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Reconstruction of Brass for Tongues and Shallots from Baroque Organs

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Abstract. The composition and microstructure of historic tongues and shallots from reed pipes of various Baroque organs have been studied. They contain Cu–Zn solid solution (α-brass with 23-29 wt. % Zn) and lead particles. Grain size in brass scatters from 10 to 200 μm. Around 50% of all GBs in brass are Σ=3 twin GBs. The high-indexed coincidence site lattice facets were observed in twin GBs. The increase of number of various facets roughly correlates with decreasing grain size. It may indicate the variation in annealing temperature used by organbuilders in Baroque Era. New brass with 25 wt. % Zn and 2 wt. % Pb has been prepared for reconstruction of historic tongues and shallots by restoration of reed pipes in Baroque organs. The morphology of lead inclusions and twin GBs has been investigated in temperature interval from 400 to 700°C and compared with that of historic alloys. The annealing temperature has been estimated.

Introduction

The organ, one of the most complicated musical instruments, is an important symbol of European culture. Organ production changed drastically in the beginning of XIX century as a result of the industrial revolution and a transition from Baroque to Romantic style music. This led to a drastic change in the sound of organs. In the second half of XX century the interest revived to the music of Baroque and Middle Age. It has been discovered that the adequate sound for this music can only be achieved if the respective old (or old-styled) instruments are used for a performance. Because the old technology based on the intuition and family tradition of medieval masters was lost, a new one has to be developed, based on the most modern analytical possibilities and achievements of materials science. An organ contains flue and reed pipes constructed of lead-tin alloys (Figs. 1 and 2). There are no moving parts within a flue pipe (Fig. 2a). Reed pipes contain an additional vibrating part, the copper-alloy tongue that crucially influences its sound (Figs. 1 and 2b). Historically accurate lead-tin alloys characterized and reproduced in a framework of the North German Organ Research project (Sweden) beautifully recreate the historic flue pipe sound [1-3]. The reed pipes, however, are still acoustically inaccurate, since only conventional Cu-alloys were available to replace damaged reed pipe tongues. Historic pipe organs have regional sound qualities since they were constructed from locally available materials, however local restoration efforts would be redundant and expensive. The aim of this work is to reproduce the brass very similar to the historic one and to estimate the temperature of annealing used by Baroque organbuilders for the thermal treatment of tongues.

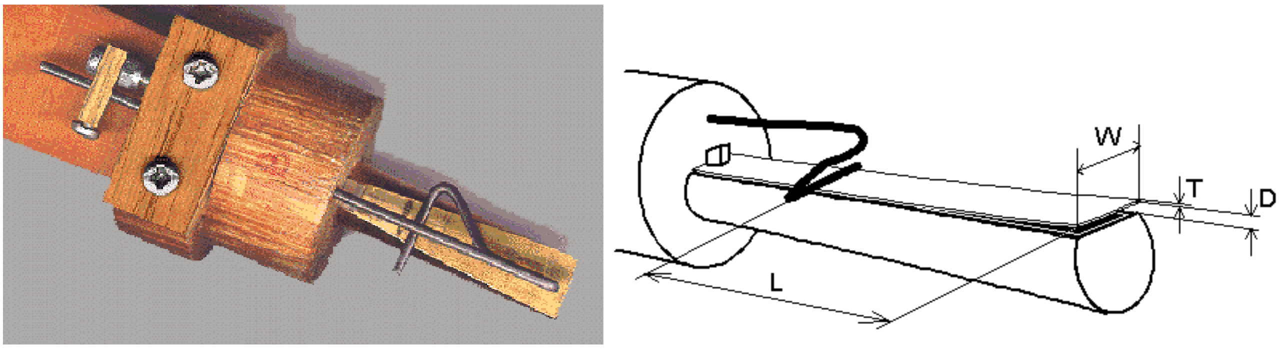


Fig. 1. Photograph and scheme of the tongue-shallot region of an organ reed pipe.

