Can We Look over the Shoulders of Historical Brasswind Instrument Makers?—Aspects of the Materiality of Nineteenth-century Brass Instruments in France

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This paper reports on a multidisciplinary research project into the materiality of brasswind instruments, in which chemical analyses, metallography, electron backscatter diffraction (EBSD), wall-thickness measurements, and neutron and X-ray tomography were applied. It presents in a condensed form summary results and conclusions drawn from the project. Full details are published in conference proceedings including papers of the present authors and those by Jean-Marie Welter, Wolfram Schillinger, Cyril Grenot, Edward H. Tarr, and Rainer Egger.[1]

Introduction

The activities of several instrument makers in nineteenth-century France mark a high point in the history of brass-instrument production. The names of just a few of the foremost craftsmen of this great era include Raoux, Labbaye and Millereau, the Courtois family, Gautrot, Sax (all in Paris), Kretzschmann (Strasbourg), Müller and Tabard (Lyon). A large number of their instruments have been preserved. They are well known from a musical and organological point of view, but many technical details of their manufacturing techniques are still uncertain. Unfortunately, the artisans themselves remain silent, as almost no primary source material apart from the instruments themselves has survived.

A highly multi-disciplinary research project within the context of experimental archaeometallurgy has uncovered some of their secrets. It was carried out by the Bern University of the Arts (direction, musicology) in collaboration with the Swiss Federal Laboratories for Materials Science and Technology (metallography, ED-XRF) and the Paul Scherrer Institute (metallography, neutron and X-ray tomography). Of paramount interest were questions regarding materiality and working techniques. The goal was to support the “historically informed” production of replicas by the Egger brass instrument workshop in Basel. For this purpose research on the following themes was undertaken:

- for the reproduction of brass sheets, the chemical composition of the historical instruments as well as sheet thickness had to be known.
- for the production of replicas, knowledge of original working techniques (e.g., annealing temperatures) had to be discovered.
- for copying the original geometry, internal dimensions of the historic instruments were needed.

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For determining the chemical composition of the instruments, ED-XRF analyses were applied. This method needs no sampling and is mobile. It can be performed wherever the instruments are located, as is also the case with another non-invasive and mobile technique, ultrasonic wall thickness measurement, which was also employed on the instruments. On the other hand, X-ray and neutron imaging were of necessity performed in the laboratory where the machines are located. Instrumental working techniques can be studied only by means of metallographic methods, which require adapted sampling. This method is often not suitable or even adaptable for use with items of valuable cultural heritage, such as the musical instruments under investigation.

Prior to this study, little was known concerning the materiality of nineteenth-century French instruments, except for the fact that they are made mostly of brass. Whereas until the eighteenth century brass was produced using a cementation process and hammered into sheets,[2] in the nineteenth century (in France at the latest after 1820, according to Welter[3]) brass was alloyed in a direct process and available in the form of rolled sheets. Our knowledge of instruments of the nineteenth century is based primarily on the work of Louise Bacon on British-made instruments, some of which were made of brass containing lead, while others contained no lead.[4]

The more than fifty instruments under study in our research project represent a significant selection of nineteenth-century French instruments, supplemented by some foreign examples (see list in the Appendix). Most of them belong to Swiss collections, such as the Music Museum, Basel and the Burri Collection, Bern; others are in private or foreign collections. The following sections of this essay outline separately the four investigative techniques and their conclusions that served to answer the questions framed above.

1. Energy dispersive X-ray fluorescence spectrometry (ED-XRF)

This non-invasive method has been used repeatedly, with good results, for material analysis on brasswind instruments.[5] For the present project, some 300 ED-XRF analyses on approximately fifty instruments have been carried out with a mobile system (NITON XL3t GOLDD+, produced by Thermo Scientific). Measuring only the garland and the tubes, but not all parts of the instrument, this method requires one hour for each instrument. ED-XRF is a surface-centered analytical technique with which elements between magnesium and uranium in the periodic table can be analyzed simultaneously. The excitation source of the machine sends electro-magnetic waves to the material under study. The atoms of the sample material react with a specific electromagnetic wave, which then is detected.[6] The result of these analyses is a spectrum with several peaks for each element. The instrument software converts this spectrum into values of atomic per cent and mass per cent. With the software used it was not possible to quantify arsenic, however. The machine was calibrated with several standard copper-alloy materials. Each sample spot on an instrument was analyzed two or three times, for thirty or sixty seconds each. Only clean brass spots without plating and without patina or visible corrosion were chosen. From these analyses a mean and a standard deviation were calculated.

As an example, the results for the Müller keyed bugle (no. 20, see Appendix) are presented in Figure 1b. For this instrument two different alloys were detected, one with about 1% lead, from which the bell, yard, and the ferrule belonging to the yard were produced; and another with around 2% lead, from which the sleeve, leadpipe, and a key were produced. A typical characteristic (which can also be seen in other instruments) is that the leadpipe contains more lead than the other tubing elements (bell and yard). Forty such datasets form our database for French brass instruments manufactured during the nineteenth century.

Figure 1a: Keyed bugle by Müller (Lyon, mid-nineteenth century; Appendix, no. 20). Bern, University of the Arts. Photo by Adrian v. Steiger. Measuring points are indicated by reference numbers.

