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ASSESSMENT OF THE CHANGE IN THE TIN CONCENTRATION IN BRONZES TO THE BASIC COMPONENTS OF THE SOUND OF BELLS

The subject of the study was to determine the impact of changes in mechanical properties of high-tin bronzes on the basic components of the sound of a bell. Change in the tin concentration in the range of about 7.5 to 20 parts wt. in a casting alloy significantly affects the mechanical properties of the alloy such as Young's modulus or hardness. The free vibrations of bells were obtained with the help of the finite element method. In the numerical analyses the mechanical properties of standard alloys were adopted. The obtained natural frequencies of the bell made of a bronze with different tin concentration in copper were compared with the acoustic properties of a real bell casted on the basis of the same ribs. A significant effect of the increase in the alloying share of tin on the obtained results was stated. In addition, the acoustic analysis of aluminum bronze C95500 have been performed. Based on the obtained results, authors stated that this material can replace the commonly used high tin bronze C91300 for the unit production of bells.

Keywords: high-tin bronze, components of the sound of bell, frequency analysis, mechanical properties, velocity of sound

1. Introduction

The bell is a musical instrument. The usable quality of the bell depends on its shape and the material from which it is made [1-3]. Both of these parameters have changed over the centuries [4-6]. This inseparable pair determines the quality of the sound. Apart from the evolution of the bell shape, it should be noted that today the basic alloy for the production of bells is high-tin bronze with a tin concentration of about 20% with a maximum of 1÷2% admixtures. An example of such bronze is UNS C91300 alloy called "bell metal" or ASTM (B22). Due to the strategic importance of tin as a metal, which will become increasingly difficult to obtain in the coming years, research is being carried out into its replacement with a cheaper substitute. For the production of bells, this problem seems to be difficult due to their functional nature. The bell alloy should have appropriate mechanical parameters, namely it should have high strength and hardness, adequate elasticity and speed of wave propagation with the ability to damp of long-term vibrations [7]. In addition, this alloy should enable to obtain good castings, i.e. it should has a good castability and reproduction that gives high density/contents castings with low porosity [8]. The bell bronze contains in a certain proportion two structural components: eutectoid ($\alpha + \delta$) that is a mixture of phase α and phase δ, responsible for acoustic properties, and phase α that is solid solution of tin in copper, responsible for mechanical properties. Under real crystallization conditions, all solid solutions in Cu-Sn alloys are supersaturated solution at ambient temperature. This is the result of a very slow process of tin diffusion in copper. The composition of the phase α at ambient temperature has a tin content close to its limit (15.8% Sn) solubility at 600°C. As the amount of tin increases, the amount of eutectoid ($\alpha + \delta$) increases. Its participation in the structure of tin bronzes is usually in the range of 10÷45%. Increasing the amount of eutectoid is accompanied by an increase in hardness, density, Young's modulus and speed of wave propagation with a decrease in the vibration damping coefficient [9]. Connection the above-mentioned features with the conditions of crystallization and the way of utilization is not easy, and the choice of bell bronze composition consists therefore in the search and selection of compromise solutions in the area between two opposing extremes: sonorousness and durability. The material of bells "playing" with a high acoustic power must

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have a limited participation of the fragile component, because it works in conditions of very strong dynamic loads, which leads to fatigue of the material, and thus cracks. In turn, small bells can and should have more eutectoid ($\alpha + \delta$) in the alloy structure, and therefore a larger proportion of tin. The idea is to take full advantage of the valuable acoustic properties of bell bronze when the material does not work under extremely difficult dynamic loading conditions.

The effect of other alloy additions as well as accidental admixtures and impurities on the properties of bell bronze cannot be ignored [10]. This is because the most of the random alloying ingredients are harmful to bell bronze. Elements such as aluminum, phosphorus, magnesium, bismuth, iron, cobalt, nickel, silicon and arsenic deteriorate the mechanical and acoustic characteristics of the alloy at its content of the hundredths of a percent already. The content of bismuth and phosphorus should be limited to 0.002%, arsenic to 0.02%, antimony, lead, iron and aluminum to 0.5% (for each of these elements). Their total contents should not exceed 1.5-2%. Additionally, the properties of bell bronze are influenced by the method of melting of the charge and refining the alloy, the kinetics of the solidification process depending, among others, on the mass of cast and thermophysical properties of the mold.

