



International Congress of Science and Technology of Metallurgy and Materials, SAM -
CONAMET 2013

Coppers from the Battle of Trafalgar: Metallurgical Analysis of Structural Fastenings from the French ships *Fougueux* (1785-1805) and *Bucentaure* (1804-1805)

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Abstract

In this paper, the characterization results of an array of copper spikes, recovered from the Camposoto site (San Fernando, Andalusia, Spain), are presented. The research of the site, developed by the Underwater Archaeology Centre (CAS) of the Andalusian Historical Heritage Institute (IAPH), allowed identifying the underwater remains as the French Navy ship *Fougueux* (1785-1805). This was a 74-gun ship, one of the vessels of the combined Franco-Spanish fleet, which on October 21st, 1805, fought against a British fleet in the Battle of Trafalgar. By means of Optical Microscopy (OM) and Scanning Electron Microscopy (SEM), information about the thermo-mechanical processes which affected the objects was obtained. In addition, the chemical composition of the materials was determined by Energy Dispersive X-ray Spectrometry (EDXRS). This data is considered a good indicative of the last steps of the manufacturing process and the quality of the alloys used. Aiming to perform a comparative study, some samples from the site Bajo Chapitel (located in the Cadiz Bay), were analyzed. The artifacts of this site are most likely associated with the *Bucentaure* (1804-1805), another French ship that fought in the mentioned battle.

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Selection and peer-review under responsibility of the scientific committee of SAM - CONAMET 2013

Keywords: XIXth-century French ships - Fastenings - Naval architecture - Metallography - SEM EDXRS

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1. Introduction

In this work, the results of the macroscopic and microstructural characterization of an array of copper spikes, found in the Camposoto site (San Fernando, Andalusia, Spain), are presented. The archaeological research of the site, performed by the Underwater Archaeology Centre –*Centro de Arqueología Subacuática* (CAS)– of the Andalusian Historical Heritage Institute –*Instituto Andaluz de Patrimonio Histórico* (IAPH)–, allowed identifying the remains as belonging to the French ship *Fougueux* (1785-1805) (Rodríguez Mariscal et al. 2010). This 74-gun vessel was part of the combined Franco-Spanish fleet that on October 21st, 1805, fought against the British fleet in the Battle of Trafalgar, in Cape of Trafalgar, south of Iberian Peninsula (Márquez Carmona 2000).

Additionally, some samples from the site Bajo Chapitel (located in Cadiz Bay), also under study by the CAS, were analyzed. At this location a variety of remains were found, possibly associated with the *Bucentaure* (1804-1805), another of the ships that took part in the mentioned battle (Martí Solano 2008). These artifacts were compared with those of the *Fougueux* (1805), in order to study technological similarities and differences between them. Gathering new information will permit, as well, performing a more precise assessment of the remains found in the area where the *Bucentaure* sank.

2. Experimental Procedure

2.1. Analyzed Materials

The artifacts from the *Fougueux* (1805) are two copper spikes (see McCarthy 2005), which originally belonged to the ship's structure. The samples were selected from an array of fastenings recovered from the site, where they were found in isolation, on the surface (Fig.1). The pieces come from a ship area that possibly corresponds to the projection of the keel, detected during other surveys (Rodríguez Mariscal 2010).



Fig. 1. (a) remains of fastenings (bolts, spikes and sheathing tacks) recovered from the Camposoto site; (b) some examples of spikes, located *in situ*. Photos: courtesy of CAS-IAPH 2011.

Artifacts CAMP/CA 07 – 85/3 and CAMP/CA 07 – 85/10 have a rectangular shank section with two opposed parallel sides and the other two tapering to the end. The head of the first is square and flat, while irregular in the second case; whereas the tip of both ends is wedge shaped. This kind of nail was frequently used for fastening the following structural ship elements: external planking - frames; internal planking - frames; and deck planking - deck beams.

As was mentioned, in order to make a comparison between technologies of both vessels, two spikes recovered from the site Bajo Chapitel (*Bucentaure*) were also analyzed. These pieces (BCH/CA 05 – 10 and BCH/CA 07 – 117/1) are morphologically similar to the objects previously described (Fig.2).

