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ScienceDirect

Physics Procedia 69 (2015) 636 – 645

Physics Procedia

10 World Conference on Neutron Radiography 5-10 October 2014

Non-destructive investigation of "The Violinist" a lead sculpture by Pablo Gargallo, using the neutron imaging facility NEUTRA in the Paul Scherrer Institute

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Abstract

The Violinist (1920), the only sculpture made by Gargallo using lead sheet and wood, is being corroded by carbonation, most probably due to the organic vapours released by the wood inside, a material not chemically compatible with lead. Hydrogen plasma has been tested and proved to be an effective treatment meaning that the sculpture has to be dismantled in order to give the plasma gas access to the lead carbonate crusts on the inner surface of the lead sheet. Prior to dismantling, a complete exploration and diagnosis of this lead sculpture has been carried out through neutron imaging at the Paul Scherrer Institute. This non-destructive technique has produced different sets of images including radiography, tomography and 3D reconstruction. Despite the presence of a core made of an organic material such as wood, the digital processing of the images and their in depth visual analysis have yielded new three-dimensional information of inaccessible details of the sculpture, allowing us to assess its present state of conservation and the manufacturing technique and materials used by the artist. The results presented in this article highlight how information from neutron imaging can be of great value when it comes to set the strategies for future conservation treatment

Selection and peer-review under responsibility of Paul Scherrer Institut

Keywords: lead sculpture; corrosion; lead carbonation; Pablo Gargallo; PSI; neutron imaging; neutron tomography; 3D reconstruction; conservation; NTD

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Selection and peer-review under responsibility of Paul Scherrer Institut
doi:10.1016/j.phpro.2015.07.090

1. Introduction

The Catalan artist Pablo Gargallo (1881-1934) is one of the most important sculptors of modernity in Spain, well known for his use of void and concave volumes in his sculptures. The Violinist (ref. no. MNAC 010972) (Fig. 1 a and b), one of the icons of the Museu Nacional d'Art de Catalunya in Barcelona, is made out of 2mm thick lead sheets, hammered with nails and assembled with soldering over a wood structure making it a very fragile sculpture and very sensitive to deformation specially during handling. It measures 55.3 x 31.8 x 21.6 cm and weighs 11.9 kg. It is a unique fragile piece which has gone out of the museum in very rare occasions.

Made in 1920 and maybe inspired by his friend and violin player Francesc Costa, it is the first of a series of nine sculptures made in the so called lead interval (Ordóñez, 2004; Dagen et al., 1991), a period of 3 years, from 1920 to 1923, in which Gargallo worked with this metal for its malleability and softness. The Violinist is the only one made in this way, all the others being manufactured using much thicker lead sheets with no wood structure.

a b

Fig. 1. Frontal views of The Violinist, by Pablo Gargallo: (a) picture taken between 1920-1924; (b) present state.

1.1. Sample condition

Due to its fragility, there have been some plastic deformations of the lead sheets together with splitting or broken solders caused by mishandling or shocks. These changes in the shape and position of different parts, noticeable by superimposing an old picture of The Violinist (Fig. 1a) to a recent one (Fig. 1b), affect the position of both hands and that of the locks of hair on the head, some of which are also broken or showing fatigue cracking caused by repeated bending. The tails of the swallow tailed suit which were originally stiff are now completely folded and adapted to the shape of the buttocks and legs.

On the other hand, some years ago different swollen areas on both legs of The Violinist were noticed for the first time (Fig. 2a). With time these areas grew larger and higher, and began to open up while a white substance began to show through. In order to identify its composition different samples were taken from the swollen areas on both legs (Fig. 2b), filling with synthetic stucco the hole left by sampling. The results from the chemical analysis confirmed the presence of basic lead carbonate hydrocerussite. During the last two years there appeared more areas swelling up and the process seems to be speeding up. New blisters can also be found at the back of the neck, on the right shoulder, on the left hip and between both legs. The sculpture, which had been on show in the permanent collection of the museum from 2004, was taken to the conservation laboratory in 2012 where it is now kept in a perspex case with silica gel in a controlled atmosphere of low relative humidity just below 39%, waiting for treatment.

