Available online at www.sciencedirect.com
ScienceDirect
Procedia Materials Science 8 (2015) 712 – 721
Procedia Materials Science
www.elsevier.com/locate/procedia

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

Naval Crossfire: a Comparative Analysis of Iron Projectiles from mid-18th to Early 19th Centuries European Warships

Nicolás C. Ciarlo[a,b,c,*], Ariel N. López[c,d], Horacio M. De Rosa[c,d], Mercedes Pianetti[e]

[a]*Underwater Archaeology Program (Programa de Arqueología Subacuática), National Institute of Anthropology. 3 de febrero 1370/78, Buenos Aires, C1426BJN, Argentina.*
[b]*National Research Council (Consejo Nacional de Investigaciones Científicas y Técnicas). Av. Rivadavia 1917, Buenos Aires, C1033AAJ, Argentina.*
[c]*Archeometallurgy Group (Grupo de Arqueometalurgia), Materials Laboratory, Department of Mechanical Engineering, School of Engineering, University of Buenos Aires. Paseo Colón 850, Buenos Aires, C1063ACV, Argentina.*
[d]*Institute of Engineering Sciences and Technologies (Instituto de Tecnologías y Ciencias de la Ingeniería) "Hilario Fernández Long", School of Engineering, University of Buenos Aires. Paseo Colón 850, Buenos Aires, C1063ACV, Argentina.*
[e]*Scanning Electron Microscopy Laboratory, Department of Mechanics, National Institute of Industrial Technology (Instituto Nacional de Tecnología Industrial). Av. General Paz 5445, Buenos Aires, B1650KNA, Argentina.*

Abstract

The ordnance of early Modern main maritime powers (i.e. Great Britain, France, and Spain) played an important role in conflicts for supremacy of the seas. Therefore, it was subjected to various innovation processes, in order to improve their efficiency. This study presents the characterization results of an array of iron projectiles recovered from the following sites: 1) the sloop-of-war *HMS Swift* (1763-1770), 2) the Spanish ship *Triunfante* (1756-1795), 3) the French ship *Bucentaure* (1804-1805), and 4) the site Deltebre I (1813). Based on data obtained using Optical Microscopy (OM), Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray Spectrometry (EDXRS), a comparative analysis was performed, in order to clarify the technological differences and similarities that were present in the projectiles used by the mentioned ships.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Selection and peer-review under responsibility of the scientific committee of SAM - CONAMET 2013

Keywords: European Modern metallurgy – Navy ships – Iron ordnance – Projectiles – Metallography

* Corresponding author. Tel.: +54 (11) 4 783 – 6554 / 4 782 – 7251.
*E-mail address:*nciarlo@yahoo.com.ar

2211-8128 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Selection and peer-review under responsibility of the scientific committee of SAM - CONAMET 2013
doi:10.1016/j.mspro.2015.04.128

1. Introduction

1.1. Historical maritime archaeology

Historical maritime archaeology covers a field that has not been fully defined yet, but it is generally regarded as the specialty that studies the diverse human activities in the aquatic environment −among which maritime navigation stands out− and land operations associated with them, during historical times (in the particular case of America, post-Columbian). Research within this field has expanded the knowledge of multiple topics concerning modern occidental society, such as military activities, trade and commerce, diverse operating companies and European colonialism (Flatman and Staniforth 2006). Regarding warships, Gould has highlighted the contributions made towards the knowledge of the dynamics of technological change during the modern age, based on the study of different archaeological sites (Gould 2011). This kind of research is frequently characterized by an interdisciplinary orientation. In this regard, archeometallurgical studies of shipwreck remains have allowed broadening and deepening the knowledge of diverse aspects, and have provided information on matters where occasionally no previous historical record was available. Framed within the specialties mentioned, this study presents the characterization results of an array of iron round projectiles from the following sites:

