The Influence of Rotation Speed on the Structure of Centrifugal Tin Bronze Castings

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Abstract
The paper presents the results of an experimental study concerning the influence of centrifugal casting on the structure of castings from CuSn10 alloy. The cast parts were tin bronze bushings of exterior diameter Dex = 130 mm and wall thickness b = 25 mm. In the first part of the paper the structure of parts gravity cast in sand and metal moulds is compared to the structure of centrifugal castings. In the second part the influence of speed on the centrifugal castings is studied.

Keywords
casting, centrifugal casting, gravitational casting, copper-tin alloy

1. Introduction

Over the last period of time centrifugal casting has raised increasing interest due to the benefits of this procedure as to the structure, mechanical properties and cost of castings [1, 2, 3, 8, 9]. Centrifugal castings are more compact and have superior mechanical properties. The consumption of liquid alloy during casting is significantly smaller, productivity is higher at reduced manufacturing costs. Furthermore, the procedure allows obtaining castings of gradient structure and properties. At present this procedure is applied especially for the casting of hollow parts (engine bushings, oil industry bushings, bearing bushings, rolling mill bushings, etc.).

The interest in this casting procedure is materialised in research reports and publishing [6, 7, 10, 11], inventions and PhD theses of the last few on topics from this field [3, 4, 5, 12].

2. Aim of the Paper

In centrifugal casting the rotation speed is an easily adjustable parameter. This paper highlights aspects related to the influence of this parameter on the structure of centrifugal castings from bronze with 10% tin. Currently this is the procedure used for the casting of copper alloys, particularly for the manufacturing of bearings. The aim is to provide results that facilitate the selection of the optimum speed for the casting of such parts.

3. Working Method

The conducted research was experimental and included two stages. In the first stage a comparison was performed between the structure of the centrifugal castings and the structure of similar parts gravity cast in sand and in metal moulds. The research was aimed at highlighting the influence of centrifugal casting (namely of the spinning of the moulds) on the structure of castings from CuSn10. The second phase included a concrete analysis of the influence of mould speed on the structure of these castings [4].

Tubular cylindrical parts were cast. Figure 1 shows the dimensions of the parts gravity cast in sand and metal forms with an interior cylinder core. The centrifugal castings had similar dimensions, however with a tapering of the exterior surface that was necessary such as to allow the extraction of the part from the spinning metal form. In this case the average part wall thickness (at middle length, the cross-section used for the analysis of the structure) was of 25 mm, as in the case of the gravity castings.

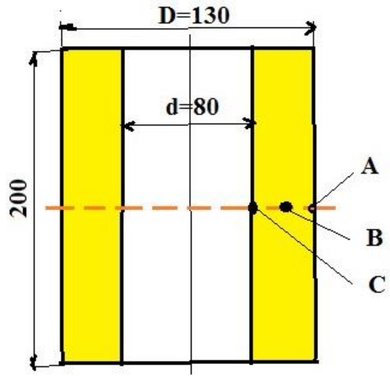


Fig. 1. Dimensions of the experimentally cast parts
(A, B, C – points where the structure was studied) [4]

In the first stage the parts were cast by three procedures, namely by gravity casting in sand moulds (of 20 °C temperature), by gravity casting in metal forms (of 300 °C temperature) and by centrifugal casting in metal forms covered with graphite paint (of 250 °C temperature). Table 1 features the parameters of the casting processes. Table 2 shows the average chemical composition of the cast alloy.

Table 1. Parameters of the casting process of the test samples [4]

No.	Parameter	U.M.	Casting procedure		
			Gravity casting in sand moulds	Gravity chill casting	Centrifugal chill casting
1	Mould material	-	Sand	Steel	Steel
2	Temperature of the liquid alloy	^{o}C	1100-1150	1100-1150	1100-1150
3	Mould temperature	^{o}C	20	250	300
4	Mould speed	rpm	0	0	800

Table 2. Average chemical composition of CuSn10 alloy used for the experimental test samples

