contribute to this process more actively as compared with other elements. The factors affecting the intensity of the segregation process for alloying elements, the density of which is several times higher than the density of other alloy components, are determined. The causes of the appearance of tin, as an element with a maximum density, surrounded by the compounds with a minimum density are investigated. As established, the process of segregation occurring during the centrifugal casting reduces the uniform distribution of alloying elements throughout the billet bulk and significantly increases the allowances for machining. As shown, in the process of continuous casting, the force of gravity acts on the melt, but does not cause the separation of denser alloying elements during the shaping of the billet. As revealed, only one factor determining the amount of allowance for machining for the continuous casting process is the depth of the deformation hole on the outer surface of the billet, which is necessary to engage and remove the billet from the mould. The depth of the deformation hole is established, at which the shear stress of the cut corresponds to the shear stress on the cut for samples of the studied bronze grades. A three-dimensional model is constructed and proposed for determining the yield of suitable continuous casting of hollow billets depending on both the surface temperature of the billets and the forces acting on the billet from the side of the withdrawal-roll set. To assess the ef-

fect of technological parameters on the yield of the continuous and centrifugal casting processes, the web method is applied, which allows to expand the understanding of the various mechanisms of formation of billets. The study shows that, in comparison with the known indicators of the continuous-casting yield of 95.06−96.04% for billets with outside dimensions of 80−150 mm, one could increase the yield of casting up to 97.29−97.72%. It is concluded on the expedient fabrication of billets from antifriction alloys by continuous casting, since it allows increasing the yield of suitable casting by 22.35−47.72% for the studied standard size of billets.

Keywords: centrifugal and continuous casting, cast billets, suitable casting yield, surface deformation hole.

1. Introduction

Hollow billets, which are made of copper alloys, are widely used in the industry: from antifriction sleeves in mechanical engineering to facing tubes of propeller shafts in shipbuilding. Bronze alloys having antifriction properties contain corresponding alloying elements (tin and lead), due to which the indicated properties are possible. In modern engineering, 70−75% of machine parts are produced by various casting methods (see, *e.g.*, Ref. [1] and references therein). At present, hollow billets of metals and alloys are cast mainly on centrifugal and continuous casting machines. Hollow billets with a length of 300 mm are made on centrifugal machines, and billets of unlimited length are made on continuous casting machines.

This work deals with studying the process of fabrication of hollow billets with antifriction properties, which today are fabricated on centrifugal machines (300 mm long) and on continuous-casting machines. As known, the advantages of centrifugal casting are to obtain internal cavities without the use of rods (relative to the basic technological process of hollow billets in a sand-clay mixture) and a certain amount of alloy savings due to the absence of the gating system. However, during centrifugal casting, slags accumulate on the inner surface of the billet that causes an increase in machining allowances. The work [2] concerns the determining the yield for the whole complex of technological operations, starting from the charge and ending with the finished casting or billet. In the same work, the definition for the yield of casting is given, which can also be used in our article: forms, losses to the gating system, scrap and fabrication returns. In general, centrifugal casting is used for the manufacture of castings of limited length (300 mm) [3, 4]. This circumstance is due on the one hand to the limitation of the drive power of the centrifugal casting machine, and on the other hand, the limitation on the length of the billet is because this contributes to the displacement of the axis of the billet during its fabrication, which ultimately increases the allowances for machining. Therefore, in this paper,

the proposed consideration of fabrication of hollow billets with a diameter of 80–150 mm on centrifugal and centrifugal casting machines.

In addition to centrifugal casting in the developed countries of the world, the continuous casting process is widely used. At present, the continuous casting process is used for casting billets of the iron-based [5–11] and copper-based [12–16] alloys. In the papers [17–19], the mechanical properties of metals and alloys are presented using the so-called 'cobweb' method, which is essentially a method of presenting information by a radial diagram. This method allows expanding the information field on the different characteristics and is easy to use.

2. The Purpose and Research Tasks

The goal of the work involves the implementation of two stages, the essence of which is as follows bellow.

The first stage is as follow:

• to identify the pattern of formation of hollow billets on centrifugal and continuous casting machines and explain the mechanism of the process of segregation of denser alloying elements to the outer wall of the billet;

• to choose the process of forming hollow billets, excluding stratification of alloying elements having different density, which will allow to produce billets with minimal allowances for machining, to have a uniform distribution of alloying elements in the billet volume.

The second phase is as follows: to determine the mechanism of the process of engaging the billet with rolls of the cage during continuous casting, to determine the rational depth of the deformation hole, which will reduce the allowances for machining.

To achieve this goal, it is necessary to perform the following tasks:

• to investigate the mechanism of formation of a layer of alloying elements having an increased density in centrifugally cast billet, of antifriction alloys, depending on the speed of rotation of the billet;

• according to the macrostructure of the samples, to estimate the distribution of alloying elements of various density over its volume and, calculate the amount of allowances for mechanical processing related to this distribution;

• on the basis of experimental data (macrostructure), to determine the uniform distribution of alloying elements of different density by volume of continuously cast billets and evaluate the machining allowances for blanks from antifriction alloys;

• to set the critical value of the depth of the deformation hole, at which the maximum allowable and shear stresses on the shear for a particular billet will be equal;

• to determine the interval of the rational depth of the deformation hole formed on the side of the billet for billets from 80 to 150 mm;

• to evaluate the increase in the yield of continuous casting at rational values of the effort from the rolls to the billet and the temperature of its surface in the withdrawal-roll set;

• concerning the continuous casting process, to derive the dependence of the indicators of the yield of useful casting on the surface temperature of the billet and the forces acting on it from the side of the withdrawal-roll set;

• to build a three-dimensional model of the yield of suitable casting of continuously cast billets with a diameter of 150 mm from bronze БрО8Н4Ц2-type.

3. Contributing Ingredients for Experimental Study

To implement the study of formation of hollow billets from antifriction alloys using the methods of centrifugal and continuous casting, the following materials and equipment along with calculation methods were used.

Materials are as follow: БрО8Н4Ц2- (Cu−8% Sn−4% Ni−2% Zn) and БрО5Ц5С5-type (Cu−5% Sn−5% Zn−5% Pb) bronzes.

Technological processes are as follow:

• preparation of melts of the studied bronzes for the manufacture of hollow billets;

• melting of the charge in the melting furnace IC-0,5F-400;

• bringing the chemical composition to indicators that comply with regulatory documents;

• implementation of the uniform distribution of chemical elements throughout the furnace by electromagnetic stirring of the melt.

Equipment and experimental studies are as follow:

• the process of obtaining a melt, and pouring it into centrifugal and continuous casting machines;

• the melt of one of the investigated alloys is melted in a single furnace of the appropriate capacity, both centrifugal casting and castings are carried out from the same furnace;

• performing experiments on a centrifugal casting machine;

• the process of shaping billets with an external diameter of 80−150 mm on a centrifugal casting machine with drive rotation speeds equal to 1450 rpm and 965 rpm using a common industrial Inovert frequency converter, 150 kW/hour;

• the execution of experiments on a continuous casting machine with an outer diameter of 80−150 mm on a continuous casting machine.

Manufacturing processes are as follow:

• fabrication of samples from the cross section of hollow billets of stamps bronze БрО5Ц5С5 and БрО8Н4Ц2 to control the distribution of alloying elements in the cross section of the samples;

• grinding, etching, and photographing of the samples;

• fabrication of samples for etching and study of the macrostructure of billets obtained at different frequencies of rotation of the drive of a centrifugal casting machine;

• grinding and etching of samples for the study of the macrostructure of the billets obtained by the centrifugal casting machine;

• determination of efforts to overcome the sliding friction force in a pair billet–graphite crystallizer, taking into account the effort to overcome the static friction force;

• fabrication of samples from the cross-section of continuously cast billets for the study of their macrostructure: grinding and etching of samples for the study of the macrostructure of billets obtained by a continuous casting machine;

• fabrication of samples from the blanks of the studied bronzes to determine the temporal resistance during compression;

Methods are as follow:

• determination of forces acting on the billet in the transverse and longitudinal direction;

• determination of force acting on the billet by the rollers 1 (Fig. 1) pulling the cage;

• determination of force, acting in the direction of the axis of the billet and creating shear stresses of shear;

• determination of the mechanical properties of samples obtained from continuously cast billets;

• determination of the shear stress of the cut of samples from the studied bronzes obtained by the method of continuous casting;

• determination of the deformation depth wells on the billet surface by the depth indicator of the mark IG 100.