- The HMS *Swift* (1763-1770), a sloop-of-war commissioned to Port Egmont, the first British settlement in the Malvinas/Falkland Islands. During one of her trips, she was forced to reach the shore and enter in the Deseado estuary (Santa Cruz province, Argentina), where she ran aground on a rock and sank (Elkin et al. 2011).
- The Spanish 64-gun ship *Triunfante* (1756-1795), which undertook several missions serving the Spanish Navy (*Armada Española*), including war, as well as scientific and diplomatic actions. During her last days, she belonged to the squadron commanded by Gravina, and foundered in the Gulf of Roses (Catalonia, Spain) while defending the area from the French Navy (*Marine Nationale*) forces (Nieto et al. 2013).
- The French 80-gun ship *Bucentaure* (1804-1805), flagship of the combined Franco-Spanish fleet that fought against the British fleet in the Battle of Trafalgar (October 21st, 1805). The vessel, in very poor condition, sank within days in Bajo Chapitel (Bay of Cadiz, Spain) due to a storm (Martí Solano 2008).
- The site Deltebre I (1813), a cargo ship belonging to the Royal Navy, part of a fleet commanded by Lt. Gen. John Murray, that tried unsuccessfully to free the city of Tarragona from Napoleonic troops in 1813. It foundered due to a storm in the Ebro Delta (Catalonia, Spain) (G. Vivar −director of the Centre d'Arqueologia Subaquàtica de Catalunya−, pers. comm. 2012).

A series of technical aspects were determined, specifically related to the manufacturing procedure and the quality of the material used. A comparative analysis of the pieces was performed with the results obtained, in order to clarify the technological differences and similarities present in the projectiles used by the mentioned ships.

1.2. Ordnance on board

The sea consisted on a prominent scenario for the process of configuration and global expansion of the main maritime powers (Great Britain, France, and Spain). The activities developed through their vessels were crucial, mainly concerning overseas trade and conflicts for the supremacy of the seas. Regarding the latter, the ordnance available for the respective navies was an aspect of great interest, given that it represented the main means to arbitrate armed conflicts between the actors (Fig. 1). As appropriately expressed by Torrejón Chaves: "...sails and cannons were decisive elements in the consolidation of modern European states" ["*...velas y cañones fueron elementos decisivos en la consolidación de los Estados modernos europeos*"] (Torrejón Chaves 1997: 293).

During the period considered, each of the Armies mentioned possessed a governmental entity in charge of establishing regulations that concerned ordnance design, production, provisioning, and handling on a warship. The obtention of cannons and cannonballs used on board, along with other manufactures destined to naval construction and equipment (e.g. fastenings, ironwork, and anchors), demanded much of the iron production of the time (Alcalá-Zamora y Queipo de Llano 1999; Corbera Millán 1999; Rodríguez-Villasante Prieto 1999). A wide variety of projectiles, depending on the objectives pursued when challenging an enemy (e.g. inflict damage on the hull, rigging and sails, or its crew) could be fired from cannons, which were muzzleloader (Moore 1801; O'Scanlan 1831).

Fig. 1. Representation of a cannon crew, firing on the upper deck of a British ship, ca. 1790 (Source: Museum Victoria, Australia).

Particularly, round shot were those used primarily to produce damage to the hull, aiming to sink the ship (Fig. 2-a). This kind of projectile could also be heated (red hot shot) or covered with a flammable preparation (fire ball) in order to set fire to the decks or make ammunition storage area (magazine) blow up. On the other hand, grapeshot and canister shot projectiles, frequently spherical shots, provoked a far reaching spray with a broad scope of action, very effective in producing casualties in the crew (Moore 1801; O'Scanlan 1831; Sullivan 1986) (Fig. 2-b and 2-c).

Fig.2. Different types of cannonballs: (a) round shot (*Swift*); (b) grapeshot (*Bucentaure*); (c) canister shot (Deltebre I site). Scale: 5 cm.

1.3. General notions on the production of cast iron

The great demand of guns and ammunition has been considered the main incentive for the development of blast furnace iron and steel industries from 16th century on (Tylecote 1976). Then, as nowadays, this technique produced pig iron, which was cast into molds or could be processed, through what is known as indirect method, to obtain wrought iron. Two products were thus obtained; wrought iron, with low carbon content, high melting point and ductile qualities, and cast iron, with lower melting point, higher carbon content and suitable for molding, though fragile. It is worth mentioning that the first of these materials could also be obtained by directly reducing the iron ore. The indirect method competed with that second method in varying degrees since the appearance of the blast furnace until the late eighteenth century (Tylecote 1976; Buchwald and Wive 1998).

Originally, the direct reduction method outmatched the alternative in the manufacturing of wrought iron, given its efficiency regarding fuel consumption and ore optimal use. However, enhancements in blast furnaces (e.g. increase in volume), in addition to technological changes in refining processes, positioned the indirect reduction process as the primary means for the manufacturing of iron and steel (Tylecote 1976). Initially, blast furnaces used charcoal as fuel and reductant. They operated with a mainly acid slag and in low temperatures, which generated a product that tended to produce white iron (with carbon combined in the shape of cementite). But since the introduction of coke instead of charcoal, the tendency switched towards obtaining more basic slag. Furthermore, higher temperatures began to be used. These features resulted in a process by which grey iron (carbon in graphite state) was more easily obtained (Tylecote 1976).