Keyed Bugle, Müller no. 20	Cu %	Zn %	Pb %	Sn %	Sb %	Ni %	Fe %	Mn %	Co %
Pos. 1: Bell	66.2	32.3	1.2	<0.05	<0.05	<0.05	0.11	<0.05	<0.05
Pos. 2: Yard	64.9	33.5	1.2	<0.05	<0.05	0.07	0.08	<0.05	<0.05
Pos. 3: Sleeve	66.1	31.7	1.8	<0.05	<0.05	<0.05	0.09	<0.05	<0.05
Pos. 4: Ferrule	65.8	32.6	1.3	<0.05	<0.05	<0.05	0.08	<0.05	<0.05
Pos. 5: Lead pipe	64.9	33.0	1.8	<0.05	<0.05	<0.05	0.08	<0.05	<0.05
Pos. 6: Key	63.9	33.9	1.9	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Standard deviation	0.2-1.3	0.2-1.4	0.1-0.4	-	-	0.01	0.01-0.02	-	-

Figure 1b: Chemical composition of the parts of the keyed bugle in Figure 1a (method: ED-XRF; the results are means, the standard deviation relates to the different results).

Not all data spots are included in the scatterplots shown in Figures 2 and 3. We have excluded sleeves, ferrules, keys, valve mechanisms, garlands, and mouthpieces, since these parts can be produced by methods different than that for the tubes. One result of interpreting the data is shown in Figure 2: The French instruments are in presumed chronological order. Measurements for zinc content are aligned vertically. The shapes of the data points (circle, rhombus, square, etc.) serve to differentiate the instruments from each other. Figure 2 allows the assumption that the zinc content of the brass alloy increased and became more and more stable during the course of the nineteenth century. The mean content of zinc for the second half of the century is 32.5 ± 1.3% mass zinc. Two of the twenty instruments from this period, nos. 43 and 18, show larger variations in composition. In the case of no. 43, the Gautrot factory (with up to 200 employees)[7] seems to have used whatever sheet brass was at hand. The bell of no. 18 is made from a zinc-poor alloy, typical for the first half of the nineteenth century and not found in the other parts of the instrument. It can therefore be surmised that the manufacturer of no. 18, Labbaye (a smaller atelier), took an old sheet or bell from his stock to produce this instrument part.

Our study did not connect the specific composition of an alloy to any particular maker. The main reason for this may be that in most cases only a small number of instruments from each manufacturer were analyzed. The metallic composition of these instruments varies without any discernible trend over a broad range, as can be seen in Figures 2 and 3.

Particularly interesting is the lead content in the brass alloy, as shown in Figure 3. Although it was possible to manufacture lead-free brass by the direct process at that time (as seen, for example, in the tongues of organ pipes made since 1820[8] and in some

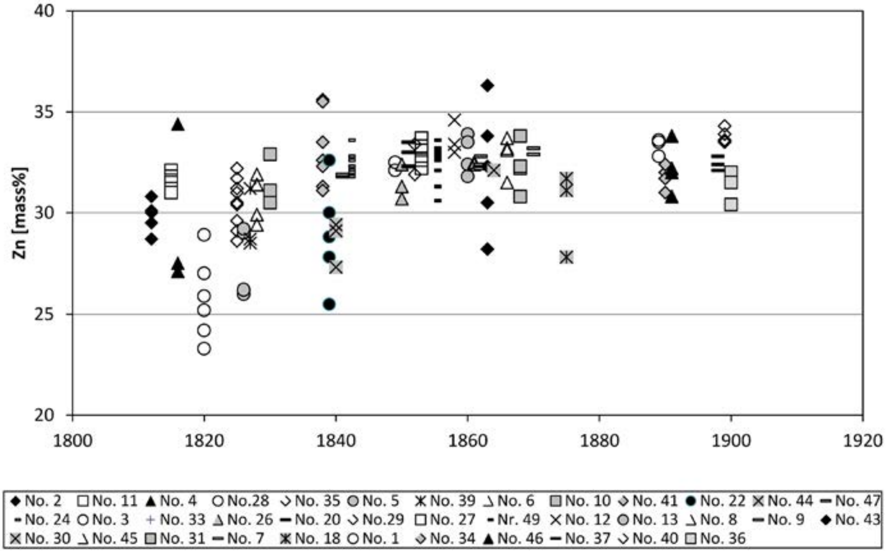

Figure 2: Zinc content in French brass instruments of the nineteenth century, based on measurements of the main tubes.

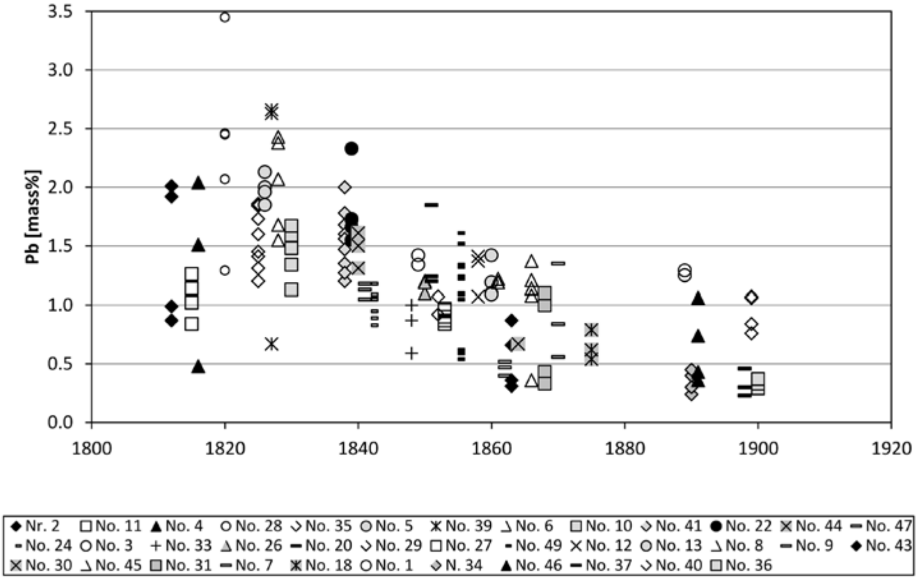

Figure 3: Lead content in French brass instruments of the nineteenth century, based on measurements of the main tubes.

brasswind instruments from Great Britain),[9] we detected lead in all the nineteenth-century brass instruments we analyzed. Compared to the German instruments included in our study and contemporaneous English instruments (see note 9), the amount of lead found in French instruments is greater. A decrease in the lead content in French instruments over the course of the nineteenth century can be clearly identified. For the second half of the nineteenth century the mean content of lead is 0.9 ± 0.4 mass percent. These values vary over a broader range than those for zinc content. A number of maximal content values are associated with leadpipes (nos. 7, 28, 20, and 45), but other similar trends cannot be identified.

