J Solid State Electrochem (2009) 13:1767–1776
DOI 10.1007/s10008-009-0876-4

ORIGINAL PAPER

Electrochemical techniques applied to the conservation of archaeological metals from Spain: a historical review

Joaquín Barrio · Jorge Chamón · Ana Isabel Pardo · Margarita Arroyo

Received: 2 May 2009 / Revised: 19 May 2009 / Accepted: 24 May 2009 / Published online: 12 June 2009

Abstract The conservation and restoration of archaeological metals is one of the most complex conservation issues. Therefore, conservators usually employ the most advanced techniques, with the purpose of obtaining positive results for the preservation of the objects. One of the aims of conservation treatments is avoiding the reactivation of corrosion processes. Electrochemical treatments applied on archaeological metals were employed in Spain since the beginning of the twentieth century. During its history, the treatments were praised and reviled, practiced and discontinued. Conservation criteria have also exerted an influence over electrochemical treatments. Nowadays, electrochemical techniques are provided with control devices, such as potentiostatic control and could be considered again as a very valuable option, in combination with traditional and vanguard techniques, to recover the archaeological metallic heritage.

Keywords Heritage · Archaeology · Metals · Science history · Conservation · Restoration · Electrochemistry

Introduction

This paper aims to present a historical overview of electrochemical techniques applied to the conservation of metallic archaeological heritage. It reflects the perspective of an archaeological heritage conservator and will differ and complement the viewpoint of chemists and electrochemists. These techniques are evaluated within the framework of the deontological principles that rule conservation and restoration. Also, it deals with the peculiarities of archaeological metals. Compared to historic metals, they present different conservation problems as they have suffered a burial environment and have undergone a different corrosion process. Archaeological corrosion entails a severe degradation that distorts the original surface of the objects.

To understand completely the current situation of electrochemistry applied to conservation in Spain, it is necessary to be acquainted with the development, and usage of electrochemical techniques in the newborn museum workshops where archaeological collections were treated during the beginning of the twentieth century. Therefore, this is a contribution to the history of conservation science of archaeological Spanish heritage; a study of the similarities, differences and influences from the European countries.

The potential of electrochemical techniques and other forthcoming reliable techniques for metal conservation treatments, such as laser or low pressure plasma, are evaluated in the light of the before-mentioned background and the experiences of the *Laboratorio/Servicio de Conservación, Restauración y Estudios Científicos del Patrimonio Arqueológico* (SECYR).

J. Barrio · J. Chamón (✉) · A. I. Pardo · M. Arroyo
Dpto. Prehistoria y Arqueología, Laboratorio/Servicio de Conservación, Restauración y Estudios Científicos del Patrimonio Arqueológico (SECYR), UAM Campus de Cantoblanco, 28049 Madrid, Spain
e-mail: jorge.chamon@uam.es

J. Barrio
e-mail: joaquin.barrio@uam.es

Early electrochemical methods applied to the conservation of metals

In general terms, this stage covers from the very beginning of the twentieth century to the 1950s, leaving out the period of

Spanish Civil War. In that moment, electrochemical and chemical cleaning treatments were introduced in the conservation workshops of Spanish museums and collections.

During this period, the *restauración de oficio* (artisan restoration) was usually exerted by highly skilled artisans without any formal training. In the case of the *Museo Arqueológico Nacional* (MAN), there are documentary proofs of the existence of such conservator-artisans since 1875 [1]. The application of non-artisan proceedings, particularly chemical ones, was quite exceptional, as these artisans had no knowledge. For that reason, electrochemical cleaning was still minority in those days, as conservation and protection of iron and bronze objects were carried out employing very traditional methods: boiling, red-hot heating, natural wax impregnations, etc. Most of these procedures practised in Spain were inspired by the pioneering work of G.A. Rosemberg [2], who had introduced *chemical* cleaning techniques practiced in Copenhagen Museum since the end of nineteenth century. The development of these new cleaning methods has acknowledged him as being one of the fathers of Scientific Conservation of archaeological metals [3].

These kinds of treatments could have been used with some Celtiberic weapons (5th–2nd BC) from the necropolis excavated by the Marquis of Cerralbo, as it is suggested by some photographs taken at the beginning of twentieth century. The photographs showed that the weapons were displayed in cabinets. A whitish shade could be noticed on the weapons, presumably from the wax consolidations of superficial soil and the lack of an efficient removal of the corrosion products (Fig. 1).