In accordance with the mechanical requirements to which ordnance was subjected, grey iron castings –which were less fragile– were frequently used in the making of cannons (Tylecote 1976; Samuels 1992; Setién and Díez-Aja 2008). As for cannonballs, their manufacturing did not require the same care and attention as the former, given the function to which they would be destined, and thus a variety of microstructural types was found in projectiles of the kind belonging to the period of concern (Samuels 1992; Medina and López 2011). For what has been mentioned, the microstructure present in the cannonballs is considered as corresponding to a wider sampling of the cast iron material used, influenced more by the state of general metallurgical technique applied in the place and time of their manufacturing, than by the specific quality of their use, as was indeed the case of cannons. Their projectiles may then be taken into account as representative of technological aspects of that kind.

1.4. Manufacturing and use of cannonballs in the final stages of the 18th century

The material with which the greatest amount of the ordnance was manufactured was cast iron. Even though bronze cannons were superior to those made of iron in many aspects, the imperative need to produce a huge amount of pieces led to the widespread use of the latter, which was cheaper. That encouraged improvements in the quality of cast iron, in particular to obtain a product of lower weight and greater resistance (Torrejón Chaves 1997). The latter resulted in technical advantages such as the reduction in the weight of the vessels, maneuverability being thus favored, and the possibility of using a larger load of powder. That is how iron ordnance received special attention and capital investment by the States and was subject to diverse innovation processes related to manufacturing techniques and features of materials used (their quality varying depending on the source of obtention), in order to improve their efficiency. Operations associated with the production of cast iron cannons were very delicate. As pointed José Alcalá-Zamora y Queipo de Llano "a miniscule negligence when weighing the loads of the ore, a small excess of flux, the poor preparation of the sand of a mold, a careless blow when hand deseaming, irremediably rendered the piece useless" ["*una negligencia minúscula en el pesaje de las cargas del mineral, un pequeño exceso de fundente, la mala preparación de la arena de un molde, un golpe descuidado en el descortezo, inutilizaban la pieza sin remedio*"] (Alcalá-Zamora y Queipo de Llano 2004: 80).

For most of the 18th century, the artillery manufacture in Spain was centralized in the royal factories (*Reales Fábricas de Artillería*) at Liérganes and La Cavada (Cantabria), facilities that were equipped with a total of six blast furnaces by the end of the century (Alcalá-Zamora y Queipo de Llano 1999, 2004). This author refers to the extraordinary quality of cannons produced there, their attributes being considered almost as remarkable as those of bronze guns (Alcalá-Zamora y Queipo de Llano 1999). However, due to the high demand for ammunition, there were also attempts to supply from other blacksmiths (Rodríguez-Villasante Prieto 1999). Considering the latter, and the fact that for ammunition a poor quality iron obtained in the first blast furnaces castings was usually used (Rovira 1787; Setién and Díez-Aja 2008), it is likely for the quality of the cannonballs to have been markedly heterogeneous, at least compared with cannons.

The Diderot and d'Alembert *Encyclopedia* provides an illustrated description of the manufacturing method of round shots. Basically, they were done by casting in an earth mold: it was square and bipartite, each of the two halves having, in negative, a hemisphere and a half section of the sprue. The two halves were joined together by scarph joints, located at the respective vertices. In turn, through a special support, several molds of similar size could be grouped to perform a simultaneous casting (Fig. 3).

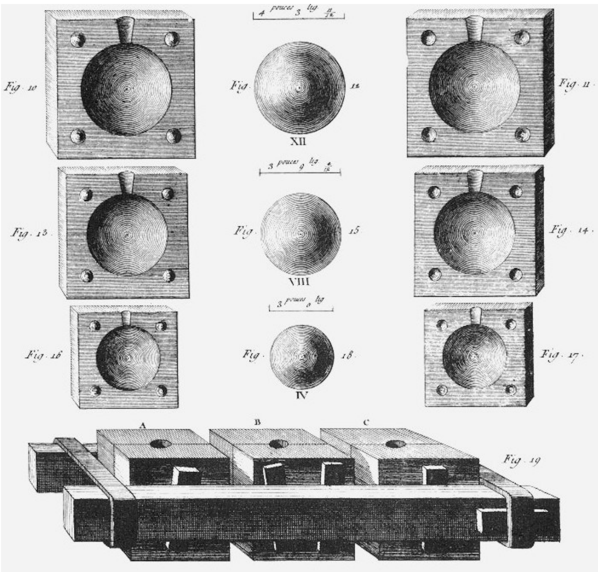


Fig. 3. Casting molds for cannonballs of different calibers (from Diderot and d'Alembert 1767, *Arts Mechaniques*, *Fonderie des Canons*, detail of plate XX).

