An experimental study of the welding techniques used on large Greek and Roman bronze statues

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ABSTRACT: There are two key techniques in the manufacture of large Greek and Roman bronze statues. First, the statue is cast in several pieces by the indirect lost-wax process, and then the pieces are joined by a flow fusion welding process. The principle of ancient flow fusion welding consists of pouring molten bronze between the bronze pieces to be joined. Our laboratory experiments contribute to the understanding of this joining process by studying the thermal and physico-chemical parameters that control the fusion welding of binary copper-tin alloys (bronzes). The results obtained were compared with observations of ancient joins on large bronze statues, but some questions remain unanswered. In particular, whatever experimental conditions were used, we were unable to produce a weld longer than a few centimetres, whereas some ancient welds can be up to a metre long. The use of a 'magic' additive, which could act as a welding flux is thus suspected.

Introduction

This paper reports the first results of experimental work undertaken at the Centre de Recherche et de Restauration des Musées de France to study the welding process used on large Greek and Roman bronze statues. These are life-size or larger metal statues, dating from the second half of the 6th century BC to the 5th century AD. Recent technical studies have shown that such statues were not cast in one piece, in spite of an exceptional control of the lost-wax process, but resulted from welding together the previously-cast parts. Indeed, it would be easier to make a large statue by casting separate smaller parts rather than casting it in one piece. It allowed the mould geometry to be simplified and the use of smaller quantities of metal for one cast. As a result of avoiding the complexities of large castings, the foundrymen had to find effective ways of joining the parts of their statues (Steinberg 1970).

Evidence of joining on large bronze statues

The earliest Greek evidence of welding is contemporary with the first large bronze statues at the end of the 6th or beginning of the 5th century BC (Bouquillon *et al* 2006, Formigli *et al* 1984, Mattusch 1988). Archaeometallurgical techniques such as simple observation, radiography, endoscopy and tomography give systematic evidence of welded joins on ancient statues. There are many different features that can be characteristic of the presence of a welded join:

- differences in the corrosion of the surface, as for example on the neck of a 1st century BC statue of a naked young man, probably Alexander the Great (Rolley 1994), from Agde (Hérault). The statue was made in at least six parts produced using the indirect lost wax process and then joined by welding the head, arms and legs to the torso. Note the welding is in basins along the main join between the head and the body (Fig 1; Mille and Azéma forthcoming).
- an excess of filler metal as seen inside the junction between the left leg and the body of a sleeping Eros of the 2nd century AD from the Louvre museum. This shows the weld spilled over, indicating that an excess of filler metal had been poured (Fig 2).
- there is often a concentration of small spherical porosities along the weld which joins the two parts. A bronze fragment from a monumental statue from Vieil-Evreux (Eure), dating to the 2nd century AD is

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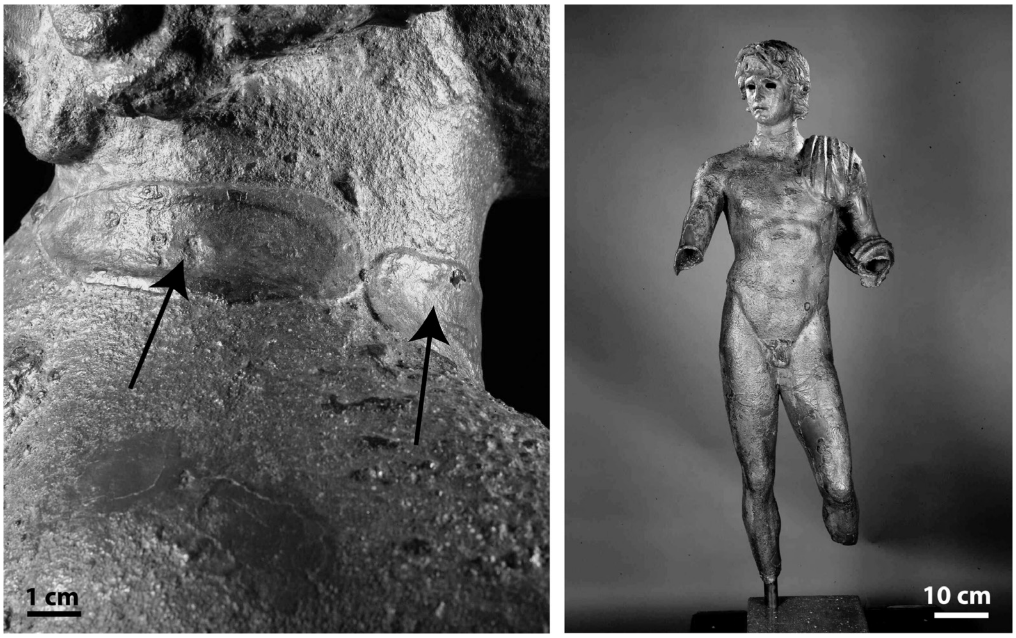

Figure 1: Right: statue of a young man, Cap d'Agde museum, height 1.4m. Left: the back and side of the neck showing welding in basins along the main join between the head and the body.