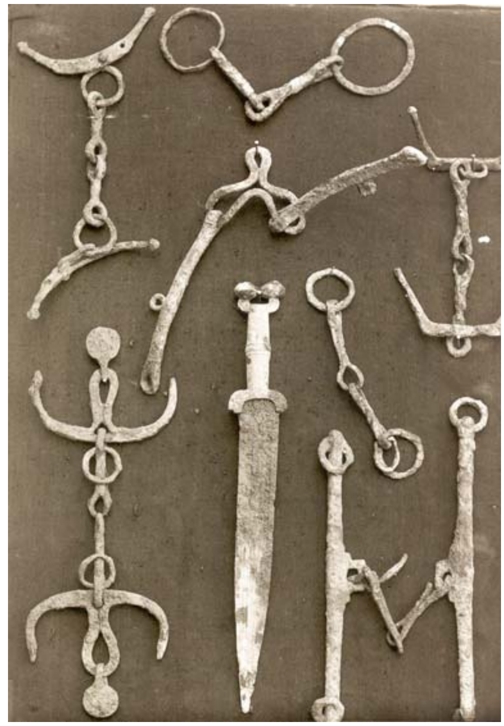

Fig. 1 Celtiberian iron objects and weaponry exhibited in their original case. Very probably, they have been covered with natural waxes or *ceresina.* The surface of these objects is different from those showed on Fig. 4 (Archivo Cabré. IPCE. Blánquez and Rodríguez, 2004)

The most renowned answer to these inefficient treatments was carried out at the MAN [4]. The aim was to create a specialised electrochemical workshop. In 1929, the museum applied to the *Subsecretaría del Ejército of the Spanish Army* for the transfer of the Infantry Commander, José Magaña Marín. In 1930, the transfer was authorised, and this military man, a specialist on electrolytic techniques, arrived to the MAN. His aim was to develop and apply the new conservation procedure.

The original document refers to the *servicio de reparación por electrolisis*, *de los hierros y bronces pertenecientes al Estado:* the Department of Electrolysis applied to iron and bronze objects propriety of the State (Archivo MAN 1930/Expte.128). On February the 27th that year, a set of six Iberian iron objects, very fragmented but quite significant, were handed in to him: falcata blades and handles, soliferrum remains, etc., all of them affected by heavy corrosion. The objective was to achieve some preliminary cleaning results, prior to the implementation of an in-house laboratory facility. On the document, Magaña himself recorded, handwritten, that the objects were returned a week after, the 7th of March. It is understood that the director and the curators of the Museum approved of this experiment on metallic objects cleaning. The following picture presents a falcata sword showing evident traces of electrochemical cleaning procedures (Fig. 2).

Without a doubt, Magaña ought to be outstandingly trained and practised on these procedures, as he was employed at the National Factory of Electrochemical Etching (*Fábrica Nacional de Grabado Electro-Químico S.A.*). While he was still working at the Factory, he wrote a letter to Prof. Gómez Moreno, Director of the MAN. On the letter, he enclosed the estimate for the implementation of a proper laboratory, equipped with the best material available at the time: battery, control boards, tank, rheostats, electric measurement equipments, etc. The estimate was quite expensive for that period of time—2.825 pts.

The Electrochemistry Laboratory was equipped with this material and ought to be performing these techniques at full capacity in the years prior to the Civil War. These treatments were known as *inmunización*, immunisation treatments and were usually employed for the conservation of archaeological iron objects. During the War, all the objects of the Museum were packed, and the building was used as a storage place in order to house many national

Nota de los objetos y fragmentos de hierro que se entregan a Don Jose Magaña para su restauracion.

=.=.=.=.=.=.=.=.=.=.=.

Una espada falcata casi completa

Un fragmento con parte de empuñadura.

Un fragmento con parte de empuñadura.

Un fragmento de la parte media de una falcata.

Un fragmento de la parte media de una falcata.

Un fragmento de soliferreum en destrozos

Son en junto seis objetos perfectamente determinados

Madrid 27 Febrero 1930

Recibi

Devueltos el 8 Marzo 1930

Fig. 2 Original document referring to the set of iron materials treated with electrochemical techniques for the first time in Spain (Exp. 128/Archivo MAN)

historical heritage objects. Presumably, the archaeological metallic objects suffered damage under improper conditions. The disposition of the metallic objects, almost piled up, can be seen in some photographs of the storage cases of the MAN, taken during the 1940s (Fig. 3).

The documents of the museum archive demonstrate that electrochemical cleaning treatments of metals were continued after the War. In 1945, the new Director of the Museum applied for a conservator to the *Dirección General de Bellas Artes*, the Spanish chief institution in charge of cultural affairs. He was to carry out specifically chemical and electrolytic treatments and was asked to employ artistic and non-artistic criteria for the conservation of metals (Archivo MAN, exp. 1945/1) [3, 4].