During its heyday, iron produced in the mentioned Spanish facilities was the grey type, with an average specific gravity of 6.9 – 7 g/cm^3, according to tests with 17th century cannonballs (Alcalá-Zamora y Queipo de Llano 2004). It should be noted that the reported value is lower than the value stated in Muller's *A Treatise of Artillery* (1768:2) (specific gravity of cast iron: 7.4 g/cm^3) (Muller 1768), suggesting that artifacts from Liérganes and La Cavada, when equivalent in size, were lighter than the British of the time. In projectile diameter vs. weight tables, discrepancies can also be noted between English and French cannonballs of the same caliber (Muller 1768). It is possible for this to have been related to discrepancies between units of measurement, given the application of different methods of calculation, which did not maintain proportionality between different calibers, and/or with the fact that specific gravity used was slightly different in both cases. In this regard, the values expressed suggest that sometimes French pieces were relatively heavier than English ones, while in other cases the relationship was reversed. Based on the above, it can be argued that the discrepancy in the weight-diameter relationship in projectiles belonging to each navy partly responded to the fact that the cast iron used had different characteristics.

The navies of each country were not only equipped with manufactures produced within their frontiers. It was not an uncommon practice to import artillery pieces, especially cannons, from certain production facilities, valued for the quality of their products (e.g. Liérganes and La Cavada, in Spain; and Carron, in Scotland) (Rodríguez-Villasante Prieto 1999). According to Torrejón Chaves, the production from Carrón supplied the Royal Navy and other European navies with the best cast iron cannons of the 18th century. Spain was supplied with a great number of pieces coming from that factory and made in accordance with Spanish requirements, even though many of them did not make it pass the quality tests (Torrejón Chaves 1997). Additionally, this period was characterized by the transfer of technology (i.e. specialists, technical and scientific progress, machinery and instruments) which was momentarily interrupted, or at least reduced, in certain periods of conflict (Alcalá-Zamora y Queipo de Llano 1999).

During the second half of the 18th century, a great amount of progress was done in France and England concerning metallurgy, both in theoretical and applied fields, many times driven by specialists, products and knowledge from other regions, which were mainly stimulated by military needs (McCloy 1952). Innovations introduced in the last third of the century thanks to the contribution of local experts, as were Benjamin Robins (England, 1707-1751), Jean-Baptiste Vaquette de Gribeauval (France, 1715-1789) and Francisco Javier Rovira (Spain, 1740-1823), transformed a variety of practices concerning the artillery of the corresponding navies (McCloy 1952; Torrejón Chaves 1997). It is worth noting that the production of cannons and ammunition in Spain was influenced both directly and indirectly by the development of those centers of production (e.g. the presence of French smelters or the replication of English methods and machinery done in the Royal Factories) (Torrejón Chaves 1997). Likewise, the products obtained in Spanish facilities were exported to England and France due to their high quality (Santana et al. 1999).

2. Experimental procedure

Eight projectiles were studied, their main dimensions and sources indicated in Table 1. The results of the metallographic analysis, performed by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM), and of the chemical composition, by Energy Dispersive X-ray Spectrometry (EDXRS), are presented below.

Table 1. Dimensional features of the pieces analyzed.

Site	Country	Sample	Weight (g)	Diameter (mm)
Deltebre I (1813)	Great Britain	D1	Round shot (fragment)	
		D2	91	29
Bucentaure (1804-1805)	France	B1	219	40.1
		B2	Grapeshot projectile (fragment)	
Triunfante (1756-1795)	Spain	T1	227	43
		T2	52	34.1
Swift (1763-1770)	Great Britain	S1	45	25.9
		S2	1,450	90

3. Results and Discussion

3.1. Characterization by means of LM and SEM-EDXRS

3.1.1. Deltebre I site (1813): samples D1 and D2

The sample D1 is a fragment of a round cannonball, most likely of 18 pounds. The microstructure of the piece is consistent with a grey iron, with pearlitic matrix with steadite (Fig. 4-a). Through EDXRS analysis phosphorus was detected, which is consistent with the microstructure observed. Polygonal particles were also found, identified as manganese sulfide and titanium compounds (Fig. 4-b and 4-c).