It should be mentioned that both the pouring temperature and conditions of carrying away of heat [1,11-14] affect the acoustic properties of alloys, that is, for the same bell shape, it is possible to achieve different acoustic effects depending on the mold technology and method of running castings [15] used by foundries.

The authors of this paper decided to examine the effect of changing the tin concentration in tin bronze on the bell's acoustic properties and the possibility of replacing tin bronze with a material with similar mechanical parameters. Based on the available standard data of foundry bronzes, three high tin bronze as well as nickel tin and aluminum bronze were selected for research. In addition to similar mechanical parameters, the choice was determined by the impact of alloying additions on the physic-mechanical properties of copper and tin bronzes. With the increase of aluminum concentration in copper to 7.5 parts wt. its hardness HB increases slightly, above 7.5 to 12.5 the hardness increases rapidly. The change in hardness occurs as a result of eutectoid phase change β, $\beta \rightarrow \alpha + \gamma_2$ [16,17]. The modulus of elasticity of Cu-Al alloys depends on the structure of the alloy and when the alloy has a phase γ_2 the value of the module increases strongly up to about 200 MPa. Aluminum bronzes with the addition of nickel are characterized by a high compactness of the casting wall, which should promote the speed of sound propagation. Nickel slightly increases the hardness of copper due to the increase in the microhardness of the solid α solution, but with the same content in nickel bronze, the α phase microhardness increases by nearly 30% [16]. Nickel also reduces porosity, stabilizes the structure, increases the resistance and strength of the alloy [10].

2. Methods and materials

Five types of materials, three alloys of high tin bronze as well as nickel-tin bronze and aluminum bronze were accepted for the study. The chemical composition and mechanical properties (based on available standard data) of the above materials are summarized in Table 1 and Table 2, respectively.

These materials are characterized by different tin concentration, while in tin bronze this concentration varies from 7.5% to 20%, in nickel-tin bronze this content is 5%, while aluminum bronze is devoid of this element. These materials were adopted for analysis due to similar values of the modulus of elasticity, which has a decisive impact on the acoustic properties.

The components of the sound of bells were analyzed for two objects that were created on the basis of the same rib, with dif-

TABLE 1

Chemical composition of analyzed materials

Chemical composition	Cu [%]	Sn [%]	Zn [%]	Fe [%]	Ni [%]	Al [%]	Mn [%]
C90300	86÷89	7.5÷9	3÷5		1.0	0.005	
C91000	84÷86	14÷16	1.5		0.8	0.005	
C91300	79÷82	18÷20	0.25		0.5	0.005	
C94700	88	5	2		5	0.005	
C95500	78			3÷5	3÷5.5	10÷11.5	max 3.5

TABLE 2

Mechanical properties of analyzed materials

Mechanical properties	Tensile strength [N/mm^2]	Yield strength [N/mm^2]	Elongation [%]	HB	Mass density [kg/m3]	Elastic modulus [MPa]	Poisson's ratio
C90300	303	152	18	70	8800	96527	0.34
C91000	220	150	2÷7	105	8780	110000	0.34
C91300	241	207	0.5	170	8640	117000	0.34
C94700	310	138	25	85	8860	103400	0.34
C95500	655	290	10	208	7530	110000	0.32

ferent sizes. One bell ("small") had a weight of about 30 kg, and the other bell ("big") had a weight of about 300 kg. Numerical tests and experimental research were carried out. Experimental studies were conducted for bells casted on the basis of the same ribs (templates). The analysis of the results for the "small" and "big" bell was aimed at the selection of tin-free bronze or with a low tin concentration that meets the condition of sonorousness and durability while maintaining the visual effect, i.e. color of cast.

3. Results and discussion

Numerical analyzes were performed using the finite element method and the SolidWorks Simulation module. The finite element size was chosen based on the h-adaptive method. With this assumption for "small" bell no. of DOF was equal 612861, and for "big" bell no. of DOF was 2268576.