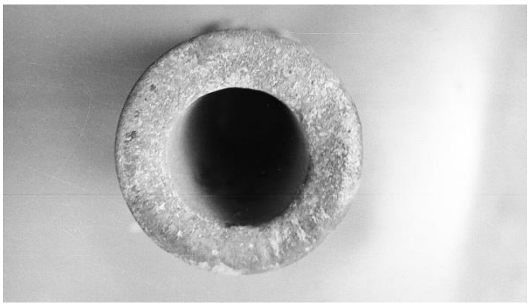
Contained element, %										
Cu	Sn	Zn	Pb	P	Mn	Fe	Ni	As	Sb	Bi
89.48	10.26	0.04	0.15	0.03	0.002	0.035	0.024	0.004	0.008	0.001

In the second stage similar parts were centrifugal cast. Four speeds were used: n_1 = 800 rpm, n_2 =1000 rpm, n_3 = 1300 rpm and n_4 =1500 rpm. The centrifugal castings were cut transversally ad mid-length, and the structure of the alloy was analysed in this section. The points of study of the structure are shown in Figure 1 (points A, B, C). Figure 2 shows the castings and the centrifugal casting machine used in the experiment.

4. Results

Figure 3 shows three phase diagrams for the Cu-Sn alloy, for three different cooling rates. The phase diagram of Figure 3a corresponds to a stable equilibrium. Figures 3b and 3c show metastable equilibria resulted from diverse cooling conditions. The phase diagram shows the structure obtained by very slow cooling obtained in laboratory conditions. At cooling in solid state the alloys of this system undergo eutectoid transformations that yield characteristic structures of eutectoid type. The particularity of this type of transformations is that they are relatively strongly influenced by the cooling rate. Consequently also the properties of the alloy are influenced by the modality of cooling. The influence of the cooling conditions on the structure is revealed in the metastable phase diagrams. Figures 3b and 3c shows the structures obtained by annealing and by casting in metal moulds, respectively. It is evidently practically impossible to plot such diagrams for the entire range of cooling conditions encountered in industrial practice. The diagram is valid for the solidification and cooling of parts gravity cast in metal moulds and shows an extension of the α+δ bi-phase zone (solid solution + inter-metal compound) towards smaller concentrations of tin (reaching 8% tin, thus below 10% Sn) as compared to the other two diagrams (Figure 3a and 3b). This means that in the primary structure of bronze castings with 10% Sn phase δ appears in the eutectoid type mechanical mixture. This appears in the interdendritic zone. Its percentage and dispersion is directly influenced by the cooling and casting conditions, respectively.

a)



b)

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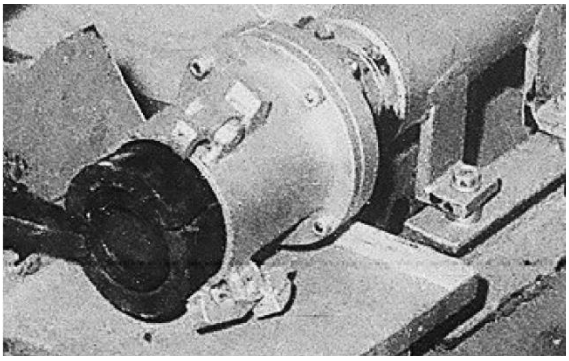

d)

Fig. 2. Experimental castings from CuSn10 [4]

a) Parts from CuSn10 gravity cast in sand moulds; b) Part from CuSn10 gravity chill cast; c) Centrifugal casting from CuSn10 and cut out metallographic test samples; d) Centrifugal casting machines used for the casting of test samples in the experiment