1.2. Lead corrosion

Lead and wood are two non compatible materials. Lead is often affected by corrosion when used in combination with wood (Graedel, 1994; Hallebeek, 1994; Tetreault et al.,1998). Lead can be attacked by emitted volatile organic compounds (VOCs) such as formaldehyde, formic and acetic acids coming from some timbers, polyvinyl acetate (PVA) wood-glue and medium density fibreboard (MDF) binders. These organic compounds, and specially acetic acid, transform lead into lead carbonate which is the white, granular powder we see showing through the blisters on the legs (Fig. 2b).

The museum objects conservation community has been aware of the phenomenon for several decades and the chemical process that causes it is well-understood (Oddy, 1975). Carbonation occurs on the surface of the metal according to the following chemical process: acetic and some other acids, in the presence of carbon dioxide, catalyze with lead to produce lead acetate and lead hydroxide. Lead acetate and lead hydroxide together react with carbon dioxide and form lead carbonate. Lead carbonate then releases acetic acid and the process becomes self-sustaining (Blackshaw, 1979). It is important to recognize that the formed lead carbonate is not just a substance clinging to the surface of the metal, it is the very surface of the metal transformed to powder. For practical purposes, a portion of the lead is gone and lead carbonate is left in its place. The lead carbonate releases acetic acid which can continue the process until the sound lead is progressively consumed as in the case of The Violinist, from the inside, outward.

a b

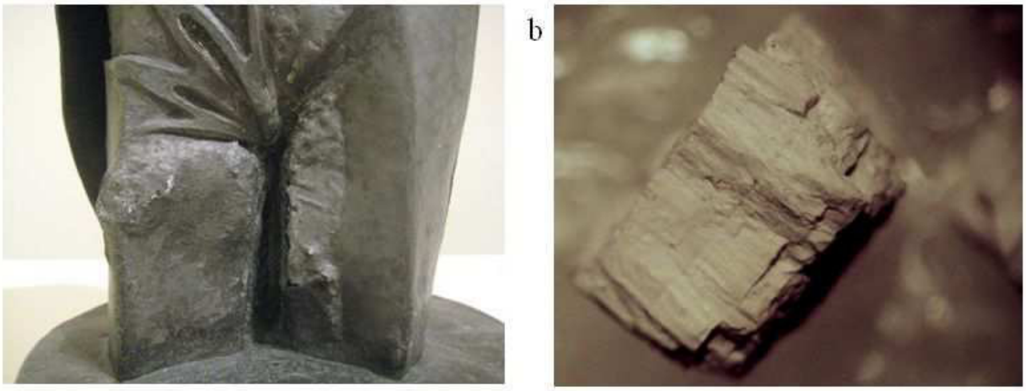

Fig. 2. (a) Plastic deformation on both legs due to advanced lead carbonate corrosion; (b) macrophotography of sample of lead carbonate taken from the blister in the left leg. The fine parallel lines grow with every new layer of lead carbonate formed most probably due to an increase in relative humidity.

Unfortunately Gargallo used two non compatible materials, lead and pine wood, to create his Violinist. Corrosion on the inner face of the lead sheet started right at the time he finished his sculpture and has been going on hidden for nearly a hundred years until today, when it is already visible from the outside.

1.3. Preliminary research

In order to identify the phase composition and morphology of corrosion products, as well as to evaluate the main treatments suggested for corroded lead, a preliminary research was conducted with a number of Majorca lead coins from the collection of the Gabinet Numismàtic de Catalunya in the Museu Nacional d'Art de Catalunya in Barcelona which were affected by lead carbonation (Alcayde et al., 2005). Three different treatments were tested, namely electrochemical, chemical with EDTA and hydrogen plasma, the latter being the most effective one in terms of corrosion product reduction, homogeneity and respect for the surface texture.