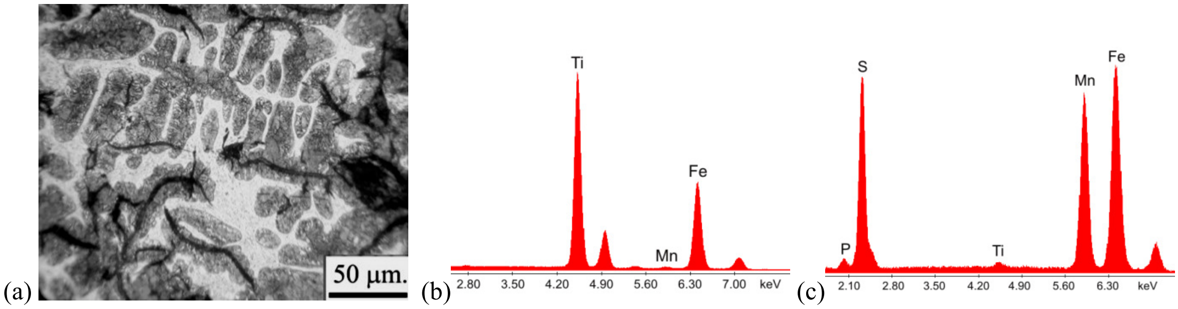


Fig. 4. (a) grey pearlitic iron with steadite; (b and c) spectra that reveal the presence of Ti and MnS compounds in the microstructure.

The other piece (sample D2) belongs to a canister shot projectile measuring 29 mm in diameter (Fig. 5-a). It presents two central marks, diametrically opposed, that could correspond to the insertion of the sprue and gas vent, or eventually to a connecting runner between pieces (serial casting). Its microstructure corresponds to a grey pearlitic iron, with a significant amount of steadite, in accordance with the presence of phosphorus in the alloy composition. Titanium particles were also detected in this piece (Fig. 5-b and 5-c). The presence of this kind of intermetallic compounds has been previously reported in other casting artifacts from the period, and may be regarded as indicative of the ore source used in the raw material (Samuels 1992; Medina et al. 2012).

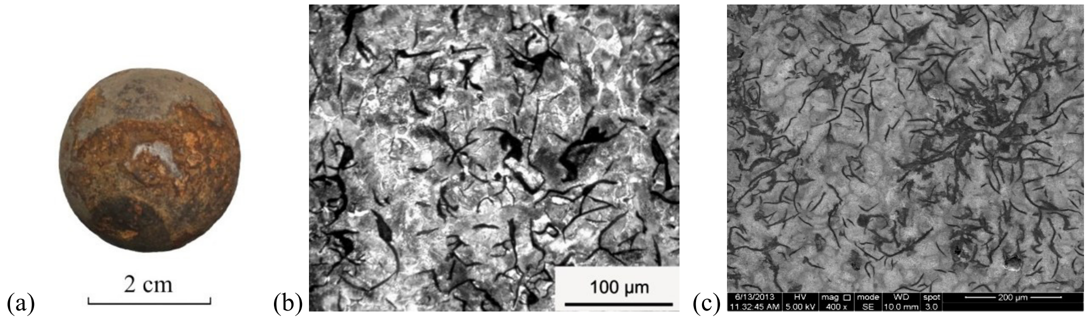


Fig. 5. (a) picture of the piece; (b and c) optical micrograph and SEM image of the grey pearlitic iron with steadite.

3.1.2. *Bucentaure* (1804-1805): B1 and B2 samples

Sample B1 belongs to a grapeshot projectile, recovered from the inside of a 12-pound cannon. In the piece it is possible to identify the imprints from the sprue and the mold parting line (Fig. 6-a). It has a grey pearlitic iron microstructure, presenting steadite as well. The latter is consistent with the existence of phosphorus, detected with EDXRS (Fig. 6-b and 6-c). In the periphery of the piece cementite was recorded, which could be due to a higher cooling rate in the area during the casting process (Fig. 7-a).

The second sample (B2) belongs to a shot fragment from the previously mentioned artifact (grapeshot) and equals B1 sample in size. In this case only the sprue area and its surroundings were subjected to analysis. The microstructural features of both pieces in that area are similar. As previously mentioned, the presence of cementite is attributed to the higher cooling rate of the surface (Fig. 7-b).