Based on both of these mean values, the project defined an "average French alloy" for the second half of the nineteenth century for brasswind instruments to be CuZn32–34Pb1 (i.e., 65–67% copper, 32–34% zinc, ±1% lead). Rolled sheets with this composition now form the base material for Egger's replicas of nineteenth-century French instruments, such as the invention-horn by Raoux-Millereau (no. 31), and a trio of natural, slide, and valved trumpets by Antoine Courtois (nos. 33 and 49).

The next question is: What sheet thickness should Egger use?

2. Wall thickness measurements

Using information on wall thicknesses, an instrument maker can actually observe his historical colleague at work. The following questions can be answered: Which brass sheet thickness did he use? And how was the flare of the bell worked?

For this study more than 1000 wall-thickness measurements on the fifty-three instruments (see the Appendix) included in the project were performed with a GE Krautkramer CL 5 device. This transportable apparatus is generally employed to monitor metal thicknesses in the production of automobiles and aircraft, with the help of ultrasound. The process takes a few seconds and leaves no traces—the contact fluid merely has to be removed. The software assists the operator in taking precise measurements. Our measurement values are rounded to the nearest 10 microns. The device was calibrated with the help of a set of brass samples of known chemical composition and thickness. According to primary tests, the variation in the zinc and lead content of the alloys found in our project instruments do not lead to significant inaccuracies in the results. The impact of the curvature of a sample on the result, particularly in small leadpipes for horns and cornets, is unknown.

At the thinnest points detected on our historic instruments, the metal measured less than 0.2 mm. These are typically found on the bells, e.g., in instruments made by Kretzschmann; other tubes, especially those produced towards the end of the century, are of more substantial material, up to 0.6 mm thick. A typical example is the *cor solo*

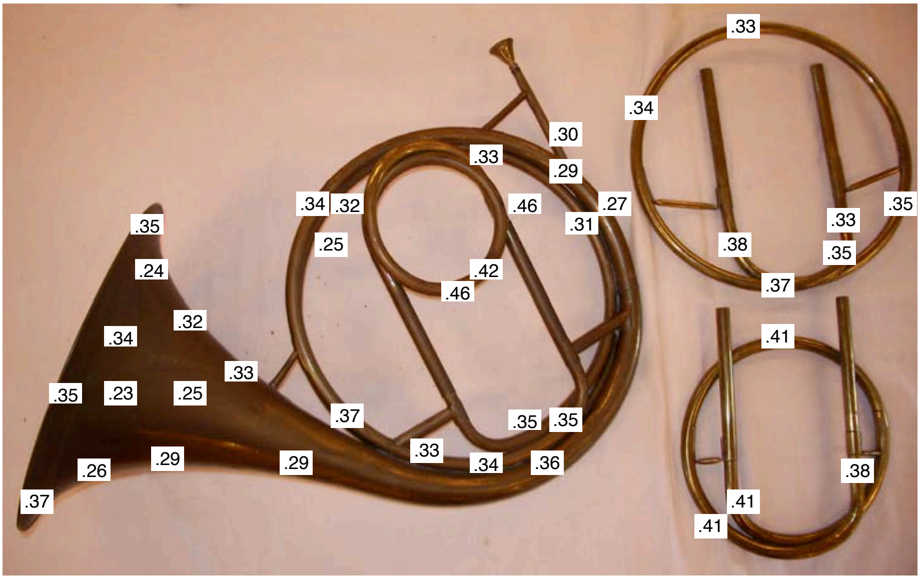

Figure 4a: *Cor solo* by Lucien-Joseph Raoux (Paris, ca. 1820; Appendix, no. 28). Basel, Historisches Museum. Photo by Adrian v. Steiger.

by Julien-Joseph Raoux (no. 28). Figures 4a and 4b show the measuring positions and thickness data for this instrument. The following measurements are in millimeters:

Garland	0.35 / 0.35 / 0.37
Bell (flair section)	0.26 / 0.29 / 0.29 / 0.24 / 0.32 / 0.33 / 0.23 / 0.25
Bell (tube section)	0.36 / 0.29 / 0.34
Yard	0.37 / 0.35
Crook 1	0.42 / 0.46 / 0.46
Crook 2	0.41 / 0.41 / 0.38
Crook 3	0.33 / 0.35 / 0.37 / 0.34 / 0.33 / 0.35 / 0.38
Leadpipe	0.35 / 0.31 / 0.32 / 0.33 / 0.34 / 0.33 / 0.30

Figure 4b: Wall thickness measurements of the cor solo in Figure 4a (in mm).