Basic methodological research goal is the development of a method of reducing allowances for mechanical processing in the fabrication of billets on continuous casting machines. This method consists in the following:

• determination of the critical depth of the deformation hole at which the current tangential cut stress (τ) is equal to the maximum permissible cut stress (τ_{max}) of the billet: $\tau = \tau_{max}$;

• determination of the range for the current depth of the deformation hole (h_{cur}), which corresponds to the condition $h_{cr} < h_{cur} < h_{giv}$ (h_{cr} is the critical deformation of the billet surface, h_{giv} is a normatively given specified depth of the deformation hole);

• determination of the rational reduction of $h_{cur} < h_{giv}$ to reduce the allowance for machining.

4. Methods for Determination of Tangential Cut Stresses and Forces Acting on the Billet

This section presents methods for determining the tangential stresses on the shear, the determination of forces acting on the billet, both in the direction of its axis, and in the direction perpendicular to the axis of the billet. It is necessary to find out how the forces applied to the billet and its temperature at the time of formation of the deformation well affect the yield of the continuous casting.

Figure 1, *a* shows a diagram for determining the area of a circle segment (cross-section of the billet of radius R) for different values of the depth of the deformation hole (h_1−h_4). At the engagement of teeth *2* with two rollers *1* of billet *3* (Fig. 1, *b*), the tangential shear stresses (see formula (1) below) emerge.

Figure 1 demonstrate the action of external forces in the formation of a deformation on the surface of the billet when it engages with the rollers.

Figure 1 shows the pattern of forcing teeth *2* of the roller *1* of the surface of the billet, and shows the relationship between the values of h_{cr}, h_{optim}, and h — the specified value of extrusion. In the process of applying force P, the teethes *2* of rollers *1* are pressed into the solid of the billet to a depth h in the range of 1.0−1.5 mm, which creates an engagement of the rolls with the billet (Fig. 1).

The cut stress is determined from the equation

$$\tau_{aver} = P_h / S_{segm}, \tag{1}$$

where P_h is a force from the withdrawal-roll set to the lateral surface *4* of the billet (Fig. 1, *b*).

The equation for calculation of the segment area [20] reads as

$$S_{segm} = 0.5\,R^2(\alpha - \sin a), \tag{2}$$

where S_{segm} is the area of the segment formed because of forcing the surface of the billet with the withdrawal-roll set, α is an angle (in radi-
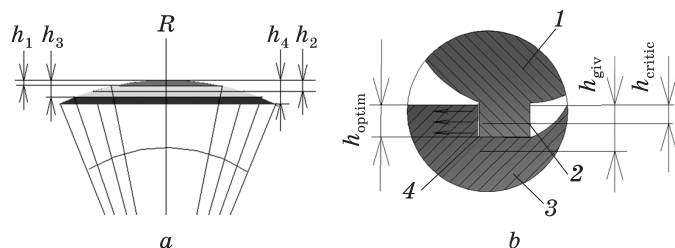

a

b

Fig. 1. Illustration of the engagement of the billet with rollers pulling the cage: (*a*) scheme of the change in the cut surface area at various values of the depth of deformation well (hole); (*b*) *1* designates the upper pressure roller, *2* designates the teeth on the roll surface, *3* designates the continuously cast billet, *4* designates the lateral surface of the deformation well

Fig. 2. Diagram of the effect of force P_v from the rollers on the side surface of the billet. Here, *1* — support of the withdrawal-roll set; *2* — mainstay of the withdrawal-roll set; *3* and *4* — flywheel and screw creating a force P_v in a pair of 'rolls–billet'; *5* and *6* — device, which is holding caster roll; *7* — mainstay of the device, which is holding the roll; *8* — continuously cast billet
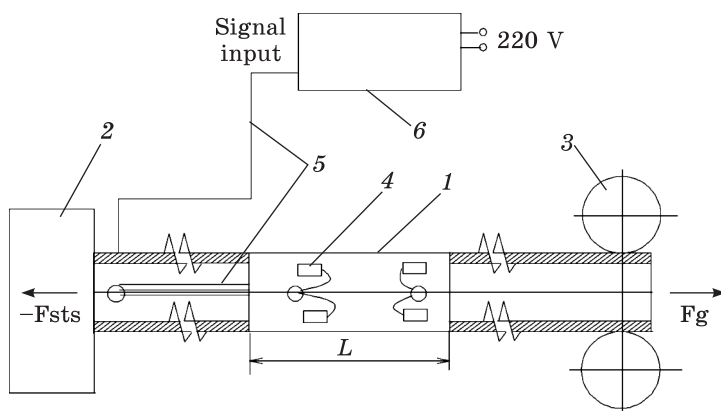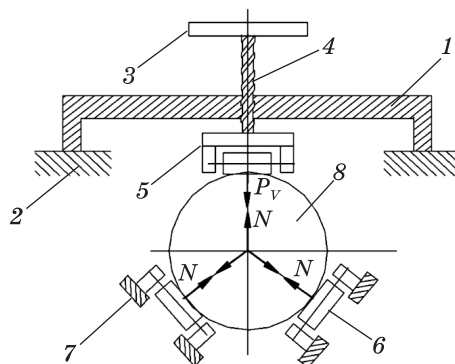
Fig. 3. Diagram of the device, which allows determining the ejection force billet produced at the pulling roller cage: *1* — a metal fixture for fastening thereon strain gauges *4*; *2* — continuous casting mould; *3* — rolls of cage; *5* — wires from strain gauges to an information processing device; *6* — a device for processing a signal from strain gauges; *L* — the length of the base, for which the calculation of force arising in the billet is carried out

ans) located in the centre of the billet, which limits the width of the tooth located on the rolls of the pulling cage.

Let us determine the angle in radians through the radius of the billet and the depth of the deformation hole h:

$$\alpha = 2 \arccos(1 - h/R), \qquad (3)$$

where h is a depth of deformation hole (in meters), R is a radius of continuously cast billet.

The values of the tangential cut stress τ and the depth of the deformation h are related to the effect of forces on the billet both in the longitudinal stress P_h and in the direction perpendicular to the axis of the billet P_v. The method of determining these efforts is illustrated in Figs. 2 and 3. Figure 2 represents a diagram of the engagement of the billet during its movement from the mould of the continuous casting machine.

The calculated force on the billet, which causes the formation of a deformation hole, is determined by the formula:

$$P_v = P_v/n, \tag{4}$$

where n is the number of props between the rollers and billet. As follows from Fig. 2, in this scheme of engagement of the continuously cast billet in the withdrawal-roll set, the number of stops is 3. The force was determined by tensionmeters, which were installed perpendicular to the axis of the billet on the compression line of the withdrawal-roll set to the lateral surface of the billet.

Figure 3 demonstrates a device for determining the effort to extract the billet from the mould (P_h), directed along its axis. The device contains a device *1*, on which strain gauges are attached to determine the force P_v. To improve the accuracy of the measurement, device *1* is made of a tubular shape. The wall thickness of the device *1* is selected from the condition of permissible strain gauges *(Δl* in the longitudinal direction of the billet). The use of radial diagrams in this article is expedient for clarity of determining the influence of some factors of centrifugal and continuous casting processes on the yield of casting, allowances on machining and the uneven distribution of alloying elements.

5. Results and Discussion of the Comparative Analysis of Mechanisms Affecting the Yield of Casting during Shaping the Hollow Moulded Billets

Let us carry out comparative assessment of the yield of suitable hollow castings produced with different mechanisms for the formation of hollow billets of antifriction alloys, which contain alloying elements with an increased density, such as tin and lead.

Note that the maximum allowances for machining cast hollow billet obtained in centrifugal casting machines are determined based on [21, 22] and is not more than 3.5 mm. However, results of experimental studies (Fig. 4, *a*, *b*) show that the actual machining permission for casting in БрО8Н4Ц2 and БрО5Ц5С5 bronze goes beyond permissible.

In Figure 4, as an example, the macrostructures of centrifugally cast billets with a diameter of 150 mm (made of БрО8Н4Ц2 bronze) are presented at different speeds of rotation of the drive of a centrifugal casting machine.