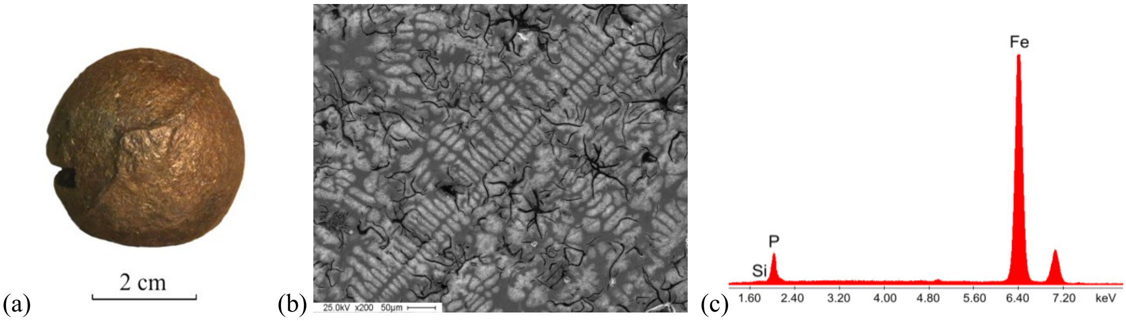


Fig. 6. (a) B1 sample picture, where the insertion of the pouring channel can be appreciated; (b) SEM image of the microstructure; (c) spectrum showing phosphorus present in steadite.

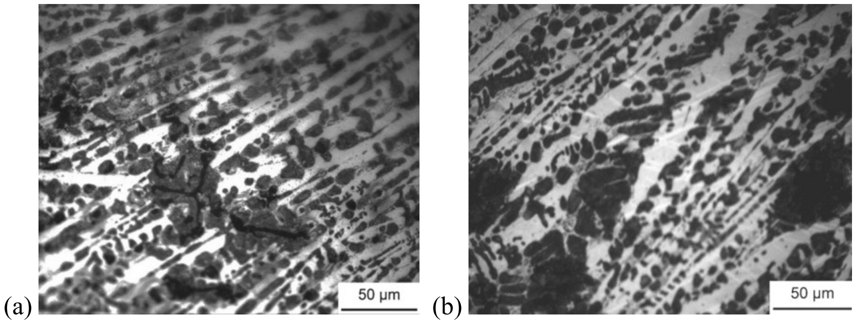


Fig. 7. (a) microstructure with predominant cementite near the surface (B1); (b) microstructure of white iron in the area of the sprue (B2).

3.1.3. *Triunfante* (1756-1795): T1 and T2 samples

Sample T1, belonging to a grapeshot projectile, is affected by a superficial corrosive process. Regarding microstructure, the presence and shape of cementite and graphite are consistent with a mottled cast iron, with a martensitic matrix (Fig. 8-a). The detected martensite indicates austenite quenching, either due to the casting process or a subsequent treatment. The first alternative is considered unlikely given that the presence of graphite tends to be associated with slow casting cooling. By using SEM and EDXRS analysis the presence of MnS (manganese sulfide) polygonal particles could also be detected (Fig. 8-b and 8-c). The other grapeshot bullet analyzed (T2 sample) has been extensively affected by corrosion, although it remains spherical in shape. In its interior cementite formations can be distinguished, that indicate the white type nature of the casting the projectile was made of (Fig. 9).

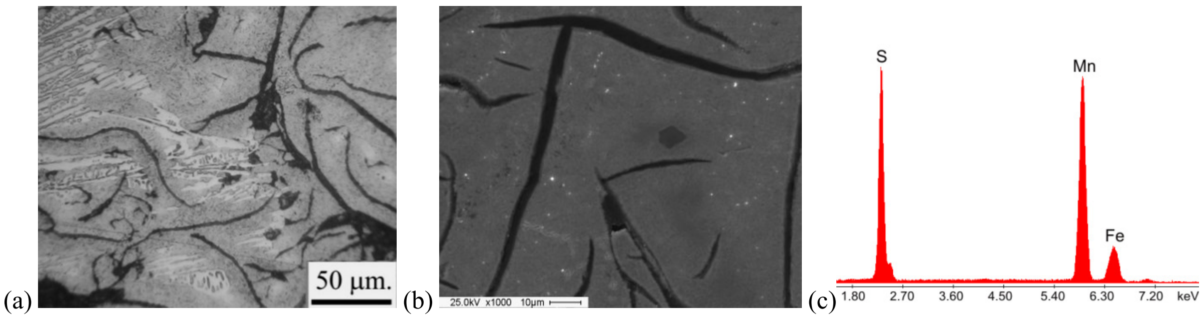


Fig. 8. (a) optical micrograph, belonging to a mottled iron with martensitic matrix; (b) SEM image, where a polygonal MnS particle can be distinguished; (c) EDXRS Spectrum of the particle observed in figure 8-b.