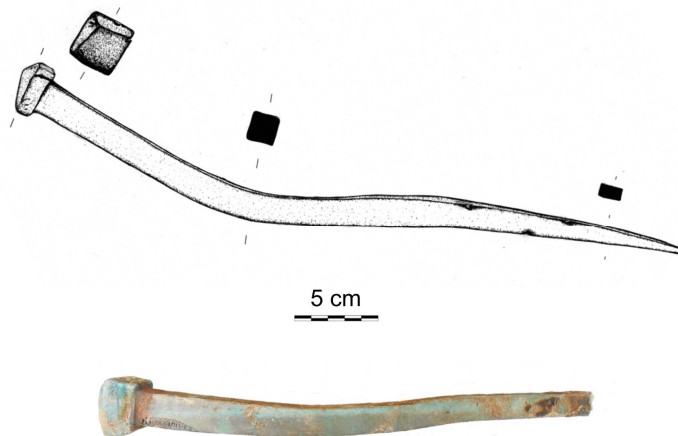


Fig. 2. Copper spikes from the site Bajo Chapitel: BCH/CA 05 – 20 (above) and BCH/CA 07 – 117/1 (below, analyzed). Drawing and photo: courtesy of CAS-IAPH 2011.

It is worth noting that this type of piece, made of either copper or copper alloy, began to be used by European maritime powers in the last third of 18th century, as a consequence of the serious problems caused by the contact between copper sheathing and structural iron fastenings. Iron bolt deterioration even led to the foundering of vessels in some cases, provoking numerous casualties and the loss of material resources (Harris 1966; Staniforth 1985; Bingeman et al. 2000).

Nevertheless, despite the advantages of copper, iron fastenings were cheaper and, for many craftsman, had better mechanical features than the former. That is why vessels were neither nailed/bolted needlessly, nor where copper pieces used in hull sectors where there was no risk of galvanic corrosion (McCarthy 2005). Regarding this, remains of the copper sheathing were found in the Camposoto site, which is consistent with historical information about the introduction of this kind of protection in French warships (Rodríguez Mariscal 2010).

2.2. Methods and Instrumentation

For the purpose of the present study the following analytical instrumental techniques were applied: Optical Stereoscopic Microscopy (OSM), Metallographic examination by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM); and elemental chemical determination by X-ray Energy Dispersive Spectroscopy (EDXRS). The equipment used for the implementation of these techniques was, according to the previous citation order: Arcano Stereomicroscope ZTX, Reichert Me F reflective metallographic microscope (Materials Laboratory, Department of Mechanical Engineering, School of Engineering, University of Buenos Aires, FI-UBA), scanning electron microscope Philips SEM-505, equipped with an EDAX Genesis (Scanning Electron Microscopy Laboratory, Department of Mechanics, National Institute of Industrial Technology, INTI-Mecánica).

3. Results and Discussion

3.1. Optical Microscopy

3.1.1. Fougueux, spike CAMP/CA 07 – 85/3

Two samples were analyzed, corresponding to the head-shank and the shank-tip zones of the spike. Observations made on longitudinal sections revealed a single-phase microstructure (with the characteristic reddish copper color) of variable grain sizes, annealing twins and elongated –apparently non-metallic– inclusions. In the head area, grains present shape variability (Fig.3-a); whereas in the shank, a tendency to equiaxial morphology can be notice (Fig. 3-b).