For samples, the hollow billet obtained on the machine of centrifugal casting, samples were taken at three points *I*, *II*, and *III*, the respective vicinities of the outer layer billet (point I), the middle of the thickness of its wall (point *II*) and in the vicinity of the inner surface of the billet (point *III*, Fig. 4). To study the content of the main chemical elements, Zn, Sn, and Ni, samples were taken from a БрО8Н4Ц2

Fig. 4. Macrostructure of the hollow centrifugally cast billet sample of БрО8Н4Ц2 at 965 rpm (*a*) and 1495 rpm (*b*) [22]
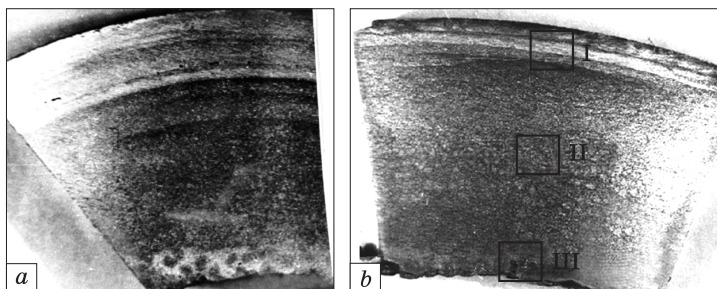
bronze billet. Quantitative analysis of alloying elements near points *I*, *II* and *III* (Fig. 4) was determined in the chemical laboratory PJSC 'Svitlo Shakhtarya' (Ukraine). The test results for determining the basic chemical elements of БрО8Н4Ц2 near points *I*, *II* and *III* in the samples obtained by the centrifugal method are presented in Table 1.

The increased tin content in the bronze alloy of the brand БрО8Н4Ц2 (Table 2) confirms the separation of Sn at the outer wall of the billet, which confirms the data presented in Fig. 4, *a* and *b*. Analysis of the macrostructures of the cross-section of the billets showed the following. In accordance with the periodic table, we summarized (in Table 2) times the ratio of the relative atomic masses of the main chemical elements found in bronze alloys of БрО8Н4Ц2 and БрО5Ц5С5.

Table 1. **The distribution of chemical elements
in the transverse section of the billet [23]**

Method of obtaining billets	Point number	The average content of alloying elements in the cross-section of the billet, %		
		Zn	Sn	Ni
Centrifugal (Fig. 4)	*I*	1.89	10.32	4.62
	II	1.86	8.45	4.60
	III	1.81	8.43	4.49

Table 2. **Values of relative atomic masses and their
multiplicity for various chemical elements of the БрО8Н4Ц2
and БрО5Ц5С5 alloys, relative to the atomic masses of tin and lead**

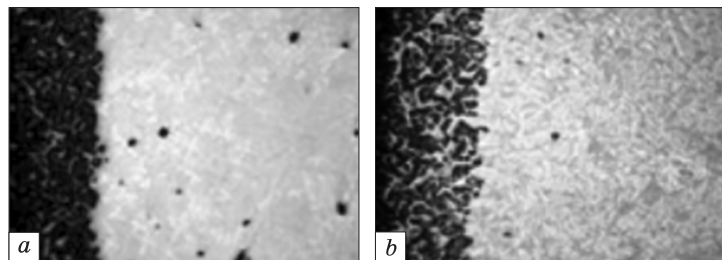| Name of chemical elements	Atomic mass of chemical elements	The ratio of the excess of the atomic mass of tin (a.m. Sn = 118.69)	The ratio of the excess of the atomic mass of lead (a.m. Pb = 207.2)
Zn	65.38	1.81	3.17
Cu	63.546	1.87	3.26
Ni	58.7	2.02	3.53

Fig. *5*. Separation of reinforcing dispersed particles in the aluminium-based alloy AK12 [3]: *a* — the structure of the alloy AK12 + 10% Al_2O_3 + 2% C obtained by rotating the drive 1200 rpm; *b* — the structure of the alloy AK12 + 5% Al_2O_3 obtained by rotating the drive 1000 rpm

As follows from Table 2, tin and tin−lead bronzes are more susceptible to delamination of such chemical elements as tin and lead, whose atomic mass greatly exceeds the other chemical elements of the alloys. It follows that the atomic masses of Sn and Pb in bronze alloys exceed in weight by 1.81−3.53 times, while, in aluminium alloy AK12 (84.3−90% of Al, 10−13% of Si, and 2.7% of impurities: Fe, Mn, Cu, Ti, Zr, Mg, Zn) [3], this excess is 0.639−1.5 times. At the same time, at the speed of rotation of the centrifugal-casting machine drive in the fabrication of alloy AK12 of 1200−1500 rpm, the effect of separation of reinforcing dispersed particles was obtained (Fig. 5). In Ref. [3], it was shown that, as in the case of antifriction copper alloys (Fig. 4, *a* and *b*), the speed of movement of solid reinforcing particles under the action of centrifugal forces depends on the frequency of rotation of the drive motor of a centrifugal machine.

Studying the macrostructures, we revealed some regularities for the formation of the centrifugally cast billets. They follow below.

(1) It is determined that the higher the rotational speed of the centrifugal casting machine drive, the denser the tin is deposited in the vicinity of the outer surface of the billet. For example, when casting the same БрО8Н4Ц2 bronze at a speed of 965 rpm, a wide layer was obtained at the outer surface enriched with tin (Fig. 4, *a*), and in the case of a drive rotation speed equal to 1450 rpm, compacted (thin) tin layer.

(2) As follows from Fig. 4, *a*, a tin is easily oxidized with elements of surface or refining slag. In the slags, reactions can occur, because of which the tin salts are formed: SnO_2 $SnCl_2$, SnS or SnS_2, SnF_4. The specific gravity of tin salts is significantly less than the specific gravity of pure tin; moreover, salts can be included in the complex compound formed because of the reaction with slag. This may explain the presence of tin in the places where the lightest components of the alloy are located; it is slag with tin salts adsorbed on its surface and the heaviest are pure tin (at the outer surface of the billet).

(3) There is a condition when an increased amount of tin is necessary on the surface of the machine part. This is an increase in the antifriction properties of the surface of the part. However, the following process discrepancies can be found here: first, tin in this place exceeds the required stoichiometric ratio for the formation of compounds with copper (*e.g.*, compounds Cu_3Sn_8); secondly, compounds that are more saturated with tin, being present at the outer surface of the billet, cause rapid wear of the part during operation.

(4) These studies are confirmed by earlier studies [21], which also indicate the segregation of denser alloying elements and uneven distribution in the radial direction of the billet.

(5) To obtain billets with a uniform distribution of alloying elements by volume of the billet, it is advisable to remove the entire tin-rich layer of the billet as an allowance for machining, which leads to unnecessary consumption of expensive alloying elements.

(6) The application of the technological process of centrifugal casting for casting hollow billets with alloying elements such as tin and lead is not economically feasible. First, the machining allowances reach 10.0–15.0 mm, and secondly, there is a cost overrun for alloying elements such as tin (in bronze БрО8Н4Ц2) and lead (БрО5Ц5С5).

(7) From Figures 4 and 5, it follows that the speed of rotation of the drive of the continuous casting machine affects the centrifugal forces that cause segregation of denser particles and elements of both copper and aluminium alloys at the outer walls of the billet.

Thus, experimental studies of the centrifugal casting process of hollow billets made of bronze of the БрО8Н4Ц2 and БрО5Ц5С5 (Fig. 4, *a*, *b*) showed the following:

• as determined, the allowances for machining for the outer side of billets with a thickness of 50–55 mm, at speeds of rotation from 965 rpm to 1495 rpm, are in the range of 7.8–15.0 mm per side;

• shrinkage porosity, accumulation of liquates and non-metallic inclusions, and the possibility of defects in the form of longitudinal and transverse cracks, as well as gas bubbles, are formed on the inner surface of the billet.

In addition, during centrifugal casting of the studied tin bronzes, the uniform distribution of alloying elements over the volume of the billet is disturbed. This circumstance leads to a change in the properties of the outer surface of the billet due to the increased content in the specified area of the billet for alloying elements like Sn and Pb. Note that the centrifugal casting method is used for billets with much larger outer diameter and wall thickness, which can result to higher machining allowances.