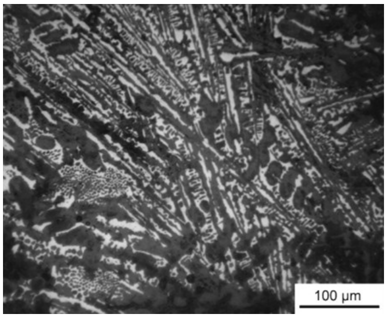
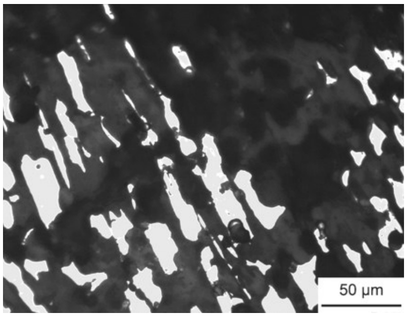


Fig. 9. Optical micrograph of the centre of the cannonball, in which some voids produced by the metallographic preparation, can be observed in the corroded area, together with cementite, that remains unaffected by corrosion.

3.1.4. *Swift* (1763-1770): S1 and S2 samples

The S1 sample belongs to a canister shot projectile, while S2 belongs to a 6-pound round shot fragment. The microstructures of both samples present a continuous oxide matrix, crossed by cementite plaques (Fig. 10-a and 10-b). These features allow identifying the material with which the pieces were made as white iron. Other original alloy microconstituents could not be determined, given they were already completely turned into oxide due to corrosion processes.

(a) 

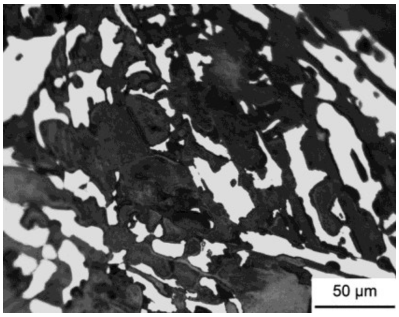
(b) 

Fig. 10. (a) optical micrograph of the canister shot projectile (S1); (b) 6-pound cannonball microstructure (S2).

4. Conclusions

Eight spherical cannon projectiles were studied (round shot, grapeshot and canister shot ammunition), coming from four European warships that sank within a time range from 1770 to 1813. In light of the historical written documentation consulted, it is considered that the characteristics of the projectiles are consistent with the state of metallurgical technology of the time. The OM and SEM analysis indicated that all pieces are made of cast iron. Specifically, the samples analyzed revealed some diversity in their microstructure, and also exhibited differences regarding the presence or absence of some minor elements (such as Ti and Mn), according to the EDXRF analysis. The variations seem not to have represented any advantage for the operability of the artefacts. Indeed, they are probably related to the provenance of the raw material used and the slight differences in the technical procedures of each centre of production. Nonetheless, the information recorded so far does not allow to determine a trend defined by a particular type. According to the results obtained, studies are intended to continue analyzing new samples from these and other sites of the period, in order to expand the understanding of metallurgical and military technology used aboard navy ships.

Acknowledgements

The authors would like to thank Jorge Pina and Gisela Maxia, from the Scanning Electron Microscopy Laboratory, Department of Mechanics, National Institute of Industrial Technology (INTI). Thanks also to Gustau Vivar Lombarte, from the Catalan Centre for Underwater Archaeology (CASC) of the Archaeological Museum of Catalonia (MAC), Girona, for enabling us to work with artifacts from the Deltebre I and *Triunfante* sites. To Cármen García Rivera and Josefina Martí Solano, from the Underwater Archaeology Centre (CAS) of the Andalusian Historical Heritage Institute (IAPH), Cadiz, for providing us the opportunity to work with the *Bucentaure* materials. Last but not least, to Ana Castelli, for her invaluable help with the article translation.

References

Alcalá-Zamoray Queipo de Llano, J., 1999. Aportación a la historia de la siderurgia española, in *Hierro al mar*. Instituto de Estudios Cántabros and Asociación Tajamar, Cantabria, Spain, pp. 72-84.