The results of all measurements made on the project instruments are published in the conference proceedings.[10] The interpretation of these figures can be taken a step further: given sufficient measurements, and taking into account the degree of reduction in thickness due to hammering and filing, the original thickness of the brass sheet used for each bell or tube can be estimated. As every manufacturing process leads to a reduction of the wall thickness, never to an increase, the thickness of the original sheet is always greater than the largest measured value. Our preliminary study on today's instruments by Egger shows that the reduction of material thickness due to hammering varies from 0 mm to 0.10 mm, while final processes, such as filing, reduce the thickness by about 0.05 mm (minimum: 0.03 mm). Raoux therefore used a sheet of minimum 0.4 mm thickness for the bell and yard of his horn in Figure 4a (thickest spot of the bell: 0.36 mm; in the yard: 0.37 mm). Each of the three crooks is made from different sheet material.

Figure 5 shows the wall thicknesses of our twenty French horns. Measurements of wall thickness in the bells are plotted above the zero line; yard thicknesses of the same instruments, below that line. The short horizontal lines show the thicknesses of the original sheets inferred from the measurements.

Conclusions: Many of these measurements are very low values, some less than 0.2 mm. However the original sheet metal was not so thin as this might lead one to expect. On every bell and yard there are also thicker spots. We assume therefore that the sheet metal in general could not have been thinner than 0.40 to 0.45 mm in the first half of the nineteenth century, and up to 0.50 towards the end of this century. Exceptions are the bells of nos. 11 and 47, and the yards of nos. 4 and 24 (for instrument specifications, see the Appendix). It is our hypothesis that the typically low wall thickness of historic instruments is a result of the work carried out on the material and not of the original dimensions of the raw sheet itself.

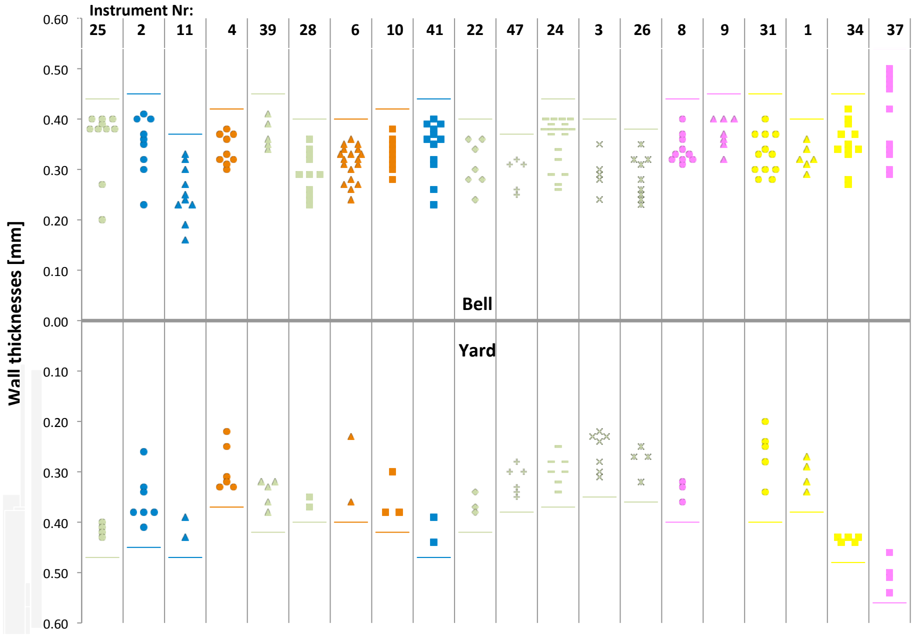

Figure 5: Wall thickness measurements for twenty French horns from the nineteenth century. The Raoux horn (see fig. 4 a/b; Appendix, no. 28) is sixth from left. The horizontal lines above and below each instrument show the assumed thickness of the original sheets.

These supposed thicknesses of sheet metal must be understood as approximations, because the thickness of material in nineteenth-century France was not always measured according to the metric system (oral communication from Welter; see also his introduction to the copper industry and French brass making[11]).

Now that we know the sheet quality and thickness of the materials used by the historic instrument makers in nineteenth-century France, we still lack information about the working techniques they employed.

3. Metallography

Metallographic investigations in this project were based on optical microscopy, chemical analyses of the soldered parts and inclusions in the metal by SEM/EDX (scanning electron microscope/energy dispersive X-ray spectroscopy), Vickers hardness testing, and electron backscatter diffraction (EBSD). These techniques deliver information on the physical structure of the metal grains and metal phases. Metallography produces conclusive results regarding the working processes applied to the metal, such as soldering, hardening, and annealing techniques, which cannot be determined by the other means.[12]

Sample preparation for metallographic investigation is the only invasive method used in this project. It has, of course, been applied only for a few samples. The use of invasive examination methods requires valid justification. The team discussed this issue in detail, especially with the project archaeometallurgist, who has extensive experience in conducting research on extremely valuable objects. The questions to be answered included:

- What material was used for soldering?
- What is the final state of the metal in the finished instrument?
- Is alpha brass the only brass phase always present?

Unfortunately there are no non-invasive or minimally invasive methods capable of "looking" into the metal and determining the form of the grains (which would provide information on the final working state) without sampling. Concerning minimally invasive methods, it must be mentioned that very small samples may be altered by sample preparation and are often not representative of the metal in general. For this reason, a minimally invasive technique would actually be more damaging than useful. Thus we chose a normal invasive approach to resolve the above questions concerning traditional methods of instrument making and working techniques such as shaping, annealing, and soldering.

It was decided to perform sampling on meaningful objects that had already suffered damage. It is important that such interventions are carried out by highly qualified researchers using accurate methods, and that the interpretation of the results be given highests priority. In short: if invasive techniques are unavoidable, they should be conducted correctly! Four samples were taken from the bell, garland, and tubing of the Millereau horn (see Appendix, no. 34) and one from the bell of the totally destroyed Kretzschman horn (no. 2). They were compared with samples of today's instruments made with historically informed techniques by Egger, with the aim of comparing his working techniques with those of the historic instruments themselves.