Works [17–19] present studies that allow one to evaluate some characteristics of the quality of metals and alloys or their fabrication pro-
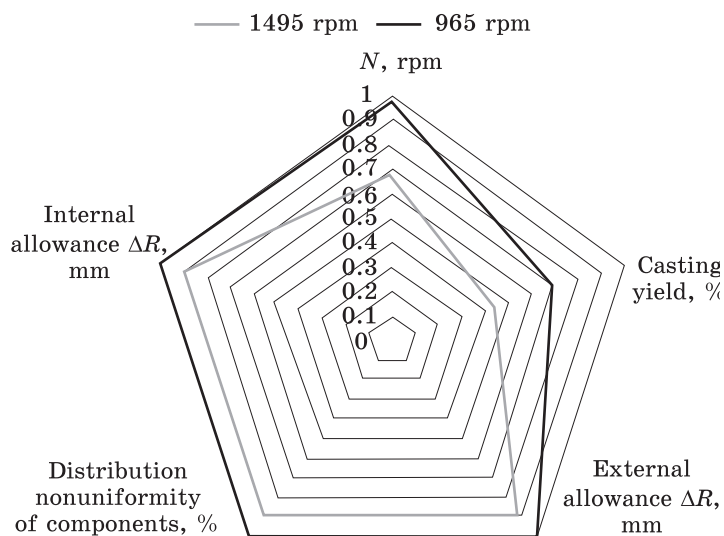
Fig. 6. Determination of the influence of the number of revolutions of the billet on the yield of centrifugal casting using the radial diagram

cesses using the radial diagram. Therefore, in this work, it is necessary to determine the mechanism of formation of a layer of one or several alloying elements near the outer surface of centrifugally cast billets and determine the effect of the rotational speed of the machine drive on this process. This raises the need to solve the problems of determining the feasibility of changing the technological process in the fabrication of billets of copper alloys and the prospects for further increasing the yield of billet with a diameter of 80−150 mm.

Let us estimate the yield of casting billets with a diameter of 150 mm and a wall thickness of 50 mm from bronze of the БрО8Н4Ц2 and БрО5Ц5С5 grades on a centrifugal casting machine.

On the basis of the obtained experimental data on the determination of the mechanism of formation of centrifugal billets, the result of which is Fig. 4, *a* and *b*, the yield of centrifugal billets made from antifriction alloys was calculated. In this case, it was planned to obtain billets with external diameters of 80, 110, and 150 mm after removing the machining allowance from the billet.

Based on the data in Table 3, we determined that the values of the yield of the casting are not constant. Thus, with a constant length of the billet, the indicators for the yield of a suitable casting are a function of the outer diameter of the billet. For instance, with an increase in the outer diameter of the billets from 80 to 150 mm, it increases from 46.0 to 61.87%. It is shown in Fig. 6, the effect of the number of revolutions of the hollow billet (at a constant melt temperature $T = 1150\,°C$) on the

machining allowances, the uniform distribution of tin over the cross section of the billet and the yield of centrifugal casting. Figure 6 shows the values of allowances for machining, the uneven distribution of alloying elements over the cross section of the billets and the yield of casting at the number of revolutions of the billet of 1495 rpm and 965 rpm.

The use of the radial diagram allowed us to trace the effect of the number of revolutions of the billet on the allowances for mechanical processing, on the external and internal surfaces of the billet, as well as on the degree of uneven distribution of the alloying elements in the cross section of the hollow billet. These indicators, ultimately, allow us to estimate not only the yield of centrifugal casting, but also assess the quality of the billet according to parameters such as uneven distribution of elements over the volume of the billet.

Thus, summarizing the study of formation of hollow billets with a diameter of 80–150 mm by the method of centrifugal casting we can conclude that the yield of centrifugal casting, which ranges from 46.0 to 61.87% (for specified size), reduces the economic efficiency of fabrication of billets. In addition, centrifugal casting causes an uneven distribution of alloying elements over the cross section of the billet, has allowances of 5.5–15.0 mm on the side on the outside of the billet and from 4.0 to 10.0 mm on the inside of the billet.

For comparison of the macrostructures on the horizontal continuous casting machine, an experimental casting of hollow billets of bronze of the БрО8Н4Ц2 and БрО5Ц5С5 grades of the same size was made.

The work [28] concerns a comparative assessment of the quality of billets obtained by continuous and centrifugal casting. The article showed that continuously cast billets, as compared to centrifugally cast, have more uniform distribution of alloying elements in the volume of the billet, as well as have a high yield of casting. However, in Ref. [28], the mechanism of the stratification of alloying elements in the radial direction of the centrifugally cast billet was not considered. In addition, the mechanism for forming the thickness of the layer of alloying elements having an

Table 3. **Experimentally obtained allowances for the machining of hollow centrifugally cast billets with a length of 300 mm**

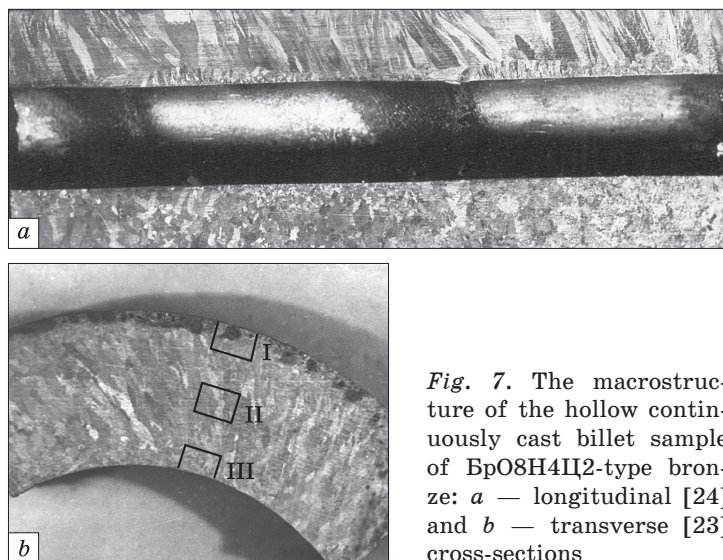| Type of billets	Bronze type (grade)	Casting diameter + + allowances	The diameter of the billet, mm	Machining allowances		Average yield casting, %
				Inner diameter, mm	Outside diameter, mm	
Cuffs, holders	БрО5Ц5С5 БрО8Н4Ц2	90/40 120/51 165/80	80/50 110/60 150/90	4.0–5.5 6.0–9.0 7.5–10.0	5.5–10.0 8.0–10.0 10,0–15.0	46.00–59.84 52.49–61.06 55.38–61.87

Fig. 7. The macrostructure of the hollow continuously cast billet sample of БрО8Н4Ц2-type bronze: *a* — longitudinal [24] and *b* — transverse [23] cross-sections

increased density relative to the rest of the alloy elements was not determined, since this relates to the amount of allowances for machining.

The experimental conditions consisted in the fact that bronzes of БрО8Н4Ц2 and БрО5Ц5С5 grades were melted in one furnace; the melt was fed both to a continuous casting machine for casting billets with an outer diameter of 150 mm, and to a centrifugal casting machine for casting billets of a similar size. Bronze БрО8Н4Ц2 and БрО5Ц5С5 billets were cast in different days. As an example, Fig. 7 shows the macrostructure of the cross-section and longitudinal section of a billet of the БрО8Н4Ц2, grade bronze obtained by the method of continuous casting.

Analysis of the macrostructure of continuously cast billets showed that near the outer surface of the billet there are no layers of any alloying elements. This indicates a uniform distribution of chemical elements

Table 4. **The distribution of chemical elements over the cross-section of the billet after continuous casting**

| Method of obtaining billets	Point number	The average content of alloying elements in the cross-section of the billet, %		
		Zn	Sn	Ni
Continuous casting the upper wall of the billet (Fig. 7, *a*, *b*)	Upper wall surface (*I*)	1.79	7.26	3.84
	Centre wall (*II*)	1.81	7.47	3.92
	Lower wall surface (*III*)	1.85	7.52	3.89
Continuous casting the bottom wall of the billet (Fig. 7, *a*)	Upper wall surface (*I*)	1.88	7.59	3.93
	Centre wall (*II*)	1.85	7.63	3.95
	Lower wall surface (*III*)	1.92	7.69	4.02
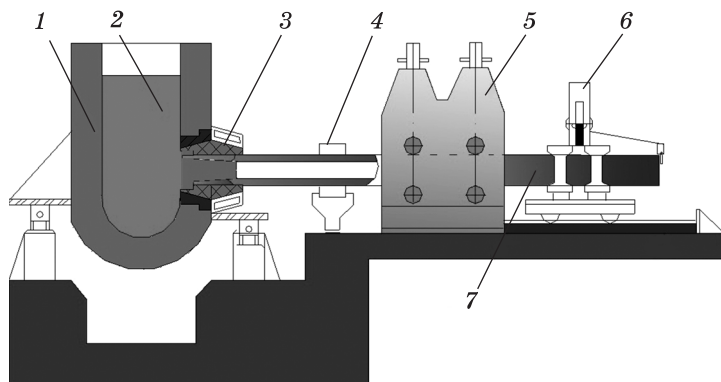
Fig. 8. Diagram of a horizontal continuous casting machine for hollow billets of copper alloys [28], where *1* denotes metallic reservoir carcass, *2* denotes melt, *3* denotes crystallization unit, *4* denotes secondary cooling, *5* denotes pulling cage, *6* denotes device for cutting billets, *7* denotes billet

throughout the volume of the billet and is confirmed by the results of chemical analysis of continuously cast billets at points *I*, *II*, *III* (Table 4; Fig. 7, *a*, *b*). Thus, the process of continuous casting by eliminating the segregation of denser alloying elements to the walls of the billet can significantly reduce the allowances for machining.

