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Structure of Historical Brass Tongues and Shallots from Baroque Organs

B. Baretzky[1,a], M. Friesel[2,b], A. Petelin[2,3,c], A. Mazilkin[1,4,d]
and B. Straumal[1,4,e]

[1]Max-Planck-Institut für Metallforschung, Heisenbergstrasse 3, D-70569 Stuttgart, Germany

[2]Chalmers University of Technology, Fysikgränd 3, SE-412 96 Gothenburg, Sweden

[3]Moscow State Institute of Steel and Alloys (Technological University), 4, Leninsky pr., Moscow, RU-119049, Russia

[4]Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Moscow District, RU-142432, Russia

[a]baretzky@mf.mpg.de, [b]friesel@fy.chalmers.se, [c]sasha@misis.ru, [d]mazilkin@issp.ac.ru,
[e]straumal@issp.ac.ru

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Abstract. The composition and microstructure of historic tongues and shallots from reed pipes of various Baroque organs has been studied. They contain Cu-Zn solid solution (α-brass with 23-29 wt. % Zn) and lead particles. Lead is mainly present as spherical bulk or lens-like grain boundary (GB) inclusions. However, in two samples Pb wets the brass GBs. In this case Pb forms the branched root-like structures. Grain size in brass scatters from 10 to 200 μm. Around 50% of all GBs in brass are $\Sigma=3$ 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. The annealing temperature has been estimated using the faceting phase diagram for twin GBs in Cu.

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 been 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, the new one has to be developed, based on the most modern analytical possibilities and achievements of the 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 study the composition and microstructure of historic tongues in order to completely reproduce the beautiful warmth and blazing fanfare of Baroque and Medieval music by developing reed pipe tongues with appropriate acoustic properties.

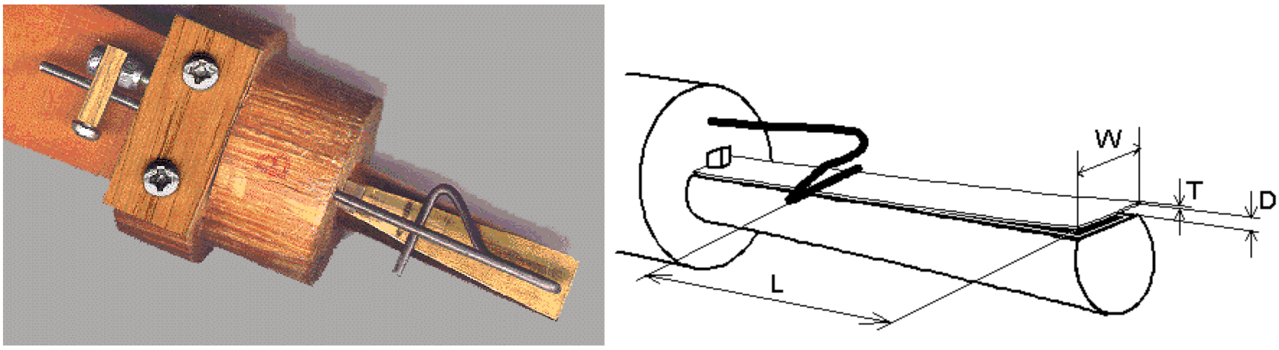


Fig. 1. Photograph and scheme of the tongue-shallot region of an organ reed pipe.

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). 4 of 8 studied samples were manufactured by famous German organbuilder Apr Schnitger. His role in the history of organ manufacturing is comparable with that of Stradivari for violins. 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 the X-rays diffractometry (SIEMENS –500 diffractometer with a graphite monochromator and line position sensitive gas flow detector, Cu$K_{\alpha 1}$ 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 Zeiss Axiophot light microscope.