The following preparations were required: mounting the sample in synthetic resin, grinding and polishing the sample to a grain size of 1 micron, etching for the microscopic study, dismounting the sample, and polishing electrolytically for examination with electron backscatter diffraction (EBSD).

Figure 6 shows the grain structure in the garland of the Millereau horn (no. 34). The alpha brass grains as well as the dark lead inclusions are easily seen. The metal shows a secondary recrystallized grain structure from which the annealing temperature can be deduced. Recrystallization takes place when, after a phase of shaping (cold work), the worked metal piece is annealed.[13] For a brass alloy with the composition of horn no. 34 (CuZn32Pb0.4), the recrystallization temperature varies between 520°C and 600°C. If the annealing temperature is raised near to the maximum, the grains no longer grow so regularly and finely as they do when they are near the minimal temperature, forming instead both large and small grains. This discontinuous grain growth is called

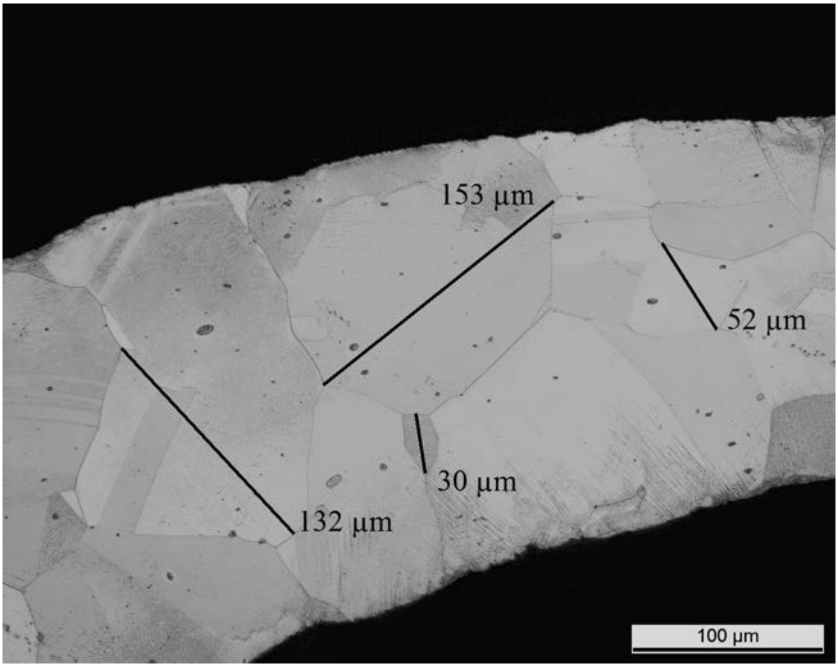

Figure 6: Metallographic section of the garland of the horn by Millereau (Appendix, no. 34), etched by Klemm. Alpha brass with lead inclusions (dark), secondary recrystallized grain structure with twins (parallel lines), and strain lines on the surface are visible.

secondary recrystallization. The presence of straight parallel lines (so-called twin lines) shows that annealing occurred after cold working. The strain lines prove that the final cold work was done when the garland was already fixed in place.

One technique possibly capable of providing data on grain size, grain orientation, and metal phases is electron backscatter diffraction (EBSD). In Figure 7 we see that only a limited number of very large grains occur, most of the grains are smaller. This supports the metallographic interpretation of the secondary recrystallized structure. (This, however, has to be qualified owing to a restriction on the interpretation of this kind of graph since this technique also counts all inclusions and twins as grains, as well, which means that most of the small grains in the statistic graph are not real).

From this and the other samples obtained from instrument nos. 2 and 34 (samples taken from bell and garland), we can conclude that annealing was the last working step, done at the highest possible temperature or longest possible time period, during which a secondary recrystallization of the structure took place. The EBSD investigations further show traces of a last deformation, which are manifest in slightly deformed twins. Interpreting these results, we can assume that the instrument makers tried to attain maximum reduction of the tensile stress in the metal with a final step of minor solidification.

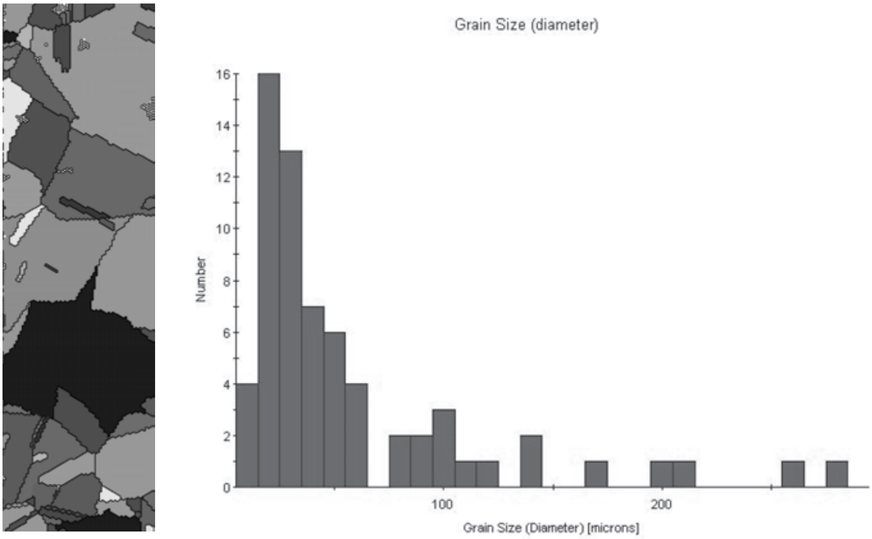

Figure 7: EBSD results for a part of the metallographic section in the bell of the Millereau horn (Appendix, no. 34). Left side: grain plus boundary picture; right side: graph showing the distribution of the grain size.