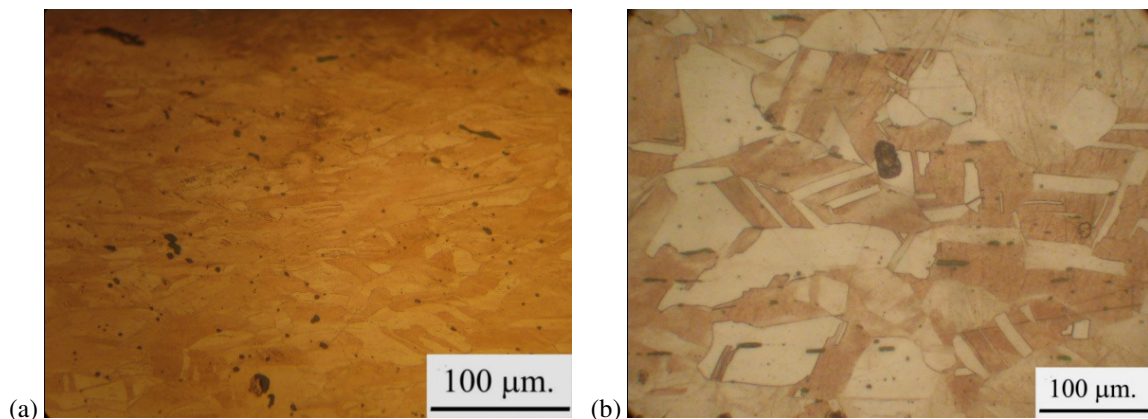


Fig. 3. (a) single-phase microstructure formed by copper grains of variable shape and size; annealing twins and inclusions are also present (head); (b) microstructure with a tendency to equiaxiality –compared with that observed in the head–, annealing twins and inclusions (shank). Etchant: NH_4OH , H_2O , H_2O_2

The described structure suggests that the spike was manually manufactured, by hot forging. Variations observed are associated with differential strains undergone by each zone during the manual fabrication process. In the head, the effort applied during shaping was probably done in many directions; in the shank, this work is likely to have been perpendicular to its axis. The orientation of non-metallic inclusions may be considered as further evidence of that process, since these inclusions are randomly ordered in the head, whereas in the shank they are markedly aligned in the longitudinal direction (Fig.4).

3.1.2. Fougueux, spike CAMP/CA 07 – 85/10

Two samples were analyzed; one corresponding to the head-shank zone (longitudinal section, seen in plant) and the other to the shank-tip (longitudinal section, seen in profile). From the observations made, a single-phase microstructure with different grain sizes, annealing twins and non-metallic inclusions can be distinguished. In the head zone, annealed grains with irregular shapes and dimensions are also noticeable. There is no evidence of plastic deformation or preferential orientation (Fig.5-a). Inclusions show no defined alignment, but towards the head-shank transition they begin to acquire a notorious change. They finally converge in the shank, where their orientation is clearly in accordance with the forming direction (Fig.5-b).

These features may be associated with a manufacturing procedure similar to that experienced by the previous spike, although in this case the shape and size of grains suggest that the heating and working processes applied to give shape to the head were more uniform.