The obtained vibration frequencies for the tested materials are shown in Table 3 (for a "small" bell) and Table 4 (for a "big" bell). These tables also contain the components of sound in nature, which were obtained by recording the sound of bells during operation and converting to sound components using the Wavanal program. The first five basic sounds were compared.

On the basis of the obtained numerical results, it can be stated that the increase in tin concentration in high-tin bronze alloys causes an increase all frequency components in bells. In addition, a 50% increase in tin concentration (from 7.5 to 15%) causes increase vibration frequencies about 6.4%, and a further expansion of 25% tin concentration (from 15 to 20%) causes growth vibration frequencies about 3.8%. However, the vibration frequencies for nickel-tin bronze are slightly lower than the vibration frequencies for high-tin bronze. Aluminum bronze has such mechanical properties that the vibration frequencies are higher than for high tin bronze with a tin concentration of approx. 20%. Based on the results of numerical tests, it can be concluded that casting a bell from an alternative material, i.e. aluminum bronze C95500, should ensure that castings with good acoustic properties and maintaining visual qualities. So it is possible to replace the scarcity of tin with a cheaper and more easily available ingredient. An additional technological aspect, when changing the material, will be less sensitivity to solidification conditions and structure stability for small and large bells.

Based on the comparison of theoretical longitudinal velocities of sound ($v_s = \sqrt{E/\rho}$) in the analyzed alloys (Fig. 1), it was found that C95500 aluminum bronze is characterized by a higher value of this velocity than the theoretical longitudinal velocities of sound in bell bronze.

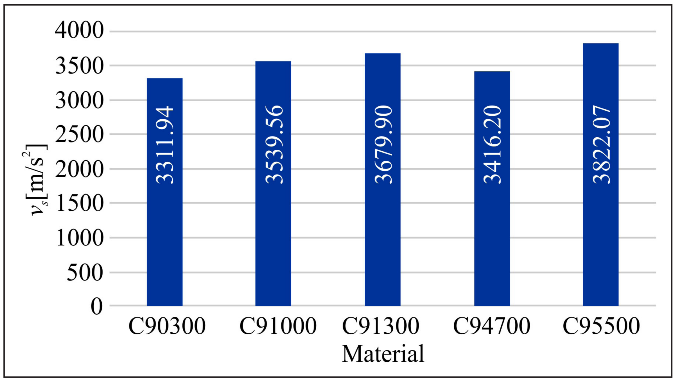

Fig. 1. Longitudinal velocities of sound in the analyzed alloys

The relation between the basic sound components hum : fundamental : tierce : quint : nominal, which should ideally be

TABLE 3

Frequency of vibrations of a "small" bell made of analyzed materials

	Numerical vibration frequency [Hz]					Real vibration frequency [Hz]
Material	**C90300**	**C91000**	**C91300**	**C94700**	**C95500**	
Hum	522.1	557.98	580.11	538.54	599.85	611
Fundamental	1057.1	1129.7	1174.5	1090.4	1219.6	1175.5
Tierce	1249.5	1335.4	1388.3	1288.8	1440.4	1426
Quint	1584.7	1693.7	1760.8	1634.6	1821.8	1871
Nominal	2095.9	2240.0	2328.8	2161.9	2417.0	2388.5

TABLE 4

Frequency of vibrations of a "big" bell made of analyzed materials

	Numerical vibration frequency [Hz]					Real vibration frequency [Hz]
Material	**C90300**	**C91000**	**C91300**	**C94700**	**C95500**	
Hum	231.49	247.39	257.2	238.77	265.96	260.5
Fundamental	468.8	501.01	520.88	483.55	540.88	521
Tierce	554.18	592.26	615.75	571.62	638.85	623.5
Quint	702.25	750.51	780.27	724.36	807.37	776.5
Nominal	929.7	993.6	1033	958.97	1072.1	1047