As follows from Table 4, at a continuous casting, alloying elements are distributed more evenly in comparison to centrifugally cast billets.

The second stage of the study is aimed at studying the force interaction of the surface of the continuously cast billet and the withdrawal-roll set, which can change the yield indicators for continuous casting.

These studies can be divided into the following ones:

• determination of the critical values of the depth of the deformation hole (*h*), at which the tangential stresses on the shear will be equal to the maximum allowable stresses of the billet in the temperature range of 100–200 °C;

• determination of the rational values of *h* at which it is possible to reduce the allowances for machining;

• determination of the dependence of changes in the allowance for machining and develop a three-dimensional mathematical model of the influence of such factors as the force (*P*) of the interaction of the billet with the rolls of the cage and temperature (*T*) of the surface of the billet at the yield of continuous casting.

A more promising process for the fabrication of copper alloy billets is a continuous casting process, which receives considerable attention in many leading countries of the world [27, 28]. In Ukraine, there is the fabrication of billets from copper alloys by the method of continuous casting [27, 28] too, so these works are devoted to improving the

Fig. 9. A deformation well (hole) on the surface of a continuously cast БрО8Н4Ц2-bronze billet at 100 °C

stability of the continuous casting process when casting hollow billets from copper alloys, improving the quality of continuously cast billets.

We use the continuous casting machines designed for casting solid and hollow billets with diameters from 80 to 150 mm (see scheme in Fig. 7) to carry out experimental studies to determine the effort of extracting the billet from the mould (P_h) and the effort of interaction of the billets with the withdrawal-roll set (P_v). In addition, this machine was applied to determine the depth of the deformation well, using the ГИ 100 indicator depth gauge. The machine shown in Fig. 8 described in the work [28].

Fabrication of hollow billets from copper alloys by the method of continuous casting on horizontal machines is the most efficient way to manufacture these products. The process of continuous casting is characterized primarily by a continuous process of manufacturing billets, which leads to the fabrication of billets of unlimited length. The most significant advantages of the continuous casting process are that, firstly, this process is easily automated, and secondly, it allows to increase the yield of casting to 95−97%. In addition, it is also relevant to conduct research on the issue of rational reduction of allowances for mechanical processing for billets obtained by the method of continuous casting.

It was determined that deformation wells (Fig. 9) are formed on the surface of the billet because of force action on it from the side of the withdrawal-roll set. This allowed for billets with an outer diameter of 80−150 mm to reduce the machining allowances for the external wall of the billet from 5.5−15 mm to 1−1.5 mm per side (Fig. 9), which in turn, allowed increasing the yield of casting. Figure 9 demonstrates so-called deformation well (hole) on the surface of the billet.

The depth of the deformation well (hole) was measured using an indicator gauge ГИ 100. For each ratio of temperature (T) and force (P) acting on the billet from the rolls, six measurements are recommended. This amount of experimental data, when processed according to the method described in [20], allows obtaining a regression equation that described the results of experiments with a 95% probability. The results of the experiments are listed in Table 5.

An important place in experimental studies is the determination of the critical depth (h_{cr}) of the deformation hole on the surface of the billet formed by the teeth of the rolls of the pulling cage (position *1* in Fig. 1 and position *6* in Fig. 2). The average value of h_{cr} defines the

difference between the set value of machining allowances (h_{giv}) and h_{cr} for each standard size of 80, 110, and 150 mm billets. The difference $h_{\mathrm{giv}} - h_{\mathrm{cr}}$ allows determining the degree of reduction of allowances for real machining, which allows increasing the yield of continuous casting.

Let us obtain a condition, under which it is possible to determine the value of the tangential stress on the cut, at which it is possible to engage the billet.

The value of the effort to extract the billet from the mould has a value close to a certain value P_h. The change in the cross-sectional area of a circle segment leads to a significant change in the tangential stress of the cut in the temperature range of the billet under investigation.

For Equation (1), there is a whole series of points satisfying the condition

$$\tau_{\mathrm{st}} = P_h/S_{\mathrm{segm}} = \langle \tau_{\mathrm{st}} \rangle. \tag{5}$$

For condition (5), we have to find values of the depth of the deformation hole (we will call them critical) for the temperature range 100–200°C and the effort of interaction between the rollers of the pulling cage and the billet.

Combining Eqs. (2) and (3), one obtain

$$\tau_{\mathrm{st}} = 2P_h/\{R^2[2\arccos(1 - h/R) - \sin a]\} = \langle \tau_{\mathrm{st}} \rangle, \ h > h_{\mathrm{cr}} \tag{6}$$

Thus, an equation is obtained that relates the depth of the deformation hole (h) to the tangential stress on the cut. The value of h in our case is a function:

$$h = f(P, T). \tag{7}$$

Let us obtain dependences of the deformation-hole depth on the force P_v (Fig. 4) and on the surface temperature of the billet located in the rolls of the pulling cage (position *6* in Fig. 2). For this, it is necessary for various values of force P_v to determine the depth h for the

Table 5. **The results of an experimental study of the determination of the critical depth of the deformation hole in the continuous casting of bronze brand БрО8Н4Ц2 with a diameter of 150 mm**

| Indices of T (°C) and P (N)	$h_{1\mathrm{cr}}$, mm	$h_{2\mathrm{cr}}$, mm	$h_{3\mathrm{cr}}$, mm	$h_{4\mathrm{cr}}$, mm	$h_{5\mathrm{cr}}$, mm	$h_{6\mathrm{cr}}$, mm	$\langle h_i \rangle$, mm
100 and $4 \cdot 10^3$	0.11	0.12	0.10	0.12	0.10	0.13	0.113
100 and $6 \cdot 10^3$	0.56	0.53	0.53	0.54	0.54	0.55	0.545
100 and $8 \cdot 10^3$	1.19	1.11	1.18	1.14	1.15	1.14	1.152
150 and $4 \cdot 10^3$	0.57	0.61	0.59	0.56	0.58	0.59	0.583
150 and $6 \cdot 10^3$	0.95	0.91	0.92	0.94	0.95	0.92	0.931
150 and $8 \cdot 10^3$	1.25	1.21	1.24	1.23	1.26	1.23	0.237
200 and $4 \cdot 10^3$	0.96	0.93	0.91	0.94	0.92	0.94	0.933
200 and $6 \cdot 10^3$	1.21	1.19	1.29	1.24	1.22	1.31	1.243
200 and $8 \cdot 10^3$	1.56	1.44	1.62	1.42	1.53	1.54	1.495
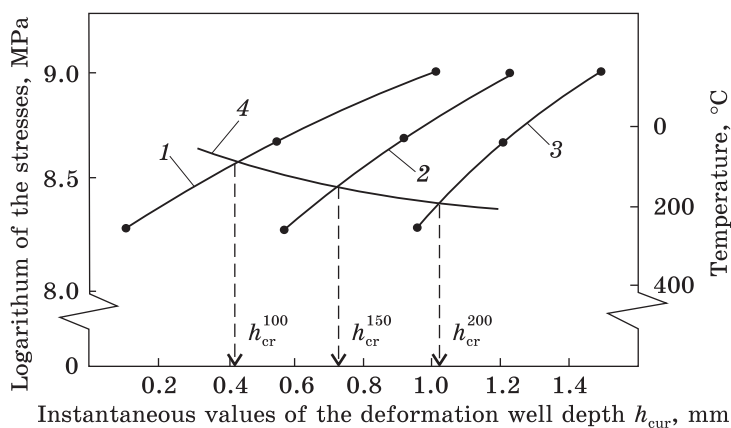
Fig. 10. Determination of the critical values of the depth of the deformation hole (well) on the surface of the БрО8Н4Ц2-type bronze billet depending on the temperature of the billet surface. Here, *1*, *3* — dependences of the change of the magnitude of the tangential shear stresses depending on the depth of the deformation well for 100, 150, and 200 °C, respectively; *4* — temperature dependence of the maximum allowable stress $\sigma = f(T)$

surface temperature of the billet of 100 °C and 200 °C. Temperature measurements on the surface of the billet were performed using a D 300-type TV measured temperature within the range [–20 °C; +600 °C]. The retention of a given temperature was carried out by adjusting the technological parameters of the continuous casting process and the rate of passage of water in the mould of the continuous casting machine. The depth *h* of the deformation hole was determined using an indicator depth gauge ГИ 100.

