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Characterization of sliding bimetallic bearings from steel-bronze obtained from horizontal centrifugal casting

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Abstract: The paper presents the characterization of bimetallic bearings as mechanical testing and SEM analysis. Also, a proper simplified structure of the horizontal centrifugal casting mechanism is applied, which uses a high-frequency current for the heat of bimetallic bearings from steel-bronze. The chemical stability treatment of the borderline alloy layer at the interference of internal cylindrical steel surface and external bronze surface by adding into Cu-Sn filler a supplier non-ferrous metal was performed. The experiment results have shown that the bimetallic bearings of steel-bronze achieved good physical properties and adhesion between antifriction steel with bronze that validated this simplified structure of the horizontal centrifugal casting process.

1. INTRODUCTION

The centrifugal casting remains an interesting casting process used for manufacturing high-quality products to obtain rotationally symmetric workpieces at low costs. There are a variety of centrifugal casting materials from cast iron, steels and stainless steels, aluminum, alloys of nickels, and copper to advanced composites. A large application is fabricated to develop functionally graded material (FGM) parts which are characterized by a gradient of chemical composites, microstructure, or phases, altering from one end to another. FGM is achieved by the combination of two or more materials to obtain predictable properties. because of its simplicity process and less technology requirements than other methods [1-4].

The centrifugal casting process can be divided into three types, such as True centrifugal casting (e.g. horizontal, vertical, or inclined casting), Semi-centrifugal/centrifugal casting, and Centrifuge mold/centrifugal die casting. The

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process itself makes use of centrifugal force generated from the revolution cylindrical mold forcing molten metal against the mold wall to achieve a predictable shape/form, where the quality of the tubular part is directly influenced by pouring temperature, mold/die speed, the preheated temperature of the mold. The metal liquid is required to be at a specific temperature to reach the desired thickness and length before freezing. The thickness wall of a part is directly determined by the volume of liquid getting into the mold, without necessary an enhancer and a canal system, where this metal charge is pushed on the mold wall by the centrifugal force to reach a uniform distribution on to entire surfaces of mold. That happens when the installation spindle speed reaches a predictable speed ensuring the inner surface of the part takes on a cylinder-like shape, which means that its axe coincides with the revolutionary axe [5-14].

In this paper, the authors have used centrifugal casting by using high-frequency current (HFC) for bimetallic bearing heating, in which the heat leaving the system is done in three phases, first by a source to mold and semifinished from radiation until the metal is transformed into a liquid state, second by radiation, convection, and conduction until metal solidification and third as before until cooling of bimetallic bearing. The exchange of heat with the environment leads to a change in the solidification speed and physical and mechanical properties of the metal. During the time of the free surface of the mold revolution around its horizontal axe phenomenon occurred, such as diffusion in its base and superficial stress of liquid metal.

During the revolution of mold around its horizontal axe, a liquid particle of metal is action by the appearance of two forces (Fig. 1), the centrifugal force (Fc) and the gravitational force (G), in which the resultant force (Fr) is changed at half rotation from (Fc+G) to (Fc-G) due to a modification of thickness wall in radius way and an eccentricity (e). This gravitational force is decreased when the mold reaches a predictable spindle speed. The formula for these parameters is presented below [9]:

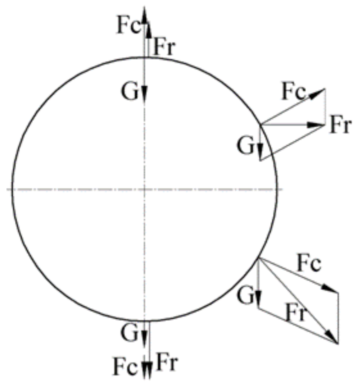

Figure 1. The action forces on liquid metal during rotation around the horizontal axe.

$$F_{c_y} = m \cdot x \cdot \omega_y^2 \tag{1}$$

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$$G = m \cdot g \tag{2}$$

$$e = \frac{g}{\omega^2} \tag{3}$$

Where: **m**-is mass [kg], x-displacement of X-axe [mm]. **g**- gravitation acceleration [m/s^2], **ω**-angular speed [rad/s], and **e**-eccentricity [m].