In that sense, the nomination of the archaeologist J. Cabré, a man interested on all vanguard techniques—photography, drawing, planimetry, conservation, etc.—as “curator in charge of promoting the conservation of materials”, in 1942, ought to be quite helpful for the recovery of electrochemical cleanings at the MAN [5, 6].

Fig. 3 Storage case from the MAN where pre-Roman objects—metallic objects included—piled up in disorder. Photograph taken by J. Cabré, *circa* 1940 (Archivo del MAN)

Rise and development of electrochemical cleaning techniques in Spain

In our opinion, this was the very moment when the so-called *scientific conservation* was introduced in Spanish institutions and museums, concerned with conservation in any way. *Scientific conservation* postulates as an alternative to the *restauración de taller* (workshop restoration), the artisan conservation that had been in use since the establishment of those institutions or since the moment they hired a conservator as part of their workforce. Electrochemical cleaning techniques of archaeological metals were at the peak then. They were implemented not only in respected and long-established museums, such as the MAN, but all over Spain (Fig. 4).

Determinant factors for the development of electrochemical techniques

1. The following institutions recruited chemists as technical workforce: the Spanish Institute for the Conservation and Restoration of Works of Art (ICROA), *Museo de América*, *Museo Arqueológico de Barcelona*, etc.
2. The intense conservation activity of newborn ICROA, founded in 1961 by Prof. G. Nieto, whose aims, among others, were to promote the implementation of *scientific conservation* techniques in the workshops of museums all over Spain. Electrochemical procedures applied to the cleaning of archaeological metals were remarkably promoted.
3. The influence of foreign scientific literature: Plenderleith, Stombolov, Organ, France-Lanord, etc. Plenderleith was the most influential author and the first one to have an impact on Spanish conservators. He promoted electrochemical reduction as a useful technique for the conservation of archaeological metals, especially iron objects.

The book from H.J. Plenderleith, *The conservation of Antiquities and Works of Art* (1956) [7], translated into Spanish in 1967 [8], was the reference work for every Spanish conservator at that time. Without a doubt, the book summarises and explains in detail every treatment employed in the 1950s and provides the results of practical experiences carried out at the British Museum Laboratory. This compendium was very popular among chemists and conservators due to its very understandable language, making electrochemical and electrolytic reduction affordable to beginners. Chapter VIII, devoted to Metal, defines the practical procedures of the electrochemical and electrolytic reduction plainly: materials, treatment periods, methods, graphic descriptions of the equipment, etc. Every Spanish museum repeated mimetically the process described in the book.

The patina of the objects was not taken into account: “The sludge is removed by brushing the object under running water” [8], “(…) revealing a metallic surface upon which are retained any details or ornaments. If the metallic surface is not entirely cleaned, it will be necessary to repeat the reduction with fresh zinc and caustic soda.” [8]. The treatment, then, must be continued until the metallic object has been turned into a real “backbone”.

The works of A. France-Lanord [9], R.M. Organ [10] and T. Stambolow [11], published in the following years, were not as widely spread as the book from Plenderleith despite their higher technical level. They were available at the specialised libraries and institutions, but they were less significant for the diffusion of electrochemical conservation techniques among the conservators, as they lacked the proper scientific training. Of course, there were exceptions to this rule. In spite of not becoming widespread, these publications contributed to the diffusion of electrochemical techniques that were conceived as *scientific conservation*. For example, the work from A. France-Lanord, written for museum curators and archaeological conservators, included

Fig. 4 Celtiberian weaponry treated with electrochemical techniques during the 1960s (MAN)

relevant specifications, such as the preservation of the *epidermis*—the primitive surface of the object—and the adjustment of the treatments to the state of conservation of the object. He points out to the consideration of aesthetic criteria in conservation. This idea was determinant to the future cessation of electrochemical cleaning.

How did these scientific texts influence the conservation activities in Spain?

1. They contributed to the general widespread of electrochemical cleaning techniques for the conservation of metallic objects, among both the conservators of ICROA and other museums in Spain. As we have mentioned, this was one of the aims of Prof. G. Nieto.
2. They promoted the inclusion of electrochemical cleaning methods as part of the *Conservation of Archaeological Metals* subject, included on the programme of the Conservation and Restoration Colleges since 1967. Thus, the graduates from the colleges were acquainted with those procedures, and they employed them while exerting their profession, very often in *museos provinciales*, local museums placed all over Spain.
3. The lack of specific criteria on cleaning and conservation of the patina was a key factor on the widespread of electrochemical techniques. The aesthetic aspects of the treatments were not considered, at least not clearly, even if they have been highlighted in *Venice Charter* [12].
4. As a consequence of it, many objects were massively cleaned, above all iron objects, in Spanish museums and also in the newborn ICROA laboratories.