TABLE 5

Relations between basic sound components for a "small" bell

	C90300	C91000	C91300	C94700	C95500	Casted bell
Hum	1	1	1	1	1	1
Fundamental	2.025	2.025	2.025	2.025	2.033	1.924
Tierce	2.393	2.393	2.393	2.393	2.401	2.334
Quint	3.035	3.035	3.035	3.035	3.037	3.062
Nominal	4.014	4.014	4.014	4.014	4.029	3.909

TABLE 6

Relations between basic sound components for a "big" bell

	C90300	C91000	C91300	C94700	C95500	Casted bell
Hum	1	1	1	1	1	1
Fundamental	2.025	2.025	2.025	2.025	2.034	2
Tierce	2.394	2.394	2.394	2.394	2.402	2.393
Quint	3.034	3.034	3.034	3.034	3.036	2.980
Nominal	4.016	4.016	4.016	4.016	4.031	4.019

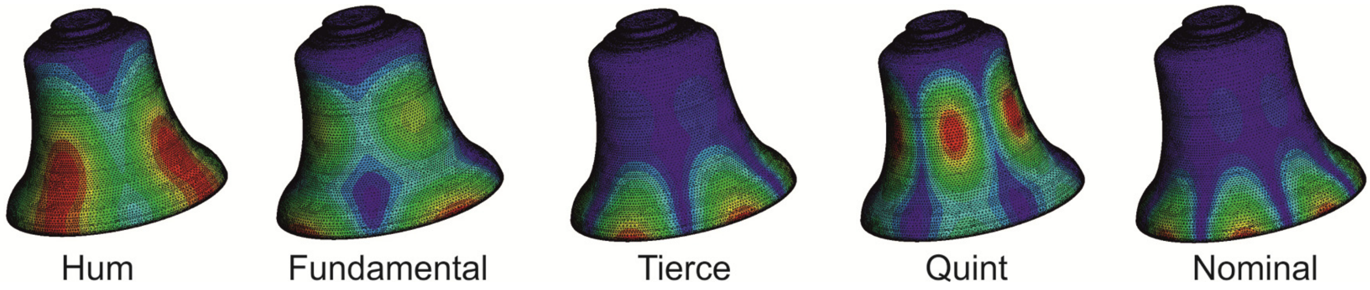

Fig. 2. Modal shapes (with mesh) for the musical partials of analyzed bells predicted by FEM

1, 1:2, 1:2.4, 1:3, 1:4 [2] as well as the modal shapes were analyzed. The test results are shown in Table 5 and Table 6, and vibration modes corresponding to the musical partials [2,3] for the „small" bell are shown in Fig. 2. Regardless of the size of the bell and the used material, the vibration modes differ only in their amplitude, which of course has an impact on the obtained sound.

In Table 5 and Table 6 it can be seen that the relationship between sound components for all analyzed materials are very similar, although not perfect, it is at least satisfactory. It causes that one can consider making bells from any analyzed material. Only the material or the size of the bell should be selected to achieve the desired tone.

Comparing the numerical vibration frequencies with the real frequencies, higher vibration frequencies of real objects than bells made of high-tin bronze and nickel-tin bronze, while lower than the bells made of aluminum bronze were found. The inconsistency to this statement is quint for the "big" bell made of C91300. The sound components for the bell weighing about 300 kg are similar to those of the casted bell. On the other hand, the numerical results for a bell weighing about 30 kg differ significantly from the real bell. It should also be mentioned that the casted material is not without casting defects, which can significantly disturb the characteristics of natural frequencies of the solid, and the overall compliance of real results with numerical research, including maintaining the distance between the analyzed components of sound is, according to the authors, decisive.

4. Conclusions

Reducing the tin concentration below 20% adversely affects the acoustic properties of bells, reducing the velocity of sound propagation in the casting as well as reduces the amplitude of the bell's natural frequencies. However, the authors see the possibility of replacing high tin bronze C91300, which is commonly used to make bells, by aluminum bronze C95500. The casted bell, regardless of its weight, should have good acoustic properties, which was confirmed by numerical calculations. The mutual relations between sound components for aluminum bronze and high-tin bronze should be considered favorable with high compatibility of results. Of course, along with the material change, it is necessary to adapt the shape of the bell profile to the specific tone of the final casting.

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