

Medieval window lead comes from Pedralbes (Catalonia) and Altenberg (Germany): a comparative study

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Introduction

The topic of this essay is a comparison between the medieval lead in the windows of the Monastery of Pedralbes (Barcelona) and in the Cathedral of Altenberg, near Cologne. We are at present involved in two different restoration projects at these locations, both of them dealing with medieval windows which include a preserved medieval lead network. Considering the relevance of these windows, the fact that they date from similar periods (Altenberg is from around 1280 and Pedralbes from between 1330-1340) and the exceptional character of their medieval lead-network (they both date from the 14th century), we thought it would be very interesting to focus on this topic in order to trace similarities and differences, contributing in this way to a better knowledge of the few medieval window leads still preserved. This comparative work is basically based on the working methods, carried out in two different countries around almost the same period.

The Monastery of Santa María de Pedralbes

The monastery of Santa María de Pedralbes, located outside the city of Barcelona, was built around 1328 by royal initiative and dedicated to the Order of Saint Clare. Due to its monastic and closed character, the monastery has preserved, among many works of art from different periods, an exceptional ensemble of stained glass windows, most of them dating from the 14th century¹ (ca. 1328-1330).

We still do not have at present any information available from the church archives, which would hopefully give us some important information on the author, dating, later interventions, etc. Nevertheless, what is almost certain is that this ensemble of 14th century windows in Pedralbes, due to their homogeneity in style, iconography and technique, were made in a short period of time and can be attributed to the same artist. By stylistic comparison with the 14th century windows preserved at the Cathedral of Girona, from around 1350-1360, also from an unknown artist, the so called Master of the Presbytery², we can almost be sure that the windows in Pedralbes and Girona were made by the same person, the

¹ Ainaud de Lasarte, J., Vila-Grau, J., Escudero i Ribot, M. A., Vila i Delclós, A., Cañellas, S., Mundo, A. M. *Els vitralls de la catedral de Barcelona i del Monestir de Pedralbes*. CVMA, Espanya 9, Catalunya 4. Institut d'Estudis Catalans. Barcelona, 1997, p. 26. Apart from the 14th century windows, there are also a few 18th century windows and some pieces from the 15th and 16th century.

² Ainaud de Lasarte, J., Vila-Grau, J., Assumpta Escudero i Ribot, M., Vila i Delclós, A., Marques, J., Roura, G, Marquez, J.M., *Els vitralls de la Catedral de Girona*. CVMA, Espanya 7, Catalunya 2. Institut d'Estudis Catalans. Barcelona, 1987, p. 17-19.

ones in Pedralbes being an earlier work. In this case, it would be important to remember that this is the same author associated with the two well known glazier's tables which were used for making some of the panels, today preserved at the museum of the Cathedral of Girona.

In November 1972, the municipality of Barcelona took charge of a global conservation and restoration programme in the monastery. As a result, in September 1998, one of the 14th century windows in the church (OII) was dismantled³. This window consists of two lancets and a total of 51 panels. It depicts in the lower panels Saint Peter and Saint James under a baldachin. The upper panels represent geometrical and decorative motives with a rich variety of colour (picture 1). This structure of composition, repeated throughout the remaining of the 14th century windows, is also very similar to the one in the Girona windows.

After the preliminary inspection of the panels, the most striking fact was the excellent condition of the original glass (apart from some of the red glasses, there are no corrosion phenomena) and the presence of a medieval lead-network in most of the panels⁴. As far as we know, only the windows from the Monastery of Pedralbes and the ones from the Monastery of Santes Creus in Spain have a preserved medieval lead network⁵. This fact makes the lead in Pedralbes one of the oldest preserved examples in Spain, and gives to this discovery an exceptional relevance.