Experimental

The tongues and shallots were taken from various historic organs manufactured in Baroque Era between 1620 and 1730 and installed in seven locations in Germany (Lower Saxony), The Netherlands and Latvia (Kurland) (see Table 1 in [4]). 4 of 8 studied samples were manufactured by the famous German organbuilder Apr Schnitger. His role in the history of organ manufacturing is comparable with that of Stradivari for violins. New brass with 25 wt. % Zn and 2 wt. % Pb has been prepared for reconstruction of historic tongues by induction melting in vacuum from pure components (99.99% Cu, 99.999 % Zn and 99.999 % Pb). The cast alloy was cut into samples and annealed at 973, 873, 823, 773, and 673 K in order to study the influence of annelaing temperature on the morphology of grain boundaries (GBs) and lead inclusions. The composition of alloys and spatial distribution of components were investigated by Electron Probe Microanalysis (JEOL 6400), Secondary Ion Mass Spectroscopy (IMF-6F) and by inductively coupled plasma optical emission spectroscopy (ICP-OES). The phases contained in the alloys were determined by X-ray diffractometry (SIEMENS–500 diffractometer with a graphite monochromator and line position sensitive gas flow detector, Cu$K_{\alpha l}$ radiation was used). For the investigation of microstructure the non-vibrating parts of the tongues (positioned inside of the wooden block, Fig. 1) were carefully ground with 4000 SiC paper and polished with 3 and 1 μm diamond paste. The samples were than etched in 50% HNO_3 aqueous solution. The microstructure was photographed in polarized light in bright and dark field with the aid of an Carl Zeiss Jena Neophot 2 light microscope equipped with a digital 6.5 Mpix Canon EOS 300D camera and ImageExpert^{TM} software for image processing.

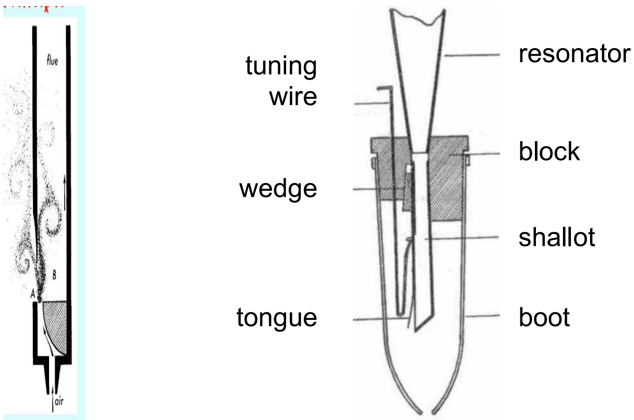
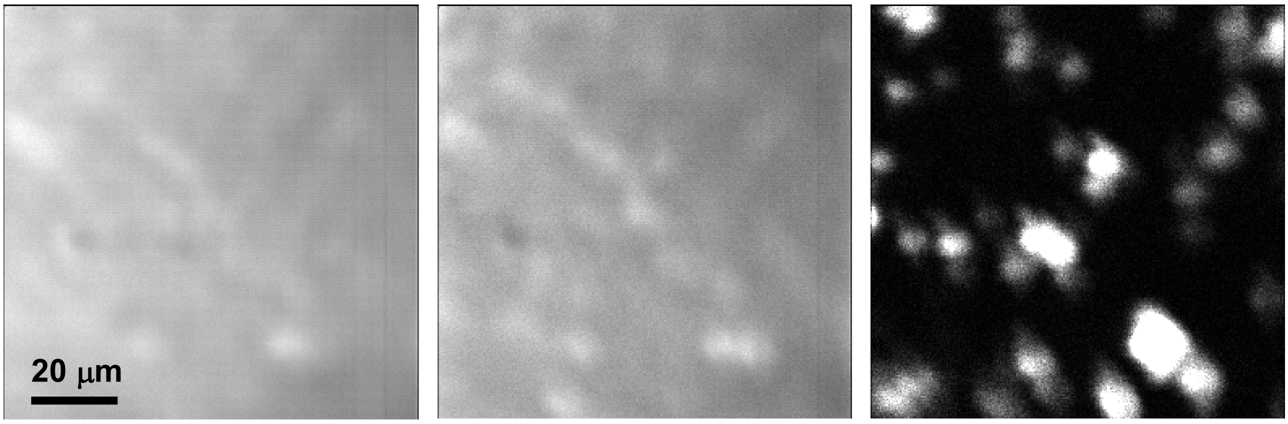