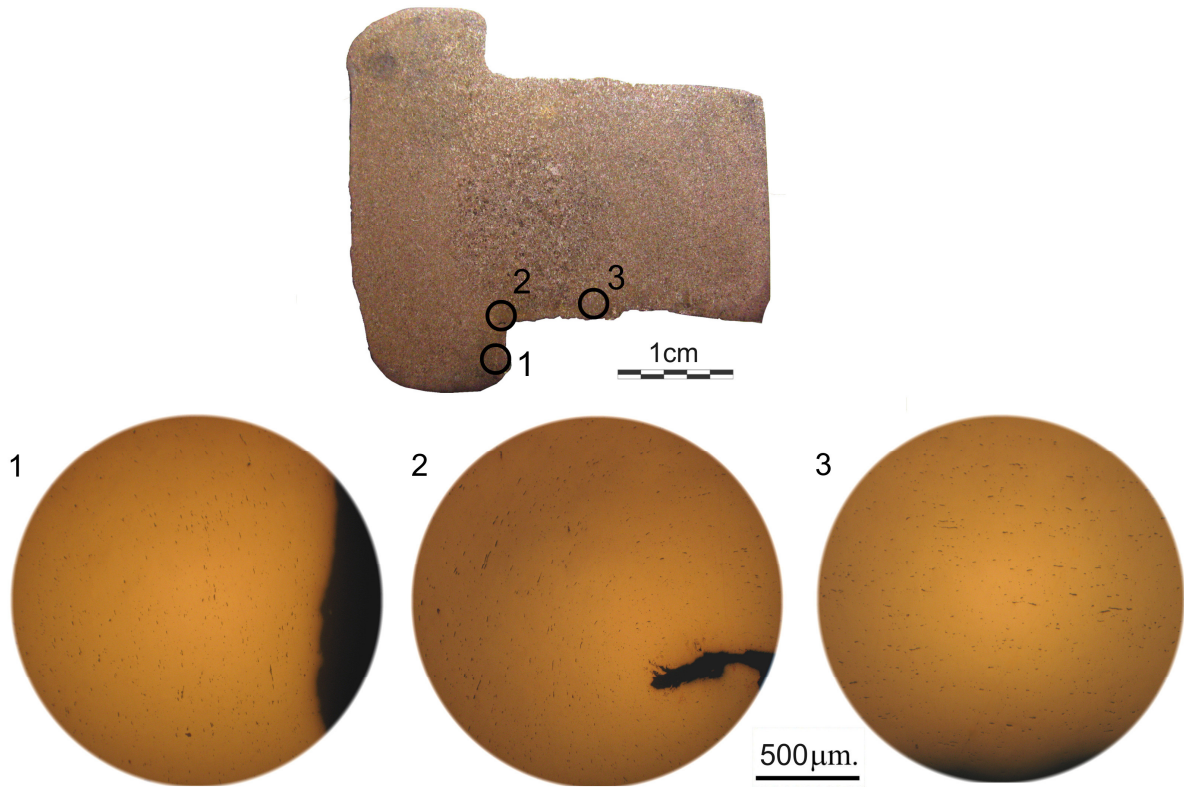


Fig. 4. Optical micrographs of the head-shank transition zone, where the orientation of inclusions according to shaping direction can be seen (spike CAMP/CA 07 – 85/3).

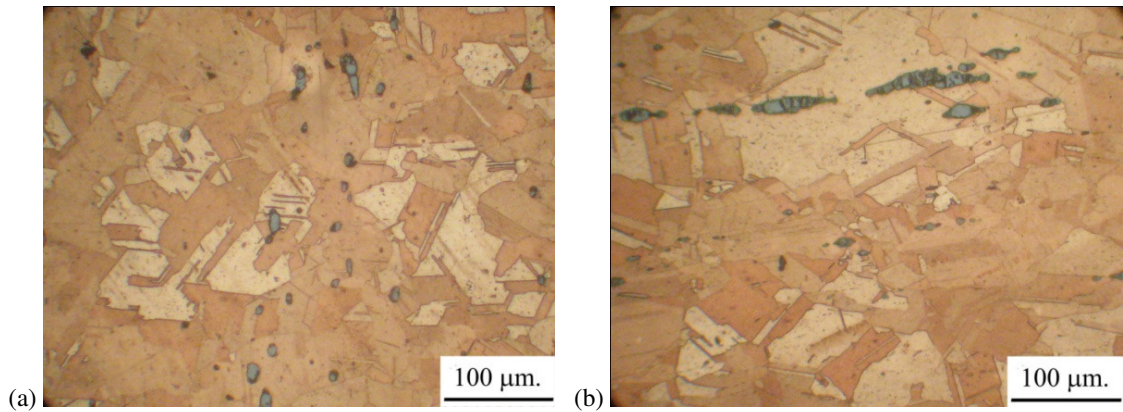


Fig. 5. (a) single-phase microstructure of copper grains of different shape and size, with annealing twins and inclusions, randomly ordered in the head; and (b) markedly aligned in the shank (spike CAMP/CA 07 – 85/10). Etchant: NH_4OH , H_2O , H_2O_2

On the other hand, in the tip and shank, grains of different sizes with some deformation are detected. In general, the former may be associated with an instance of deformation followed by a recrystallization process that unevenly affected the material, whereas the latter would be related to an instance of ulterior (final) cold hammering.

The grain size variation extends from the center to the periphery and from the tip to the shank. On the periphery, very small grains can be observed, while inward the spike these are larger (ten times the size of the smaller ones). The most noticeable difference is seen at the end of the shank, adjacent to the tip (Fig.6), whereas in the tip itself, the grain size is more regular within the whole section.



