THE INFLUENCE OF CASTING PARAMETERS ON THE SOUND OF A BELL

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Abstract

A comparative analysis of sound emitted by two identical bells cast of bell bronze at different pouring temperatures was carried out. The influence of pouring temperature on the change of sound, the structure, and the porosity of castings was assessed. The obtained results were compared with the simulation results concerning vibration of numerical models received from the SolidWorks program. It was proved that higher pouring temperature results in the reduced porosity of a bell casting with simultaneous improvement in the quality of sound thanks to the revealing of the basic constituents of sound demanded for bells (hum, prime, tierce, nominal).

Keywords: Bell, tin bronze, porosity, sound

1. INTRODUCTION

People attempted to produce large and small bells using a variety of materials: cast iron, cast steel, zinc and aluminium alloys, glass, china, or pottery. But the alloy consisting of about 80 wt.% of copper and 20 wt.% of tin is still regarded as the basic material for production of bells, the so-called 'bell bronze' (UNS C91300). Despite many trials of replacing the costly tin with other elements, no alloy of so good acoustic properties was achieved [1].

The alloy composition, however important, is not the only factor determining alloy properties. A problem of meeting the demands with respect to the material properties gets even more complicated as the additional variables, thus far neglected or impossible to control, are taken into account. The requirements which are to be fulfilled by the bell alloy are as follows: good casting properties, high quality of a casting made of high-quality alloy, long lifespan, and nice sound.

The relationship between the above mentioned features and the crystallization conditions or the way of ringing is not obvious in any case. There were incidents that some large-scale projects failed to combine these properties. It is known to have happened that bells cracked after a short time of using them, e.g. the Aleksejevskij bell, which worked for one year only; and the largest bell in the world, the Tsar Bell, also known as Tsarsky Kolokol, of mass equal to 250 $x10^3$ kg, has never stricken a note. Since 2000 the largest (the heaviest) ringing bell in the world is the Bell of Good Luck at the Foquan Temple in Pingdingshan city, China, which mass is $116 \cdot 10^3$ kg [2].

The shape of bells changed over the centuries [3-5] nevertheless their construction was designed in such a way that the suitable strength and proper sound should be achieved. Properly selected parameters: wall thickness, bell diameter, and the applied alloy, are decisive with regard to the sound tone and timbre [6-8]. The proper mechanical strength is easy to achieve by increasing the bell wall thickness, but the relationship between the shape of bell and its sound is hard to grasp, especially for the reason that the bell sound consists of a series of merged tones and overtones which give the so-called strike tone [9, 10].

The traditional way of bell production by the method of template moulding forces the specified position of a mould during metal pouring, however the position should be considered as improper because it prevents taking advantage of directional solidification [11]. The arising internal defects of bell's wall in the form of cavities of shrinkage porosity can disturb the vibration of bell casting by introduction of additional nodal points. Therefore the authors decided to prove the influence of the pouring temperature on the material and acoustic properties of bells of uniform size and shape.

2. METHODS OF EXAMINATION AND THE RESULTS

Bell castings of mass equal to 6 kg were produced in bentonite-bonded sand moulds. The material was C91300 bronze alloy poured either from 1090 °C or from 1140 °C. The influence of the change in pouring temperature on the porosity of bell castings, their structure, and the microhardness of the material was investigated. The porosity of castings was assessed by means of the industrial Nikon XT H 450 CT scanner, their microhardness was measured with Vickers microhardness tester at the load of 50 g both for the α-phase and for the (α+δ) eutectoid mixture. Structural examinations were carried out by means of optical microscope Nikon Eclipse MA-200 for samples cut out of the sound-bows of the cast bells.