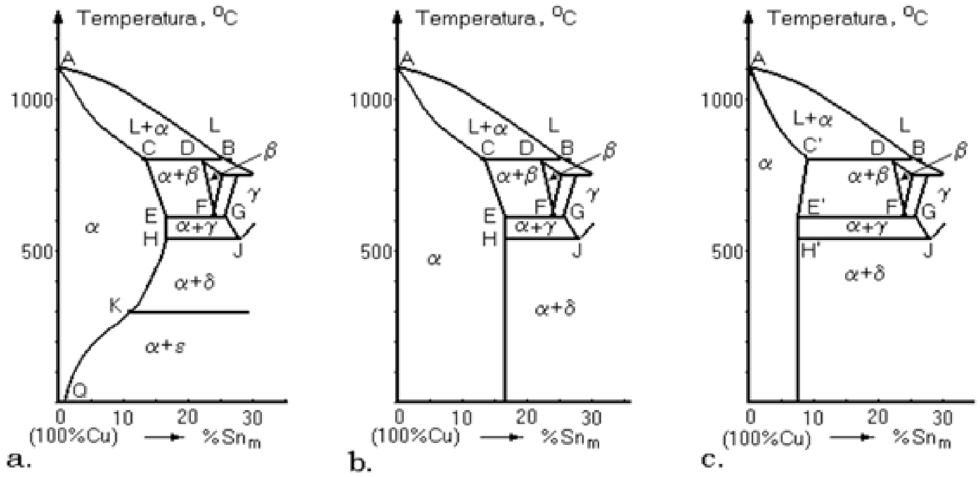

Fig. 3. Phase diagram of the Cu - Sn binary system (with 0 -30% Sn content)

a. stable phase diagram; b. – metastable phase diagram (after annealing); c. –metastable phase diagram (for casting in metal moulds) [4]

Figures 4÷6 show the microstructures in the walls of the parts cast by the three procedures (in points A, B, C - Figure 1). Structure differences depending on the deployed casting procedure can be noticed, as well as radial structure differences in the casting wall (depending on the distance from the exterior lateral surface – the casting-mould interface). In all cases the structure consists mainly of α solid solution and α+δ eutectoid mixture. Dendrites are formed in the primary solidification of the alloy (in the solidification interval). They consists of layers of α solid solution with different concentrations of tin. The central zone of dendrites is poorer in tin, while the marginal layers (that are deposited at smaller temperatures) these are richer in tin. The interdendritic zone solidifies with the crossing of the peritectic horizontal line, and upon the eutectoid transformations at 585 °C and 520 °C it consists practically of phase δ (bright white areas in the middle of the interdendritic zones). This structure corresponds to the metastable phase diagram of Figure 3c. The structures in the three cases of casting differ by form, magnitude of the dendritic formations and by the weighting of the two phases in the mass of the alloy. These differences are explained by the influence of the cooling rate on the Cu-Sn phase diagrams, and on the tin content in the alpha solid solution, respectively.