The Cathedral of Altenberg

The old Cistercian Abbey of Altenberg, near Cologne, built around 1270, has one of the biggest preserved ensembles of Cistercian medieval grisaille windows in Germany. The windows were restored several times throughout the centuries and in consequence releaded. Although the present lead network in most of the windows dates approximately from the 1970's, there are three windows which have survived this releading and for the most part still contain a medieval lead network (NV, NVI and NVII). It is interesting to point out that contrary to Spain where, as far as we know, only the windows from Pedralbes have preserved their medieval lead, in Germany these are more numerous. These ornamental grisaille windows depict geometrical and foliage motives using mainly greenish glass (picture 2). This sober decoration is one of the main characteristics of the Cistercians Order. In 1995 Glasmalerei Peters, Paderborn, took charge of the restoration and documentation of most of the windows in the cathedral.

³ The restoration works are been carried out at the Secció d'arqueologia Urbana from the municipality of Barcelona.

⁴ Only two panels have been recently releaded, probably at the end of the 19th century (CVMA, Espanya 9, Catalunya 4).

⁵ Recently, new windows with medieval lead have been discovered: in the church of Cervera and in an church in Girona.

Some important aspects on the production of medieval window lead

Lead, in the form of comes, has always been, since the beginning of the production of stained glass, the main element used for keeping the pieces of glass together. The many advantages of this metal, its malleability, flexibility, low melting point, low cost, resistance to corrosion, etc., have made it an ideal material for this purpose, with no rival in this field until the introduction of copper and concrete in this century.

As far as we know, the oldest written source on the production and use of lead comes for windows still in existence is the manuscript of the monk Theophilus⁶, written around 1120. He describes the process of melting and casting the lead in moulds, the making of the soldering bars, the soldering processes, etc. Along with Theophilus, the treaty of Antonio da Pisa⁷, dating from around the end of the 14th century, is the most contemporary source relating to the windows in Pedralbes and Altenberg. The processes described in these two manuscripts, which remained almost unaltered until the 16th century, can be followed in these windows, helping us to understand the working methods of that period.

In medieval times, lead was cast into two-piece wooden or iron moulds to form the typical H-profile comes. Since these comes were cast, their hearts were flat and very smooth. Much later, in the 16th century, the use of a lead mill for shaping the leads into H-profile comes was introduced. Most of these early mills produced the typical lead milling marks on the heart of the comes, which neither the comes from Pedralbes nor the ones in Altenberg have.

During the Middle Ages, the manual process of casting lead would result in comes with a large variations in shape, much more irregular than later leads made with a lead mill. Medieval lead does not have the straight corners so typical to modern lead, being more rounded, especially at the joints between the heart and the leaves. These irregular, but more rounded shapes had a great influence on its durability, giving them a better resistance to deterioration by avoiding the stress which is normally placed on sharp corners.

In Pedralbes, as in Altenberg, the hearts of the comes are quite thin and flat, with very irregular thickness (0'6-0'9 mm in Pedralbes and 0'4-0'6 mm in Altenberg). On the other hand, these hearts have quite a regular height (3 mm in Pedralbes and 3-4 mm in Altenberg). The total height, including the leaves, is 5-6 mm in Pedralbes and 6,5-7 mm in Altenberg. This means that the leaves in Altenberg (1,6 mm) are thicker and more rounded than the ones in Pedralbes (1 mm). Concerning the stability of stained glass windows, it is important to remember at this stage, that the height of the heart plays a much more important role than the breadth.

⁶ Theophilus, *On Divers Arts*. Translated by Hawthorne and Smith, New York, Dover Publications Inc., 1979, Book II, p. 67-71.

⁷ Pisa, A. da, *Arte Delle Vetrate*. End of the 14th century. Editalia, 1977. Introduction by Salvatore Pezzella.

The average leaf-breadth in the same lead came is, in both ensembles, not very regular and homogeneous, oscillating approximately between 4 and 6 mm in Pedralbes and 4 and 5 mm in Altenberg. This means that in Pedralbes there are more variations of leaf-breadth in the same came. One exception to this rule can be found in the reinforced double leads in Altenberg. This double leading, which are the same ones used for the general lead-network, gives the impression of a broader came. Through this difference in breadth, we can deduce the important aesthetic role that was given to the lead-network as a design element of the general composition during medieval times.