A fascinating additional aspect of the metallographic study is the micro-hardness test according to Vickers. Figure 8 shows the cross-section of the same sample from the yard of horn no. 34. The hardness is measured at 16 points, indicated by the diamond marks, arranged on a grid of lines 20 micrometers apart within the thickness of 0.42 mm. The analysis shows that both exterior regions of the metal are harder,

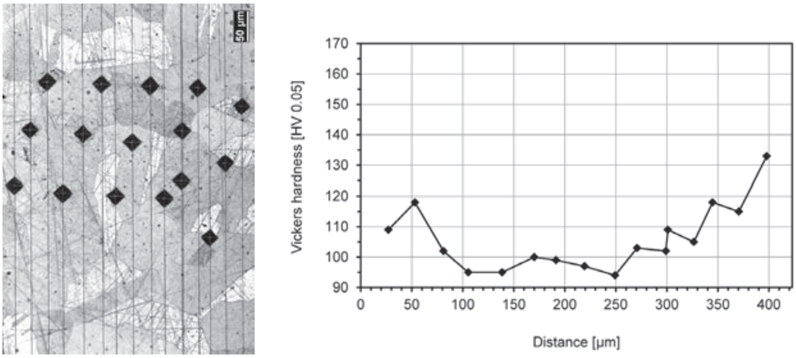

Figure 8: Left: metallographic section of the yard of the Millereau horn (Appendix, no. 34), etched by Klemm, with marks of the diamond head of the Vickers hardness tester. Right: corresponding Vickers hardness progression in the sheet of the yard.

whereas the interior region is softer. This may be a result of general shaping and/or the final filing and polishing of the instrument after the last annealing, resulting in a hardening of the exterior grains of the brass.

Figures 9 and 10 show the results of the metallographic study and micro-hardness test of a sample from the bell of an instrument by Egger (note that Egger uses historically informed manufacturing techniques). The alloy differs in this case from that in instrument no. 34, the Egger instrument using a modern CuZn37 alloy. The higher zinc content makes the modern alloy harder than that found in no. 34. Nevertheless, we can see that there are no fundamental differences between this "modern" instrument and the historical one: the grain structure is similar. The same is true for the distribution of hardness values: again, the metal surface is harder than the middle region. We can therefore conclude that Egger instruments are worked in a very similar way to the historical instruments.

We are aware that this interpretation is based on just a few samples, but the results are nonetheless surprising. The effects of aging of the material are not discussed here, but will be one of the topics of subsequent research, in preparation.

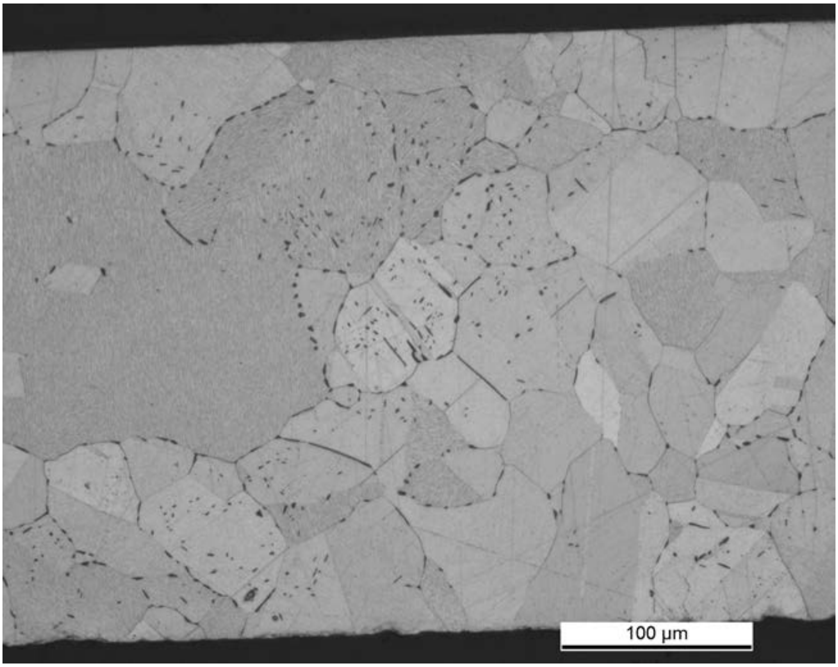

Figure 9: Metallographic section of the bell of a failed modern instrument by Rainer Egger, etched by Klemm. Alpha brass with beta phase along the grain boundaries, secondary recrystallized grain structure with twins (parallel lines).

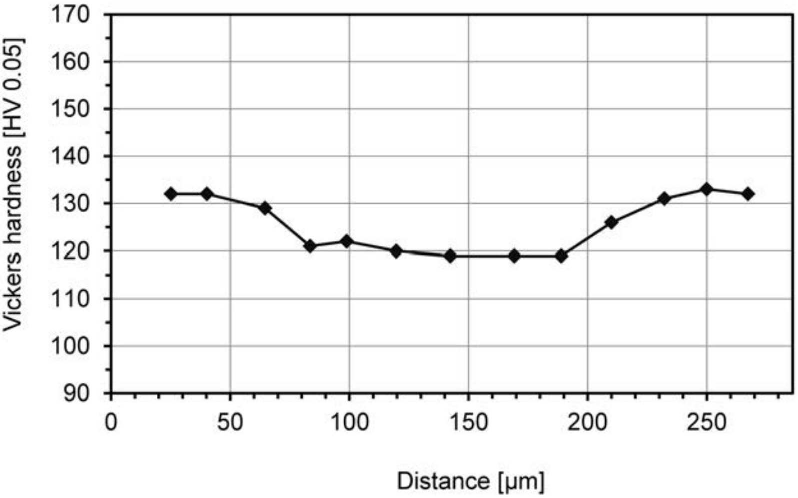

Figure 10: Vickers hardness progression in the brass of the bell of a failed modern instrument by Rainer Egger.