The moving of liquid particle metal can be approximated at a rotation of mold around its horizontal axe with a point moving of rotated pendulum, which means that the higher speed is positioned in the inferior point, respectively the minimal speed in the superior point. Going further, this observation means that the solidification of the cylindrical mold surface would be located below the axis of the mold rotated [8, 15-21]. If the centrifugal force is ten times greater than the gravitational force the displacement effect is low, going on the layer solidification during mold revolution with a uniform growth around of symmetry axe and independent of the shape of the free surface of the liquid metal. Each solidification point of the cylindrical layer wall could be in different states of crystallization process during one revolution mold. The growth speed solidification metal layer is uniform, and the separation borderline between the mold surface and solid-liquid phase is concentric. The free surface geometry of liquid metal in every rotational position is determined with hydrostatic equations. The horizontal casting process uses HFC at heating applied of bimetallic bearings with steel baseless 0.3% C and bronze alloy charge in Fig. 2 is presented.

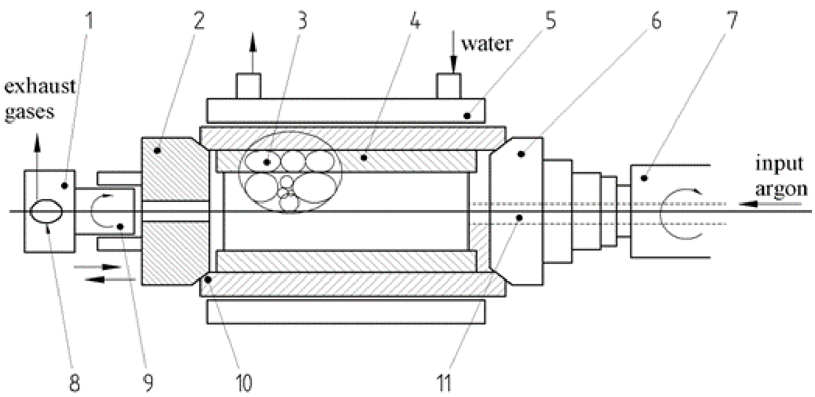

Figure 2. The horizontal centrifugal casting process uses HFC at heating. **1**-is locating support with hydraulic acting, **2**-cover clamp, **3**- cylindrical steel support, **4**-semifinished in vacuum, **5**-inductor, **6**-cover of clamp and action, **7**-device of acting and turning, **8**-holes of exhausted gases, **9**-hole of center, **10**-chamfering, and **11**-central channel of input argon gases.

The bronze charge was melted by induction process and got into a hole of steel support, while the pure argon gas at a pressure of 0.05 atm was got in the central entry. The geometric inductor form is cooling with water allowing heating of external surface support from steel at a temperature of 1000°-1150°C that realized the melting of bronze. The concentric distribution of melted alloy is assured by the centrifugal force until the solidification. The revolution of the device is made until the cooling temperature reaches 300°C when the bimetallic bearing is realized. In the melting and deposition of metal phases within of cylindrical steel mold by applying a horizontal centrifugal casting process (HCCP) the fluid flow by circular streamlines positioned in a horizontal plane was obtained. At a symmetrical axial flowing of rotation, the speed-***v***, and pressure-***p*** depend only on the radius-***r*** (Fig. 3).

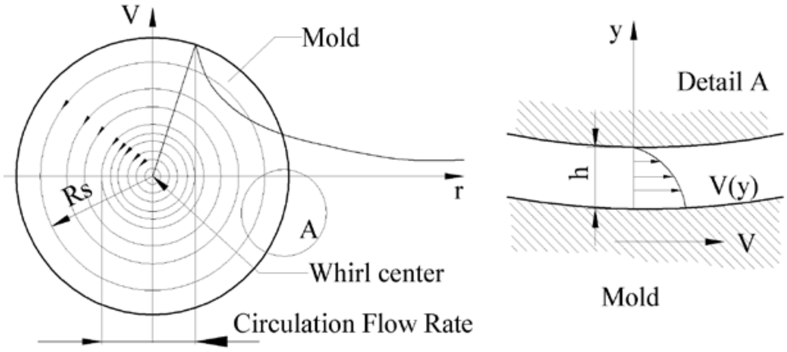

Figure 3. The moving of metal melting on circular trajectories.

The interpretation of the flow field was performed by the Euler method which described the flow in a fixed spatial point by evaluating the changing elements. The state equation of stationary flow in a streamlined tube is obtained from differential Euler Eq. and then by the integration obtained the Bernoulli Eq. with the formula:

$$\frac{v^2}{2} + \frac{p}{\rho} = ct \qquad or \qquad \frac{v^2}{2} = \frac{1}{\rho} \cdot \frac{dp}{dr} \tag{4}$$