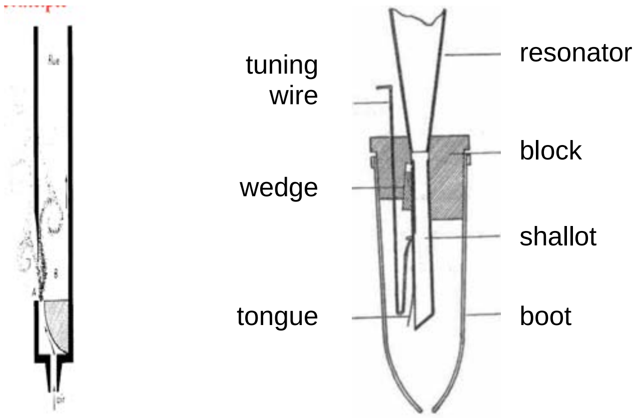


Fig. 2 (a) Scheme of the flue pipe and (b) reed pipe

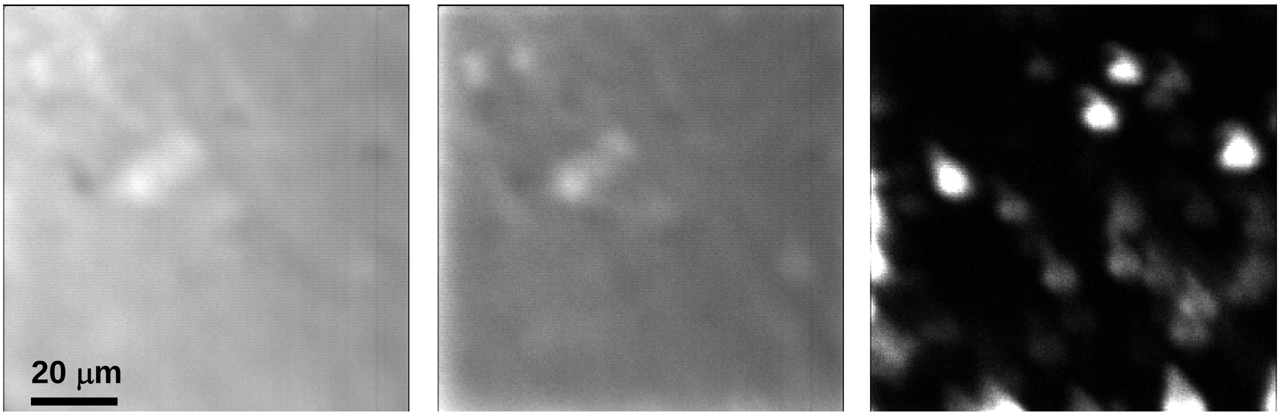
Results and discussion

The composition of studied tongues is given in the Table 1. The main components are Cu, Zn and Pb. Total amount of other elements is below 1%. All studied historical tongues and shallotes 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 [4]), no β-brass is present in the alloys. The trace elements like Fe, Sn, In etc. are soluble in the α-brass and do not build any strengthening particles.

The grain size in various tongues scatters from 10 to 200 μm (Table 1). The microstructure contains many twin grain boundaries (GBs) (Figs 4 and 5). 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 (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. It means that the lead does not wet the brass GBs. However, in two studied samples (Tangermünde, H. Scherer d.J., 1620 and Lüdingworth, A. Schnitger, 1783) lead form continuous layers along GBs (Fig. 5). In the tongue from Lüdingworth (A. Schnitger, 1783) the GB lead layers are rather short and localized among 2-4 neighbouring grains. In the tongue from Tangermünde (H. Scherer d.J., 1620) the GB lead layers are long (several hundreds of microns), their length exceeds the mean grain size, and they cross almost whole sample (Fig. 5). Their shape is similar to roots of a tree. A drastic change in the morphology is due to the change of wetting 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 the lead forms the continuous layers at the brass GBs. Lead separates the brass grains one from another.