Fig. 2 (a) Scheme of the flue pipe and (b) reed pipe

Results and discussion

The main components of studied historic tongues are Cu, Zn and Pb [4]. Total amount of other elements is below 1%. All studied historical tongues and shallots contain only two phases: Cu-Zn solid solution (α-brass with 23-29 wt. % Zn, see Fig. 3 a,b) and lead inclusions (Fig. 3c). The distribution of Zn and Cu is rather uniform (Fig. 3 a,b). Since Zn concentration is below the solubility limit in Cu (35 wt.% Zn at 200°C and 39 wt.% Zn at 450°C [5]), no β-brass is present in the alloys. Trace elements like Fe, Sn, In etc. are soluble in the α-brass and do not form any strengthening particles.

The grain size in various historic tongues scatters from 10 to 200 μm [4]. The microstructure contains many twin grain boundaries. Their portion among all GBs scatters from 40 to 60%. The morphology of lead inclusions is different in different tongues. The majority of tongues contain mainly the spherical lead inclusions in the bulk of the α-brass grains. Similar inclusions are present in our reconstructed alloy too (A, Fig. 4). The minor part of lead inclusions is located in GBs. They have a lens-like shape (B, Fig. 4). The contact angle ϕ at the lead particles formed by the brass/Pb interphase boundaries and brass GBs scatters from 60 to 150° in various tongues and is in the same interval in our new alloy. It means that the lead does not wet the brass GBs. However, in two studied historic tongues (Tangermünde, H. Scherer d.J., 1620 and Lüdingworth, A. Schnitger, 1783) lead formed continuous layers along GBs. Few GBs in our samples after annealing at 673 K also contain lead layers (Fig. 5). A drastic change in the morphology is due to the change of wetting



(a) Cu (mass 63) (b) Zn (mass 64) (c) Pb (mass 208)

Fig. 3 Distributions of Cu (a), Zn (b) and Pb (c) in the reed pipe tongue from Vilnius (A.G. Casparini, 1776) obtained by SIMS.

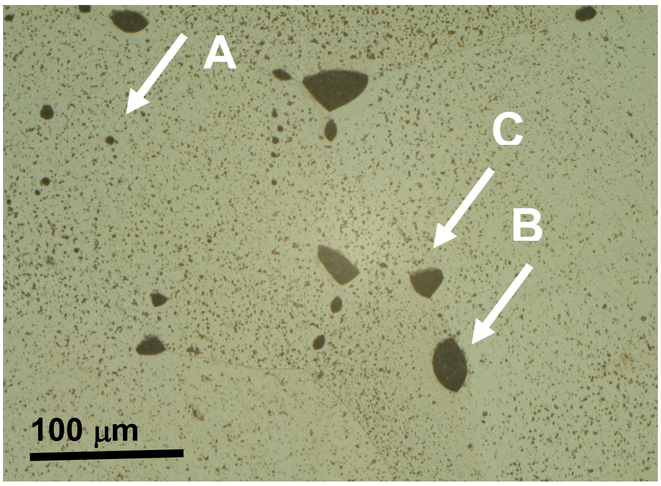


Fig. 4 Microstructure of the model alloy at 400°C. Lead forms round particles in the bulk (A) and lens-like particles in GBs (B) and GB triple joints (C).