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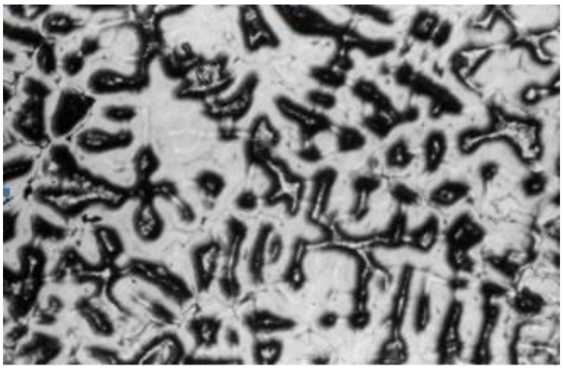
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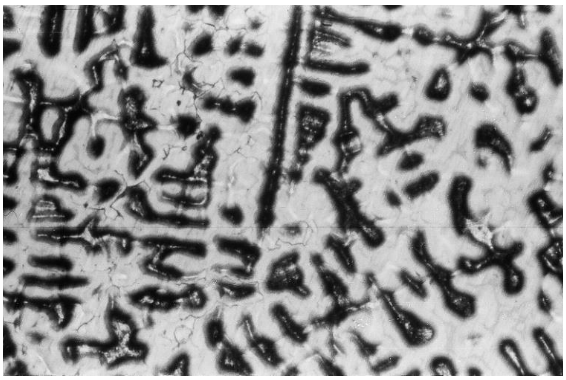
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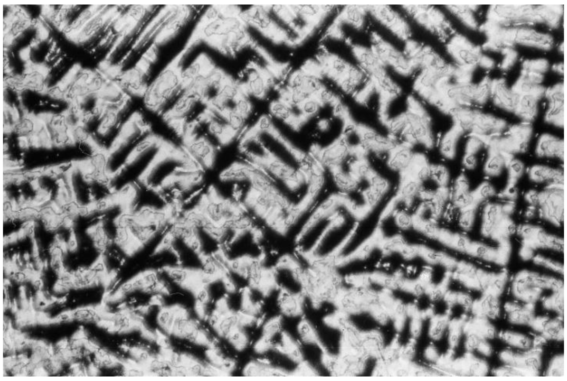
Fig. 4. Structure of the parts gravity cast from CuSn10 in sand moulds in various areas of the wall (enhanced ×200) [4]
a) Point A - Area of the exterior surface; b) Point B - Area of the wall axis; c) Point C - Area of the interior surface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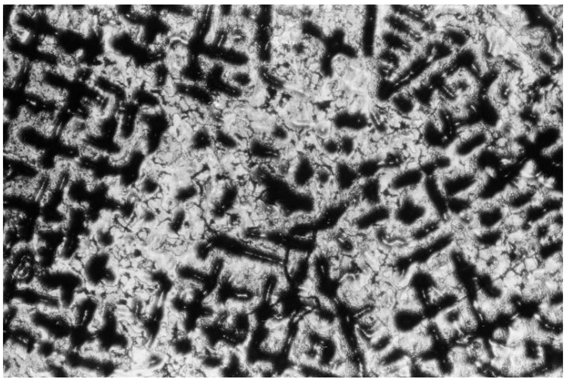
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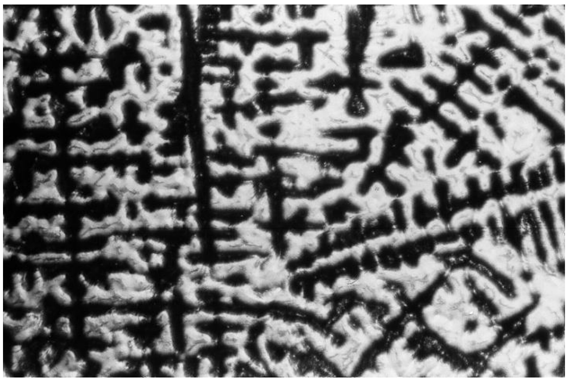
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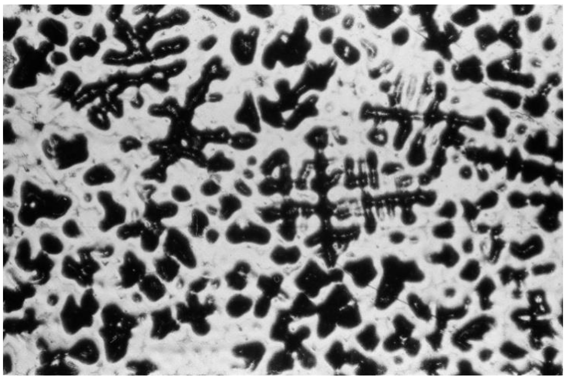
Fig. 5. Structure of the parts gravity cast from CuSn10 in metal moulds, in various areas of the wall (enhanced ×200) [4]

a) Point A - Area of the exterior surface; b) Point B - Area of the wall axis; c) Point C - Area of the interior surface