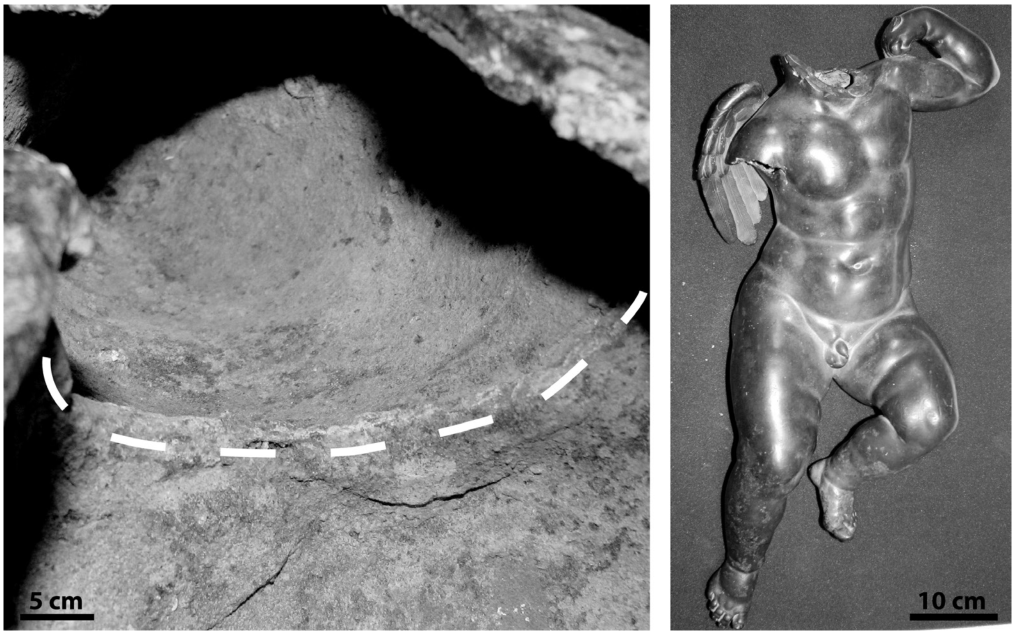

Figure 2: Right: sleeping Eros, Louvre museum, 0.63m. Left: the inside of the join between leg and body. The dashed white line runs along the join where an excess of filler metal can be seen.

a good example of such a feature (Fig 3).

- a discontinuity on an X-radiograph which marks the contact between the two parts, as seen between the left leg and the body of a statue of Apollo, dating to the 2nd century AD, from Vieil-Evreux (Eure) (Fig 4).
- a number of small rectangular repairs along a line, like the ones on a statue of Jupiter, dating to the end of the 1st century AD, from Vieil-Evreux (Eure) (Fig 5).

Ancient flow welding: similar to modern fusion welding processes?

Archaeometallurgical study has revealed that the joining technique is a process known as flow welding (Steinberg 1970). The basic principle is to pour molten bronze (the secondary casting) whose composition is similar to that of the two pieces to be joined (the primary castings) along the join. The flow-welded joins can be divided into two main types depending on how the edges of the primary castings are prepared. The bronze can be cut away to half its thickness to make a channel in which the molten bronze can run (Fig 6A) or a space is left between the two parts to be joined and the welding metal is directly poured through this space (Fig 6B). In the latter case, a small refractory system has to be put in place underneath the castings to prevent metal leaks inside the statue. In addition, it is frequently observed that the welded linear joins on bronze statues are punctuated by basins, first recognised on the Riace statues

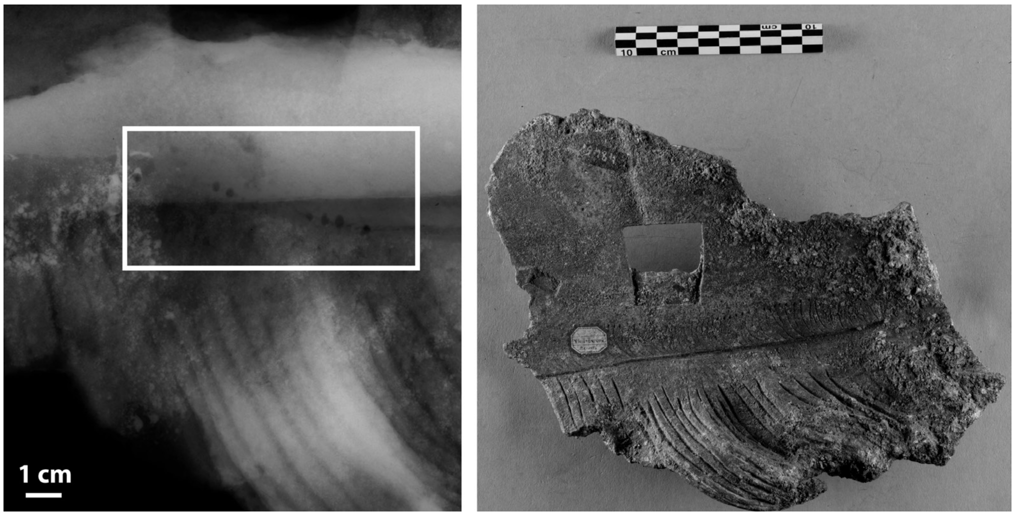

Figure 3: Right: fragment from a monumental equestrian statue, Evreux museum. Left: X-radiograph showing porosities (dark spots) along the weld which joins the two parts.