The performed porosity examinations revealed that the bell volume is filled with the alloy to the extent of about 84 % in the case of higher pouring temperature, while the alloy percentage in the volume of bell cast from lower temperature was about 68 % (**Figure 1**). In turn, the percentage of material discontinuities in the form of gas bubbles or shrinkage porosity calculated with use of Nis-Elements D program was equal to 5 % and 18 %, respectively (**Figure 2**).

a) b)

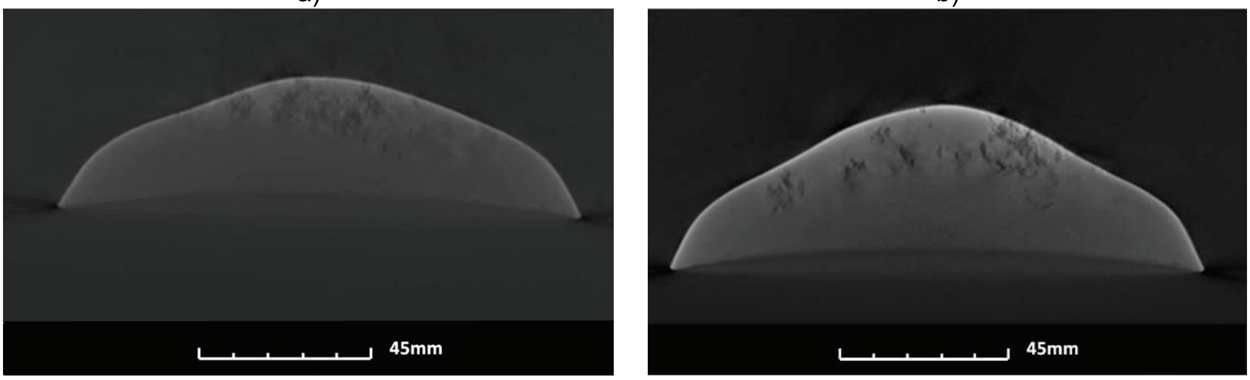

Figure 1 CT images from porosity examination at various pouring temperatures: a) 1140 °C; b) 1090 °C

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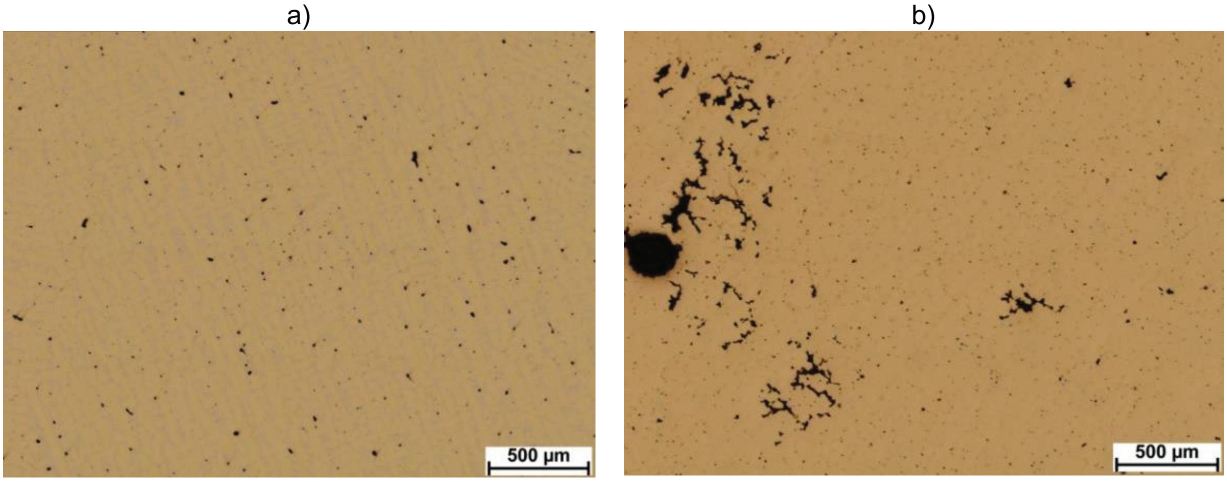
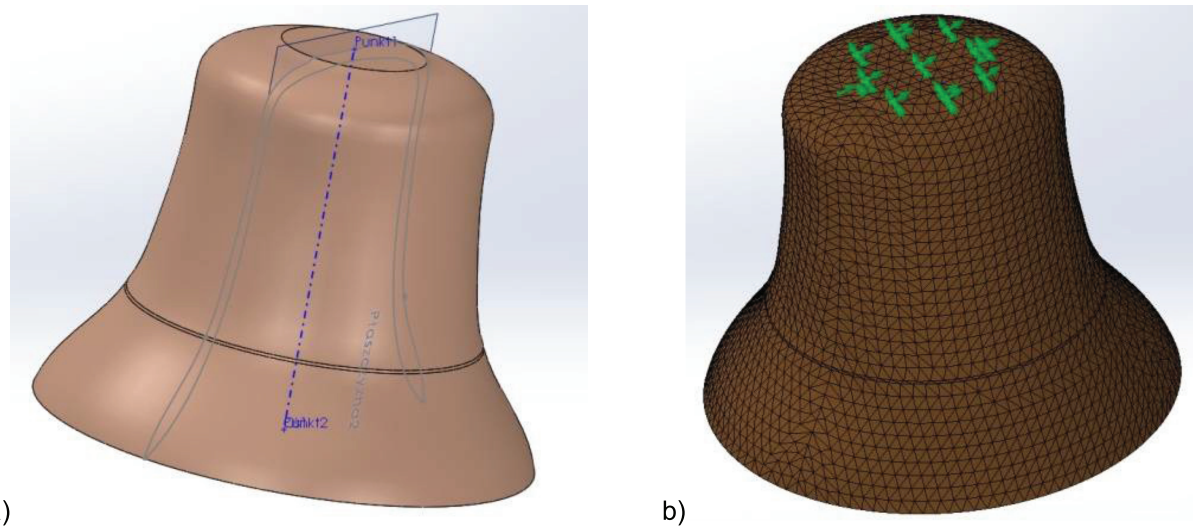