Figure 4 shows that in the case of the part gravity cast in a sand mould, the dendritic formations of solid solutions are large, the branches are thicker. The solid solution dendrites are richer in tin. In the case of gravity casting in metal moulds, as well as in the case of centrifugal casting the structure is finer. In the case of gravity casting on metal moulds the dendrite formations are thinner and stretched with their main axis significantly longer than the secondary axes. Further a tendency of orientation of the main axes by a certain direction (the direction of heat transmission) can be noticed. In the case of centrifugal casting in metal moulds the structure is also finer. The dendritic formations are significantly shorter, what can be explained by their fractioning consequently to the spinning of the mould and the vibrations caused by this. In the two cases of metal mould (gravity and centrifugal) casting the weighting of phase δ is greater, what can be explained by the greater cooling rates. As to the differences in structure in the wall of the same part, these are smaller and more difficult to notice. Differences in dendrite orientation appear, and very small differences in their size. Thus, in the case of the two gravity castings (Figures 5 and 6), the graining along the axis of the part (the thermal axis) is slightly larger compared to the marginal structures where the solidification and cooling rates are greater. In the case of the part gravity cast in a metal mould in the axis of the part (in the hot spot of the part, Figure 4b) the absence of dendrites can be observed and a slightly higher weighting of phase α than in the marginal areas. This can be explained by a smaller local cooling rate. In the centrifugal casting (Figure 6) the absence of dendrite orientation can be noticed, caused by the alloy set into rotation during solidification. Further, in this part the dendrite formations have the smallest dimensions in the area of the exterior surface. In the area of the interior surface (Figure 6c), where the hotspot of this casting procedure is located, slightly larger dimensions of the crystals are noticeable.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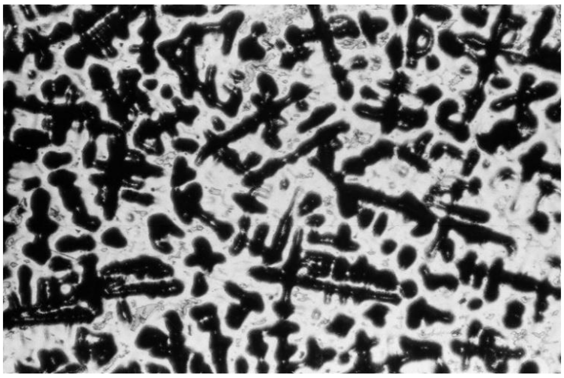
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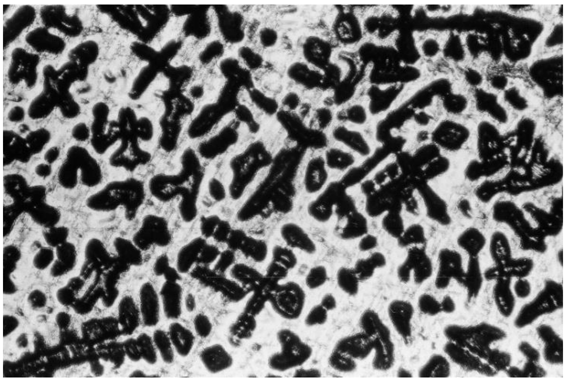
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Fig. 6. Structure of the centrifugal castings from CuSn10, speed n_2 = 1000 rpm in various areas of the wall (enhancement ×200) [4]

a) Point A - Area of the exterior surface; b) Point B - Area of the wall axis; c) Point C - Area of the interior surface

In order to highlight the influence of chill speed on the structure of the CuSn10 alloy, in the second stage of research parts were cast at five different speeds, ranging from 800 rpm to 1500 rpm. The parts were of exterior diameter De = 130 mm, interior diameter di = 80-90 mm and length L = 150 mm. Figures 7 ÷ 8 show the castings and the metallographic samples used for structure analysis. Figure 9 shows the microstructures obtained at various speeds. The photographs of Figure 9 show the structure in points located on the wall axis in the cross-section at mid-length of the part. Figure 9 shows a slight diminishment and fragmentation of the dendrites with the increase of speed.

Fig. 7. Centrifugal castings from CuSn10 [4]

Fig. 8. Centrifugal castings, test samples and metallographic samples for determining mechanical properties and structure analysis

The additional pressure caused by the centrifugal force increases the compactness and homogeneity of the structure. The pressure that acts continuously on the liquid particles favours the forming of a large number of crystallization centres. At increased speeds this process intensifies in the liquid metal, thus yielding a fine-grained structure.

The centrifugation of the liquid metal causes the small density non-metal inclusions (*e.g.* gas and other inclusions, oxides, etc.) to be pushed towards the interior surface of the part. A more compact structure is obtained, free of pores, micro-shrinkholes and light inclusions. These defects will concentrate towards the interior surface of the part wall.

When the solidification rate increases, tin, the main alloying element of this type of bronze has an increased solubility in the base metal (copper). This means a modification of the theoretical phase diagram by the diminishement of the α solid solution zone at high temperatures and its expansion at low temperatures (Figure 3c).