A lead model resembling more or less the shape of the sculpture with an inner pine wood core was also produced and treated in the plasma oven. The humidity content in the wood was responsible for the very long time required to achieve a reasonably good vacuum in the oven. The final result of the treatment in the inside of the lead sheet was very poor and very little carbonate was removed. This had two important implications: the plasma treatment needed accessibility to the inner side of the lead sheet, and the sculpture had to be dismantled at least to some extent to remove the wooden core.

As a result a complete investigation on its materials and manufacturing technique was to be conducted in advance in order to have enough information to plan the dismantling strategy and at the same time to have a precise map of the situation inside the sculpture.

2. The Violinist project at NEUTRA

Since the beginning of the century, neutron imaging has been successfully used as a non destructive transmission imaging technique in the investigation of sculptures and other cultural heritage objects. The results obtained by both methods are partially complementary because of the different interaction behaviour of each type of radiation with matter, allowing the study of a great variety of materials and aspects. Whereas in X-radiography the attenuation coefficient increases with increasing atomic number, with neutrons no clear correlation with the atomic number can be found and attenuation seems to behave randomly. Some light elements such as hydrogen, lithium and boron show high attenuation coefficients when measured with neutrons, while some heavy metals such as lead are practically transparent (Mannes et al., 2014).

The Violinist was the perfect object for a neutron imaging case study. The thickness of lead used in this particular sculpture made X-ray radiography not feasible since the energy needed to go through the whole volume would result in an overexposure of the wooden inner structure. On the other side, neutron imaging, capable of going through lead easily, was the right technique but the inner wood structure of the sculpture would pose a large obstacle due to its high hydrogen content.

The present study was carried out at the neutron imaging facility NEUTRA of the Paul Scherrer Institute (PSI), which is situated at the spallation neutron source SINQ (Lehmann, 2001). The sculpture was taken to Switzerland packed in a special double crate designed to reduce vibrations during the trip, and inside a multi-level foam mould with precise contact points. Safety and security was our major issue given its fragility and the responsibility assumed to take it out of the Museum after so many years.

The NEUTRA experiment was planned in three steps corresponding to three different types of images: thermal neutron radiography, tomography and 3D reconstruction.

3. Experimental procedure

3.1. Neutron radiography

For a neutron tomography a multitude of projections has been recorded at equidistant angular steps over 360° obtaining 2D shadow images of the sculpture.

First of all the different parameters for the experiment were set and the procedure for the acquisition of the projections was established. Test radiographies were taken at intervals of 15º turning 180º in order to place the sculpture right in place in front of the neutron beam and to decide on the best exposure time. The movements of the table and the turntable were set in the computer software. For security reasons the sculpture was placed a bit further away from the scintillator to prevent the violin from touching it and break or make the sculpture fall off the turning base. Since the sculpture was taller than the scintillator, it was decided to capture all the information in two runs, one for the upper half and one for the lower one. Each half made a whole turn of 360º. The final number of projections was decided, according to the radio activation measured after the first 24 exposures, being a total of 1125 projections for each complete turn, so as to compensate for the longer object-scintillator distance and to obtain better sharper images. The exposure time was set to 20 seconds. Once the shutter in the flight-tube opened, the sequence of exposures began to be captured with a CCD camera, taking a total of 15.6 hours to obtain 2250 projections-radiographies.

High resolution projections have been obtained showing quite a sharp image of the sculpture (Fig. 4a). The wooden core, visible for the first time as it is, appeared like a dark blob in the middle of the figure allowing the lead sheets to be seen only on the silhouette. It is along this silhouette where the features of The Violinist's lead suit could be studied.

The projections showed some highly attenuated areas either due to geometry or due to the attenuation coefficient of the materials. In the first case high attenuation occurs in parts of the sculpture not seen on the silhouette of the image, producing a blurred effect in the tomography, in parts where the thickness of wood structure is bigger, like the cylindrical base of the figure and in the cross sections where arm and torso are aligned. High attenuation coefficients were observed in dark spots in soldered areas due to flux remains and in spots due to organic materials, like the chips of wood in the sleeves or the stucco lump in the blister on the right leg.

