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The Evaluation of Mechanical Properties of High-tin Bronzes

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Abstract

High-tin bronzes are used for church bells and concert bells (carillons). Therefore, beside their decorative value, they should also offer other functional properties, including their permanence and good quality of sound. The latter is highly influenced by the structure of bell material, i.e. mostly by the presence of internal porosity which interferes with vibration of the bell waist and rim, and therefore should be eliminated. The presented investigations concerning the influence of tin content ranging from 20 to 24 wt% on mechanical properties of high-tin bronzes allowed to prove the increase in hardness of these alloys with simultaneous decrease in the tensile and the impact strengths (R_m and KV, respectively) for the increased tin content. Fractures of examined specimens, their porosity and microstructures were also assessed to explain the observed regularities. A reason of the change in the values of mechanical properties was revealed to be the change in the shape of α-phase crystals from dendritic to acicular one, and generation of grain structure related to the increased Sn content in the alloy.

Keywords: Mechanical properties, Tin bronzes, Bell material, Microstructure

1. Introduction

Technical Cu-Sn alloys called tin bronzes usually have the structure of α-solution. They are classified with respect to the Sn content as low-tin bronzes (< 5% Sn) or high-tin bronzes (> 5% Sn). The wide range of crystallization temperature of α-solution bronzes favours the segregation phenomenon. Therefore, the phases, which – under equilibrium conditions – would occur at larger tin concentration values, come to existence already at low tin content in the alloys being cooled under real conditions. They accompany the α phase, which itself is also non-uniform as to tin concentration. In the course of solidification and subsequent cooling, the β phase being the solid solution on the basis of Cu_5Sn chemical compound, which exhibits the valence electron concentration per atom equal to 3/2, is subjected to eutectoid decomposition into α and γ phases. The γ phase, in turn, by one of the reactions possible at lower temperature values is transformed into δ, ξ, or ε phases. The influence of segregation can be to a certain extent eliminated by the prolonged homogenizing.

As the tin content in the alloy increases, the technological properties, and especially the sliding properties, are improved, there occurs better castability, lower shrinkage, the hydrogen solubility is reduced, and the corrosion resistance increases, particularly in single phase alloys [1].

The high-tin bronzes found their application for example in production of bells. It should be mentioned that contemporary bell alloy is composed of Cu and Sn in proportion of about 4:1. No wonder that the bell bronze is well-known as the corrosion resistant material, being simultaneously the highly decorative alloy. Its strength properties are quite other problem.

Historical bell bronzes, besides the mentioned basic components, contained additions of Pb, Zn, Bi, Ag, Sb, Ni, Fe, P, S, and Si. Some of this addition (Pb, Zn, Ni, Fe, Ag, Sb) were introduced on purpose, while others, such as sulphur and phosphor, were contaminations introduced accidentally during bronze melting process, mainly from charcoal and coke [2]. There are interesting studies by Jaromir and Katerina Audy, who examined chemical compositions of a series of bells from various periods of time [2, 3]. Their works allow for tracing back the changes in the composition of bell bronzes through the ages, characterised by the distinct increase in tin content from about 10 wt% to even 24 wt% nowadays. This is accompanied by the reduction of harmful additions (S, Bi, Ag) from the initial value of about 2.5 mass % to about 0.5 mass % at present. Such trends in composition changes were also observed by other researchers [4-6]. Audy & Audy [3] indicate that the chemical composition of bell bronze used in Czechoslovakia (in 1960-1990 period) consisted of 20.25 wt% Sn, 0.9 wt% Pb, 0.1 wt% Zn, 0.2 wt% Sb, 0.3 wt% Fe, 0.5 wt% P, and Cu as the remaining part. However, their earlier publication [2] gives somewhat different data with respect to the bell bronze, namely: 20.25 wt% Sn, 0.25 wt% Fe, 1.5 wt% Pb, and Cu as the remaining part. It should be noticed that the contemporary bell bronze used in France exhibits very high tin content and the addition of silver, the composition being 26.5 wt% Sn, 1.5 wt% Ag, the remaining part: Cu [2]. The addition of silver is claimed to influence the sound quality; it also lowers the melting point, but obviously increases material costs.