4. Neutron and X-ray imaging

X-ray and neutron imaging are non-destructive testing methods which can be used to perform 2D (radiographic) as well as 3D (tomographic) investigations. Both methods are based on the principle of transmission measurements, resulting in shadow images of the examined object. The radiation is partially attenuated by the object according to Beer-Lamberts law:

$$I = I_0 \cdot e^{-\mathrm{SK} \cdot \mathrm{d}}$$

where I is the intensity of the transmitted radiation, I_0 the intensity of the incident radiation, SK the attenuation coefficient (labeled $\sum$ for neutrons and µ for X-rays), and d is the thickness of the object. The resulting images can differ considerably, as a result of different interactive behaviors of the radiation with the atoms in the object; while the X-ray photons interact with the electrons in the atomic shell, the neutrons interact with the nucleus. As a result, there is a strong correlation between the attenuation coefficient for X-rays and the atomic number, yielding a high transparency for materials containing light elements (e.g., organic materials) and low transparency and high contrast for materials with high atomic numbers, such as metals. Neutrons show a different behavior, with no correlation to the atomic number; nevertheless, the attenuation behavior can be regarded as partially complementary to that of X-rays, as some light elements such as hydrogen show very high attenuation coefficients, while metals are generally more transparent to neutrons than to X-rays (lead, for example, is practically transparent to neutrons).

In this project, X-ray and neutron imaging methods were used to take inside measurements along the body of the instrument and to gather information on inner features and tool marks. The measurements were used for the production of the replica by Rainer Egger. The tool marks showed that the examined instruments (nos. 20, 34, 42, and 51) had been finished using a spinning lathe.

Figure 11: Neutron (left) and X-ray (right) radiographs for the Müller keyed bugle (Appendix, no. 20; for an overview of the chemical composition, see Figure 1).

As can be seen in Figure 11, the neutron and X-ray radiographs of the Müller keyed bugle (no. 20) show different features in the respective images. As a consequence of the high transparency for metals, the wall thickness can be determined from the neutron radiograph, which is not possible in the X-ray image. Furthermore, the neutron radiograph features high contrasts for areas with hydrogenous material such as organics (felt, leather) and condensed water (visible as small droplets on the inner surface of the instrument). While the joints are visible in both types of radiographs, the X-ray image gives additional information on the distribution of the soldering material and inhomogeneity of the material in general.

Summarizing, it can be stated that neutron and X-ray imaging yields valuable information about the instruments with respect to their geometry (material thicknesses, inner dimensions) and to how they were made. Both methods allow measurement of the inner bore profile, particularly in areas where it is not possible to take measurements with traditional tools. The resulting information can be exported to CAD documents and can serve for the manufacture of replicas. This is especially true for tomographic investigations, where a volume data set is created bearing 3D-information of the complete instrument; here a surface-model can be created, which can be imported directly to the CAD software.

5. Conclusions

The present study shows that relatively high lead content is a characteristic attribute of nineteenth-century French instruments, and that it is higher than in contemporaneous German and English instruments. Furthermore, we can conclude that the sheet material worked in France in the nineteenth century was not extremely thin and that the last phase in the production process was a small degree of cold-working after extended annealing.

All these results reveal the working techniques of the artisans, i.e., *how* they manufactured these instruments. Parallel historical research (not presented in this paper), investigating the few surviving workshops, iconography, and bankruptcy inventories of several instrument makers, such as Auguste Courtois and Adolphe Sax, provides insights into *what* kind of work was done. These sources show the types and numbers of tools used in the workshops. The presence of mandrels for tubes, for example, makes it clear that not only bells but also tubes were largely manufactured with the help of mandrels, and not by tube sinking.

Two topics that have been excluded from this project form the focus of a follow-up study (in preparation). On the one hand, there is the highly controversial issue of the influence of the wall and therefore of the materiality of the metal on the player and on the sound of a brasswind instrument (whereas the influence of the material, e.g., leaded brass, on the instrument maker is obvious). On the other hand, there is the equally significant issue of the aging of brass and therefore of the difference between the original historical material and its representation by today's measurements.

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Notes

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[4] Alice Louise Bacon, “A Technical Study of the Alloy Compositions of Brass Wind Musical Instruments (1651–1867) Utilizing Non-destructive X-Ray Fluorescence” (Ph.D. diss., University of London, 2003).

[5] See Bacon, “Technical Study,” for Great Britain; Vereecke et al., “Chemical Composition,” for Nuremberg.

[6] For details on this method, see Vereecke et al., “Chemical Composition,” 64–66, where restrictions in analyzing brass are also mentioned.

[7] See Haine, *Les facteurs.*

[8] B. Baretzky, M. Friesel, and B. Straumal, “Reconstruction of Historical Alloys for Pipe Organs Brings True Baroque Music back to Life,” *MRS Bulletin* 32 (March 2007): 249–55.

[9] Bacon, “Technical Study,” 216.

[10] Adrian v. Steiger, “Zur Vermessung historischer Blechblasinstrumente,” in Skamletz et al., *Romantic Brass Symposium II*.

[11] See Welter, “The French Brass Industry.”