Figure 4: Right: statue of Apollo, Evreux museum, height 0.69m. Left: the bright horizontal line on the X-radiograph marks the position of the weld line between the left leg and the body.

Figure 5: Right: statue of Jupiter, Evreux museum, height 0.92m. Left: rectangular bronze patches hiding the numerous defects in the welding of the head to the body.

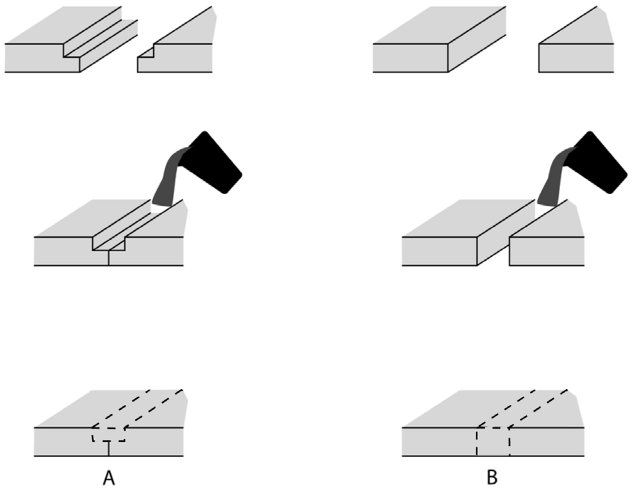

Figure 6: Two ways of preparing the primary castings for welding. A: the base metal is cut away to half its thickness to make a channel through which the molten bronze can run; B: a space is left between the two parts to be joined and the welding metal is directly poured through this space.

(Formigli 1984; Fig 1). The function of these basins was probably two-fold: they increased the contact area and also acted as heat reservoirs through the accumulation of liquid metal at this point.

In modern metallurgy, at a temperature above 1000°C fusion welding induces a partial fusion of the pieces to be joined by using an external source of heat, like an electric arc or a blowtorch, in order to achieve the continuity of the matter with a filler metal (Schwartz and Aircraft 1951; Murry 1994). Antique flow welding and modern fusion welding seem very similar processes, and we aim in our research to verify that the same thermal and chemical mechanisms are involved. In the case of flow welding, the molten bronze would act both as a filler metal, which fills the join, and as the main source of heat which induces the partial fusion of the two edges to be joined. Such a high-temperature joining technique involving a fusion mechanism definitely shows the high level of knowledge achieved by the Greek and Roman foundrymen. Their skill is evident when compared to that of foundrymen of the early Renaissance who proved unable to replicate this process; see for example the so-called ‘Colleone statue’ from the 15th century AD in Venice, where unsuccessful attempts at flow welding can be seen (Morigi and Morigi 2008). At this period the craftsman had to secure their assemblies by using mechanical means, and tried to improve the flow of metal into their moulds in order to produce a casting in a single pour (Bewer *et al* 2008).

Metallographic examination is a technique well-suited to the detailed characterisation of the weld area. However, this method has two main problems: first, it requires a large sample size because the width of a weld zone frequently exceeds 10mm. Such a sample would cause significant damage, so such investigations are therefore rarely undertaken. The second issue is that the observation of a single section does not allow generalizations about all the welded joins on a statue. Indeed, the join could differ in its shape depending on its location and could present irregularly-distributed defects. Even if metallographic sections of antique joins allow the basic principle of ancient welding to be determined, their number will never be sufficient to give a full and correct description of the technical process. Laboratory experiments not only appear to be an effective way to overcome part of the problem, but they also throw light on the working conditions of antique welding processes, and on the different thermal and physico-chemical parameters which control them.

Experimental study

The aim of our study was to contribute to the understanding of ancient welding processes through experiments in the laboratory. These were conducted using the ‘high temperature’ platform developed in the C2RMF, and enabled us to test the parameters that could influence the processes. The thermal parameters were studied in cooperation with CEMHTI (Conditions Extrêmes et Matériaux: Haute Temperature et Irradiation, UPR 3079 of CNRS). The characterization of the samples was carried out at the C2RMF and at the CEA Le Ripault.