The solidification of solid solutions yields primary structures of dendritic type. Their number and dimensions are influenced by the magnitude by the solidification interval and the cooling rate. In the case of the cast bronze, areas poorer in tin and thaus softer formed at the beginning of solidification are included in the mass that is richer in tin, and thus harder. In the field with increased tin content the soft dendrite trunks and branches are clearly visible. Under the action of the centrifugal force the isolated dendrites move towards the periphery and merge with the solid-liquidus area, a phenomenon occurring until the viscosity of the alloy increases. The interdendritic liquid that solidifies and forms β phase is thus influened during its relative movement towards the interior of the mould, what on its turn may influence the graining and the local chemical composition of the casting.

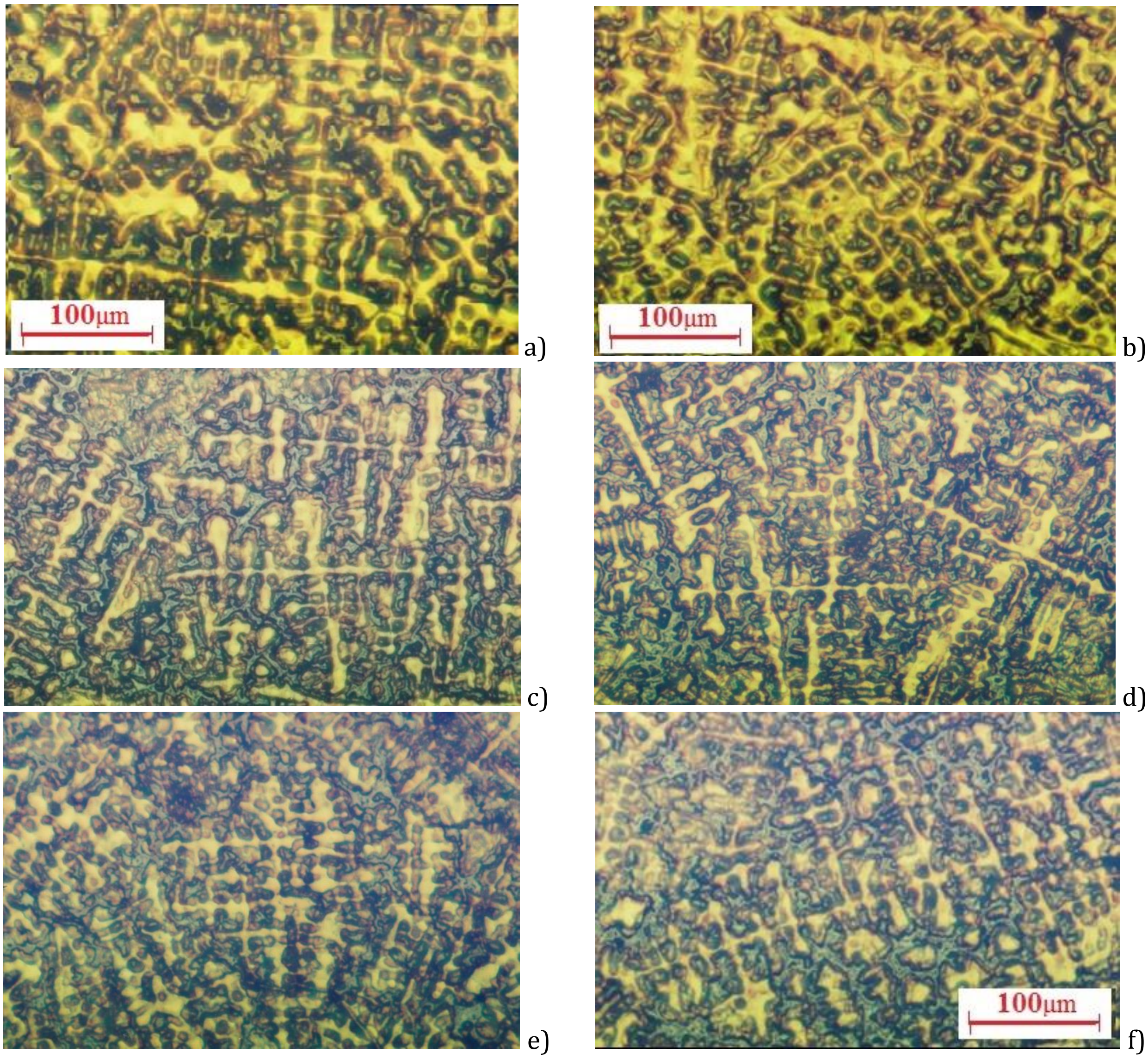

Fig. 9. The influence of speed on the structure in the middle of the part wall (magnitude of dendrites) in the case of centrifugal castings from CuSn10 (×150, reactive– 1900 ml H_2O + 50ml H_2SO_4 + 50 ml HNO_3 +40g CrO_2+7.5g NH_4Cl) [4]