Table 1. Composition and microstructural features of studied historic tongues and shallotes

Location	Organbuilder and year	Zn wt. %	Pb, wt.%	Other ele-ments, wt.%	Grain size, μm	Pb particles, morphology and size, μm	Portion of twin GBs	Twin facets, CSL planes
St. Stefan, Tangermünde,Germany	Hans Scherer d. J., 1620 (tongue)	25	2.85	<1	50-400	A,B,C,D 10-30		$9R$ (010)
St.-Johannes Hamburg, Germany	Arp Schnitger 1680 (shallot)				30-80	A,B,C 2-8	<50%	$9R$ (110) (010)
St. Jakobi, Lüdingworth, Germany	Arp Schnitger 1682-1683 (tongue)	25	2		10-30	D, few A 10μm thickness	<50%	$9R$ (010) (110)
Dedersdorf, Germany	Arp Schnitger 1698 (tongue)	23	1.3	<0.2	80	A,B,C 10-30	>50%	$9R$ (010) (110)
Dedersdorf, Germany	Arp Schnitger 1698 (shallot)	28	2.3	<0.1	80	A,B,C 10-30	>50%	$9R$ (010) (110)
Ugale, Latvia	Cornelius Rhaneus, 1701(tongue)	23	1.5		100-150	A,B 5-30 (few)	>50% Fine twins	$9R$
Netherlands	1730 (tongue)				150-200	A,B,C 2-20	<50%	$9R$ (010)
Magnuskerk, Anloo, Netherlands (tongue)	Johannes Radeker and Rudolf Garrels, 1719	29	4	<1	180-200	A 5-50	>50%	$9R$ (110) (120)



(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.

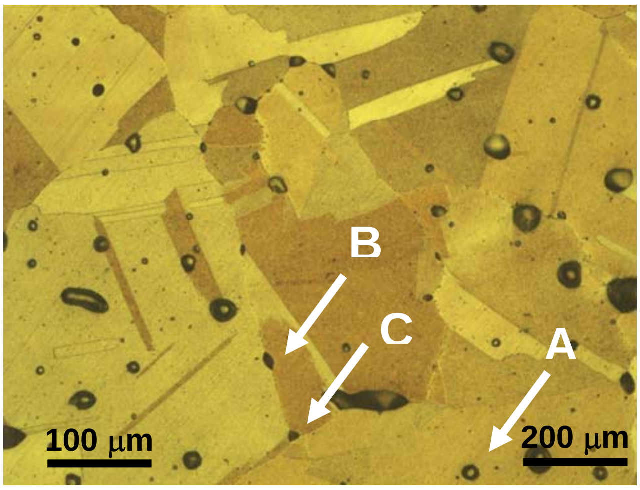


Fig. 4 Microstructure of the tongue from Anloo (J. Radeker and R. Garrels, 1719). Lead forms round particles in the bulk (A) and lens-like particles in GBs (B) and GB triple joints (C).

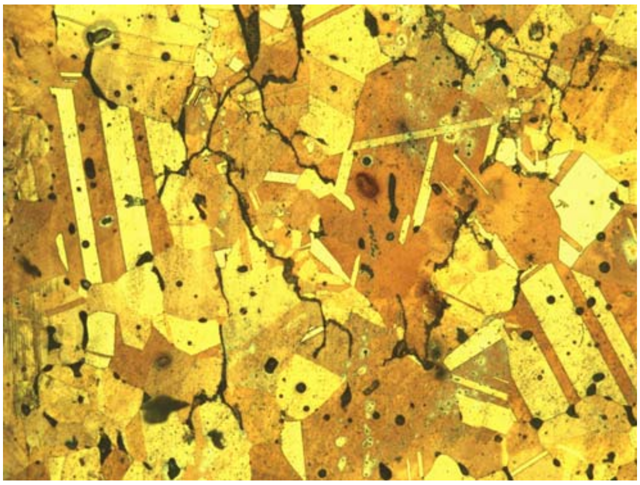


Fig. 5 Microstructure of the tongue from Tangermünde (H. Scherer d.J., 1620). Lead forms round particles in the bulk, lens-like particles and crack-like layers along GBs.