By that time, the International Conservation and Restoration Institutions were also interested in these problems. The Committee for Laboratories of the International Committee of Museums (ICOM), sitting in Espoleto, Italy, 1964, dealt with the conservation problems of bronze and non-ferrous metal objects. The same Committee, sitting in New York, 1965, discussed on the delicate issue of the electrolysis applied to the conservation of ancient metals, a controversial matter. Due to the interest that the question had raised, this committee made a survey on the issue, among the professionals and institutions.

The Triennial Meeting of the ICOM Committee of Conservation, held in Amsterdam, in 1969, presented the activities of ICOM Working Group of Metal, coordinated by R. Organ, whose aim was to fulfil the work on electrochemical and electrolytic treatments of mineralized metallic antiquities. These examples, taken from the most important international institutions on conservation and restoration, ICOM, show the interest and concern about the implementation of those treatments.

In Spain, the results of the massive implementation of these cleaning techniques can be appreciated in the only Spanish conservation journal: *Informes y Trabajos del Instituto de Conservación y Restauración de obras de Arte, Arqueología y Etnología,* edited by ICROA.

Capabilities and limitations of electrochemical cleaning techniques: case studies

The first case study is the treatment of the metallic objects—iron and bronze objects—from the Celtic necropolis of Miraveche (fourth–fifth century BC) [13], excavated during the 1930s. Those objects were submitted to a previous conservation treatment during the 1940s, very influenced by authors like G. A. Rosenberg:

- Iron objects were boiled in water.
- The objects were impregnated with a certain mineral called *ceresina.*

This traditional conservation treatment was only partially acceptable, and it contributed to accelerate the inner corrosion process of iron objects. Moreover, it concealed the finest details of the decorative pattern. Due to their frail conservation state (thick, brittle and unstable corrosion), they were handed in to the ICROA, on November, 1964, in order to perform a second treatment. It was considered a *scientific conservation*, compared with the first one. The conservators that performed it were Mr. Arce and Mr. Villanueva, assisted by Mr. Cabrera, chemist of ICROA. The procedure followed line-by-line the treatment described in the book by H. J. Plenderleith:

- Mechanic cleaning of the soil deposits and thick hydroxide corrosion by means of a drill.
- Electrochemical cleaning, employing granulated zinc and a 5% caustic soda solution, heated at 50ºC. Brush with wire brushes. Rinse in boiling water. Dry in stove. Coat with bedacryl–methyl methacrylate dissolved in xylene.
- Paraffin coat damascene prior to the reduction.

The final result of the treatment can be appreciated in detail in the original photographs published in the paper. The objects have completely lost all traces of the original surface coating. Some of the swords show the *morceau de dentelle* (a jagged profile, described by France-Lanord), typical of these aggressive cleaning.

The second case study refers to the Iberic falcata sword of Almedinilla, one of the most outstanding pre-Roman weaponry objects, housed in the MAN. A monograph from G. Nieto and A. Escalera [14] details the intervention, very popular and highlighted in that moment. The falcata sword was discovered in 1867, and apparently, it was found broken. Very probably, it was repaired with a brass brazing and iron clinches, as these procedures were commonly employed at the end of the nineteenth century.

Moreover, a previous cleaning intervention is recorded, performed by M. E. Cabré in June, 1934. He was authorised by the Director of the Museum to *carry out personally the cleaning, using the proper methods and techniques* (…)—without specifically mentioning electrolysis. The results of the treatment were the removal of oxides and soil, unveiling the damascene of the handle.

During the 1960s, the falcata sword came back to the ICROA, showing a reactivation of the corrosion. It was submitted to a further restoration in 1966 (performed by Mr. Arce). The details of the procedure were registered, and the intervention was similar to that mentioned before: mechanic cleaning of the silver damascene by means of a drill, paraffin coating of the damascene prior to the reduction, electrochemical cleaning, brushing with wire brushes and steel wool, rinsing in boiling water, drying in stove and coating with cellulose acetate and paraffin. As the preservation of falcate sword's metallic core was almost complete, the treatment was less aggressive and the original epidermis of the object was lost only in the areas affected by blistered corrosion (Fig. 5). The following image (Fig. 6a, b) shows the result of the intervention.