[12] Hermann Schumann, *Metallographie* (Leipzig: Deutscher Verlag für Grundstoffindustrie, 1991; David A. Scott, *Metallography and Microstructure of Ancient and Historic Metals* (New York: Getty Conservation Inst., 1991).

[13] Günter Gottstein, “Recovery, Recrystallization, Grain Growth,” in idem, *Physical Foundations of Materials Science* (Berlin: Springer, 2004), 303–56.

Appendix

List of instruments used in the study

B.B.mim: MIM Brussels. p.c.: private collection. CH.B.hm: Musikmuseum Basel. CH.BE.burri: Sammlung Burri Bern.

01	Horn	Raoux-Millereau, Paris	ca.1889	B.B.mim 1312
02	Horn	Kretzschman (!), Strasbourg	early 19th cent.	p.c. Mürner, Bern
03	Hunting horn	Marcel-Auguste (?) Raoux, Paris	mid-19th cent.	CH.B.hm 1980.2265
04	Hunting horn	Courtois neveu ainé, Paris	1816–1837	CH.B.hm 1980.2270
05	Trombone	Halary, Paris	around 1825	CH.B.hm 1980.2692
06	Horn	Courtois frère, Paris	1813–1844	CH.B.hm 1980.2315
07	Cornet	Millereau, Paris	1866–1887	CH.B.hm 1980.2261
08	Horn	Gautrot, Paris	1845–1882	CH.B.hm 1980.2333
09	Horn	Gautrot, Paris	1845–1882	p.c. Mürner, Bern
10	Horn	Courtois neveu ainé, Paris	around 1830	CH.B.hm 1980.2314
11	Horn	Kretzschmann, Strasbourg	early 19th cent.	p.c. Pick, Lyon
12	Cornet	Besson, Paris	mid-19th cent.	CH.B.hm 1980.2278
13	Ophicleide	Müller, Lyon	mid-19th cent.	CH.B.hm 1980.2491
14	Horn	Bauer, Prague	mid-19th cent.	CH.B.hm 1980.2458
15	Horn	Hüller, Graslitz	end 19th cent.	CH.B.hm 1980.2581
16	Horn	Michl, Graslitz	early 20th cent.	CH.B.hm 1980.2371
17	Horn	Stasny, Prague	mid-19th cent.	CH.B.hm 1980.2640
18	Cornet	Labbaye, Paris	2nd half 19th cent.	p.c. Bollinger, Bern
19	Trumpet	Bauer, Prague	mid-19th cent.	CH.B.hm 1980.2598
20	Keyed bugle	Müller, Lyon	mid-19th cent.	Univ. coll. Bern 21476
22	Horn	Guichard, Paris	2nd quarter 19th cent.	CH.B.hm 1980.2274
24	Horn	Halari, Paris	2nd quarter 19th cent.	CH.B.hm 1962.64
26	Horn	Perinet, Paris	mid-19th cent.	CH.B.hm 1980.2108
27	Trumpet	Antoine Courtois, Paris	1844–1852	CH.B.hm 1980.2248
28	Horn	Lucien-Joseph Raoux, Paris	around 1820	CH.B.hm 1980.2065
29	Slide trumpet	Adolphe Sax, Paris (not numbered)	mid 19th cent.	CH.B.hm 1980.2260
30	Signal trumpet	Adolphe Sax, Paris	1855	CH.B.hm 1980.2208
31	Horn	Raoux / Millereau, Paris	1868	p.c. Hübner, Darmstadt
32	Keyed trumpet	Beyde, Vienna	around 1830	CH.BE.burri 1184/74
33	Slide trumpet	Antoine Courtois, Paris	1844–56	CH.BE.burri 70/746
34	Horn	Millereau, Paris	end 19th cent.	Univ. coll. Bern 1
35	Horn	Courtois frère, Paris	1813–1844	p.c. Mürner, Bern
36	Trombone	Millereau, Paris	around 1900	p.c. Mürner, Bern
37	Horn	Cuesnon, Paris	around 1900	p.c. Mürner, Bern
38	Horn	Haltenhof, Hanau	1784	CH.BE.burri 1229/665
39	Hunting horn	Raoux, Paris	1st half 19th cent.	CH.BE.burri 39/100

40	Trumpet	Millereau, Paris	around 1900	p.c. Lahens, Paris
41	Horn	Müller, Lyon	2nd quarter 19th cent.	p.c. Skamletz, Basel
42	Trumpet	Besson, London	1876	p.c. Tarr, Rheinfelden
43	Saxhorn alto	Gautrot (Sax licence) Paris	1859–1865	CH.BE.burri 293/741
44	Cornet	Kretzschmann, Strasbourg	2nd quarter 19th cent.	CH.BE.burri 75/124
45	Saxhorn alto	Adolphe Sax, Paris	1866	CH.BE.burri 297/743
46	Saxhorn soprano	Margueritat, Paris	end 19th cent.	CH.BE.burri 139/194
47	Horn	Halari, Paris	2nd quarter 19th cent.	CH.BE.Burri 42/740
48	Trumpet	Saurle, Munich	first half 19th cent.	CH.BE.Burri 26/38
49	2 Trumpets	Antoine Courtois, Paris	1853–1856	Univ. coll. Bern 5019
50	Trumpet	Millereau, Paris	around 1900	p.c. Kampmann, Paris
51	Trumpet	Antoine Courtois, Paris	1862–1867	D.BDSA.t 14201
52	Keyed trumpet	Karl Gottlob Schuster, Neukirchen	mid 19th cent.	CH.BE.burri 067/75
53	Bassoon bocal	Savary le jeune, Paris	around 1825	CH.BE.burri 458/760