Fig. 6. Microstructure of copper grains of different sizes (band cross to the longitudinal direction of the shank, section adjacent to the tip).
Etchant: NH_4OH , H_2O , H_2O_2

This suggests that, during the penultimate forming operation, the piece underwent greater deformation in the periphery than in the core. When subjected to temperature, the grains that had been deformed recrystallized; while the interior grains, which presumably did not reach the critical deformation, only experienced growth. Additionally, the observed deformation of the grains is considered as the product of cold hammering during the last forming instance. Deformation can be appreciated in most grains, although the most affected are those in the periphery. This final step would have been directed to enhance the hardness of the piece.

3.1.3. *Bucentaure*, spike BCH/CA 05 – 10

The metallographic observation was performed on a longitudinal section of the shank. The piece presents a microstructure of equiaxial grains, uniform in size, with annealing twins, no signs of deformation and a typical copper or copper alloy color. Furthermore, abundant non-metallic inclusions of different size and color, with a slight orientation, can be appreciated. The larger, that appear to be copper oxides, have smaller ones adhered, that in view of their tonality correspond to different compounds. Small dark grey inclusions that look like lead particles can also be distinguished (Fig.7). The features observed can be associated with a forming process by means of hot manual hammering.

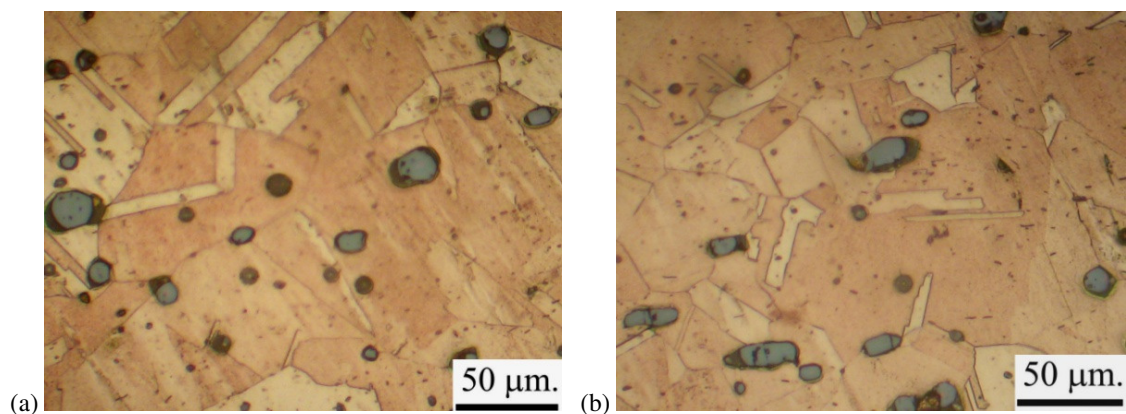


Fig. 7. Optical micrographs of the recrystallized microstructure, with non-metallic inclusions (longitudinal section). Etchant: NH_4OH , H_2O , H_2O_2 .

3.1.4. Bucentaure, spike BCH/CA 07 – 117/1

The microstructure detected in the longitudinal section of the shank consists in a solid solution or pure metal grains, mostly equiaxed, with annealing twins. It also presents abundant non-metallic inclusions, combining copper oxides with a smaller quantity of other compounds, differentiable by their color (Fig.8). In this case, inclusions present a significant alignment in the longitudinal direction of the shank. As in the previous piece, these microstructural features are consistent with a hot forming process.