The authors described the results of the electrolytic cleaning treatment as very effective, thanks to the *new methods and techniques that have been experimented in other countries and acquainted by our technicians.* They encouraged every laboratory and museum to practise these conservation techniques. The treatment of other pre-Roman swords from La Osera [15] received also positive evaluations.

Fig. 5 Detail of the central area of the falcate sword from Almedinilla. On the *right*, the typical outline produced by electrolytic cleaning can be appreciated [14]

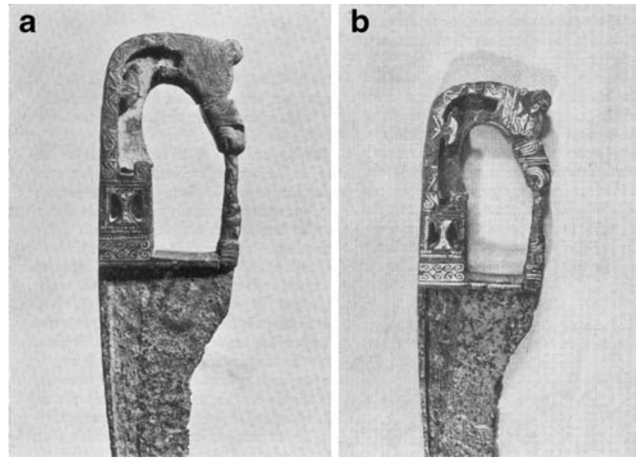

Fig. 6 Handle of the falcate sword from Almedinilla, before (**a**) and after cleaning (**b**). The silver decorative patterns can be appreciated [14]

The third case study was not published, as many of the electrolytic cleanings performed at that time. It refers to the iron weaponry from the Celtiberian necropolis of Uxama (third–first century BC) housed at the *Museo del Ejército*. The site was excavated by R. Morenas de Tejada, from 1913 to 1916. The objects recovered were assigned to several sets (Fig 7); some of them were bought by the *Museo del Ejército* (formerly the *Museo de Infantería de Toledo*) in 1916 [16, 17]. The objects were not submitted to any conservation treatment until 1965, when they were handed in to the ICROA. They were covered with soil and superficial corrosion. The intervention consisted on aggressive electrochemical techniques. It removed the patina completely, leaving the metallic core. Lastly, they were protected by applying a coating of hot coloured waxes, oil paint and graphite.

Fig. 7 Photograph taken at the beginning of the twentieth century showing the set of objects bought by the Museo del Ejército. Weaponry from the necropolis of Uxama can be seen before treatment [17]

The set was examined and analysed at our laboratory in 1998. They were affected by active pitting corrosion [18]. The aim of our study was to evaluate the effectiveness of electrochemical treatments 25 years after the intervention was done. The analyses of corrosion products by EDX and XRD showed the presence of akaganeite (ß-FeO(OH), iron hydroxide associated with chlorides) in all the objects. The pioneers of electrochemical cleaning, especially H.J. Plenderleith thought that this technique could extract the chlorides from the object. The results of our analyses demonstrates this were not so. Besides, those electrochemical techniques were harmful to the patina. Figure 8 shows active pitting corrosion on the most relevant objects of the weaponry set from the *Museo del Ejército*.

The decay of electrochemical cleaning techniques

During the 1970s and 1980s, the passion for the application of electrochemical or electrolytic cleaning techniques faded but did not disappear. More reliable treatments, such as mechanical or chemical cleaning, started to fill the gap. Spanish conservation literature reflects this change [19–22].

During the 1980s, the values of the *Carta del Restauro*, signed in Roma [23] in 1972, were introduced in Spain. Brandi′s thesis [24] posed a more restrictive aesthetic criterion, respectful with the patina of archaeological metals. Deontological ethics and legal norms were becoming more and more important and influenced the conservation decisions taken by museums and institutions. *Aesthetic Conservation* prevailed. In the light of this new aesthetic sensibility towards the objects, electrochemical and electrolytic reduction cleaning ceased. The new criterion illegitimated its use.

To summarise, this is the evolution of electrochemical cleaning applied to the conservation of archaeological metals in Spain, since the beginning of the technique, to the following development, and final decay. The procedures proposed by H. J. Plenderleith were implemented in the 1960s and 1970s by Spanish conservators very mimetically, without taking into account the specific needs of each object and lacking of a minimum control. The implementation of electrochemical techniques introduced the principles of the so-called *scientific conservation* in Spain. It entailed a positive change and an evolution of the traditional procedures. The flourishing of electrochemical techniques in Spain was possible due to the lack of a protective criterion that preserved the patina of ancient metals.