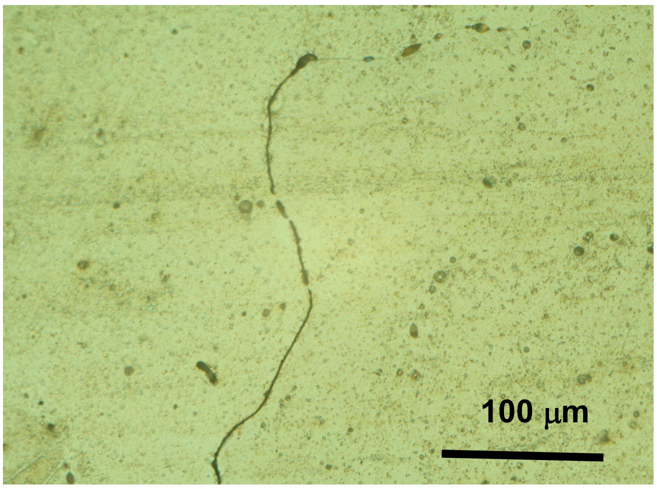


Fig. 5 Microstructure of the model alloy at 400°C. Lead forms round particles in the bulk, lens-like particles and crack-like layers along GBs.

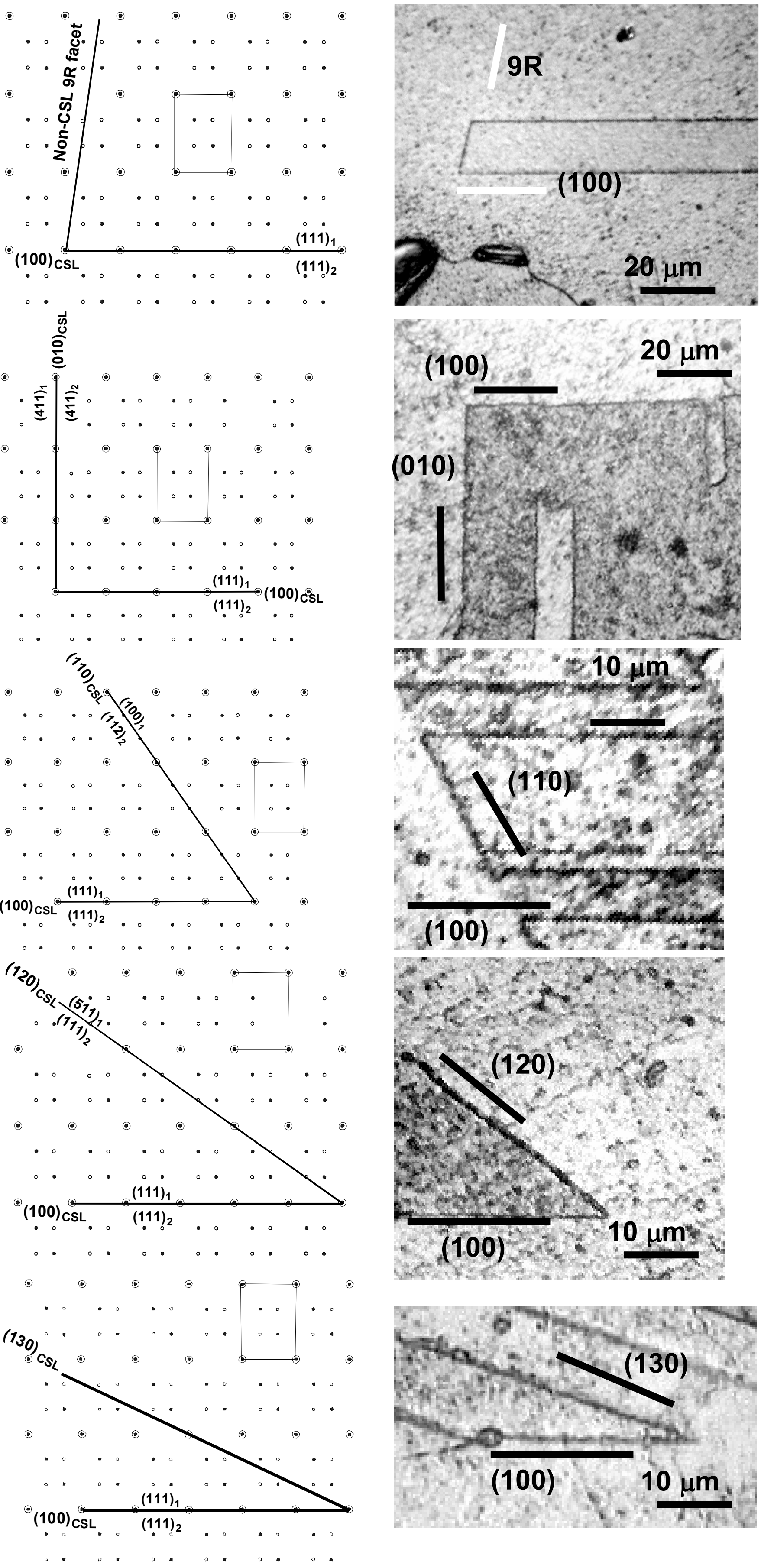


Fig. 6. Sections of Σ3 CSL perpendicular to the {110} tilt axis with position of various facets (left) and micrographs of intersections of $(100)_{CSL}$ with other facets (right). (a) $(100)_{CSL}$ and 9*R* facets, 400°C.

(b) $(100)_{CSL}$ and $(010)_{CSL}$ facets, 400°C.

(c) $(100)_{CSL}$ and $(110)_{CSL}$ facets, 400°C.

(d) $(100)_{CSL}$ and $(120)_{CSL}$ facets, 400°C.

(e) $(100)_{CSL}$ and $(130)_{CSL}$ facets, 400°C.

conditions for brass GBs and lead. If the energy of a brass GB, σ_{GB}, is lower than the energy of two interphase boundaries (IBs) between brass and lead, σ_{IB}, the contact angle ϕ between a GB and two IBs is non-zero and depends on σ_{GB} and σ_{IB}. It is defined by a condition $\sigma_{GB} = 2\ \sigma_{IB} \cos(\phi/2)$. In this case lead form the lens-like GB particles. If $\sigma_{GB} > 2\ \sigma_{IB}$, the contact angle ϕ is zero, and lead forms the continuous layers at the brass GBs. Lead separates the brass grains one from another.

The amount of twin GBs is very large both in the historic and reconstructed alloys. Sometimes twin GBs form a majority in the GB population of polycristalline samples. They can be easily seen in the microstructure (since the symmetric twin GBs are straight) and appear frequently in pairs (called "twins"). The