The amount of twin GBs is very large in the studied alloys. Sometimes twin GBs form a majority in the GB population of polycistalline samples. They can be easily seen in the microstructure (since the symmetric twin GBs are straight) and appear frequently in pairs (called “twins”, see Figs. 4 and 5). The crystal lattices of neighboring grains forming a twin GB are oriented. They build the so-called coincidence sites 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 3rd 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 (Figs. 4 and 5) are 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.

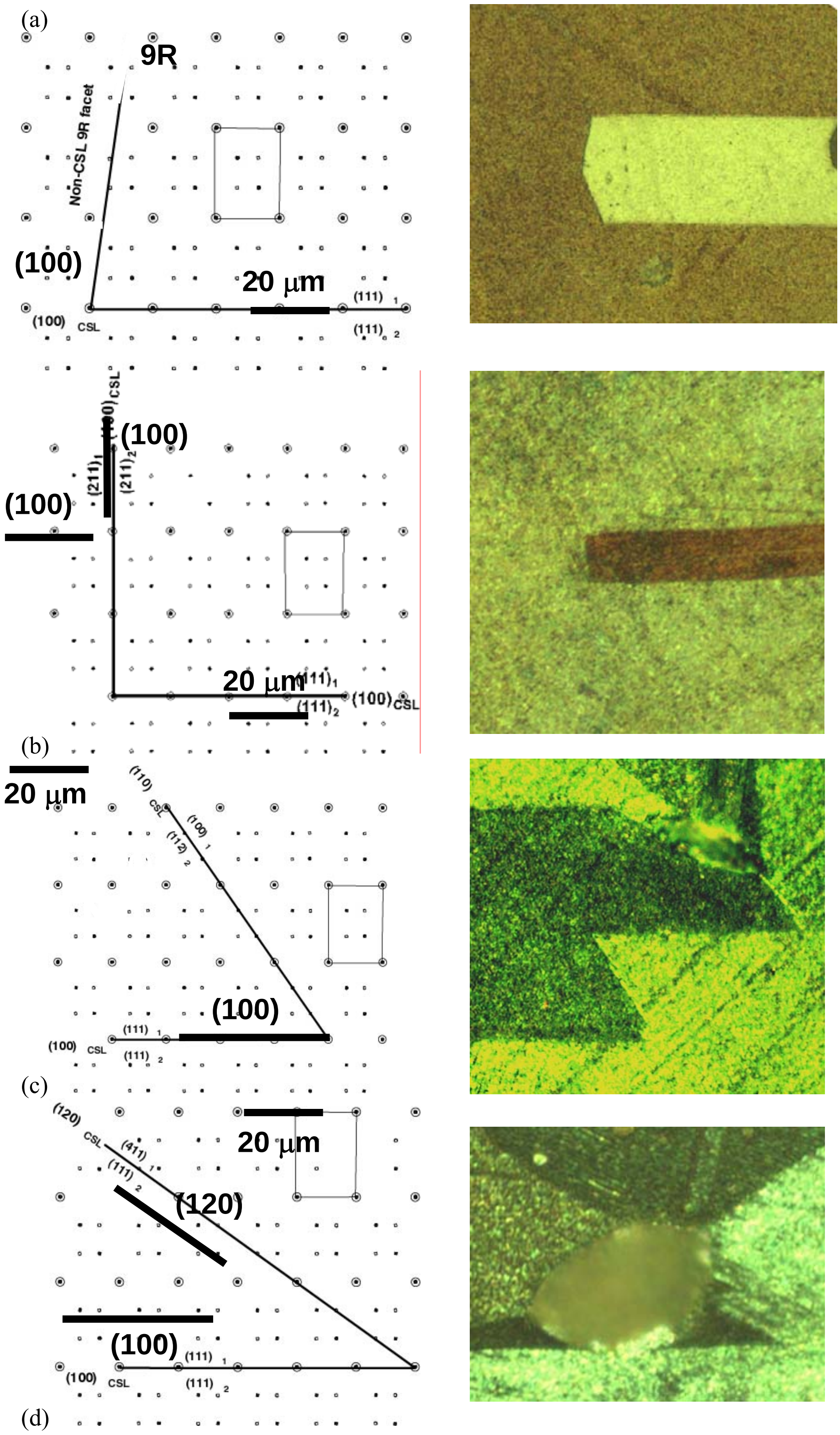


Fig. 1. Sections of Σ3 CSL perpendicular to the {110} tilt axis with position of various facets (left) and micrographs of intersections of $(100)_{\mathrm{CSL}}$ with other facets (right).