Fig. 8 Celtiberian sword from Uxama, after electrochemical cleaning. Some active pitting corrosion can be seen (photograph taken in 1998)

Iron objects were massively treated. A lesser quantity of bronze objects were treated. The intervention of several iron and bronze objects from the excavation of the most important Celtiberian, Iberian and Visigothic necropolis is an example of its widespread usage.

Those aggressive electrochemical cleaning techniques had a profound impact on the objects. The treatment was irreversible and provoked the complete loss of the epidermis of iron and bronze objects. This aesthetic deterioration conduced to the faking of the surfaces that were painted, patinated or graphited in order to veil the metallic core.

Despite the opinion held in the past, aggressive electrochemical cleaning processes does not entail the complete removal of harmful products, especially chlorides. Most of the objects submitted to electrochemical cleaning have presented active pitting corrosion after the treatment and had to be retreated.

Towards a new perspective of future: electrochemical techniques applied to the conservation of archaeological metals

In the beginning of the twenty-first century, the conservation of archaeological metals still has to face the problems presented by the heterogeneity of metal composition and the complexity of their deterioration. For that reason, new vanguard conservation treatments have been introduced: laser cleaning [25], low pressure hydrogen plasma cleaning [26], etc. They offer diverse solutions to the beforementioned problems. They can be combined or even customised to provide singular solutions for each object [27]. Therefore, the continuity of electrochemical techniques applied to the conservation of metallic objects could be reconsidered. Notwithstanding, these vanguard conservation techniques must deal with certain issues in order to overcome the serious faults and errors committed in the past. We propose the following guidelines:

1. To respect the minimal intervention criterion, granting a less aggressive treatment

2. To understand the corrosion problem scientifically and comprehend the fundamentals of the electrochemical technique
3. To apply archaeometry at the service of conservation in order to evaluate the results of the treatments carried out on metals

In light of the recent experiences, electrochemical techniques can be applied to the treatment of metallic archaeological heritage in a safe and effective way by means of potentiostatic control techniques. The use of potentiostatic control allows to:

1. Characterise the superficial alteration of the objects, specially the thin coats generated by post-conservation corrosion processes
2. Evaluate the behaviour (resistivity measurements) of coatings or barriers and their resistance to corrosion
3. Execute a minimal consolidation by means of the reduction of the oxides to metallic state. This operation should be done only if the integrity of the object is compromised.
4. Contribute to the stabilisation of metallic objects affected by active inner chlorides

Electrochemical techniques with potentiostatic control could be very valuable, combined with other vanguard techniques to help us solve the complex conservation problems of the following types of archaeological metals:

– Mineralised lead and its alloys: an epigraphic lead tablet from the Roman *villa* of Valdeherreros-La Azafuera (third–fourth century AD) was treated in our laboratory, and the experience was very satisfactory [28].The tablet was folded over itself several times. The object was fragile and cracked, and it lacked from mechanical strength due to the heavy corrosion (lead carbonate, mainly cerussite). This delicate state of conservation prevented the unfolding of the tablet and the reading of a possible epigraphic inscription. The electrochemical treatment consisted on a potentiostatic controlled reduction. Lead carbonate from the surface and cracks of the tablet was reduced to metallic state (lead). After the reduction was completed, a protective layer of lead sulphate was generated on the surface of the object by potentiostactic control. The mechanical strength of the tablet was enhanced, thus, allowing us to manually unfold the tablet without breaking it (Figs. 9, 10, 11). A previous experimental probe of the treatment was carried out on a small fragment

Fig. 10 Roman epigraphic lead tablet after electrochemical treatment with potentiostatic control. The treatment consolidated the tablet and made possible to unfold it

Fig. 9 Roman epigraphic lead tablet from the Roman *villa* of Valdeherreros-La Azafuera. Initial state of the object, prior to the intervention at the Laboratorio de Prehistoria y Arqueología of the Universidad Autónoma de Madrid and at the CENIM