A practice commonly used by the glaziers was the manual scraping and flattening of the lead leaves in order to eliminate the irregularities produced during the casting process. This was probably done on a draw-bench using some kind of sharp knife. This process, which is also described by Theophilus, is still visible on the typical patterns of lines along the outer leaves surface in the panels from Altenberg. This means that the slightly rounded profile of the leaves was even more accentuated originally. This flattening process was not made in Pedralbes, where the leaves are quite flat and do not show these patterns of lines, parallel to the length of the comes.

After the casting, one of the next steps was the drawing or stretching of the lead comes, in order to make them longer. This method, which allowed the glaziers to gain extra lead out of every came, thus saving material, had the disadvantage of making the lead weak and brittle, increasing the risk of fractures. The first written source on this practice dates from approximately the second half of the 15th century⁸. A short time later, at the end of the 15th century and beginning of the 16th century, and due to the above mentioned disadvantages, this practice was forbidden⁹. Nevertheless, this stretching of the lead comes does not seem to have been done in Pedralbes and Altenberg. Here, the different variations in the breadth of the leaves in the same piece of lead could be explained by the irregular forms of the moulds in which the lead was cast. Although it seems logical to assume that this practice was used by the glaziers right from the beginning of the production of stained glass, we still do not have enough evidences that this practice was used before the 15th century, and further research on this particular aspect is obviously needed.

Consequently, the pieces of glass were leaded up. In general, we could say that the leading up process was done almost in the same way as it is nowadays, that is, by inserting every piece of glass into the comes, then introducing the edges of one or more comes under the leaves of a main one and in this way creating a soldering joint. At this stage, it is interesting to point out that in the joints from Pedralbes and, to a minor extent, from Altenberg, there is no direct contact between the hearts of the comes. As a result, an inner space of 2 to 3 mm between the hearts is always left. Although these openings were com-

⁸ Frenzel, G., *Die Verbleibung Historischer Glasgemälde*, in „C.V.M.A.“, 16. Intern. Kolloquium Bern, 1991, p. 2-3.

⁹ This prohibition is to be found in the regulations of different guilds (Wismar -unknown date-, Rostock -1476-, Freiburg -1484 and 1513- and Prague -1527-) and in the accounts from some churches (St. Adalbert in Breslau -different times between 1487 and 1500); taken from Oidtmann, H. (1929, p. 451-452) and Frenzel, G. (1991, p. 2).

pletely covered by the solder, this method makes the joints very weak and can seriously affect the stability of the panels.

The solder was made of a tin-lead alloy, the percentage of these two elements varying from one glazier to the next. According to Theophilus, the solder was melted and then cast into the same moulds used for lead came. Through this it was possible to obtain thin solder bars and avoid the process of having to make a special mould for the solder.

As already explained by Theophilus, before the soldering of the panels, every joint was lightly scraped and, subsequently, some kind of fat or oil was applied to it in order to enhance the adhesion of the solder to the lead. The soldering was made with a glowing iron bar. A small spot of solder was applied to the tip of the soldering bar, which was then held on the joint for a few seconds, during which the solder would spread evenly.

At this stage, only by means of experience, the glazier would have to have special care in keeping the temperature of the soldering-iron above 183°C (melting point of solder) and below 327,4°C (melting point of lead), in order not to burn the underlying lead¹⁰. The obvious difficulty presented by this working method can be clearly seen by carefully looking at the soldering joints in both ensembles. Only in Altenberg we could find, here and there, some traces of burnt lead, due to too high a temperature of the soldering-iron. Contrary, in Pedralbes, none of these areas of burnt lead were found and the irregular forms of the solder probably indicate that the soldering-iron was not hot enough.