We modelled two parts of a statue with a small pair of plates (50×25×3mm). On one side of each plate was machined a half channel, and the plates were then set side by side in order to form the channel, as shown in Figure 6A. The influence of three parameters was investigated: first the alloy composition (5, 10 and 15wt% tin), then the casting temperature to determine the flow-weldability of the bronze (between 150°C and 300°C above the melting temperature of the alloy), and finally the temperature to which the plates to be welded were preheated (room temperature, 100°C, 200°C, 300°C).

A sample holder was built that would keep the plates fixed during welding while allowing the metal to circulate in the channel, but with the possibility of modifying the flow by changing the inclination of the sample holder. The samples were placed between two pieces of 15mm thick ceramic refractory; all of this was then fastened to

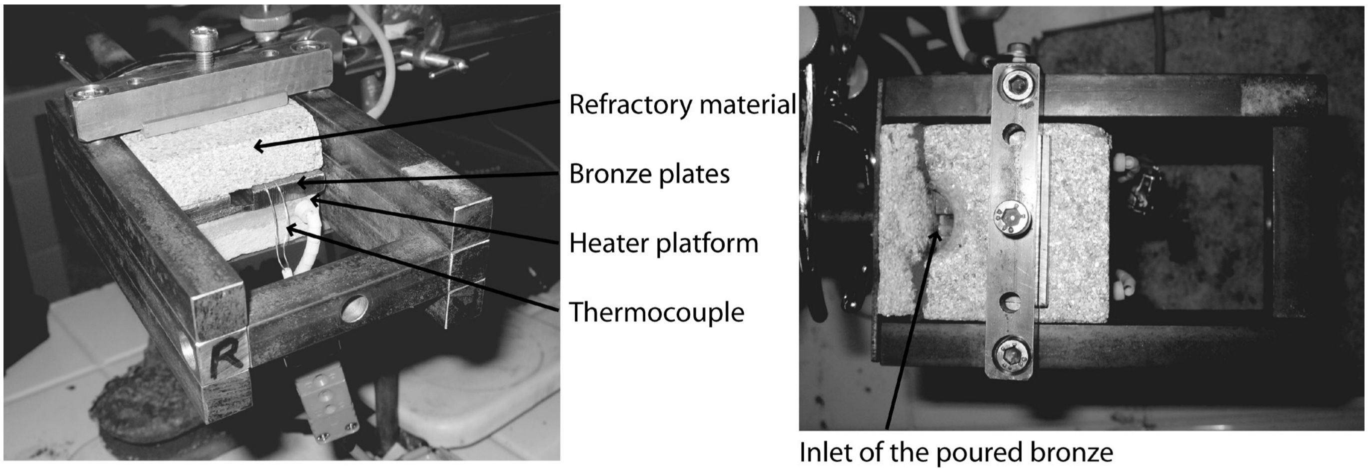

Figure 7: The experimental setup in the laboratory.

the sample holder. An opening was made in the covering refractory over one end of the channel to allow the bronze to be poured in. A heating element, manufactured by the CEMHTI, was incorporated into the lower refractory plate to allow preheating of the bronze plate (Fig 7). The assembly was placed above a sandbox to recover the excess molten metal that flowed out of the far end of the channel. A thermal camera (ThermaCAM SC 3000), loaned by CEMHTI, allowed observation of the heat transfer during casting.

An electric furnace was used to melt 100g of bronze in a crucible. The filler metal (secondary casting) had the same chemical composition as the plates (primary casting), as was the case for ancient statues. The operator carried out the casting by quickly pouring the liquid bronze into the entrance of the channel. The molten bronze flowed along the channel and ran out into the sandbox. At the same time, it gradually raised the edges of the plates to the temperature required for welding. After a few milliseconds, the deposited metal in the channel began to solidify; the casting was stopped when the channel was completely filled (Figs 8 and 9).

Results

At the end of the welding experiments cross sections were cut. The microstructure of the welded zone was then studied using optical and scanning electron microscopy at the C2RMF, supplemented by electron probe microanalyses (EMPA) at the CEA Le Ripault. Meanwhile, observations conducted on ancient statues enabled us to make comparisons with the welding experiments.

In all 37 experiments we succeeded in welding. That is to say, we were able to induce the partial fusion of the plates at the entrance to the channel, where the molten bronze was poured in. The presence of an oxide skin was never observed despite the high working temperature.

The microstructure of the bronze under the solidification conditions tested (air cooling) is composed of dendrites of α-phase (marked by a strong primary segregation) and a tin-rich $\alpha+\delta$ eutectoid that fills the interdendritic spaces.