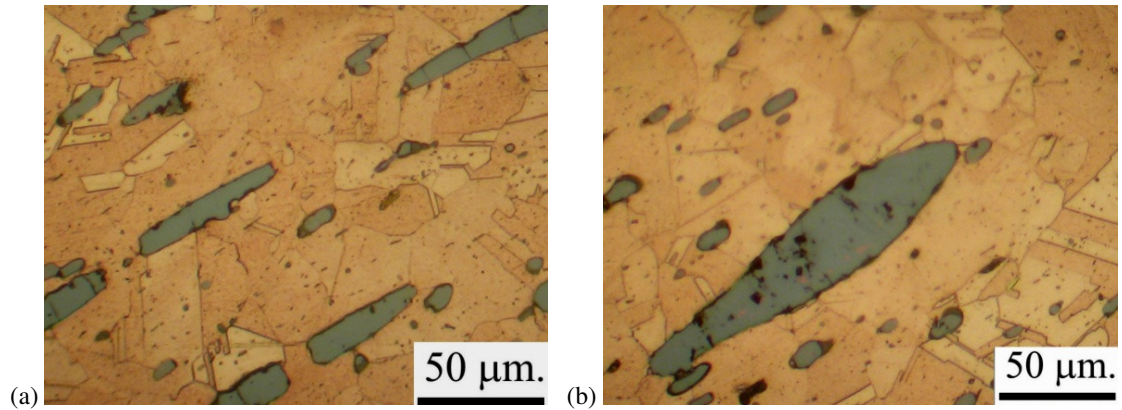


Fig. 8. Optical micrographs of the recrystallized microstructure, with elongated non-metallic inclusions (longitudinal section). Etchant: NH_4OH , H_2O , H_2O_2

3.2. Scanning Electron Microscopy – Energy Dispersive X-ray Spectrometry

3.2.1. Fougueux, spike CAMP/CA 07 – 85/3

The sample from the shank-tip was analyzed via EDXRS. The overall composition of the matrix, assessed in several sectors, indicates that the raw material used for the piece manufacturing was unalloyed copper (Fig.9-a). The (punctual) analyses of several inclusions in different sections of the piece indicate a major composition of Pb, together with small concentrations of As, Sb, and Fe (Fig.9-b).

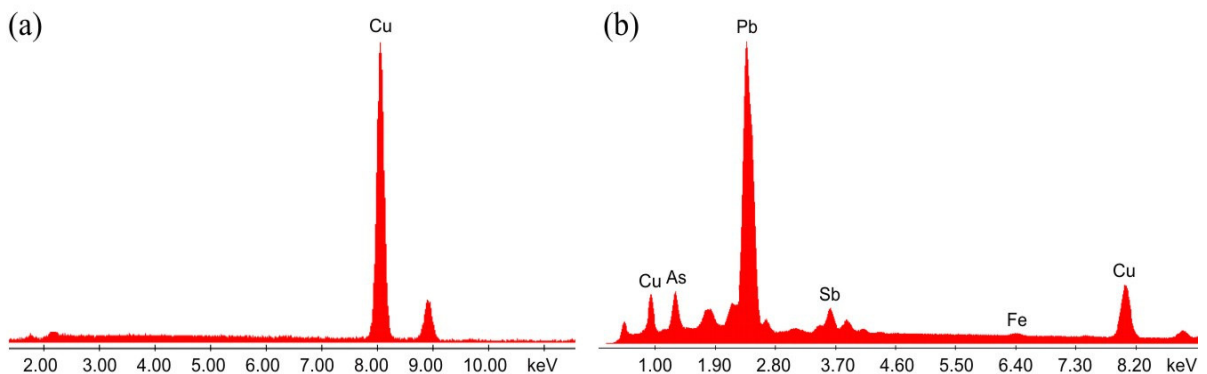


Fig. 9. Elemental composition (EDXRS spectra) of the spike: (a) overall matrix composition (tip); (b) composition of an inclusion with high lead content (shank).

3.2.2. Fougueux, spike CAMP/CA 07 – 85/10

The spectra of Fig.10-a shows the quantification obtained by EDXRS in the matrix (global analysis), which indicates that the piece was made of unalloyed copper. Furthermore, the analyses show that most of the inclusions are of copper oxide. Other inclusions were also detected, although in a smaller amount. They are composed mainly of Pb, with varying amounts of Sb, As, Sn, Bi, and Fe (Fig.10-b).