For a value of a radius- $\boldsymbol{r_1}$ corresponding to the values $\boldsymbol{v_1}$ and $\boldsymbol{p_1}$ is obtained the distributions of speeds and pressures:

$$v(r) = \frac{v_1 \cdot r_1}{r} \tag{5}$$

$$p(r) = p_1 + \frac{\rho}{2} \cdot v_1^2 \cdot \left(1 - \frac{r_1^2}{r^2}\right) \tag{6}$$

These parameters, pressures, and speeds, necessary to obtain the bimetallic bearing by using the horizontal rotational casting process (HRCP) were determined by experiments. They are directly influenced by the viscosity-$\boldsymbol{\eta}$, density-$\boldsymbol{\rho}$ of metals in melting state, and gravity acceleration-***g***. The repartition of tangential stress due to friction is:

$$\tau(r) = -\eta\left(\frac{dv}{dr} - \frac{v}{r}\right) = -\eta \cdot \frac{2B}{r^2} \tag{7}$$

The involved moment of the metallic mold and the parameter B have the formula:

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$$M_1 = 4\pi \cdot \tau \cdot B \quad (8)$$

$$B = \frac{r^2 \cdot r_1^2 \cdot (\omega - \omega_1)}{r^2 - r_1^2} \quad (9)$$

For the HCCP, an HFC was been defined some reduced significant expressions were:

a. The temperature growth of a heated body by induction is:

$$\frac{dT}{dt} = \frac{m \cdot \frac{d}{\delta} \cdot \sqrt{F}}{d} \quad (9)$$

Where ***T***– is workpiece temperature [^{0}C], ***K***–variation coefficient of a rise speed of temperature, and ***F***–frequency of induction current [Hz]. ***m***–a mass of workpiece [kg], ***d***–exterior diameter of based [cm], and ***δ***– coefficient of penetration [cm] which has the formula:

$$\delta = 503\sqrt{\frac{\rho}{\mu \cdot F}} \quad (10)$$

Where ***ρ***- is resistive of based [Ωmm^2/m], and ***μ***-magnetic permeability.

b. The ratio of temperatures for calculus of heating time is:

$$\frac{T_o}{T_e} = \frac{1}{1 + S(0,t)} = F(t) \quad (11)$$

Where ***T₀***– is the temperature at an exterior surface of based [°C], ***Te***–the temperature at an inner surface of based [°C] that is the same as the casting temperature of melting alloy, ***S***–surface based heated by high-frequency current [m^2], and ***t***–time for heating [s].

c. The Archimedes Law for rotational systems is:

$$F_c = \frac{V \cdot \omega^2 \cdot r}{g} \cdot (q_i - q_m) \quad (12)$$

Where: ***V*** –is the volume of inclusions [cm^3], ***ω***–angular revolution speed [s^{-1}], ***r***–center radius of inertial force [cm], q_i–density of inclusions [g/cm^3]. and q_m–density of alloy [g/cm^3].

d. The gravitational coefficient is:

$$K = \frac{\omega^2 \cdot r}{g} \quad (13)$$

e. The optima rotation speed of assembly-***n,*** after Constantinov [8, 9] is:

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$$n = 300 \cdot \sqrt{\frac{K}{r_i}} \tag{14}$$

Where ***n***– is optima revolution speed [rev/min], and $\boldsymbol{r_i}$–inner radius of base [cm]. The ***K***–coefficient of gravitation is taken empirically by relation:

$$K = \frac{340}{q_m} \tag{15}$$

In this case, the material was rotated with the angular speed of the mold, wherein bimetallic bearing manufacturing by HCCP requires a synchronism condition between critical revolution speed and melting temperature of the metal (Fig. 4).

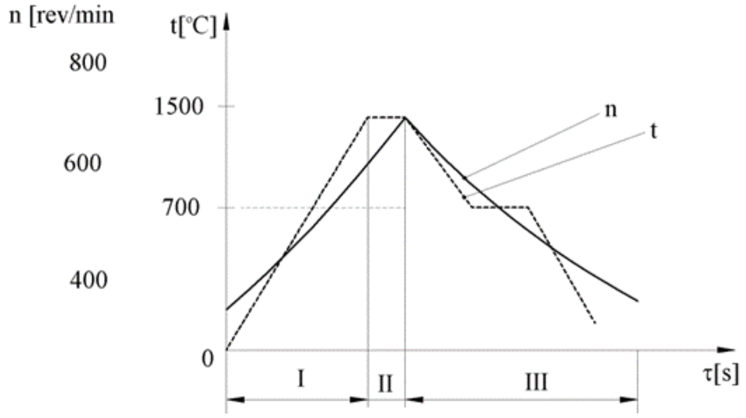

Figure 4. The states of the horizontal centrifugal casting process.
I-Period of heat beginner (rotation), ***II***-Period of stability-casting (synchronism), and ***III***-Period of solidification (stopped).