Figure 10 compares the experimental welding and an-

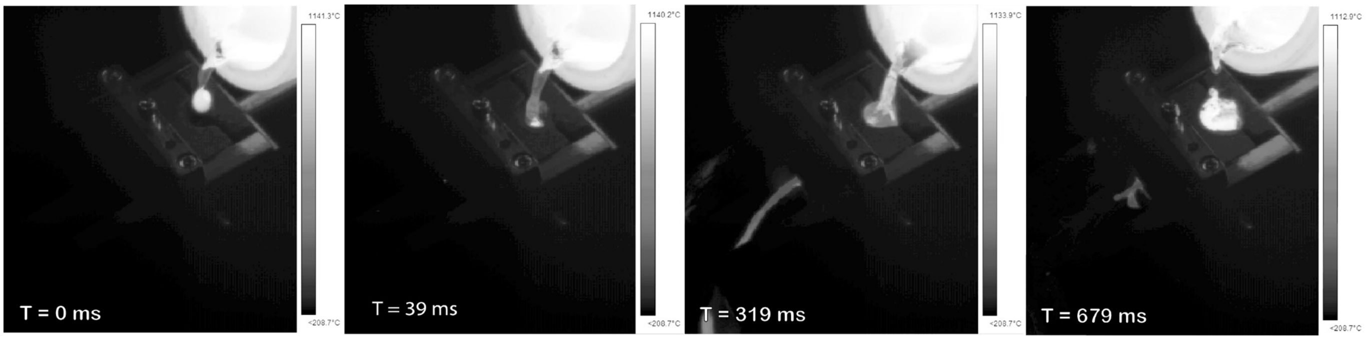

Figure 8: Images of experimental flow-welding from the thermal infrared camera at various times after pouring.

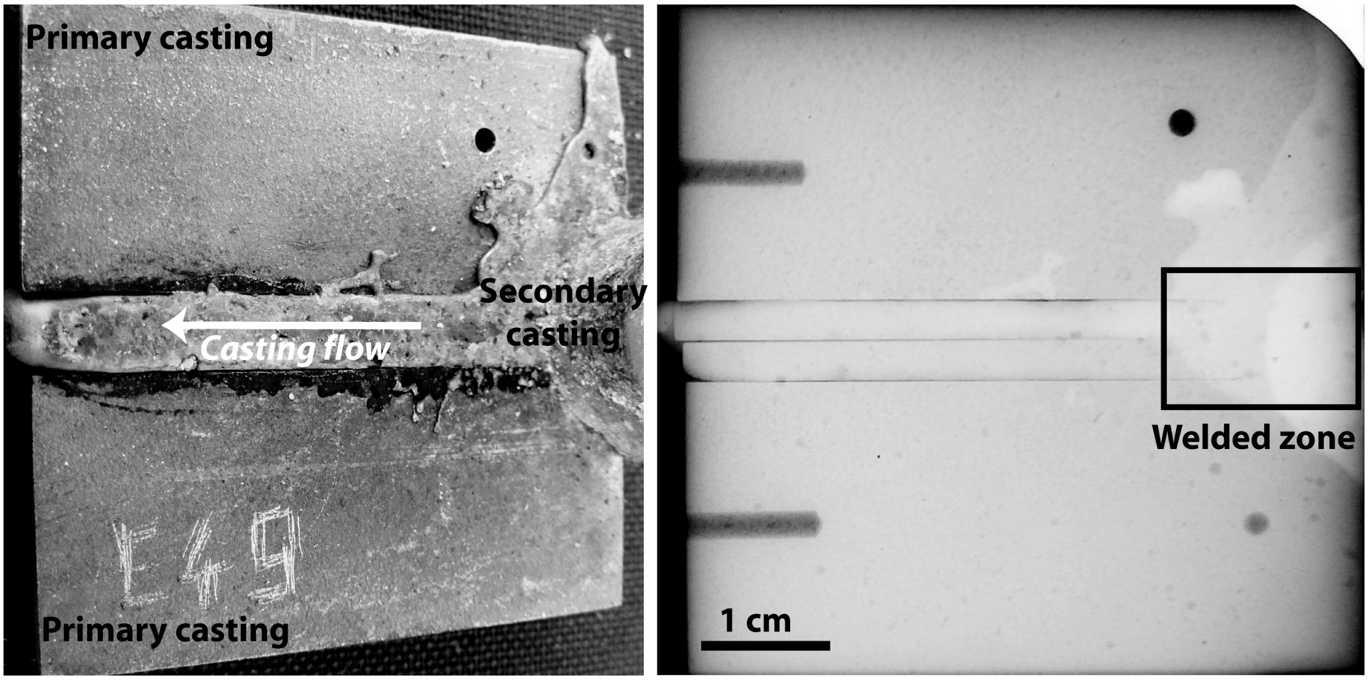

Figure 9: Photograph (left) and X-radiograph (right) of an experimental weld. The welded zone is just 1cm long and restricted to the inlet area. Beyond this zone, the limits of the channel are clearly observable. More heat must be transferred to the rest of the channel in order to improve the welding.