crystal lattices of neighboring grains forming a twin GB are specially oriented. They build the so-called coincidence site lattice (CSL). This lattice is a superlattice for lattices of both grains. To characterize a CSL, one uses the inverse density of coincidence sites Σ. In case of twin GBs each 3^{rd} lattice site of a grain 1 coincides with a lattice site of a grain 2, and $\Sigma = 3$. Similar to a conventional crystal lattice, CSL has various planes with different packing density. The elongated twin GBs which are visible in the microstructures and parallel to the $(111)_1$ and $(111)_2$ planes of both grains, and lie along the most densely packed CSL plane $(100)_{CSL}$. It can be easily seen from the schemes shown in Fig. 6. In the left column of Fig. 6 the sections of a Σ=3 CSL are shown which are perpendicular to the tilt axis <110> common for lattices 1 and 2.

What happens if a twin GB does not lie in the most densely packed CSL plane $(100)_{CSL}$? It has been shown recently, that twin GBs in Cu are always completely faceted [6]. However, in other metals like Mo or Nb the same Σ=3 GBs are faceted only partly, they contain also the atomically rough, curved portions [7]. Other facets can also appear in twin GBs in Cu. It has been observed in pure Cu that with decreasing temperature more and more facets less densely packed in CSL appear in twin GBs. Similar facets were observed also in organ tongues and shallots [4] and in the model Cu–25 wt. % Zn–2 wt. % Pb alloy studied in this work (Fig. 6).