Robert Perrin who deals with tuning and acoustics of bells and carillons gives another composition of contemporary bell bronze, including 20% of tin and 80% of copper [7]. A similar composition is confirmed by the non-published author's investigations on material compositions of contemporary bells coming from Polish and Dutch bell-foundries.

The data given by professional literature [1] prove that alloying copper with tin results in the increased hardness and tensile strength of alloys cast in sand moulds, while their unit elongation is reduced. As far as alloys poured into metal moulds are concerned, tin added in amount up to about 4% leads to the increase of unit elongation. If the tin content rises above this value, the unit elongation decreases. The impact strength of the alloy grows until the tin content reaches about 5%, then drops down. The tensile strength increases with an increase in tin content up to about 10% Sn, the yield strength increases up to about 20% Sn, and hardness grows continuously while tin content is increased. The alloy containing 4% Sn is characterised by better fatigue strength than the one with lower tin content, but further increase up to 8% Sn changes the fatigue properties in not so distinct way.

The author is, however, interested in mechanical properties of high-tin alloys with tin content within the range of 20÷24 wt% and the present work is aimed to answer how the tin content varying within this range influences the tensile strength R_m, the impact strength KV15, and hardness HB.

2. Method of investigation

Five sets of specimens were prepared in order to determine mechanical properties, including tensile strength, impact strength, and hardness of tin bronzes with tin content increasing from 20 to 24 wt% (by 1%), five specimens for each composition. The alloy was prepared from pure components melted in an induction furnace (power rating 15kW) in AC6 crucible, the slightly oxidizing atmosphere being applied at the beginning of the melting process. After deoxidizing of copper with Cu_3P, tin was introduced, and further operations were carried out under the protective coating of borax and cracked soda-lime glass, bringing the alloy to the temperature of 1040°C. At this temperature moulds prepared of 'OBB Sand' moulding material were poured directly from the crucible. Cuboidal and cylindrical castings were produced, dimensions of the former ones being either 100×80×15 mm (specimens for material hardness measurement by Brinell method, HBW3000/10) or 12×12×100 mm (specimens for impact strength tests to determine the KV15 value), the latter ones of 100 mm height and 16 mm diameter. Tensile specimens with threaded end tabs (M12 metric thread) were prepared out of the cast cylinders, their gauge diameter being 8 mm. Chemical composition of specimens was checked with EDX Genius 5000 spectrometer. The R_m values were determined by means of Zwick Roel Z100 tester at the initial force equal to 300 N and the rate of extension equal to 0.04 mm/s. All measurements were repeated five times. Structural examinations were held by means of Nikon Eclipse MA-200 optical microscope.

3. The results and their analysis

The obtained results of mechanical examination of high-tin bronzes are gathered in Table 1. An increase in tin content from 20 to 24% by weight caused the reduction of the tensile strength R_m by about 30%, of which only about 7% corresponds to the change within the range 20-23 wt% of tin. The rapid decrease occurs within the range 23-24 wt% of tin. This dependence can be seen in Fig. 1. An increase in tin content from 20 to 24 wt% results in hardening of the examined material from 198 to 308 HBW, that is by about 55%. The influence of changes in tin content on hardness of high-tin bronzes is presented in graphic form in Fig. 2. A slight decrease in hardness occurred at tin content equal to 22 wt% as compared with values obtained for specimens containing 21 wt% of tin.