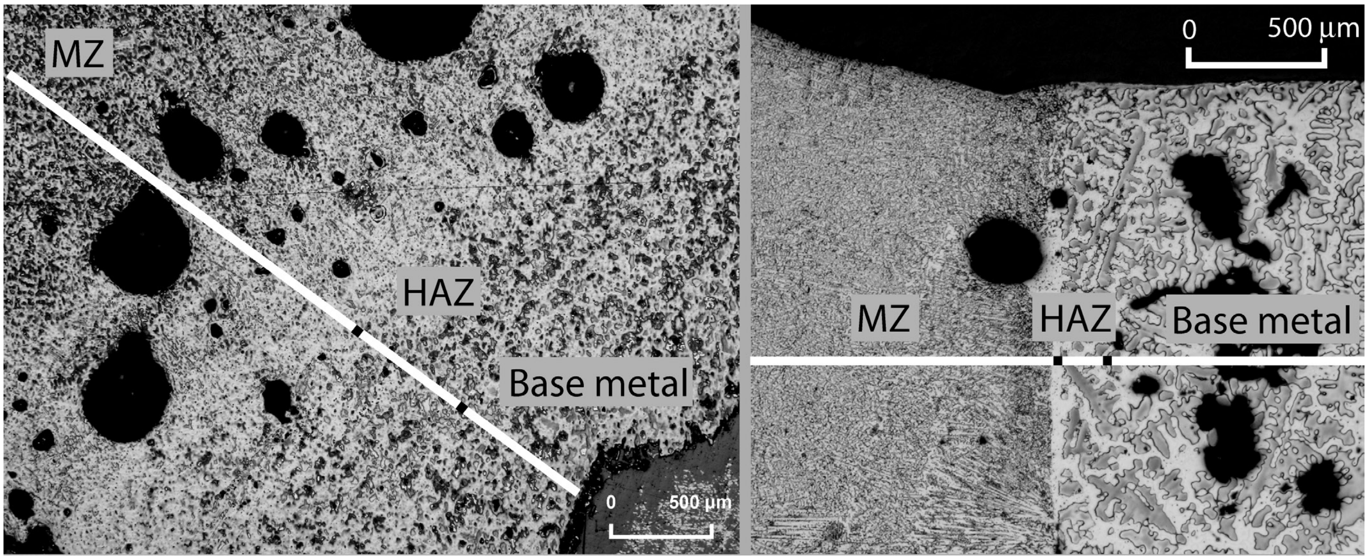

Figure 10: Cross section of welds after etching. Left: antique weld from a horse from Neuvy-en-Sullias, the bronze has 10wt% tin and 7wt% lead. Right: experimental weld, the bronze has 10wt% tin. In both images base metal is the primary casting, MZ the melted zone and HAZ the heat affected zone.

cient welding observed on a sample from the horse from Neuvy-en-Sullias (Mille 2007). We attempted to correlate the experimental conditions and the microstructure obtained during the fusion welding process. Indeed, the final structure is composed of zones of different physical and chemical characteristics influenced by parameters such as the geometry of the weld and the cooling conditions. Particularly, the temperature changes (thermal cycle) have influenced the final microstructure of the different areas of the weld. On both the ancient join and the experimental weld the following zones could be observed (Fig 10):

- The area far from the join is unaffected base metal (primary casting),
- The melted zone (MZ) is composed of a mixture of the filler metal and the re-solidified base metal,
- The heat affected zone (HAZ) is base metal that has been affected by the heat.

The grains at the HAZ – MZ interface behave like nuclei from which the dendrites of the weld metal grow

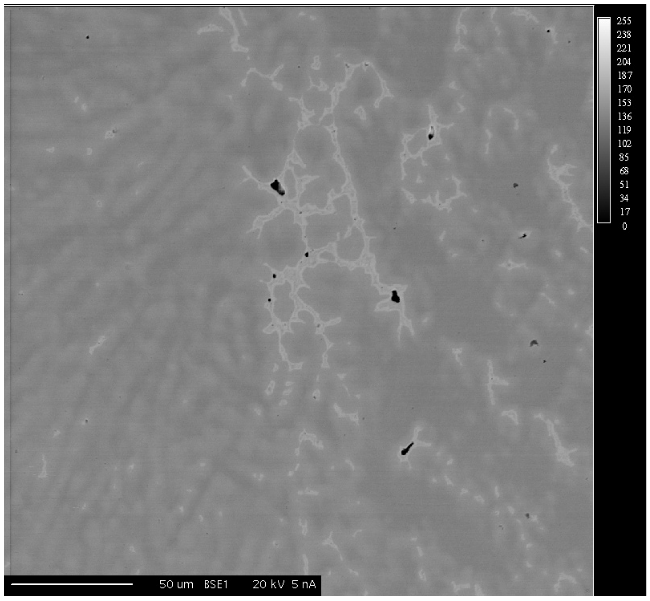

Figure 11: Back-scattered electron image showing inverse segregation at the interface between MZ (left) and HAZ (right) in an experimental weld. The bright areas, which correspond to the eutectoid α + δ solid solution, are evidence of inverse segregation. The dendrites show primary segregation with their cores marked by an enrichment of copper (darker grey).

during cooling in order to form the join (Patchett 2003). However, the difference in size of the microstructure is much more pronounced in the case of our experiments and the HAZ is much less extensive (about 20μm compared to 500μm).