Fig. 11 Roman lead tablet during manual unfolding

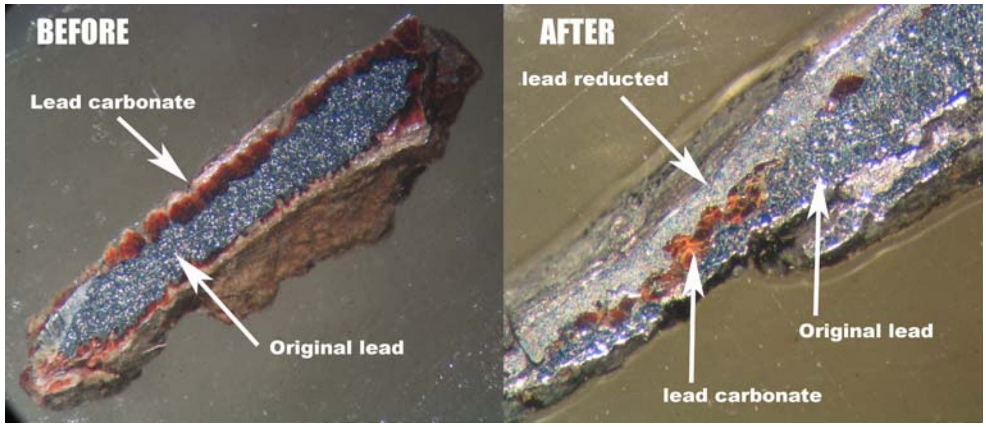

Fig. 12 Experimental probe of the treatment, carried out on a small fragment detached from the object

detached from the object before treating in order to evaluate the changes produced in it by the electrochemical treatment (Fig. 12).

– Gilded and silver-plated objects with thick crusts of corrosion on the plating
– Silver coins very affected by corrosion or presenting a strongly mineralized patina
– Silver, copper or tin metals packed with corrosion and soil. This situation is common in the case of treasures, jewellery and coins
– Very mineralised objects: the surface can be recovered by means of partial reduction
– Waterlogged archaeological metals
– Iron objects: especially during dechlorination, as an auxiliary technique

Conclusions

Taking into account the historic background and the various stages of the development and implementation of electrochemical techniques in Spain, the reported results and the current situation of the conservation of archaeological metals, we present the following conclusions:

1. Aggressive electrochemical cleaning of archaeological metals, without potentiostatic control, must be avoided. The principles of conservation does not allow it, neither will it be accepted by museums and institutions.
2. Electrochemical reduction with potentiostatic control can be a useful technique. It can be applied to very specific cases, in combination with traditional and vanguard techniques. The problems, characteristics and needs of each object must be considered individually.
3. The diagnosis of the causes of deterioration and the evaluation of the metallographic changes produced in the object as a result of the treatment must be analysed employing non destructive tests. It must be assumed that any electrochemical intervention causes minor or major changes in the structure of the object. Such changes may be accepted for the sake of the preservation of the object but must be evaluated.
4. Experimentation should be carried out on archaeological objects due to the structural and compositive heterogeneity they present. This will minimise systematic errors.
5. The choice of electrochemical techniques with potentiostatic control is a plausible option. They can be combined with other conservation techniques (traditional cleaning, laser cleaning, low pressure plasma, etc.) in order to recover the original surface of the objects.
6. Electrochemical techniques with potentiostatic control must be properly explained to the conservators and responsible of the institutions. The results expected from an electrochemical treatment must be clarified. Nowadays, hardly any of the museum conservation departments will accept to perform an electrochemical treatment on any object under their responsibility, due to the recent history of electrochemical treatments.

Acknowledgements Some of the investigations featured in this paper have been carried out as part of the following research projects: *Patrimonio Arqueológico y Conservación*: *Aplicación de innovaciones tecnológicas a la restauración de los metales antiguos*, (06/HSE/0233/2004), funded by the Consejería de Educación. Dirección General de Universidades e Investigación de la Comunidad de Madrid (Madrid, Spain), and *Aplicación de las tecnologías láser para la conservación y restauración de los metales arqueológicos* (HAR2008-05175/HIST), funded by the Ministerio de Ciencia e Innovación (Spain). We would like to thank the following people who had contributed in various senses to the research summarised in the present paper: Ms. Carmen Dávila Buitrón and Dr. M. Barril (MAN), Dr. Emilio Cano and Dr. J.M. Bastidas (CENIM-CSIC).