While the thickness of the soldering joints in both ensembles is very similar (between 1 and 2 mm), the joints in Pedralbes are considerably larger in extension. They form thick and uneven blobs of solder which spread along the came between 2 and 3 cm out of the actual joint. In many places, they even come out of the came or only partially cover it in thin and pointed blobs. In Pedralbes, many of these solder blobs are located in the middle of a came in order to cover the gaps left by slightly smaller pieces of glass which were not completely inserted into the came (picture 3). Contrary, the joints in Altenberg are more even and rounded, spreading between 1 and 2 cm out of the joints. On the other hand, while in Pedralbes all the joints are still contemporary to the lead-network, in Altenberg, many of the joints were reinforced during the restoration carried out in 1975-1976, covering the original solder. This sometimes makes it difficult to distinguish between original and later added joints.

Normally, the panels were soldered on both sides, as it had been advised by Theophilus. The fact that he advises this practice means that it was not always carried out. Nevertheless, both in Pedralbes and Altenberg, the panels were soldered on both sides. Sometimes, only the joints on the comes at the edge of the outer or inner side of the panels were left unsoldered, so that they could be easily taken out in case the

¹⁰ The melting point of lead (327,4°C) is drastically reduced to 183°C (melting point of solder) by the addition of tin (232°C). This resulted in a new alloy which was much easier and favourable to work with

panels would not fit into the stone frame. This practice was carried out at the panels from Pedralbes, where the joints at the outer side were left unsoldered.

In many medieval windows, the insertion of an iron or wooden bar in between two or three lead comes was a common practice among certain glaziers. These bars could be straight or curved, in metal or in wood. They had two different functions. The first one was the reinforcement of the panels, giving them more stability. The second was an aesthetic function, giving the different lead thickness an important decorative role. The panels from Altenberg were reinforced with these iron bars, inserted between two lead comes and located vertically at the sides of a main decorative motive (picture 4). Contrary to Spain, where no examples of this kind have been preserved, if indeed they were ever used, in Germany there are still a few medieval windows where this technique is to be found¹¹.

Sometimes the glaziers would tin the complete outer surface of the lead comes on both sides in order to gain more stability. This practice, normally called tinning, which was not used in Pedralbes, is to be found in Altenberg although limited to the above mentioned reinforced double comes. These double comes were joined together by tinning them.

Normally, one of the final steps in the making of a stained glass window is the cementing of the panels. In no single treaty before the 15th century is there any mention of the use of putty. This cement, used to make the panels wind and waterproof, thus securing the glass pieces to the lead and giving more stability to the panels, was introduced later, probably in the 16th century. It is therefore quite possible to assume that these panels were originally not cemented. A fact which supports this theory is the use of thick blobs of solder to cover certain gaps, which could normally have been covered with putty. The panels in Altenberg were cemented in the last restoration works in 1975-1976, while the ones in Pedralbes were not cemented at all.

Sometimes, the glaziers used to engrave certain marks or ciphers on the hearts of the leads at the edge of the panels in order to easily identify the exact location of every panel in the building and in the window. According to Frenzel¹², this practice gradually disappeared at the end of the 14th century, or at least no later examples have been found. He stated to have seen such marks in the panels from Altenberg¹³, although unfortunately we did not manage to find them. None of these marks were found in Pedralbes.

The glaziers reinforced the panels using one or two horizontal or vertical iron bars. These bars could be soldered to the interior or exterior side of the panels. The present bars at the interior side of the panels, are not the original ones and date from a much later period. Considering that some examples of iron bars from the 13th and 14th century have been preserved in other windows, it seems reasonable to as-

¹¹ According to Oidtmann, this procedure would be typical only for Germany (Oidtmann, H., 1912, p. 40-41). This is still to be seen in some of the medieval windows at the Cologne Cathedral, Altenberg Cathedral, Cloister of Haina, etc.

¹² Frenzel, G., 1991, p. 2.

¹³ Frenzel, G., 1991, p. 2. These marks were probably found during the restoration of the windows carried out by the firm Oidtmann between 1975 and 1976.

sume that the panels from Pedralbes and Altenberg were originally also reinforced with such horizontal bars.