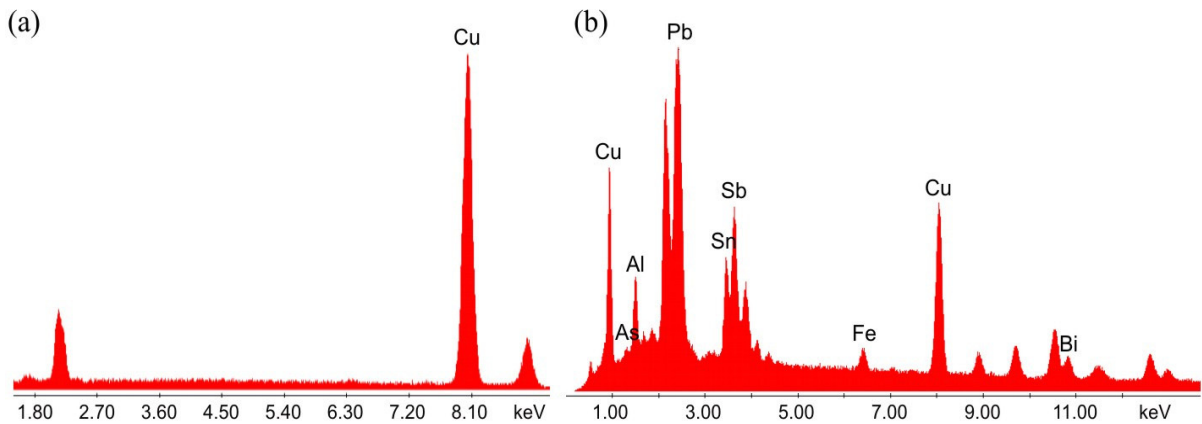


Fig. 10. Elemental composition (EDXRS spectra) of the spike: (a) overall composition of the matrix (tip); (b) composition of an inclusion with high lead content (shank).

A SEM image produced by backscattered electrons revealed differences in the chemical composition of the inclusions, by brightness differences in the image (Fig.11). Thus, it was possible to differentiate between copper oxide inclusions and those with high lead content (brighter).

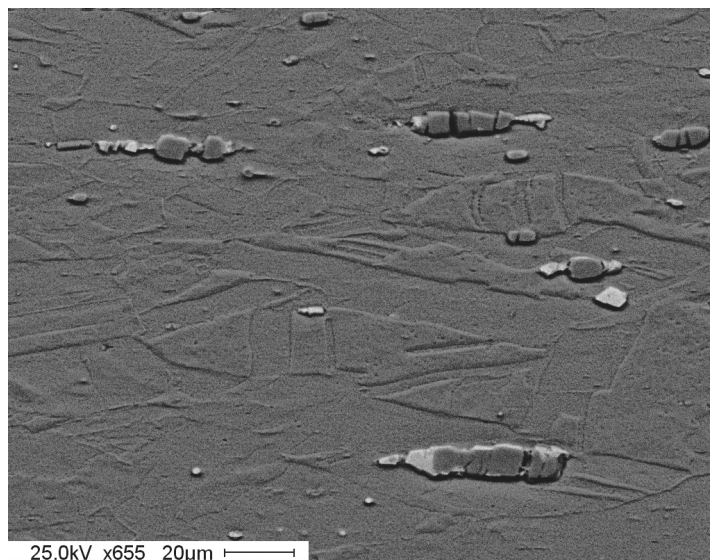


Fig. 11. Backscattered electron SEM image, where differences in chemical composition can be detected by changes in image brightness (shank). Photo: Gisela Maxia 2012.

3.2.3. *Bucentaure*, spike BCH/CA 07 – 117/1

As in the case of *Fougueux* spikes, the overall composition of the matrix corresponds to unalloyed copper (Fig.12-a). Furthermore, some of the inclusions analyzed indicate a comparable elemental composition, although with some minor differences. As was the case of the previous objects, the raw material used contained impurities of Pb and other elements (Fig.12-b).