The neck of the violin stood out of the scintillator area in some positions during the experiment and the information missing in those projections made it impossible for the tomography and the 3D reconstruction to include this part of the sculpture. Neutron radiographies have proved to be able to differentiate between the lead (metal) and the lead carbonate (corrosion product), which appears in a lighter shade. They could also capture other materials such as wood, iron and soldering flux.

3.2. Tomography

The projections acquired by neutron radiography were used to subsequently reconstruct tomograms of the sculpture, in which three-dimensional information from the interior was recorded. The cross sections are obtained with a special reconstruction software, using the information of every pixel line in the neutron radiographs in a quite time-consuming process. The cross sections can be perpendicular to the rotation axis (XY) or parallel to it (XZ or YZ) contributing to a variety of images from different viewpoints.

Despite the blurred areas lacking information, tomography has been very useful to locate the carbonate layers and the fixing nails and solders. It can also be used to find the limits of the different pieces of lead in the sculpture.

3.3. *3D volume reconstruction*

A virtual volume has been generated with all the stacks of tomograms using special 3D software (Fig. 3b). This volume has been virtually handled and freely moved around in a three coordinate spatial system. New cross sections of the 3D reconstruction have been obtained (Fig.4a and b) to study specific areas of the sculpture and to establish the limits of the different pieces of lead that make up the sculpture, determining also the way they are overlapped. Some parts were taken away allowing hidden parts to be seen. In this way it has been possible to see the inner surface of the lead in the right leg by removing part of the wooden core.

4. Results

A vast bibliography can be found on the sculptor and his work from the art history point of view, but very little has been studied or published about the material composition and the creative techniques used by Gargallo in his sculptural production. This research carried out on The Violinist by neutron imaging has yielded new information on the materials used, their spatial distribution, its construction technique and solutions as well as its present condition and extension of corrosion.

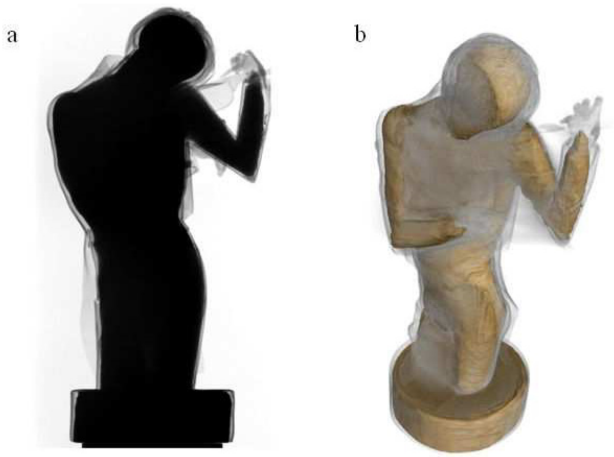

Fig.3. (a) frontal view of The Violinist seen in a neutron radiography; (b) 3D reconstruction of the sculpture with inner wood core.

4.1. Inner wooden structure

Despite the limitations of neutron radiography when dealing with organic matter such as wood, where the hydrogen from hydroscopic uptake adds to the hydrogen content of the wood, the technique has proved to be very useful even when measuring wooden samples of varied thicknesses varying from one to about 10 centimetres.

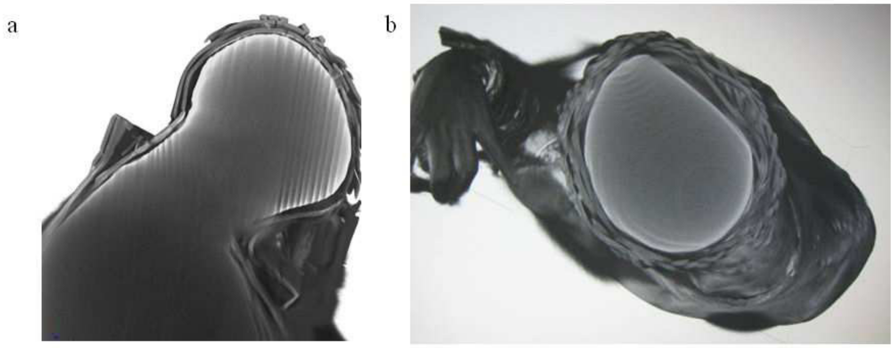

Fig. 4. (a) detail of the head and upper part of body cross sectioned in the 3D reconstruction; (b) the different lead sheets, nails and some wood grain can be identified.