Thus, in the course of the experimental studies, measurements of the depth *h* were selected, which exactly corresponded to 100, 150, and 200 °C. Extreme values (maximum and minimum) were excluded from experimental data. As a result, six measurements remained. Statistical processing of experimental results (Table 5) was carried out using the Maple program according to the method described in Ref. [29]. Table 5 shows the options for measuring the depth of the deformation hole obtained using indicator depth gauge ГИ 100.

Based on the data of Table 5, we define the critical depth of the deformation well (hole), at which the condition (5) will be satisfied at a temperature on the surface of the billet equal to 100 and 200 °C. The results of studies on the compression of samples from billets at their temperature equal to 100 °C and 200 °C showed that, as the temperature increases, the amount of compression of the samples increases, which causes an increase in the depth of the deformation hole at the value (Table 5, Fig. 10, curve *4*).

Using dependences *1–3* in Fig. 10 for БрО8Н4Ц2-type bronze, the values of the critical depth of the deformation hole on the surface of the billet were determined for temperatures of 100, 150, and 200 °C. Given the safety factor of 1.1, it was determined that the critical value $h_{cr}^{100} = 0.430$ mm, $h_{cr}^{150} = 0.731$ mm, and $h_{cr}^{200} = 1.025$ mm. At the next stage of research, it is necessary to determine the rational interval of the depth of the deformation hole that allows you to extract the billet from the mould without the limit tangential stresses and reduce the allowances for mechanical processing, which will further increase the yield of casting.

It was determined that the higher the surface temperature of the billet, the deeper the teeth of the rolls pushing its surface under constant transverse load, forming a deformation well. On samples of billets obtained on a continuous casting machine, six-fold measurements of the depth of the well were carried out using a depth gauge indicator ГИ 100 for each ratio of temperature (*T*) and force (*P*). The measurement results are inserted in Table 5.

We obtained the dependence of the influence on the yield of casting of such factors as the surface temperature of the billet located in the rolls of the pulling cage, and the force acting on the billet from the side of the rolls. From the previously cited studies, it follows that the current value of the depth of the deformation hole (*h*) depends both on the surface temperature of the billet and on the force acting from the rolls of the pulling cage. Therefore, we can write that the current value of the depth of the deformation hole:

$$h_{cur} = f(P, T),$$

where *T* is a surface temperature of the billet located in the rolls of the pulling cage (°C), *P* is force acting on the billet from the withdrawal-roll set (N).

To determine the yield of suitable casting of round shaped billets, it is necessary to take into account that, when we have a deformation well of *h* depth during machining, it is necessary to reduce the radius of the billet by $h_{cur} = \Delta r$. Since the depth of the deformation hole depends on both the force P_v and temperature (*T*), therefore, we write down:

$$h_{cur} = f(P_v, T) = \Delta r(P_v, T).$$

The yield of casting (η) for billets of circular cross-section is defined as the ratio of the masses before and after removal of allowances for machining:

$$\eta = \frac{4\pi [R - \Delta r\,(T, P)]^2 L\gamma}{4\pi R^2 L\gamma} = \left[1 - \frac{2R\,\Delta r\,(T, P) - [\Delta r\,(T, P)]^2}{R^2}\right] \cdot 100\% . \quad (8)$$

Here, *R* is a radius of the billet (m); *L* is a length of the billet (m); γ is a density of the billet material (kg/m³); $\Delta r(T, P)$ is a change in the radius of the billet due to allowances for machining. To determine the
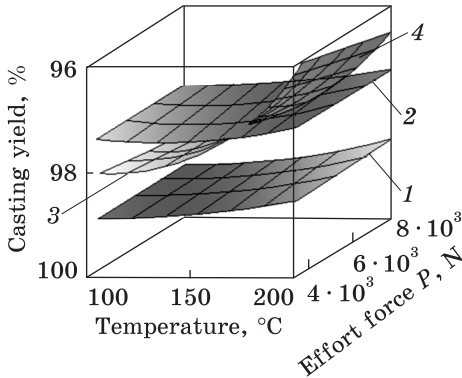
Fig. 11. Three-dimensional model for the casting yield of the БрО8Н4Ц2-bronze billets (1500 mm in diameter) depending on the surface temperature of the billets and the force from the withdrawal-roll set. Here, *1* — plane of the maximum permissible minimum values of the depth of the deformation hole (h_{cr}, see also Table 5); *2* — plane of restriction of the rational depth of the deformation hole (well); *3* — part of the dependence (6) corresponding reduction of allowances for mechanical processing (Table 5) when $h_{cr} < h(T,P) < h_{giv}$ (Fig. 1, *b*); *4*—plane that goes beyond the level of rational values for the deformation hole depth (Table 5)

rational yield of suitable casting of billets with a diameter of 80−150 mm from the БрО8Н4Ц2 bronze brand, we obtain the equation:

$$\eta = \{1 - 2R\Delta r(P,T)\,[\Delta r(P,T)]^2/R^2\}\cdot 100\%\,, \qquad (9)$$

where $4\cdot 10^2$ N $< P < 8\cdot 10^2$ H and $100\,°C < T < 200\,°C$.

Data of Table 5 and Eq. (8) enable construction of a three-dimensional model of dependences for billets of 150 mm in size (see Fig. 11).

The model in Fig. 11 includes three planes. The first plane *1* represents the points that represent the critical values of the depth of the deformation hole (h_{cr}) for different temperatures from 100 °C to 200 °C when the pulling cage rolls are subjected to the force *P*. The plane *1* is modelled *via* Eq. (5).

The second plane is a set of predetermined values of the depth of the deformation well (h_{giv}), which determine the planned values of the yield, calculated according to Eq. (9).

Table 6. **Estimated data of casting yield under transverse load ($P_v = 8\cdot 10^3$ N = const) on a billet (at 200 °C) for its various perform diameters and type of the bronze type (БрО8Н4Ц2 and БрО5Ц5С5) cast on a continuous casting machine**

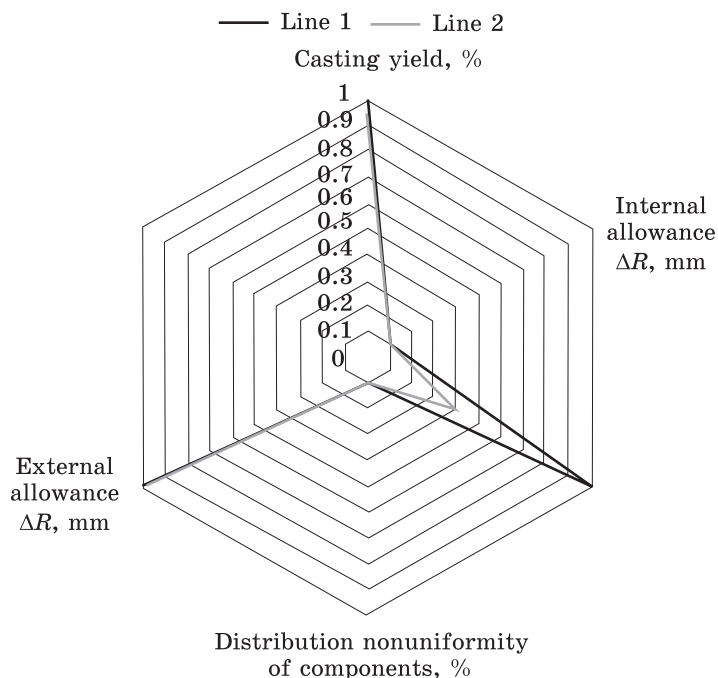| No.	The material of the billet	The diameter of the billet, mm	Machining allowances h, mm		Casting yield, %	
			Base	Calculated	Base	Calculated
1	БрО5Ц5С5	80	1.0	0.45	95.06	97.72
	БрО8Н4Ц2	80	1.0	0.50	95.06	97.51
2	БрО5Ц5С5	110	1.2	0.69	95.68	97.51
	БрО8Н4Ц2	110	1.2	0.75	95.57	97.29
3	БрО5Ц5С5	150	1.5	1.0	96.04	97.35
	БрО8Н4Ц2	150	1.5	1.0	96.04	97.35