a) CuSn10, centrifugal casting, n = 800 rpm, enhanced ×150; b) CuSn10, centrifugal casting, n = 1000 rpm, enhanced ×150; c) CuSn10, centrifugal casting, n=1000 rpm, enhanced ×150; d) CuSn10, centrifugal casting, n = 1200 rpm, enhanced ×150; e.) CuSn10, centrifugal casting, n = 1300 rpm, enhanced ×150; f.) CuSn10, centrifugal casting, n = 1500 rpm, enhanced ×150

Another influence of centrifugation on the structure of bronze castings follows from the influence of the intensive spinning on the heat transmission within the liquid alloy and on the cooling rates and temperature gradient in the casting wall. The spinning of the liquid alloy and the inherent vibration accompanying the spinning of the mould cause an intensifying of the convection what means a greater equivalent heat conductivity (compared to gravity casting). The greater heat conductivity influences the transmission of the heat, the cooling rate and consequently the crystal nucleation and growth. After the initial crystallization of the superficial layer, at the close contact of metal and chill the crystallization of the subsequent layers will be influenced not only by the heat conductivity of the mould, but also by the heat conductivity of the solidified layers. The crystallization process occurs in a mould that has two layers with different heat conductivities (of which one layer – that of the solidified alloy – groes conitnuously). The solidification process continues under these thermal cinditions until the heat evacuation rate by the mould will be equal to the heat accumulation rate in the mould. After the equalization moment of these rates, the mould temperature remains constant and the solidification of the liquid metal layer is influenced only by the transmission of the heat through the centrifuged liquid alloy layer.

The overlapping of these processes and influences yields the conclusion that centrifugal casting in metal moulds, high rate cooling in the solidification interval and the influence of the metal and mould conductivity combined with the pressure caused in the metal by the centrifugal force, has as its effect the forming of a greater number if crystallization centres and the inhibition of grain growth allowing the obtaining of a fine-grained structure.

The analysis of the micrographs of figure 9 shows that increasing the speed from 800 rpmto 1500 rpm has determined a slight finishing of the wall structure. This finishing can be noticed by comparing the Figures 9 a,b,c (structures obtained at speeds of 800 rpm and 1000 rpm) with those of Figures 9 e,f (structures obtained at high speeds of 1300÷1500 rpm). The finishing consists in the thinning of the dendritic branches on one hand, and their shortening and reduced number of ramifications on the other. This finishing is the consequence of the breaking of dendritic branches caused by the spinning and vibrations generated by the inevitable slight deviation of the rotation axis.

5. Conclusions

The obtained results yielded the following conclusions:

- in both cases of gravity and centrifugal casting the primary structure of CuSn10 parts is formed according to the metastable phase diagram, and consists of a mixture of α solid solution and an α+δ eutectoid mixture;
- compared to gravity casting in sand moulds, centrifugal casting yields a finer structure and a smaller percentage of α phase (due to the greater cooling rates);
- compared to gravity casting in metal moulds, centrifugal casting causes a fragmentation of the dendrites what on its turn causes also the fragmentation of the eutectoid (phase δ) in the interdendritic space;
- both structure differentiations are in favour of centrifugal casting, as it entails superior mechanical properties;
- the increase of speed in centrifugal casting within the studied limits (800 ÷ 1500 rpm) has a relatively small influence on the structure, which consists in a slightly greater fragmentation of the dendrites at higher speeds.

These observations are valid for castings from CuSn10 with a wall thickness of order of magnitude of 20 to 25mm.

Continued research is called for concerning the influence of the studied parameters on the mechanical properties (hardness, breaking strength, etc.). Further, for the generalisation of the results research has to be expanded to other part dimensions, and in particular to parts with greater wall thickness.

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