Where neutrons have passed through, the resulting images show even the annual rings in the wood, not to be mistaken with the circular noise produced during the tomography processing.

Although the wood core can be seen from the back behind the suit tail and in different parts through cracks and broken solders, it was not possible to determine its actual shape and dimensions just by sight. The bottom side of the base shows three different parts of wood glued together but gives no information about the rest of the core. During the visual inspection of the horizontal tomograms on the computer screen, some straight joints could be spotted at different heights all through the sculpture thanks to the change of direction of the concentric wood grain thus confirming that the internal wood core, in pinewood, was in fact a proper sculpture carved out of a block of wood made gluing 3 different vertical planks together, creating the vertical joins visible in the tomograms.

Wavy carving marks can be seen on the wood sculpture both in radiography and in tomography and make it clear it was carved with gouges, a technique Gargallo used very seldom. Chips of wood are trapped behind the lead sheet and in elbows.

The lead sheets really follow very closely the shape of the wood kernel: It is like a wood sculpture dressed in a lead suit.

3D reconstruction of the wooden core has been processed (Fig. 4b) and voids have been filled to obtain an STL file which will enable the 3D printing in a plastic material fully compatible with lead.

4.2. Location, types and number of fixing nails

The high quality of images together with their good contrast have shown iron elements in the sculpture in a brighter grey tone, allowing them to be counted and even to recognize their shape. A total of 34 iron nails and tacks were hammered into the wood core to fix the main sheets of the sculpture in specific chosen spots that were covered by the following layer of lead (Fig. 5). These nails can be seen in the radiographs, the tomograms (Fig. 5) and in the 3D reconstructions. There are 21 nails and tacks and possibly one screw in the head (Fig. 5a). These nails can fix one to three layers of lead. In some cases it is possible to measure the length of the nail inside the wood core (Fig. 5a).

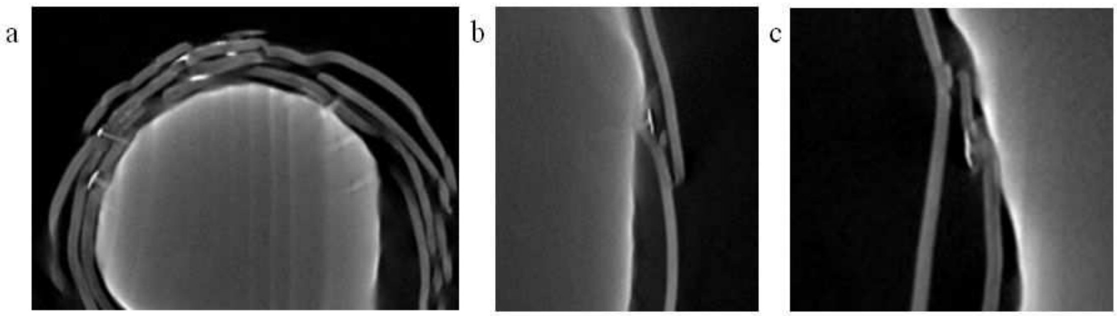

Fig.5. Details of fixing nails in tomograms: (a) in head; (b) in left hip; (c) on the back.

4.3. Low melting temperature soldering

Soldering is an assembling technique that uses low melting temperature metal alloys. Solder material is an alloy of lead, with little tin and zinc, and thus has a similar attenuation coefficient from that of the main metal, lead. The remains of flux, usually borax or resin, with their high hydrogen content have made it possible to locate in the neutron images the points where this type of assembly has been used.