Fig. 12. The influence of technological parameters (factors) of the continuous casting process on the casting yield

Planes *3* and *4* represent one plane divided into two parts. The half-plane *3* is located between the planes *1* and *2*; therefore, it has allowable values of the depth of the deformation hole, which are in the allowable interval of the values of allowances for machining (see Table 6). On the half-plane *4* at temperatures close to 200 °C, and under loads on the withdrawal-roll set close to 8 103 Pa, the depth values of the deformation well (hole) go beyond the limits of plane *2*, which leads to an increase in allowances for mechanical processing (Table 6).

As follows from Fig. 12, using the radial diagram, it is possible to visualize the degree of influence of such a factor of the continuous casting process, such as the surface temperature of the billet, equal to 100 °C and 200 °C, on the yield of continuous casting.

Figure 12 shows that at the manufacturing hollow billets, the machining allowances on the inner surface of the billet are not laid down, since the inner surface of the billet does not enter into force interaction with the rolls of the pulling cage. This circumstance is also a positive factor in favour of the continuous casting process in a comparative analysis.

Figure 12 indicates that the surface temperature of the billet affects, for a given shear stress on the shear, the depth of the deformation

well, which in turn affects the machining allowances and the yield of the casting.

Thus, performed experiment allowed as follows below:

• to determine the criterion (minimum possible) value of the depth of the deformation hole (h_{cr}), at which tangential shear stress τ is created, exceeding the limiting shear stress of the material of the continuously cast billet;

• to determine the interval of rational values of the depth of the deformation hole, which allow a stable engagement of the rolls with the billet and reduce machining allowances;

• according to the developed dependence, to construct a three-dimensional model of the influence of such parameters as the surface temperature of the billet and the forces acting on it from the withdrawal-roll set on the yield of suitable bronze alloys;

• to explain the transition of the process of hollow billets of copper alloys from centrifugal casting to continuous and determine that for billets with a diameter of 80–150 mm, the yield increased from an average of 35.48% to 51.72%.

Table 7 shows the total increase in yield for the studied sizes as a result of a two-stage reduction of allowances for machining.

Replacing the casting process of hollow billets on centrifugal casting machines with a continuous casting process allows us to increase the yield of suitable casting (Table 7).

A study carried out in this work revealed two facts. (i) On the one hand, increasing the speed of the drive of the centrifugal casting machine (CM) will reduce and compact the layer of alloying elements, which leads to a slight increase in yield (Fig. 4, *a* and *b*). (ii) On the other hand, the use of a centrifugal casting machine for the fabrication of billets with antifriction properties causes an overrun of alloying elements (Sn, Pb), since the layer enriched with alloying elements goes into mechanical processing.

This indicates that the effect of centrifugal forces on the melt worsens the uniform distribution of alloying elements throughout the billet,

Table 7. **Comparative data on the yield of suitable casting of hollow billets of bronze of the БрО8Н4Ц2 and БрО5Ц5С5 grades obtained by casting on the centrifugal and continuous casting machines**

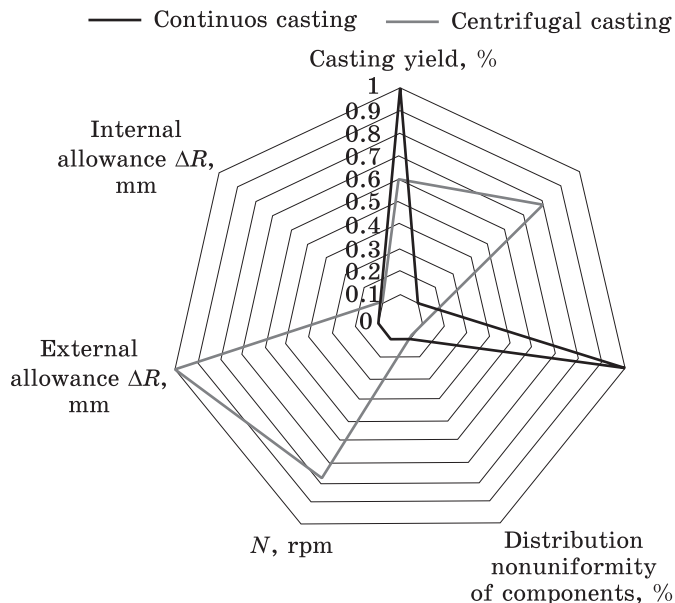| Diameter of the billet, mm	Allowance for machining (centrifugal casting), mm	Average allowance for machining (caster), mm	Yield of casting (centrifugal casting), %	Yield of casting (caster), %	Difference between the yield values, %
80/50	10–15	1.0	46.00–59.84	97.72	37.88–51.72
110/60	10–15	1.2	52.49–61.06	97.29	36.23–44.80
150/90	10–15	1.5	55.38–61.87	97.35	35.48–41.97

Fig. 13. Factors determining the yield for the continuous and centrifugal casting processes during fabrication of the 150×90 mm²-size billets

which reduces the quality of the billets and increases the consumption of expensive elements (Sn, Pb), which create antifriction properties of the billets.

For clarity, we compare two processes for the manufacture of hollow billets of antifriction alloys on the centrifugal and continuous casting machines (Fig. 13).

The yield of suitable centrifugal casting is equal to 55.38–61.89% and depends on the value of allowances for machining, both on the outer and on the inner side of the hollow billet. The value of these allowances depends on the number of revolutions of the billet during its hardening. One of the drawbacks of the continuous casting process is the excessive consumption of alloying elements, as well as their uneven distribution over the cross section of the billet, the cause of which is the presence of centrifugal forces acting in its radial direction.

The rate of yield of continuous casting is equal to 97.29–97.72% because mechanical treatment is not provided on the inner surface of the hollow billet, and an insignificant depth of the deformation hole for the billet with an outer diameter of 150 mm is less than 1.5 mm. In addition, the uneven distribution of alloying elements has a very small value (Table 4). One of the drawbacks of the continuous casting process is the temperature of the surface of the billet, during its interaction with the withdrawal-roll set, since this temperature affects the depth of the deformation hole. The advantage of the continuous casting process is the absence of forces acting on the melt (except gravity), which could

cause uneven distribution of alloying elements over the cross section of the billet.

As follows from this, the continuous casting process has advantages that make it possible to have a high yield, the absence of significant uneven distribution of alloying elements, resulting in cost overruns of expensive alloying elements found in antifriction alloys.

The studies presented in the article also have a practical focus. We determined that the method of continuous casting compared with centrifugal casting of hollow billets could significantly reduce the machining allowances and, accordingly, increase the yield of casting. For each size of the billets, there is its own interval for increasing the yield of suitable casting. Therefore, for billets with an outer diameter of 80 mm, the increase in the yield rate is $46.00-59.84\%$, $52.49-61.06\%$ for billets with diameter of 110 mm, and $55.38-61.87\%$ for billets with diameter of 150 mm. We found the allowable depth interval of the deformation hole (beginning from its critical depth), which allows the rollers to engage the billet. This made it possible further reducing the machining allowances, which increased the yield of useful casting from 95.06 to 97.72% for the studied bronze types (due to a decrease in the allowances for machining).

The dependence of the indices of the yield of continuous casting on the surface temperature of the billets and the forces acting on the billet from the side of the rolls of the pulling cage is obtained.

A three-dimensional model of the yield of continuously cast billets 150 mm in size made of bronze of БрО5Ц5С5 brand was constructed.

These studies can be applied during the design and reconstruction of the workshops of engineering enterprises in order to select the technological process in the manufacturing of the billets and their diagnostics [30, 31].