(a) $(100)_{\mathrm{CSL}}$ and 9*R* facets

(Magnuskerk, Anloo, Johannes Radeker and Rudolf Garrels, 1719)

(b) $(100)_{\mathrm{CSL}}$ and $(010)_{\mathrm{CSL}}$ facets (Dedersdorf, Arp Schnitger, 1698, tongue)

(c) $(100)_{\mathrm{CSL}}$ and $(110)_{\mathrm{CSL}}$ facets (Magnuskerk, Anloo, Johannes Radeker and Rudolf Garrels, 1719)

(d) $(100)_{\mathrm{CSL}}$ and $(120)_{\mathrm{CSL}}$ facets (Magnuskerk, Anloo, Johannes Radeker and Rudolf Garrels, 1719)

What happens if a twin GB do not lie in the most densely packed CSL plane $(100)_{\mathrm{CSL}}$? It has been shown recently, that twin GBs in Cu are always completely faceted [5]. 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 [6, 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 (Fig. 6 and last column of Table 1).

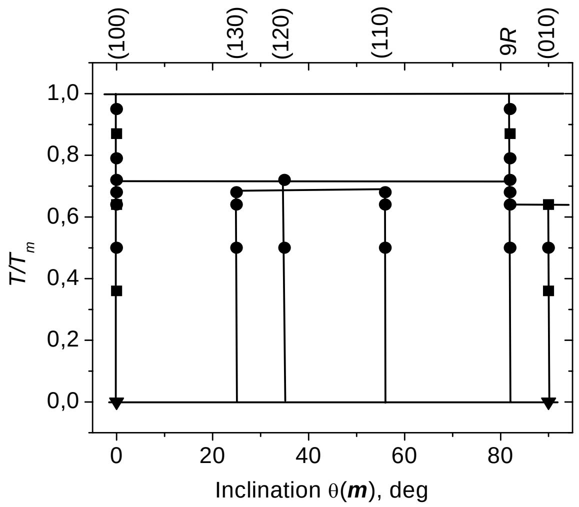


Fig. 7 (T, θ) interfacial phase diagrams for Σ3 {110} tilt GBs in Cu [5]. θ is an angular variables which measure interfacial orientation in an equatorial section perpendicular to the {110} tilt axis of the three-dimensional phase diagram. The (T, θ) phase diagram shows positions of cusps in the Wulff plot for $T < T_{Rf}$. T_{Rf}. is a temperature of a GB roughening transition. Circles●, ■ and x are experimental data o ▼ are results of modeling [5].

The phase diagram for facets in twin GBs in Cu obtained in [5] is shown in Fig. 7. It can be seen that the number of crystallographically different facets increases with decreasing temperature. Mean grain size would also increase with increasing annealing temperature. Indeed, it can be seen from the Table 1, that the number of various facets is really larger in samples where the grain size is lower. Comparing the data from Table 1 and phase diagram (Fig. 7), we can roughly estimate the temperature used by organbuilders for annealing the tongues. It is between 0.5 and 0.7 of melting temperature T_m. For brass with 23-29 wt. Zn it is between 500 and 700°C. This temperature is higher than T_m of lead (320°C [4]). Thus, Pb is liquid during the annealing, and the GB wetting conditions influence the microstructure. Obviously, the diagram in Fig. 7 has been obtained for pure Cu. Therefore, a similar diagram has to be experimentally constructed also for Cu–Zn alloys.

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