References

1. Moreno MA (2005) El descubrimiento de los vettones. In: Barril Vicente M (ed) Los materiales del Museo Arqueológico Nacional, 1st edn. Diputación Provincial de Ávila, Ávila
2. Rosemberg GA (1917) Antiquités en fer et en bronze: leur transformation dans la terre contenant de l'acide carbonique et des chlorures et leur conservation. Copenhagen
3. Moreno MA, Dávila C (2009) In: Barrio J, Cano E (ed) Metal-España08, Actas del Congreso de Conservación y Restauración del Patrimonio Metálico, 1st edn. Madrid
4. Moreno MA, Dávila C (1994) In: Escalera A, Pérez C Actas del X Congreso de Conservación y Restauración de Bienes Culturales, Cuenca 29 de septiembre a 2 de octubre, 337-348
5. Cabré ME, Morán J (1993) Juan Cabré y la Restauración. Patina 6:114–119
6. Barril M (2004) In: Blánquez J, Rodríguez B (ed.) El arqueólogo Juan Cabré (1182-1947). La fotografía como técnica documental, 1st ed. Madrid
7. Plenderleith HJ (1956) The conservation of antiquities and works of art. Oxford University Press, London
8. Plenderleith HJ (1967) La conservación de antigüedades y obras de arte. ICCR, Mº de Educación y Ciencia, Madrid
9. France-Lanord A (1965) La conservation des antiquités métalliques. Centre de Recherches de l'Histoire de la Sidérurgie, Jarville
10. Organ RM (1968) Design for scientific conservation of antiquities. IIC/Butterworths, London
11. Stambolov T (1967) The corrosion and conservation of metallic antiquities and works of art. Central Research Laboratory for Objects of Art and Science, Amsterdam
12. The Venice Charter International charter for the conservation and resatoration of monuments and sites (1964) ICOMOS, UNESCO. http://www.icomos.org/venice_charter.html Accessed 18 May 2009
13. Pellicer M (1968) Tratamiento de materiales metálicos de la necrópolis del Hierro Céltico de Miraveche (Burgos). Informes y Trabajos del Instituto de Conservación y Restauración de obras de Arte. Arqueologia Etnologia 7:25–41
14. Nieto G, Escalera A (1970) Estudio y tratamiento de un falcata de Almedinilla. Informes y Trabajos del Instituto de Conservación y Restauración de obras de Arte. Arqueologia Etnologia 10:5–30
15. Nieto G, Sánchez Meseguer J (1970) Secretaria general de los congresos arqueológicos nacionales (ed) Actas de XI Congreso Nacional de Arqueología, 1968, 1st edn. Mérida, Zaragoza
16. Barroso S (1997) Armamento celtibérico de Uxama en el Museo del Ejército. Militaria 10:357–364
17. de la Torre JI, Berzosa R (2002) Tumbas inéditas de la necrópolis de Osma (Soria) en el Museo del Ejército. Gladius 22:127–146
18. Barrio J, Hermana F, Pardo AI (1998) In: Generalitat Valenciana (ed) Actas del XII Congreso de Restauración y Conservación de Bienes Culturales, 1st ed. Alicante
19. Hernández Esteban M (1980) In: ICOM (ed) Actas del II Congreso de Conservación de Bienes Culturales. 1st ed. Teruel
20. Porta E (1986) In: Generalitat de Catalunya (Ed) Actas de VI Congreso Nacional de Restauración de BBCC, Tarragona 29 de Mayo al 1 de Junio de 1986.
21. González C, Ruíz P (1986) In: Generalitat de Catalunya (Ed) Actas de VI Congreso Nacional de Restauración de BBCC, 1st ed. Tarragona
22. González C, Silvestre R (1986) In: Generalitat de Catalunya (Ed) Actas de VI Congreso Nacional de Restauración de BBCC, 1st ed. Tarragona
23. Carta del Restauro Roma (1972) ICR, Roma. http://ge-iic.com/files/Cartasydocumentos/Carta_del_restauro.pdf Accessed in 19 May 2009.
24. Brandi C (1988) Teoría de la restauración. Alianza Editorial, Madrid
25. Barrio J, Arroyo M, Chamón J, Pardo AI, Criado A (2006a) In: Fort R, de Buergo A, Gómez-Heras M, Vázquez-Calvo C (ed) International Congress Heritage, Weather and Conservation, 1st edn. Madrid.
26. Barrio J, Chamón J, Arroyo M, Pardo AI, Borrós S, Agulló N, Tablas FG (2006b) In: UPV (ed) Proccedings 16th. International Meeting on Heritage Conservation, 1st edn. Valencia
27. Barrio J (2006) In: Barrio J (ed) Innovación tecnológica en conservación y restauración de patrimonio, serie: tecnología y conservación del patrimonio arqueológico, 1st edn. UAM, Madrid
28. Barrio J, Cano E, Arroyo M, Pardo AI, Chamón J (2005) In: Grupo español del IIC (ed) II Congreso Internacional Conservación e Investigación. Grupo Español del International Institute for Conservation 1st edn. Barcelona