The work carried out allows us to conclude that the transition to more modern methods of producing billets can not only improve the work of the operator, but also increase the economic efficiency of fabrication.

6. Conclusions

The result of the study identified the regularities for the shaping hollow billets on centrifugal and continuous casting machines.

1. The mechanism of segregation of denser alloying elements to the outer wall of the billet is determined.

2. The effect of the speed of rotation of the billet on the thickness of the layer of alloying elements at its outer surface is shown. Therefore, at the speed of rotation of the billet at a speed of 965 rev/min, the amount of allowances for machining was 15.0 mm and, at a speed of rotation of 1495 rev/min, 7.8 mm.

3. As a result of a comparative analysis of the mechanisms of formation of billets by the methods of centrifugal and continuous casting, it was found that the variation in tin content during continuous casting is 2.34% and at centrifugal 14.3%; the zinc content spread is 8.88% and 4.8%, respectively; nickel data is 5.35 and 5.59%, respectively.

4. The equality of the limit tangential stresses and stresses caused by the effort to extract the billet from the mould of the continuous casting machine made it possible to determine the critical (minimum allowable) depth of the deformation well. This made it possible to reduce the specified value of the rational depth of the well for a billet with a diameter of 150 mm made of the БрО8Н4Ц2 (Cu−8%Sn−4%Ni−2%Zn) bronze at a surface temperature of 100 °C from 1.0 to 0.43 mm. For the surface temperature of the billet of 150 °C, the reduction is from 1.25 to 0.731 mm, and, accordingly, for a temperature of 200 °C, the allowable depth of the deformation well will decrease from 1.5 mm to 1.0 mm. As a result, increased the yield of continuous casting of billets 150 mm from 96.04 to 97.35%.

A method has been developed for reducing allowances for mechanical processing in the fabrication of billets on continuous casting machines, as a result of which, for continuously cast billets with diameters from 80 to 150 mm, the yield of suitable castings was increased from 95.06−96.04% to 97.29−97.72%.

A three-dimensional model of the yield of suitable casting of continuously cast billets with a diameter of 150 mm was made of the БрО8Н4Ц2-type bronze that allows you to select the temperature interval, at which the billet is caught by the rollers at the minimum depth of the hole.

Thus, as a result of the carried out study, the practical results were also obtained in the fabrication of hollow billets from antifriction alloys with a diameter of 80−150 mm:

 • transition to the technological process of continuous fabrication of hollow billets of copper alloys allowed to increase the yield of cast hollow billets by 35.97−51.72%;

 • further research allowed additionally, for the continuous casting process, to increase the yield of casting from 95.06−96.04% to 97.29−97.72%.

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ДОСЛІДЖЕННЯ ПРОЦЕСІВ ФОРМУВАННЯ ПОРОЖНИСТИХ
ЗАГОТІВОК ІЗ АНТИФРИКЦІЙНИХ СТОПІВ МЕТОДАМИ
ВІДЦЕНТРОВОГО ТА БЕЗПЕРЕРВНОГО ЛИТТЯ

Цілеспрямованістю роботи є порівняльний аналіз механізмів формування порожнистих заготівок, що впливають на вихід придатного відцентрового та безперервного лиття бронзи марок БрО8Н4Ц2 (Cu−8% Sn−4% Ni−2% Zn) і БрО5Ц5С5 (Cu−5% Sn−5% Zn−5% Pb). Виявлено, що дія відцентрових сил викликає сеґреґацію хімічних елементів стопів, залежно від густини їх, а леґувальні елементи Sn і Pb стопу, що мають підвищену густину, активніше інших елементів підтримують цей процес. Визначено чинники, що впливають на інтенсивність процесу сеґреґації леґувальних елементів, густина яких у кілька разів перевищує густину інших елементів стопу. Досліджено причини появи Стануму як елемента з максимальною густиною в оточенні сполук мінімальної густини. Встановлено, що процес сеґреґації, який виникає за відцентрового лиття, понижує рівномірний розподіл леґувальних елементів у об'ємі заготівки та значно підвищує припуски на механічне оброблення. Показано, що в процесі безперервного лиття на розтоп діє виключно сила тяжіння, яка за час формування заготівки не спричинює розшарування більш густих леґувальних елементів. Показано, що єдиним чинником, який визначає величину припуску на механічне оброблення для процесу безперервного лиття, є глибина деформаційної лунки на зовнішній поверхні заготівки, яка необхідна для зачеплення та вилучення заготівки із кристалізатора. Встановлено глибину деформаційної лунки, при якій дотичне напруження зрізу відповідає граничній напрузі на зрізі для зразків з досліджуваних марок бронзи. Побудовано та запропоновано тривимірний модель для визначення виходу придатного безперервного лиття порожнистих заготівок залежно від температури

поверхні заготівок, від зусиль, що діють на заготовку з боку валків тягнучої кліті. Задля оцінювання впливу технологічних параметрів процесів на вихід придатного безперервного та відцентрового лиття було використано метод павутинок, що уможливило розширити уявлення про різні механізми формування заготівок. Дослідження показали, що порівняно з відомими показниками виходу придатного безперервного лиття у 95,06–96,04% для заготівок із зовнішніми розмірами у 80–150 мм вихід придатного литва можна підвищити до 97,29–97,72%. Зроблено висновок про доцільність виготовлення заготівок з антифрикційних стопів методом безперервного лиття, оскільки це уможливить для досліджуваного типорозміру заготівок підвищити вихід придатного литва на 22,35%–47,72%.

Ключові слова: відцентрове та безперервне лиття, литі заготівки, вихід придатного литва, поверхнева деформаційна лунка.

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ИССЛЕДОВАНИЕ ПРОЦЕССОВ ФОРМОВАНИЯ ПОЛЫХ ЗАГОТОВОК ИЗ АНТИФРИКЦИОННЫХ СПЛАВОВ МЕТОДАМИ ЦЕНТРОБЕЖНОГО И НЕПРЕРЫВНОГО ЛИТЬЯ

Целенаправленностью работы является сравнительный анализ механизмов формования полых заготовок, влияющих на выход годного центробежного и непрерывного литья бронзы марок БрО8Н4Ц2 (Cu–8% Sn–4% Ni–2% Zn) и БрО5Ц5С5 (Cu–5% Sn–5% Zn–5% Pb). Обнаружено, что действие центробежных сил вызывает сегрегацию химических элементов сплавов в зависимости от их плотности, а легирующие элементы Sn и Pb сплава, имеющие повышенную плотность, активнее других элементов поддерживают этот процесс. Определены факторы, влияющие на интенсивность процесса сегрегации легирующих элементов, плотность которых в несколько раз превышает плотность остальных элементов сплава. Исследованы причины появления олова как элемента с максимальной плотностью в окружении соединений минимальной плотности. Установлено, что процесс сегрегации, возникающий при центробежном литье, снижает равномерное распределение легирующих элементов по объёму заготовки и значительно повышает припуски на механическую обработку. Показано, что в процессе непрерывного литья на расплав действует исключительно сила тяжести, которая за время формирования заготовки не вызывает расслоение более плотных легирующих элементов. Показано, что единственным фактором, определяющим величину припуска на механическую обработку для процесса непрерывного литья, является глубина деформационной лунки на наружной поверхности заготовки, которая необходима для зацепления и извлечения заготовки из кристаллизатора. Установлена глубина деформационной лунки, при которой касательное напряжение среза соответствует предельному напряжению на срез, для образцов из исследуемых марок бронзы. Построена и предложена трёхмерная модель для определения выхода годного непрерывного литья полых заготовок в зависимости от температуры поверхности заготовок, от усилий, действующих на заготовку со

стороны валков тянущей клети. Для оценки влияния технологических параметров процессов на выход годного непрерывного и центробежного литья был использован метод паутинок, который позволил расширить представление о различных механизмах формования заготовок. Исследования показали, что в сравнении с известными показателями выхода годного непрерывного литья 95,06–96,04% для заготовок с наружными размерами 80–150 мм выход годного литья можно повысить до 97,29–97,72%. Сделан вывод о целесообразном изготовлении заготовок из антифрикционных сплавов методом непрерывного литья, поскольку это позволило для исследуемого типоразмера заготовок повысить выход годного литья на 22,35%–47,72%.

Ключевые слова: центробежное и непрерывное литье, литые заготовки, выход годного литья, поверхностная деформационная лунка.