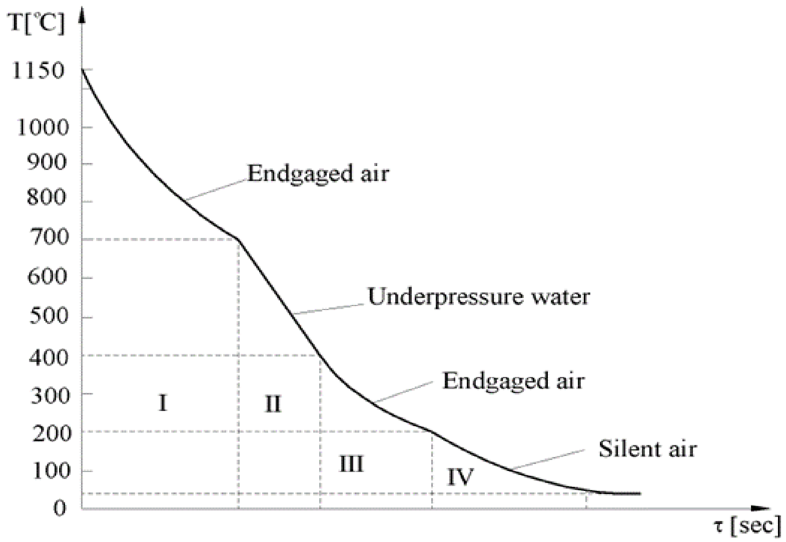

Figure 5. The diagram of steel cooling with air and water.

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1st phase of cooling: the casting assembly in rotation engaged the environment due to a cooling in turbulence air. **2nd phase of cooling:** starting the cooling with a water jet, under the pressure of 2-3atm and 20^0C, due to a fast down of workpiece temperature of 600^0C until 400^0C. **3rd phase of cooling:** cooling by engaged air until the temperature of the base is 200^0C when is stopped the revolution of the workpiece. **4th phase of cooling**: the workpiece is pulled out and the cooling is in "silent air" at room temperature.

The assembly (Fig. 2) is rotated around a symmetric axe with a continuous growth speed until optimal speed assures a uniform distribution on the inner steel base by centrifugal force. In synchronizing, the charge temperature grows up until becomes more than 50°C upper of the melting temperature, when the heat is stalled. The rotation of the assembly is continuous with a low speed since reaching 150°C, when is stopped the rotation the workpiece is pulled out from the device, and the cooling process (Fig. 5) goes on in "silent" air" mode.

During the process of centrifugal casting, the melting metal charge is engaged by the metallic mold by friction, which is action on the separation surface of the material with mold. rotating by friction. The internal friction forces (viscosity) of melting material rise became gradually predominant exceeding the liquid metal inertia, due to the acceleration of its rotation until the relative steady state becomes stable.

2. EXPERIMENT

2.1. Simplified structure of horizontal casting method

The bimetallic bearings by the horizontal centrifugal process with HFC have been fabricated from steel ANSI 18 with less than 0.3% carbon as the material base, and bronze alloy charge. Also, the geometry dimensions of bronze are the inner diameters between 14-60 mm with D/d ratio of 1.2-1.5 mm, and the L/D ratio = 0.8-1.25 mm, where ***D*** is the external diameter, ***d*** is the inner diameter and ***L*** is length.

The bimetallic bearings contend the alloy charge between 0.125-0.5 kg, and the external diameter of bronze was determined with the formula:

$$D = \sqrt[3]{\frac{4m_g}{\pi\gamma}} \qquad (16)$$

Where $\boldsymbol{m_g}$ - is the charge of bronze alloy [kg] and $\boldsymbol{\gamma}$ is bronze alloy density [kg/m^3]. The penetration depth of HFC in steel base is determined by the formula:

$$\delta = 503\sqrt{\frac{\rho_l}{\mu_l \cdot F}} \qquad (17)$$

Where $\boldsymbol{\delta}$ is penetration depth [cm], $\boldsymbol{\rho_l}$ is the specific electric resistance of steel used [Ωmm^2/m], and ***F*** is current frequency, in this case, the value is 8000-10000 Hz. The heat achieved from the mass of the metal base by the Joule effect has the expression:

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$$Q = R \cdot I_i^2 \cdot cos\varphi \tag{18}$$

Where $\boldsymbol{Q}$- is heat produced [kcal/m^2], $\boldsymbol{I_i}$-inducted current [A], and $\boldsymbol{R}$-electric resistance [**Ω**].