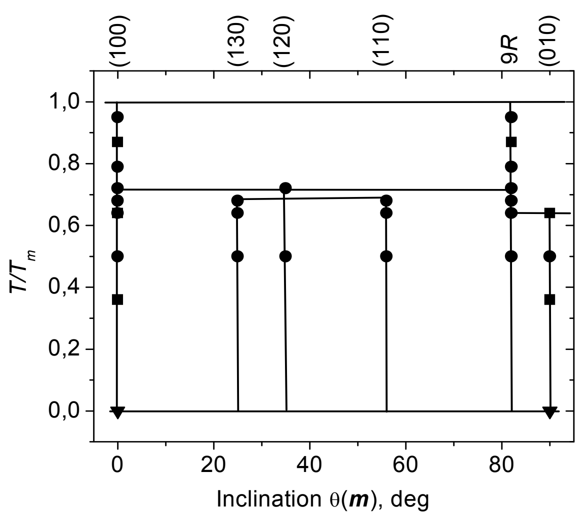


Fig. 7 The interfacial phase diagram for $\Sigma3$ {110} tilt GBs in pure Cu [6]. Inclination θ is an angular variable, which measures interfacial orientation in an equatorial section perpendicular to the {110} tilt axis of the three-dimensional phase diagram. Circles ●, ■ and x are experimental data. ▼ are results of modeling [6]. T_m is the melting temperature.

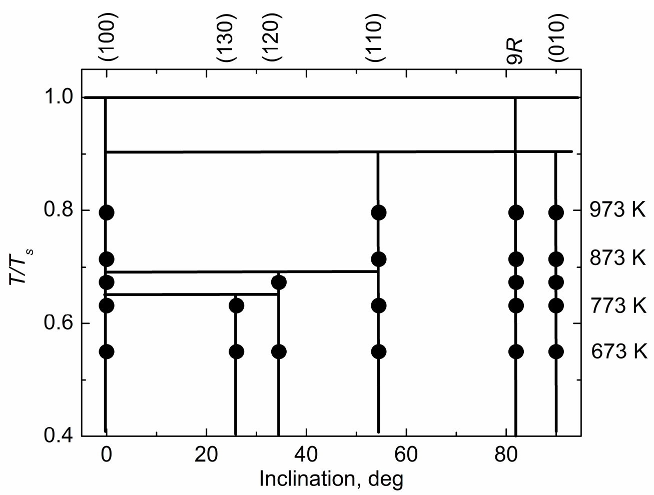


Fig. 8 The interfacial phase diagram for $\Sigma3$ {110} tilt GBs in the Cu–25 wt. % Zn–2 wt. % Pb alloy. Circles ● denote the observed facets. Inclination θ is an angular variable, which measures interfacial orientation in an equatorial section perpendicular to the {110} tilt axis of the three-dimensional phase diagram. T_s is the solidus temperature of the Cu–25 wt. % Zn–2 wt. % Pb alloy.

The phase diagram for facets in twin GBs in Cu obtained in [5] is shown in Fig. 7. Fig. 8 shows a similar diagram obtained for the Cu–25 wt. % Zn–2 wt. % Pb alloy. It can be seen that the numbers are rather similar. The main difference is that the (110) and (010) facets are stable also above 0.8 T_s in the Cu–25 wt. % Zn–2 wt. % Pb alloy. In the majority of studied historic samples (100), 9*R*, (010) and (110) facets were obseved [4]. In one tongue (Magnuskerk, Anloo, Netherlands, Johannes Radeker and Rudolf Garrels, 1719) the (120) facetes are also present. The less densely packed (130) facets were never observed in the historic tongues. The comparison with diagram Fig. 8 demonstrates that the intermediate annealing during mechanical treatment (hammering, filing) of the tongues proceeded above 773 K, most probably around 800 K. This temperature is higher than T_m of lead (320°C [5]). Thus, Pb is liquid during the annealing, and the GB wetting conditions influence the microstructure.

Conclusions

New Cu – 25 wt. % Zn – 2 wt. % Pb brass has been prepared for reconstruction of historic tongues for reed pipes for restoration of Baroque organs. The raw material for the brass tongues was obtained by Baroque organbuilders from copper smiths as thick plates [8]. The additional hammering or rolling with intermediate annealing followed by filing was used in order to reach the final tongue shape and to voice then [8]. The temperature of intermediate annealing used by organbuilders for the thermal treatment of tongues was not documented and, therefore, was estimated experimentally. The comparison of twin GB facets observed in historic tongues with the faceting phase diagram obtained for the reconstructed brass allows to conclude that the intermediate annealing of tongues proceeded above 773 K, most probably around 800 K.

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