Dating of the lead network

Neither the panels at Pedralbes, nor the ones in Altenberg have preserved their original lead network. We can deduce this by the presence of many mending leads. These mending leads, although they do not belong to the original composition, date from the same period as the lead-network. The regular releading of windows was a common practice, even short after their installation, due to different conservation reasons. Every break in the glass was then repaired by means of mending leads. There are also, but only in Pedralbes, a few later superficial mending leads without heart used to hide some fractures, soldered at both sides of the piece. Other minor leads which are also present in these panels are the lead-ties used for binding the horizontal bars, which are from a later period.

In order to date the lead network of both ensembles, different factors and considerations were taken into account. First: the fact that in both ensembles the comes have been cast in moulds. This theory is supported by different facts: the irregular form and breadth of the comes, the fact that the leaves in Altenberg have been manually scraped to eliminate irregularities and the absence of lead milling patterns, which started to appear in the 16th century. According to this hypothesis, the lead-network in both cases should therefore date from before the 16th century.

Secondly, considering that the practice of engraving marks or ciphers on the hearts of the leads at the edge of the panels disappeared at the end of the 14th century, the network in Altenberg could then not be older than the 14th century.

Thirdly, according to Frenzel's classification of historical lead comes¹⁴, the lead in Pedralbes would match category 3 (early 14th century) or 7 (1380-1550), and the ones in Altenberg category 5 (second third of the 14th century). Likewise, the reinforced double leads from Altenberg would match category 6 (middle of the 14th century). Although this classification is only approximate and it should not be taken literally, it does place these lead comes into a concrete period, that is, between the early 14th century and the beginning of the 16th century.

The last indication of dating is the time between the conclusion of the windows (Pedralbes between 1330 and 1340 and Altenberg from approximately 1280) and the first restoration, during which they were releaded. Although this space of time obviously depends on too many factors, considering that the average interval of time in which a window needs a new restoration could be approximately 25 to 75 years, it also gives us a different dating parameter.

¹⁴ Frenzel, G., 1991, p. 4.

Taking into account all the above mentioned factors, it would be quite reasonable to date the lead-network in Pedralbes from the second half of the 14th century and the one in Altenberg from the first half of the 14th century.

State of conservation

At first sight, we can say that the lead comes are, in both cases, very stiff, have little flexibility and, in comparison with modern lead, are much harder to bend. These characteristics are even more extreme in Altenberg. There is a general loss of gloss and darkening of the leads due to the formation of a dark oxidation layer on the surface. These layers are accompanied by the formation of a crust of oxidation products. These crusts are thicker in Pedralbes where they have a light brown coloration and cover the entire surface of the comes, while in Altenberg, they only cover the outer side of the leaves.

While lead corrosion phenomena are very limited, we can appreciate different traces of solder corrosion in Altenberg. These are especially evident on the leads which were in contact with the gypsum mortar, which have been more easily affected by corrosion. Likewise, the oxidation of the iron bars between two lead comes, has also led to corrosion of the solder around them.

In other places we can distinguish between different forms of cracks on the soldering joints. This is due to the great influence of the method of soldering the panels on their stability and state of conservation. Two main factors which play an important role on this deterioration process: the amount of solder applied on the joint and the stress set up between the hot and cold metal during soldering. As a consequence, too little solder produces weakness and too much solder leads to cracks around the joints, due to the different coefficients of expansion of lead and solder. On the other hand, the stress incurred between the hot and cold metal during soldering accelerates fatigue. This has led to cracks on the contact areas between lead and solder and also between two comes. Although the soldering joints in Altenberg are more discrete than the ones in Pedralbes, they are, in some places, more affected by corrosion. Nevertheless, due to the fact that the cracks in the leads from Altenberg were reinforced during the last restoration, these corrosion phenomena are limited to only a few joints. All these corrosion phenomena are exclusively present in Altenberg, showing the leads in Pedralbes no traces of lead or solder corrosion.