It is required for the casting temperature of bronze alloy (1050°C) to reach a heat temperature of the metal base, measured on an external cylindrical surface, to 1150°C due to the determination of the ratio of external/inner diameter with the expression:

$$\theta_e - \theta_s = \frac{q}{2\pi \cdot L \cdot \lambda} \ln \frac{D}{d} \tag{19}$$

Where $\boldsymbol{\theta_e}$-is exterior surface temperature [^{o}C], $\boldsymbol{\theta_s}$-interior surface temperature [^{o}C], **L**-bearing width [cm], and $\boldsymbol{\lambda}$-thermal conductivity coefficient of base metal.

The heat transfer into base materials is kept until the inner cylindrical surface is transmitted to the center by radiation, represented first phase, and then in the second phase by conduction when the bronze alloy is liquid state. The bronze alloy (Cu-Sn) being in a liquid state is drawn in the movement of horizontal revolution. The distribution temperature in whirl movement is obtained from Couette Eq. as:

$$\frac{\theta_s - \theta_i}{\theta_e - \theta_i} = \frac{R_s}{R_e - R_i} + P_r \cdot E_c \frac{R_s}{(R_e - R_i)} \left(1 - \frac{R_s}{R_e - R_i}\right) \tag{20}$$

Where $\boldsymbol{\theta_i}$-is temperature of the inner whirl surface, $\boldsymbol{P_r}$ - Prandle number for liquid alloy, and $\boldsymbol{E_c}$-Echert number.

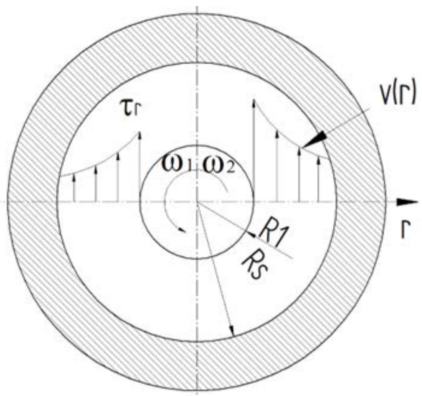

Figure 6. Horizontal centrifugal flow in cross-section.

Fig.6 presents the horizontal centrifugal flow, where the pressure distribution, speed, and tangential stress of whirl flow were been obtained in such a particular form by Navier-Stokes Eqs. Starting from the expression of pressure distribution in a radial direction and then by its integration is obtain the formula for speed distribution and pressure distribution:

$$p(r) = p(R_i) + \rho\left(\frac{A^2}{2}\right)(R_s^2 - R_i^2) + 2B\ln\frac{R_s}{R_i} + \frac{B^2}{2}\left(\frac{1}{R_i^2} - \frac{1}{R_s^2}\right) \quad (21)$$

$$v = A \cdot r + \frac{B}{r} \quad (22)$$

Where the parameters ***A*** and ***B*** have the formula:

$$A = \frac{\omega_s R_s^2 - \omega_i R_i^2}{R_s^2 - R_i^2}, \qquad B = \frac{R_i^2 R_s^2(\omega_i - R_i R_s)}{R_s^2 - R_i^2} \quad (23)$$

From imposed the boundary conditions, means $v(R_i)=\omega_i R_i$ and $v(R_s)=\omega_s R_s$ the speed and tangential distribution have the formula:

$$v = \frac{\omega_s R_s^2}{R_s^2 - R_i^2}\left(R_s - \frac{R_i^2}{R_s^2}\right) \quad (24)$$

$$\tau = \frac{2\eta B}{r^2} \quad (25)$$

In the situation that $r=R_s$, the relation (25) is:

$$\tau = \frac{2\pi \cdot \omega \cdot R_s^2}{R_s^2 - R_i^2} \quad (26)$$

The torque necessary for the device revolution is:

$$M = \tau \cdot 2\pi \cdot R_i \cdot L \cdot R_s = \frac{4\pi \cdot \eta \cdot \omega_s \cdot L \cdot R_s \cdot R_i}{R_s^2 - R_i^2} \quad (27)$$