Micrographic examination was complemented by EMPA elemental mapping that reveals the distribution of copper, tin and lead. Using this technique we detected a significant enrichment of $\alpha+\delta$ eutectoid at the MZ-HAZ interface caused by inverse segregation (Hanson and Pell-Walpole 1951, 211-240), particularly marked in the case of experimental welds (Fig 11). This phenomenon has not yet been observed in the ancient statues being studied.

These observations on the horse from Neuvy-en-Sullias allow us to confirm that the joining technique involved in the manufacture of Greek and Roman large bronze statues, known as flow-welding, implies a fusion welding mechanism since the markers of such a process (HAZ, MZ, filler metal) have been observed. The experimental results combined with the information collected on ancient large bronze statues (filler metal and base metal of an identical composition, microstructural nature of the bond) confirm that the fusion was deliberately looked for and achieved by ancient foundrymen. The expression *flow fusion welding* would then better describe the ancient joining process (*flow welding* only refers to the pouring of liquid bronze between the pieces to be joined). Consequently, we propose to name the Greek and Roman joining technique the *flow fusion welding* process.

In our experiments the temperature reached by the edges of the plates is never sufficient to achieve welding over the entire length of the channel (Fig 9). Moreover, the final solidified shape of the flowed metal in the channel strongly argues for insufficient wetting (Hanson and Pell-Walpole 1951, 150-193). Indeed, whatever the conditions, welding is only effective over a length of 10-15mm from the entry point of the metal into the channel. Greek and Roman welds stretched from some centimetres to one metre (Mille forthcoming), even if the corresponding joins usually had many defects. Consequently, it seems that the heat transfer during our experiments was insufficient to induce the fusion of the base metal that is necessary to produce a weld. The very fine microstructure observed in the filler metal of our experiments is a clear indication of too fast a solidification rate. Therefore, we must give special attention to identifying the parameters which control flow fusion welding in order to improve the results of our experiments. This will also provide us with a better understanding of the mechanisms involved.

Discussion: how to control flow fusion welding?

Our experiments showed a strong correlation between the quality and achievement of the weld, and the volume of liquid bronze which circulated in the channel during the casting, defined as the volume that solidified in the channel added to that of the excess bronze which ran off; we call this the ‘poured bronze volume’. This correlation can be easily explained by the fact that the larger the quantity of poured bronze, the greater the heat transfer. So, one way to infer the efficiency of the heat transfer and therefore to evaluate the quality of our welding, is to measure the poured bronze volume.

First, the variation of the chemical composition from 5 to 15wt% tin (*ie* a binary alloy without lead, covering the compositional range of the first Greek bronze statues) did not have a measurable effect on the poured bronze volume. Indeed, although the melting point is lowered when the tin content in the alloy increases, welding was achieved for all three alloys tested. It is important to recall here that the poured metal had a similar chemical composition to that of the base metal.

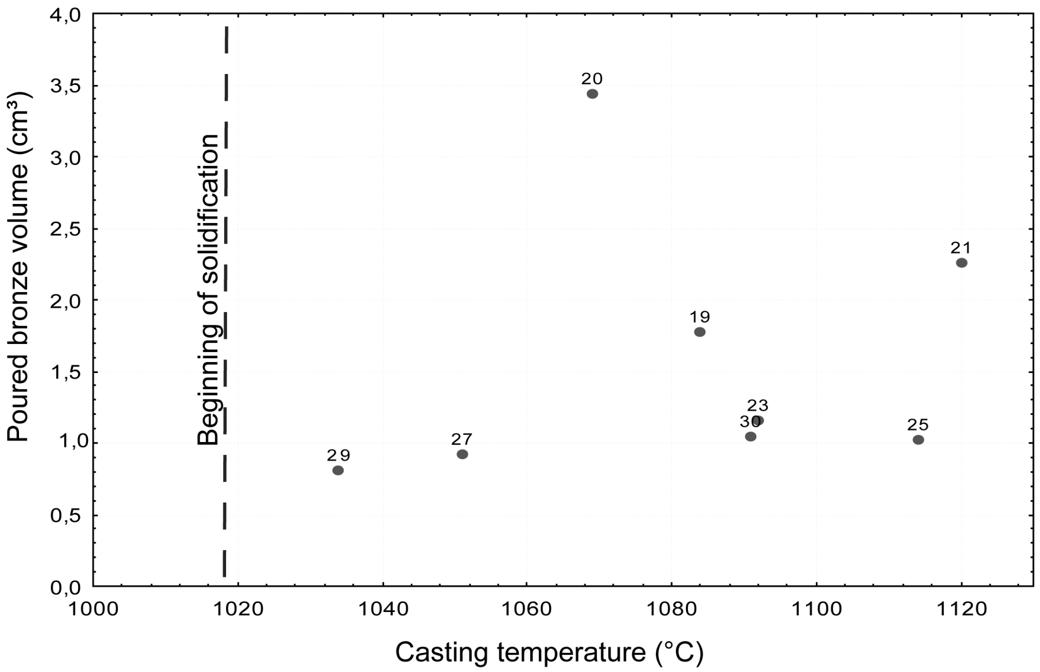

Figure 12: Poured bronze volume plotted against casting temperature for bronzes containing 10wt% tin.