Figure 2 Porosity of samples taken out of the sound-bow of bell castings at various pouring temperature: a) 1140 °C; b) 1090 °C

A difference was recorded both between the microhardness of α-phase and (α+δ) eutectoid mixture in the same casting, and between the microhardness values of the same phase found in castings poured at different temperatures. The values were as follows: about 164 HV0.05 (standard deviation 11 HV0.05) for α-phase and about 296 HV0.05 (standard deviation 15 HV0.05) for (α+δ) eutectoid in the casting poured from the higher temperature; about 133 HV0.05 (standard deviation 12 HV0.05) for α-phase and about 245 HV0.05 (standard deviation 14.6 HV0.05) for (α+δ) eutectoid in the casting poured from the lower temperature.

Also the quality of sound of the obtained castings was evaluated by analysis of the recorded audio files and identification of the basic sound components (frequencies) characteristic for church bells (hum, fundamental, tierce, quint and nominal) by means of Wavanal program developed by Bill Hibbert [12]. The tuning of A note was assumed to be 440 Hz, and the measuring range was set from 0 to 10 kHz. The same frequency range was assumed during simulations, for which the geometrical model of bell body (**Figure 3**) was created by rotation of the rib (template) designed on the basis of 3D scanning of the produced bell castings. The size of a finite element at the stage of grid generation was assumed to be 6 mm side length with 0.3 mm dimensional tolerance, what resulted in dividing the geometrical model into 24252 elements. The imposed constraints permitted no degree of freedom at the upper surface of the bell model.



a) b)

Figure 3 Bell model a) the body of a geometrical model;
b) the model with imposed finite elements grid and boundary conditions

Vibration frequencies within the range 0 to 10 kHz were determined during the frequency analysis. Taking into account the symmetric vibration modal shapes, according to Perrin et al. [13] the frequencies corresponding to the subsequent harmonic partials of the bell sound were identified. Their corresponding modal shapes are presented in **Figure 4**, and the dominant perceived note in the bell ring (the fundamental) is ‘dis’.

The results of sound analysis with use of Wavanal program presented in **Figures 5** and **6** and **Tables 1** and **2** clearly identify the partial tones of the harmonic series characteristic for the examined bell castings. The bell poured at the higher temperature of the alloy rings in the a^3 key, while the one poured from the lower temperature rings in a^4 key, i.e. an octave above.