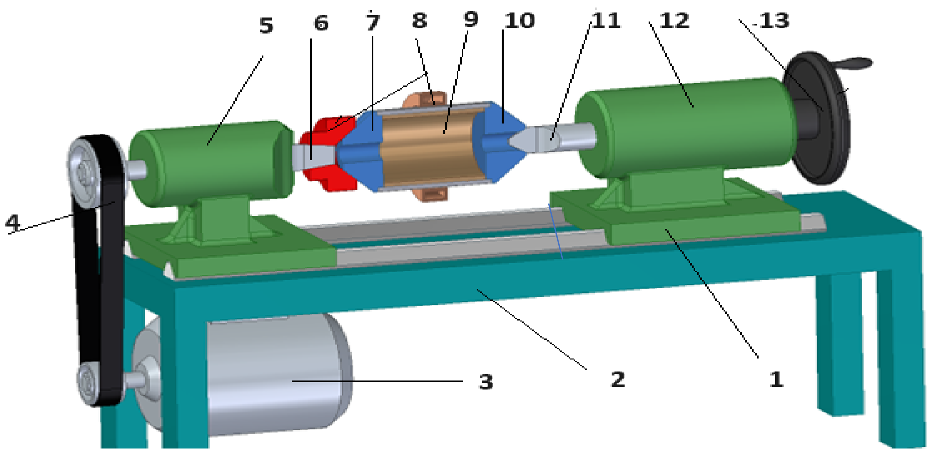

Figure 7: Centrifugal casting machine for bimetallic bearings.
1-Mobile table, **2**- Bed, **3**- Action motor, **4**- Driving belt, **5**- Headstock, **6**- Axe, **7**- Acting washer, **8**- Inductor. **9**- Casting device with semifinished inside, **10**- Side covers, **11**- Central axe, **12**- Tailstock, **13**- Wheel.

The simplified system comprises the basic equations that describe the mechanical and chemical phenomena of HFC-heated horizontal centrifugal casting of bimetallic bearings from steel-bronze, where the installation in Fig. 7 is presented.

For the experiment, several attempts were made and it was chosen as a metal base a steel tub of drawing steel ANSI 18, which is a hypoeutectoid steel with a non-homogeneous microstructure (ferrite and pearlite). This semi-finished part was subjected to homogenized annealing of steel base to avoid any possible internal stresses then it was heated by HFC as a complete austenitizing process above **AC_3** point (1100-1150°C), followed by a short keeping (fractions of seconds) to reach of whore part at desire temperature and a slowly cooling near **A_1** point (Fig. 8). The ferrite grains exhibited an increasing trend in range of 600-750°C, being necessary to use water for cooling.

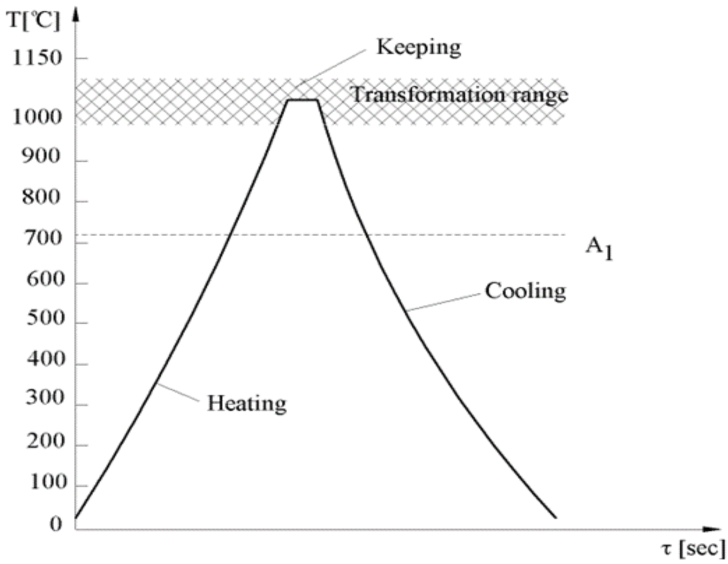

Figure 8. The short phase's diagram of homogeneous annealing for the bearing of the steel base.

This research has resolved an important problem related to the thermal annealing cycles for the homogenous steel base that concurred with a thermal cycle of the horizontal centrifugal casting of bimetallic bearings. So, at casting temperature (980°+50°C) the end cycle occurred with the internal surface temperature of the steel base positioned in the austenitizing field, which had the same pattern for the heat and cooling process. The first step of HCCP begins with the preparation of a semi-finished steel base, where the steel pipe is cut at the end and inner surface, followed by a chemical pickling in a solution of 20% HCl, neutralized within a solution of 10% alkalis and then washing in hot water at 80°C and with a jet of cold water.