Next, when the casting temperature was compared with the cast bronze volume, no clear correlation could be established. Nevertheless the results are consistent with the fact that the higher the temperature of the liquid bronze, the more bronze was poured into the channel and so the more heat was transferred to induce the fusion of the base metal (Fig 12). More bronze was cast when the preheating temperature increased but the repeatability is not yet reliable (Fig 13). Moreover, preheating also had the effect of modifying the cooling rate. The dendrite arm spacing is clearly larger when the preheating temperature rises (*ie* the cooling rate decreases); we were therefore able to reduce the difference in size between the microstructure of the base metal and the microstructure of the weld metal, thus getting closer to the working conditions of the ancient welding process. Both preheating and the elevation of the casting temperature have a positive influence, but the combined effect of these two parameters remains insufficient to achieve experimental welding at a scale similar to that of the antique examples.

Finally, in order to find means of improving the flow fusion welding through increased heat transfer, attempts were made to raise the quantity of poured metal by using a flux. A flux is a substance which, when applied to the surfaces to be joined by welding, facilitates the flow of the filler metal and prevents oxide formation. Moreover, there is now evidence that such substances were used to weld various parts of large antique bronze statues. As an example, there are some nodules of unalloyed copper in the weld join of the arm of an imperial statue from

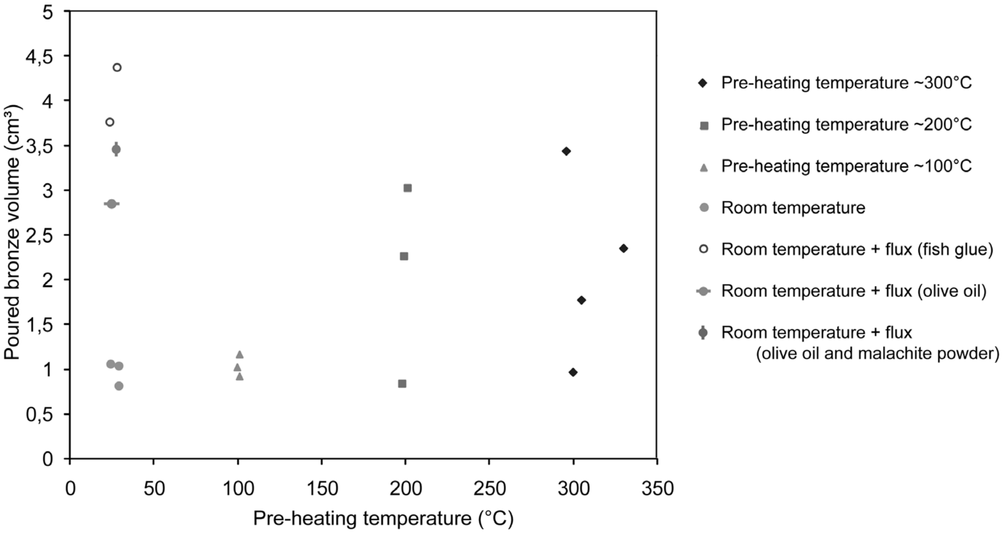

Figure 13: Poured bronze volume plotted against preheating temperature. The influence of fluxes on poured bronze volume at room temperature shows clearly. All the bronzes contained 10wt% tin.

Essegney (Vosges), which probably resulted from the reduction of copper salts applied to the surfaces before the operation (Caumont *et al* 2006). Another example comes from a colossal foot from Clermont-Ferrand, where some compound rich in phosphorus was added to the filler metal (Darblade-Audoin and Mille 2008). Some preliminary tests were performed using fish glue (for phosphorus), malachite powder (copper salts) and olive oil (organic material). They were applied to the surfaces to be joined. Experiments showed that the use of flux increases very significantly the poured bronze volume, even at room temperature (Fig 13).

Conclusions

The process previously described as flow welding, used to join the separate parts of Greek and Roman statues, can be classified as a fusion welding process, and it now seems better to call it *flow fusion welding*. We were able to reproduce such a process in our experiments, though some more work needs to be done in order to improve the heat transfer, and therefore the effective length of the weld. In future experiments we will increase the pre-heating temperature, and will try to improve the repeatability of our tests by better control of the bronze flow. We will also pay particular attention to inverse segregation; this phenomenon could play an important role in the fusion welding mechanism, particularly because it provides a high-tin phase at the HAZ-MZ interface, at the end of solidification. Finally, we will continue to explore the properties of fluxes in order to provide the heat needed to produce flow fusion welding in the ways ancient welders did.

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