Conversely, the panels from Pedralbes show a great deformation and bending towards the interior side, especially on the lower parts. This is probably due to the natural fatigue which affects lead with the passing of time. This deformation of the panels has made it more difficult in the handling of the panels during restoration, leading in some cases to pieces of glass coming out of the lead comes and fractures in the middle of a came. Wind pressure, vibration and thermal cycles are some of the main causes of fatigue failure in lead. This phenomenon is not exclusive to medieval lead. Many windows from the 19th

and 20th century also show this typical deformation. However, the panels in Altenberg are perfectly straight and flat due to the presence of reinforced double leads and to the fact that they were recently restored (between 1975-1976), then being reinforced with messing frames.

Concerning the total amount of medieval lead preserved in these windows, we could roughly state that approximately 98% of the total network in Pedralbes and 70% in Altenberg dates from the 14th century. This 2% of lead from different periods in Pedralbes can be explained by the presence of a few lead-ties and the mending leads without heart soldered at both sides of some fractures. They both date from a later intervention. Here also, some of the leads at the edge of the panels have been lost, which has made it necessary, during recent restoration, to use new lead. Contrary, the panels from Altenberg have suffered from more drastic restorations during this century, having lost approximately 30% of their medieval lead.

Lead comes composition

Although the impurities contained in the raw material (the ore) have been known since ancient times, neither Theophilus nor Antonio da Pisa mention anything on the process of removing these minor components from the lead. The production of lead with a purity above 99% had been already achieved since the Roman period and this relatively pure lead was used for stained glass windows during medieval times. The process of removing the impurities was probably carried out, although it was obviously not the work of the glaziers. We know today, that medieval lead comes are slightly different in composition to those produced after 1833, when the improvement of silver removal was introduced, producing an even purer lead. These slight differences of purity between medieval and modern lead are due to different reasons: the small percentage of impurities which remained in the lead after their first removal, (silver, tin, copper, antimony, etc.), the impurities accidentally picked up by the lead during the manufacturing process and the melting down and recasting of old lead comes taken out of windows, for use as new comes, which added tin to the new lead alloy.

At this stage, it is important to point out that the very high concentration of tin in the samples from Altenberg probably indicates that this lead is the result of re-melting an old lead network.

A good knowledge of the internal grain structure of the lead can be very important in order to obtain some extra valuable information on the re-crystallisation of the network occurred during the melting process. The thickness of these grains varies according to the composition of the lead and therefore to the different periods. In general, pure lead produced in the 19th century, has bigger grains (average grain diameter up to 77 μm) than medieval lead which contains certain amounts of impurities (average grain diameter between 10 and 30 μm). The very high concentration of tin (between 0,5 and 0,7 %) in the

samples of Altenberg probably indicates that this lead is the result of re-melting an old lead-network which still preserved the tin from the soldering joints.

Concerning the composition of the solder, this has always been mainly made of a tin-lead alloy. Nowadays, the most commonly used solder for stained glass windows contains 61,9 % of tin and 38,1 % of lead, and has an melting point of 183°C. Historically, the percentage of these two elements could greatly vary from one glazier to another. These differences are also quite evident in the different early treatises which have been preserved. For example, Theophilus recommends the use of 1 part of lead mixed with 5 parts of pure tin (that is, 16,6% lead and 83,3% tin) and Antonio da Pisa advises the use of 1 part of lead mixed with 1 part of tin (that is 50% lead and 50% tin). These differences in composition could also play an important role in the stability and the state of conservation of the windows.

The weathering of lead

Although it is not the intention of this article to give a detailed description of the different weathering processes affecting lead, we will summarise the most relevant aspects in order to have a clearer image of the condition of the panels from Pedralbes and Altenberg.

Lead is, in general, very resistant to corrosion by the atmosphere, sea water and a wide range of industrial chemicals. The formation of a protective oxidation layer and its resistance to corrosion in various aggressive environments is perhaps one of lead's best known properties. Nevertheless, certain factors can play a very important role in its resistance to weathering, enhancing the progress of the different oxidation and corrosion phenomena. These factors can be both internal, like the composition of the lead, and external, like air-pollutants.