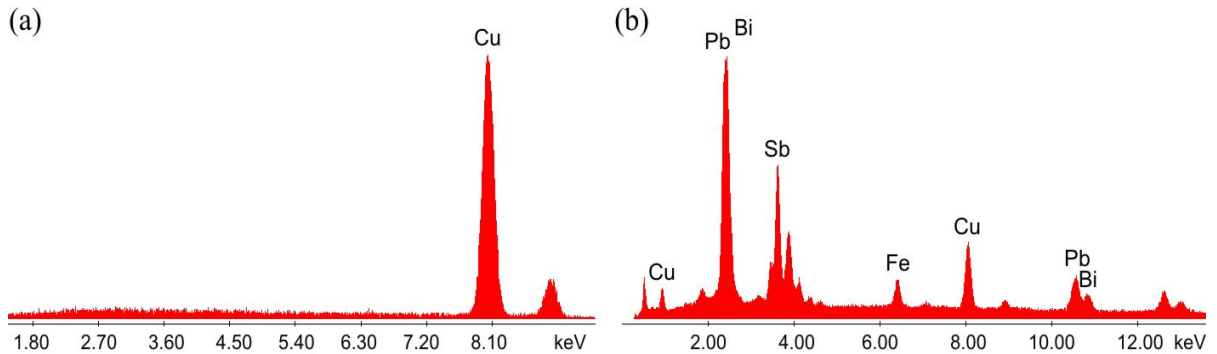


Fig. 12. Elemental composition (EDXRS spectra) of the spike: (a) overall matrix composition; (b) composition of an inclusion with high lead content.

4. Concluding Remarks

From the physico-chemical characterization of a set of spikes recovered from the sites Camposoto (identified as the *Fougueux*) and Bajo Chapitel (where possible lie the remains of the *Bucentaure*) detailed information about technical aspects of the pieces was obtained. By means of X-ray Energy Dispersive Spectroscopy, it was possible to determine the elemental chemical composition of the material used. Observations by Optical Microscopy and Scanning Electron Microscopy allowed obtaining information concerning the thermo-mechanical processes to which they were subjected. The data collected was extremely helpful to understand matters such as the qualities of the alloys used and the characteristics of the final stages of the manufacturing process. Based on these results, it was possible to assess the similarities and differences showed by the artifacts from the two mentioned warships.

All spikes were made of unalloyed copper, and by a manual hammering process. *Fougueux* (1805) pieces show some differences among themselves regarding the last forming steps. Considering grain morphology, the degree of recrystallization, and the alignment of inclusions, manufacturing process in the case of CAMP / CA 07 – 85-3 spike is likely to have been in a hot condition. Microstructure of CAMP / CA 07 – 85-10 spike, instead, suggests that during the last two shaping steps the hardening of the tip was produced by cold hammering, considering the size and the amount of strain detected in the grains in different zones of the piece. Regarding *Bucentaure* (1805) artifacts and the outcome of analyses performed so far, it was possible to determine that they were also made of unalloyed copper by hot working.

The information presented is of interest not only for its contribution to the understanding of the characteristics of modern naval technology, but also for its value as a means to evaluate materials assignment. Parting from the analysis of the microstructural characteristics and elemental chemical composition, it is possible to assign a high degree of similarity, at least in terms of alloys used and manufacturing methods, among the pieces found in the Bajo Chapitel and Camposoto sites. In that sense, results obtained are a new source of information to support the assignment of the remains found in the former as belonging to *Bucentaure*'s shipwreck.

Acknowledgements

The authors would like to thank Jorge Pina, Gisela Maxia, and Mercedes Pianetti, from the Scanning Electron Microscopy Laboratory, Department of Mechanics, National Institute of Industrial Technology (INTI), for the SEM and EDXRS analyses. Given all the samples in study were provided by the Underwater Archaeology Centre of Andalusia (CAS-IAPH), we would also be pleased to thank its director Carmen García Rivera, as well as Nuria Rodríguez Mariscal, Milagros Alzaga García and Josefina Martí Solano, not only for enabling us to work with materials from the sites *Fougueux* and *Bucentaure*, but also for the valuable information provided. Finally, to Ana Castelli, for her help with the spelling and grammar of the translation.

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