The next step is to insert into the mold the steel semi-finished for platting with bronze alloy, which is the rods of Cu-Sn alloy by adding 1% borax and 1% Sn rods. Then, the mold is rotated, and the heat with HCF the mold. The formula used for the calculus of bronze charge is:

$$G_b = \frac{\pi(D^2 - d^2)}{4} L \cdot \gamma \tag{28}$$

Where $\boldsymbol{D}$ -is the external diameter of bearing [cm], $\boldsymbol{d}$ -inner diameter of bronze [cm], L -bearing length [m], and γ -alloy density [kg/m^3]. This phase of casting is required to realize a grip between the steel base and melting bronze charge and to obtain stability of the boundary layer with a chemical method to achieve an intermetallic compound bronze ally and steel base. At this time, at high pressure and temperature Sn and Fe form a $FeSn_2$ intermetallic compound that in a chemical reaction with Cu-Sn alloy assures a stable metallic connection. For the experiment, the authors have used 3 types of bronze alloys (Bz 14T, Bz 9T, and Bz 7T) on which their main characteristics for bimetallic bearings fabrication in Tab. 1 are presented.

Table 1: The bronze characteristics for bimetallic bearing

Bronze alloy	Casting temperature [^{0}C]	Mold temperature [^{0}C]	Fluidity [m]
Bz 14T	1100-1150	200-300	50
Bz 9T	1100-1120	200-300	60
Bz 7T	1100-1150	200-400	80

The HCCP of bimetallic bearing is optimal for a liquid metal mass between 0.5-3.5 kg and predictable casting speeds that in Tab, 2 present.

Table 2: Predictable casting speeds for bimetallic bearings

Mass [kg]	0.5	1	1.5	2.0	2.5	3	3.5
Casting speed [m/s]	0.5	1	1.2	1.8	2.1	2.2	2.5

The process continued with the cooling of the bearing until mold surface cooling (200°-400°C), where the rotation of the mold was stopped, and semifinished was pulled out from the mold.

The semifinished has applied an annealing process at a temperature of 250°-300°C for two hours to avoid the internal stresses of the workpiece and then follows a slow cooling rate inside the furnace [14,17].

The phase eutectoid ($\boldsymbol{\alpha}$+$\boldsymbol{\beta}$), which is harder and brittle will be transformed into a mono-phase structure of solid solution $\boldsymbol{\alpha}$, improving the mechanical properties of bronze casting. Also, the thickness of bronze plating on the steel base is 4mm, followed by removal of 0.5-1.5 mm by cutting to achieve o well inner surface of bimetallic bearings,

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2.2. Bimetallic bearings characterization

The characterization of bimetallic bearings achieved by the horizontal rotational casting process with HFC heat consists of mechanical testing and microscopic surface morphology analysis.

Figure 9. Bimetallic steel-bronze bearing.

2.2.1. Mechanical testing

The mechanical properties of the samples were evaluated using an ELIB 30 electro-mechanical universal testing machine made by Ibertest (S.A.E. Ibertest, Madrid, Spain), with a load cell of 5 kN. All tests were carried out following the UNE-EN ISO 527 standard, at a speed of 50 mm/min. The impact strength was determined by using the Charpy impact machine (S.A.E. Ibertest) according to ISO-179. The values of all the mechanical parameters were calculated as averages over 5 specimens for each composition. The microhardness Vickers tests were performed with a load of 100 g and the application load for 15 seconds on the entire bronze zone and at a 1 mm distance between them (6 points of measuring).

Table 3: HV values of bimetallic bearings

Point of measuring	1	2	3	4	5	6
HV values [g/mm^2]]	171	169	170	171	170	172

2.2.2. Scanning microscopy analysis

The surface morphology of bimetallic slide bearings was evaluated by scanning electron microscopy (SEM) with an FEI mod Phenom (FEI Company, Eindhoven, Netherlands). The acceleration voltage was 5 kV, and the samples were previously subjected to a metallization process in a Sputter Coater EMITECH mod. SC7620 (Quorum Technologies Ltd. East Sussex, United Kingdom). Micrographs obtained by scanning electron microscopy of the fracture facies resulting from the Charpy test performed on each of the five experiments.