Gargallo used low temperature soldering to join different sheets of lead in those places that were to be seen in the final sculpture, i.e. on the uppermost layer of locks of hair, on the attachment of the upper disc to the lateral band of the base, on the attachment of the legs to the base and on he neck and pieces depicting the wrinkles on the swallow tail suit. A complete mapping of solder lines throughout the sculpture has been produced with the help of visual and tomography information.

The manufacturing process used by Gargallo very much resembles that of organ pipe construction, a process described by Dom Bedos de Celles in 1766 (Chiavari et al., 2007) and most commonly used by lead roofing artisans still in modern times.

4.4. Identification of lead pieces and construction process

It is not clear whether Gargallo got his lead sheets directly from the manufacturer or made them himself by recycling scraps and tubes and casting the molten metal on a flat bench (Chiavari, C et altri., 2007). The shape of the different parts of the sculpture were traced and cut from the sheet of lead, perhaps following the cardboard templates he might have previously drawn and tried before using the final material. Lead sheet thickness varies from 2.5 to 1.5 mm depending on the level of hammering used by Gargallo to give the different pieces their right shape. Cylindrical parts like the forearms were obtained by simply rolling up and soldering a rectangular flat piece of lead sheet. More complex shapes were obtained by a combination of bending and hammering, cutting and soldering. This implied an uneven reduction of the thickness of the lead within the same sheet as well as a difference in the surface texture.

Once all the pieces of lead, the solders and the nails were identified it was possible to make an attempt to trace the manufacturing technique of the artist (Fig. 6). Gargallo first glued the block of wood, then carved the body and base in one piece, then began to fix lead pieces with nails and solder, little by little covering the nails with every new layer of lead sheet, and soldering the final pieces so as not to leave any visible nails.

Fig.6. Hypothetical steps followed by Gargallo during the construction of The Violinist.

4.5. Location of carbonate corrosion

Unfortunately there are some places from which no useful information has been recorded, namely the area in between the two legs, and the spaces behind both arms and between arm and chest or arm and violin and shoulders.

Corrosion is visible in all three sets of images: radiographies, tomographic images and 3D reconstructions. We can even see in the 3D images the surface texture of the carbonate layers from the inside.

Fig. 7. Mapping showing corroded areas (in red) inside the lead sheet, remains of flux and nails (blue) according to the information given by the tomograms.

In tomography the lead carbonate layers appear as a fine white band attached to the inside of the lead sheets. They can sometimes be confused with the remains of flux in the soldering. The accurate and thorough analysis of the tomographic images can help us obtain quite an accurate mapping of the areas affected by carbonation (Fig. 7) and thus estimate the percentage of the total internal lead surface affected which is about 10 to 15%.

4.6. Thickness of carbonate layers

Thanks to the good resolution of the tomography images the thicknesses of both the sound lead and the thicker lead carbonate layers have been measured. The thickness of the lead sheets varies from 2,5 mm to 1,5 mm depending on the degree of hammering. Carbonation reduces the section of sound lead as the white lead carbonate crust builds up. Measurements of the lead carbonate layers range from $4x10^{-1}$ mm to nearly 2 cm in the blister on the right leg where no sound lead is preserved.

4.7. Dynamics of the carbonation process of lead

Cross sections in both tomography and 3D reconstruction show the thickness of lead sheet in different parts of the sculpture. Where carbonation of the lead occurs, the thickness of the sound lead is diminished in favour of the lead carbonate crust. The ratio between these two thicknesses has led us to a better understanding of the dynamics of lead carbonation and why in the case of The Violinist it has taken about ninety years to show up.

It is clear in the images that the lead sheets begin to show symptoms of plastic deformation only when the growth of the carbonate layer has reduced the thickness of the sound lead to approximately 25% which has happened now. Corrosion has been going on behind the lead sculpture from the very moment it was created in 1920 and with every rise of relative humidity a new fine layer has grown just on the interface with the sound lead. Today there are several areas on the sculpture beginning to swell and that means it will show more blisters in a relatively near future.

5. Conclusions

Neutron imaging has proved to be a non-destructive technique suitable for the examination of a lead sculpture. In the case of The Violinist the wooden core inside has taken the technique to the limit. Despite high neutron attenuation by the thicker wood parts which have resulted in lack of information in certain parts of the sculpture, the radiographic sequence has produced good quality tomograms and 3D reconstruction details.