Table 1.
Results of examination of mechanical properties of bronzes

Sn	R_m	σ_{Rm}	HBW 3000/10	σ_{HBW}	KV15
mass %	MPa	MPa	-	-	[J/cm^2]
20	238.12	7.25	198	3.5	1.2
21	235.81	10.11	242	2.5	1.0
22	229.78	7.92	234	0.0	0.9
23	221.10	9.48	272	6.0	0.8
24	163.33	14.72	308	3.5	0.8

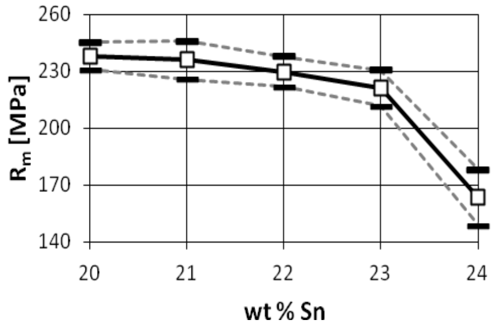

Fig. 1. Tensile strength R_m of high-tin bronzes versus tin content

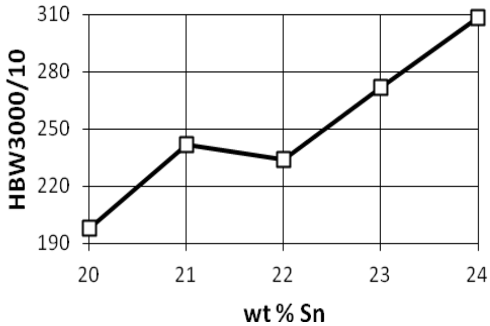

Fig. 2. Hardness of high-tin bronzes versus tin content

This drop in hardness is probably caused by microporosity of the specimen, which magnitude is shown in Fig. 3 and determined to reach 6%.

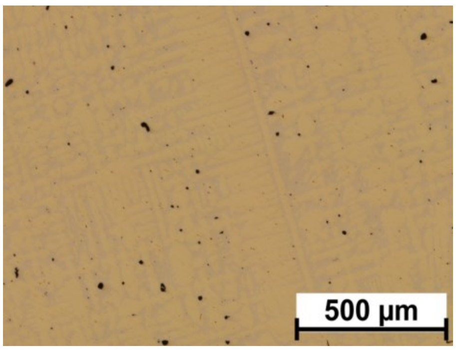

Fig. 3. Porosity of high-tin bronze specimen, 22 wt% Sn

The recorded impact strength of the examined material decrease with an increase in tin content from the value of 1.2 J/cm^2 for 20 wt% Sn to 0.8 J/cm^2 for 23 or more wt% Sn (Fig. 4). It should be noticed

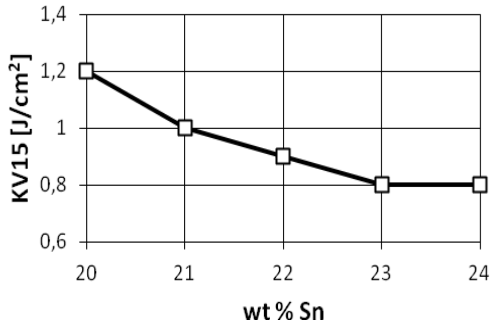

Fig. 4. Impact strength of high-tin bronzes versus tin content

that there occurred full repeatability of impact strength test results

General view of fractures of the representative specimens, with no visible plastic deformation, is shown in Fig. 5. Specimens a-d in Fig. 5 exhibit fine crystal structure with small non-metallic inclusions, distincly visible in specimens c and d, while the fracture of specimen e in Fig. 5 suggests a coarse grain structure with columnar grains. All the fractures reveal castings defects.

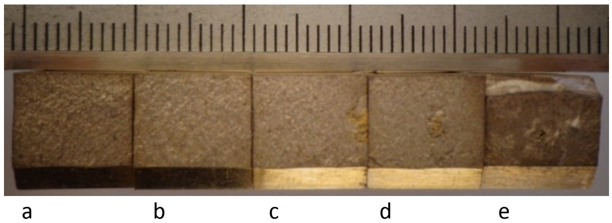

Fig. 5. Fractures of impact test specimens of various tin content: a) 20% Sn, b) 21% Sn, c) 22% Sn, d) 23% Sn, e) 24% Sn