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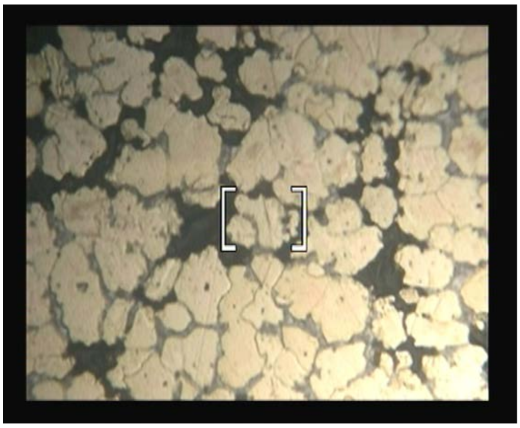
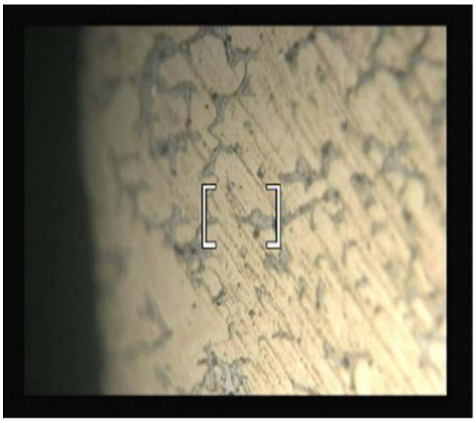
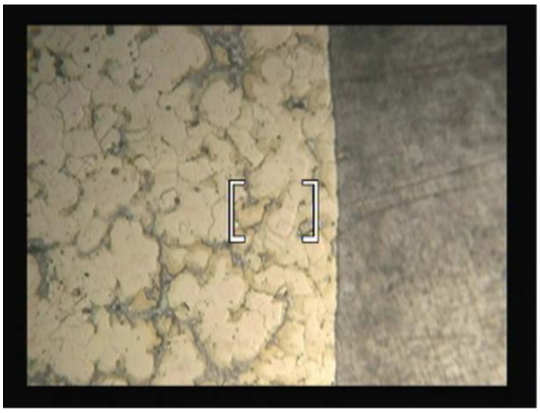


a. Bronze central area.



b. Bronze interior area.



c. Interface steel-bronze area.

Figure. 10. SEM pictures of bimetallic bearings in different areas. Magnitude of 500X.

Copper-tin alloys are more used in bearings, gears, fitting, piston rings, and valves, in our case in slide bearings of machine tools, being known for their corrosion resistance. These bearings achieved by the horizontal centrifugal casting process exhibit a denser, closer-grained structure with greatly improved physical properties.

3. DISCUSSIONS

The results of the micro-HV hardness of bimetallic bearings are available with small difference values between these 6 points of measuring, and the average value is 171 g/mm^2, which confirmed the uniform hardness on their surfaces and well heat treatment.

The microstructure of bronzes-tin alloy obtained by the horizontal centrifugal casting process consists of cored dendrites, they have a composition gradient of increasing tin as they grow. The last liquid to solidify is enriched with tin upon cooling, and forms alpha and delta phases.

Analyzing the SEM pictures from Fig. 10 can be affirmed that all the areas of bimetallic bearing show a similar microstructure, and the cross section is uniform and complete . These microstructures consist of cored dendrites of α-phase (light color) as 80%.

The coring causes the concentration of Sn in the liquid to increase. Thus, instead of solidifying to pure α-phase, the liquid transforms into α and β phases. The β -phase transforms to α and γ phases and subsequently the γ transforms to α and δ phases giving the dark region. Alloys such as this sometimes exhibit "tin sweat", which is a traditional name given to segregation in Cu-Sn alloys.

Another case is the porous presence, where can be found differences. So, in the interface steel-bronze it can't be seen as porous, in the central regions find a regular distribution of porous, nearly 5%, and the central region only has sporadic porous, less than 2%. That is a good justification for the values of micro-hardness quantified.

4. CONCLUSIONS

This technical paper has presented the main aspects of the horizontal centrifugal casting process focused on bimetallic steel-bronze bearings. As the authors' contribution, a simplified mechanism of HCCP with HFC heat of these bimetallic bearings is described showing the chemical phenomena of the process and determining some technical parameters as bronze charges, predictable casting speeds for bimetallic bearings, the geometry of semi-finished steel base bearings, etc.

The chemical stability treatment of the borderline layer of alloy (steel-bronze) is required to ensure good adherence of the bronze layer on steel base support by applying an HFC for heating. This stability was realized by adding of extra 1% tin which allowed us to obtain an inter-metallic compound of $FeSn_2$ which is in reaction with Cu-Sn alloy due to a stable metallic connection. Also, the cooling process of bimetallic bearings between 700°C to 400°C temperature was made at a higher speed to achieve a fine structure ferrite-pearlite of the steel base. The bimetallic bearing archived by the horizontal centrifugal casting process exhibited good performance and predictable quality.

The characterization of the bimetallic bearing provides the good heat treatment applied bearing and its corresponding microstructure in different areas that are complete and uniform, such as the bronze central area, bronze internal area, and interface bronze-steel area, which confirmes the installation of HCCP and validation of the process.

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

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