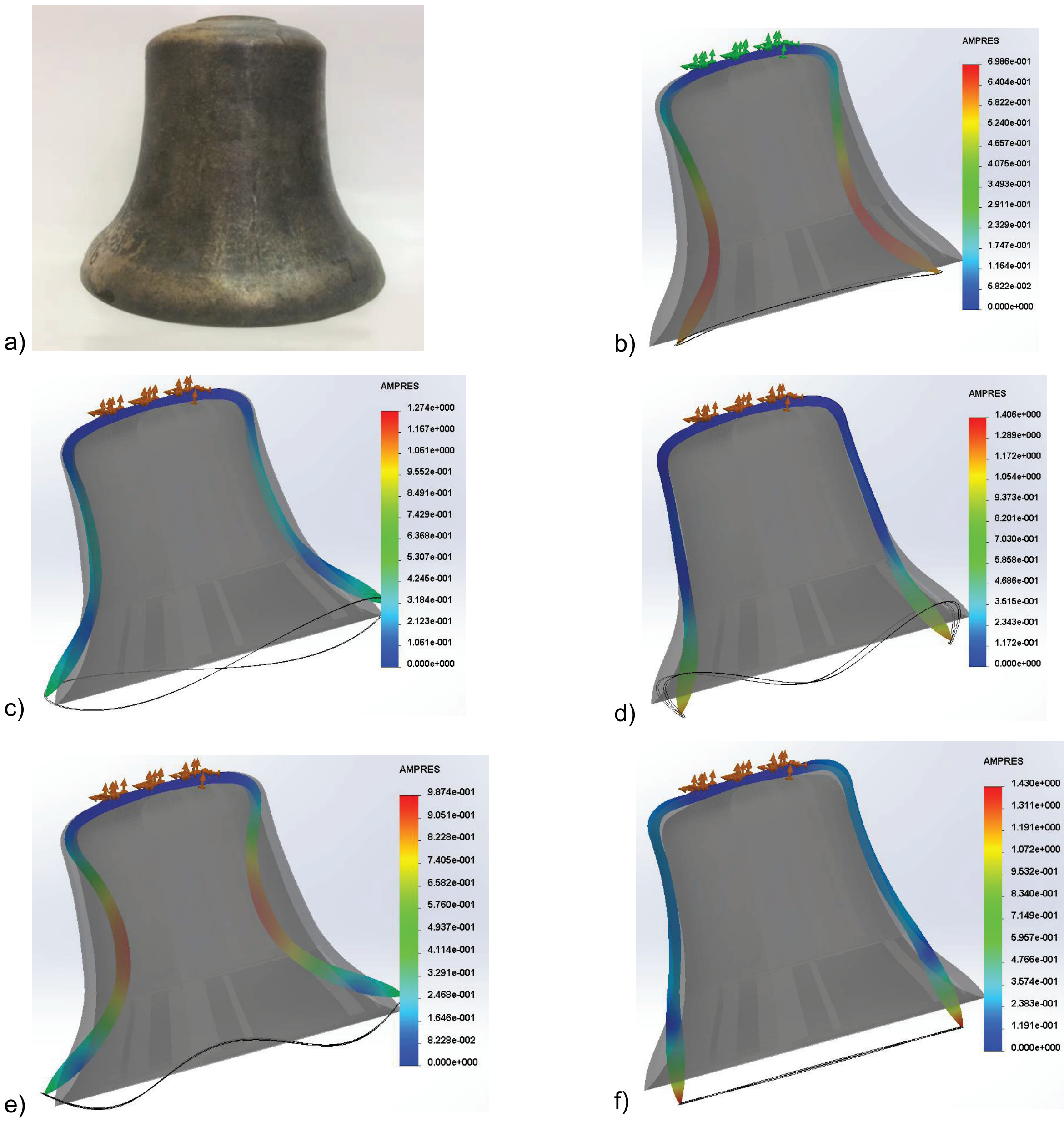


Figure 4 Modal shapes for various vibration frequencies:
a) shape of a bell casting; b) 870 Hz - hum - a[2] note; c) 2145 Hz - fundamental (prime) - dis[4];
d) 3215 Hz - tierce - fis[4]; e) 4815 Hz - quint - dis[6]; f) 5024 Hz - nominal - fis[6]