Microscopic observations confirm structural changes in bronzes taking place as the tin content increases from 20 to 24 wt% (Figs. 6-10). The comparable dendritic structures composed of α phase dendrites and α+δ eutectoid placed within interdendritic spaces were revealed in alloys containing 20-22% Sn (Figs. 6-8), while the alloy containing 23% Sn (Fig. 9) exhibits grain structure with acicular form of α phase. Further increase in tin content up to 24% resulted in the grain refinement (Fig. 10). The change of shape of α phase crystals is related to the increase in tin content in the alloy and to the non-equilibrium solidification. It can result either from the narrow solidification range which does not promote the development of dendritic structure or from generation of new crystallization nuclei in the form of β phase nucleating directly from the liquid phase. According to the phase equilibrium diagram, the peritectic transformation proceeds in the system in the restricted range. The second observed effect, beside the morphological changes, is generation of distinct grain structure. The observed changes in the structure of the examined bronzes result both in the decreased tensile and impact strength, particularly when tin content in the alloy is at the level of 23-24 wt%, and in the growth in hardness.

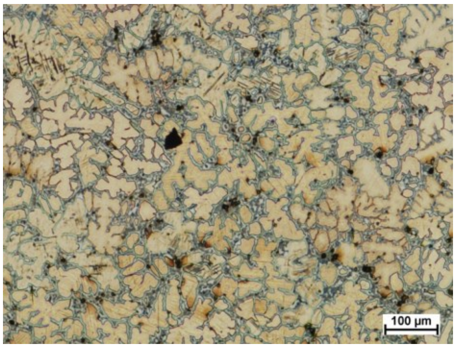

Fig. 6. Microstructure of alloy containing 20 wt% Sn

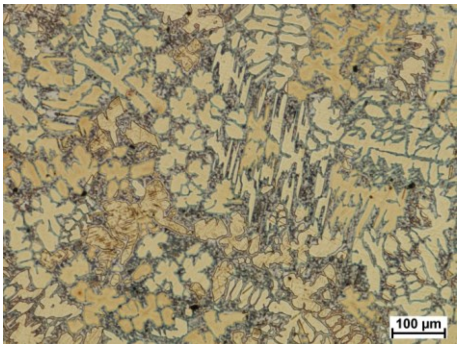

Fig. 7. Microstructure of alloy containing 21 wt% Sn

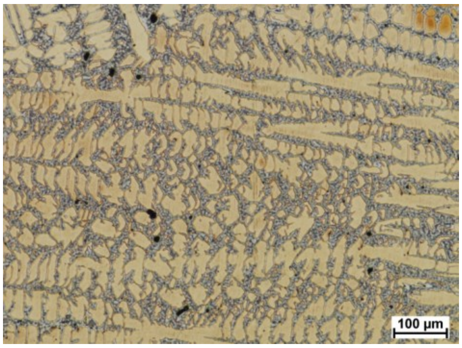

Fig. 8. Microstructure of alloy containing 22 wt% Sn

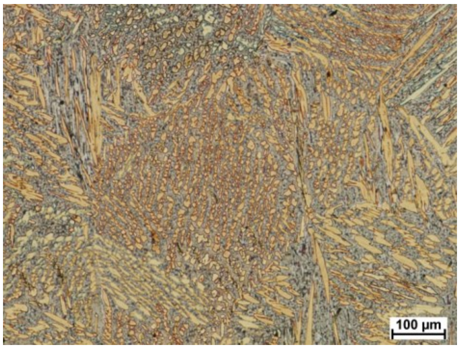

Fig. 9. Microstructure of alloy containing 23 wt% Sn

Fig. 10. Microstructure of alloy containing 24 wt% Sn

4. Conclusion

The performed examination of mechanical properties of high-tin bronzes with tin content ranging from 20 to 24 wt% revealed a decrease both in tensile strength R_m and in impact strength KV15, with simultaneous increase in hardness of the examined alloys. The revealed changes are induced by the change in the shape of α phase precipitates from dendritic one, occurring within the range of 20-22 wt% of tin in the alloy, to the acicular one developed when tin content in the alloy reaches 23 wt% or more. The change can be attributed to the non-equilibrium solidification, the narrow range of solidification temperature, and to the possible generation of new crystallization nuclei in the form of β phase nucleating directly from the liquid phase.

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