——— 2004. *Liérganes y La Cavada. Historia de los primeros altos hornos españoles (1622-1834)*. Biblioteca Cantabria, Vol. 22, Ed. Estvdio, Santander, Spain.

Buchwald, V. F., Wive, H., 1998. Slag Analysis as a Method for the Characterization and Provenancing of Ancient Iron Objects.Materials Characterization 40, 73-96.

Corbera Millán, M., 1999. Ferrerías en Cantabria, in *Hierro al mar*. Instituto de Estudios Cántabros and Asociación Tajamar, Cantabria, Spain, pp. 45-51.

Diderot, D., d'Alembert, J.-B. L. R., 1767. *Recuil de planches sur les sciences, les arts libéraux, et les arts méchaniques, avec leur explication*. Vol. 4, Paris.

Elkin, D., Murray, C., Bastida, R., Grosso, M., Argüeso, A., Vainstub, D., Underwood, Ch., Ciarlo, N. C., 2011. *El naufragio de la HMS Swift (1770): Arqueología marítima en la Patagonia*. Vázquez Mazzini Editores, Buenos Aires.

Flatman, J., Staniforth, M., 2006. Historical maritime archaeology, in *The Cambridge Companion to Historical Archaeology*, Hicks, D., Beaudry, M. (Eds.). Cambridge University Press, UK, pp. 168-188.

Gould, R. A., 2011. *Archaeology and the Social History of Ships*. Cambridge University Press, UK.

Martí Solano, J. (Comp.), 2008. Prospecciones y sondeos arqueológicos en el yacimiento subacuático de Chapitel (Bahía de Cádiz). Centro de Arqueología Subacuática, Instituto Andaluz de Patrimonio Histórico, Cadiz, Spain. Ms.

McCloy, S. T., 1952. *French Inventions of the Eighteenth Century*. University of Kentucky Press, USA.

Medina, M., López, A., 2011. Caracterización metalográfica del material de dos balas de cañón del siglo XVIII, IV Congreso Argentino de Arqueometría. Lujan, Buenos Aires.

Medina, M., López, A., De Rosa, H., 2012. Caracterización microestructural de piezas de fundición de hierro de un navío mercante español del siglo XVIII, 12° Congreso Binacional de Metalurgia y Materiales CONAMET/SAM. Valparaíso, Chile.

Moore, L. L., 1801. *The British mariner's vocabulary*. J. Cundee et al., London.

Muller, J., 1768. *A Treatise of Artillery*. John Millan, London.

Nieto, X., Pujol, M., Vivar, G., 2013. *El vaixell Triunfante: Una fita de la ciència i de la tècnica del segle XVIII*. Monografies del CASC Nº 10, Centre d'Arqueologia Subaquàtica de Catalunya, Spain.

O'Scanlan, T., 1831. *Diccionario Marítimo Español*. Imprenta Real, Madrid.

Rodríguez-Villasante Prieto, J. A., 1999. Hierro para la Armada: el Arsenal de Ferrol, in *Hierro al mar*. Instituto de Estudios Cántabros and Asociación Tajamar, Cantabria, Spain, pp. 136-143.

Rovira, F. J.

1787. *Compendio de matemáticas: dispuesto para las escuelas del Real Cuerpo de Artillería de Marina*. Imprenta de la Academia de Cavalleros Guardias Marinas, Cadiz, Spain.

Samuels, L. E., 1992. Australia's Contribution to Archaeometallurgy. Materials Characterization 29, 69-109.

Santana, A., Zabala, M., Torrecilla, M. J., Ibáñez, M., 1999. Bilbao: la montaña de hierro. Minas, ferrerías y comercio, siglos XIII-XVIII, in *Hierro al mar*. Instituto de Estudios Cántabros and Asociación Tajamar, Cantabria, Spain, pp. 28-37.

Setién, J., Díez-Aja, J. A., 2008. Aproximación histórica y metalúrgica a los primeros hornos altos españoles: las fábricas de artillería de Liérganes y La Cavada. Revista de Metalurgia 44 (4), 299-309.

Sullivan, C., 1986. *Legacy of the Machault. A Collection of 18th-century Artifacts*. National Historic Sites, Environment Canada, Ontario, Canada.

Torrejón Chaves, J., 1997. La Artillería en la Marina española del siglo XVIII. Militaria. Revista de Cultura Militar 10, 291-324.

Tylecote, R. F. T., 1976. *A History of Metallurgy*. The Metals Society, London.