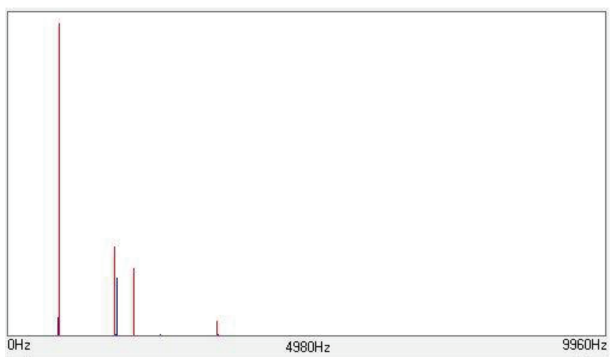


Figure 5 Vibration frequency spectrum for the bell poured at the temperature of 1140 °C

Table 1 Partial tones of the sound of the bell poured at the temperature of 1140 °C

Frequency (Hz)	Interval (cents*)	Partial name	Note
865	-2417	hum	A(2) -29
1797	-1151	prime	A(3) +36
2113	-871	tierce	C(4) +16
3494	0	nominal	A(4) -12
*cent - a unit for measuring music intervals; 100 cents make one semitone			

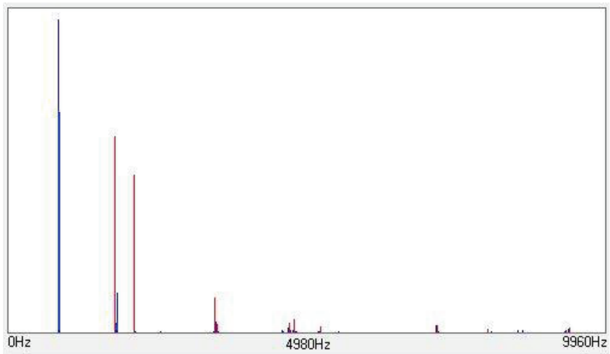


Figure 6 Vibration frequency spectrum for the bell poured at the temperature of 1090 °C

Table 2 Partial tones of the sound of the bell poured at the temperature of 1090 °C

Frequency (Hz)	Interval (cents)	Partial name	Note
1797	-2582		A(3) +36
2113	-2302	hum	C(4) +16
3457	-1450	prime	A(4) -31
3494	-1432		A(4) -12
4691	-922		D(5) -2
4764	-895	tierce	D(5) +23
5204	-742		A(5) +24
7140	-195		A(5) +24
7989	0	nominal	B(5) +19
9343	271		D(6) -10

The achieved results of investigations on the influence of casting parameters on the quality of bells indicate that as far as the reduction of porosity in small-size bells is concerned, better results were obtained for the higher pouring temperature. The local zones of cavitation revealed by CT scanning are in accordance with the results of the previously done simulation, presented elsewhere [11]. They occur mainly within the sound bow of the bell. The modal shapes for all music partial tones generated during bell vibration are of symmetric character (according to Perrin [13]), that is the axially symmetric form of church bells influences their form of vibration. The occurrence of clustered cavitation and porosity regions changes the structural character of a bell to the axially asymmetric one, and the form of vibrations becomes distorted with forced repetitions. The porosity of bells influences on the sound quality by introduction of additional nodal points, this resulting in asymmetric form of vibrations. From the acoustics point of view, localization of defects in the sound-bow is particularly unfavourable, because the sound-bow is responsible for the tone identified as nominal by the Wavanal program, while the main tone of the bell is the so-called fundamental (prime).

The presence of defects can change to a greater or lesser degree the tuning of a bell, depending on their character and position in the casting. It refers particularly to shrinkage cavities or agglomerated cavitation. In the examined case, the 'dis4' tuning obtained from simulation program at the assumption of fully filled casting was replaced in nature by 'a3' or 'a4' tuning recorded in the porous castings.

3. CONCLUSION

Higher pouring temperature allowed to obtain bell castings exhibiting less porosity than castings poured at lower temperature. Both the geometry of bell rib and the traditional position of the mould cavity foster the occurrence of the shrinkage porosity. The presence of porosity can change forms of bell vibration thus influencing bell tuning.

Tin bronzes are very sensitive to changes in the solidification conditions, therefore differences in the results of microhardness tests were observed after a change in the pouring temperature. The material hardness influences also the rigidity of a bronze casting, what further affects the acoustics of a bell. It would be reasonable to assume that this effect is stronger for small bells due to their little mass.

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