The detailed observation of the different images has yielded some very new and interesting information about the sculpture, its materials and the manufacturing technique used by Gargallo. The level of contrast allows characterization of different materials such as iron, lead, lead carbonate, flux and wood. Tomographic cross sections have given information about the different lead pieces that make up the sculpture and it has been possible to identify the different steps followed by the sculptor during the construction process.

Neutron imaging has been also useful in assessing the state of conservation and the degree of carbonation inside the lead sheet thanks to the different contrast of sound lead and lead carbonate. The processing of all the information in the thousands of tomography images using 3D software has produced the mapping of all the areas affected by lead corrosion.

Thanks to the results obtained in this study, an appropriate strategy can be set in order to minimize the risks during the dismantling of the sculpture. Having information in advance about the condition inside the sculpture will also enable conservators to foresee the steps for future treatment.

The STL (STereoLithography) format file of the wood core obtained by 3D reconstruction will enable the production by 3D printing of a new inner structure in an inert plastic material fully compatible with lead, which will ensure the stability of the system in the future.

Acknowledgements

This research project has been supported by the European Commission under the 7th Framework Programme through the "Research Infrastructures" action of the "Capacities" program, contract No: CP-CSA_INFRA-2008-1.1.1 Number 226507-NMI3.

References

Alcayde M.J., Robbiola L., Esteve J., Pugès M., Borrós S., 2005. Hydrogen Cold Plasma Reduction in a Restoration-Conservation Protocol for Metallic Archaeological Heritage. Afinidad, 62, Num. 519, pp.513-519.

Blackshaw, S. M., Daniels, V. D., 1979. The Testing of Materials for use in Storage and Display in Museums. The Conservator, no. 3, United Kingdom Institute for Conservation of Historic and Artistic Works, pp. 16-19.

Chiavari, C., Dinoi, C., Martini, C., Prandstraller, D., Poli, G., 2007. Influence of microstructure and composition on corrosion of lead-rich organ pipes. Corrosion of metallic heritage artefacts. Investigation, conservation and prediction for long term behaviour. European Federation of Corrosion Publications. Ed. CRC Woodhead Publishing in Materials. N.48, Cap. 20, p. 353.

Dagen, P., 1991. Gargallo: la nueva edad de los metales. Madrid: Fundación Cultural Mapfre Vida, pp.20-21.

Graedel, T.E., 1994. Chemical mechanism for the atmospheric corrosion of lead, J.Electrochem. Soc., 141, 4: pp. 922-927.

Hallebeek, P.B., 1994. Comparison of the corrosive properties of seven types of plywood. In: Verschoor, H. and Mosk, J. (eds) Contributions of the Central Research Laboratory to the Field of Conservation and Restoration, Amsterdam, pp. 95-108.

Lehmann, E.H., Vontobel, P., Wiezel, L., 2001. Properties of the Radiography Facility NEUTRA at SINQ and its Potential for Use as European Reference Facility. Nondestructive Testing and Evaluation 16: pp. 191–202.

Mannes, D; Lehmann, E; Masalles, A; Schmidt-Ott, K; v Przychowski, A; Schaeppi, K; Schmid, F; Peetermans, S; Hunger, K., 2014. The study of cultural heritage relevant objects by means of neutron imaging techniques, Insight - Non-Destructive Testing and Condition Monitoring, volume 56, Number 3, pp. 137-141(5), The British Institute of Non-Destructive Testing.

Oddy W.A., 1975. The corrosion of metals on display. Conservation in Archaeology and the Applied Arts. IIC, London, pp. 235-237

Ordóñez, R., 2004. Museo Pablo Gargallo. Catálago. Zaragoza: Ayuntamiento de Zaragoza, p. 69.

Tetreault, J., Sirois, J., Stamatopoulou, E., 1998. Studies of lead corrosion in acetic acid environments, Studies in Conservation, 43, pp. 17-32,