Concerning the composition of lead, the small percentages of impurities contained in medieval lead make it quite different to modern lead in terms of its resistance to weathering and durability. The very pure lead obtained after 1833, exhibits fatigue cracking, which did not occur with the older argentiferous lead¹⁵. A higher percentage of tin, antimony or copper increase considerably the tensile strength and hardness of lead at ambient temperatures, making the lead network stiffer and less elastic, but also less subject to corrosion. Copper and silver, on the other hand, alter the crystal structure of lead significantly, reducing the size of the grains in the network. They confer the new alloy better mechanical properties and enable it to withstand the flex and stress placed on it.

Likewise, the presence of fractures in the lead might also enhance corrosion. These fractures, caused by stress, advance towards the interior of the lead bulk in between the grains, separating them but without

¹⁵ Newton, R. G., *Fact or fiction? Can cold glass flow under its own weight and what happens to stained glass windows?*, in „Glass Technology“, vol. 37, nr. 4, August 1996, p. 143.

causing their fracture. These openings allow the entrance of polluted water, which might stimulate the progress of the corrosion process, gradually disintegrating the lead grains one by one.

The main external factors are: high humidity, certain gasses present in the air, like carbon dioxide, some acids like acetic and nitric acid, certain wood sorts, especially in wet environments, products dissociated from sulphur and chloride, certain commercial paints, glazes, boron and some cleaning products¹⁶.

Concerning the environmental conditions, the presence of water is essential for the corrosion of lead to take place. Certain pollutants present in water can thus enhance lead corrosion. They determine the acidity levels of water. There are two sorts of pollutants in the air affecting the weathering process of lead¹⁷: gaseous pollutants (SO₂, NO_x, O₃, Cl₂, HCl, H₂S, organic acids, etc.) and aerosol particles (chlorides, sulphates, nitrates, etc.).

The first stage in this deterioration process is the formation of a close fitting and adherent film of lead oxide or carbonate, by a rapid reaction with the newly exposed lead. This is followed by a second reaction between this film and the carbon dioxide present in the atmosphere, thus forming a protective film of lead carbonate. Further contact with the pure metal in the lead bulk is then prevented, stopping the corrosion phenomena. The reaction products formed by the carbon dioxide (CO₂) present in water with the lead ions (Pb²⁺) can be of two types: neutral or basic carbonate. These products are very insoluble and form an homogeneous layer of inorganic salts which contribute to the protection of the lead. Similarly, with sulphuric acid, a protective film of lead sulphate is formed. This, being closely adherent and insoluble in all but the most concentrated form of the acid itself, protects the lead from further attack.

Contrary, the combination of lead ions with organic species, like formic acid, acetic acid, oxalic acid, etc., can dissolve these products, making the lead lose its resistance to corrosion. Another important factor which accelerates these corrosion phenomena are the high levels of air-humidity.

Other external factors can also dissolve the oxidation film formed on the lead surface, enhancing the corrosion of the lead. For example, dilute solution of organic acid leached from damp timber can, over a period of years, cause lead to slowly corrode. Portland cement contains free alkali which can also stimulate a slow corrosive attack on lead in the presence of moisture. Another type of corrosion, the electronic corrosion, can be stimulated when two dissimilar metals are in close contact, thus creating a galvanic cell.

¹⁶ Noehl, R., *Korrosion von Fensterblei (Erstens frisches Blei, zweitens Nässe, drittens Säuren)*, in „Glaswelt“ 4 (1991), p. 26.

¹⁷ Fiaud, C., *Le problème de l'altération des plombs anciens*, in „Actes des Journées d'études du Centre International du Vitrail (Chartres)“, Bourges, 28-29 October 1993, p. 170.

Experimental research on original samples

As part of this research project, a few samples from Pedralbes and Altenberg were studied at the Bundesanstalt für Materialforschung und -prüfung in Berlin by Dr. Detlef Kruschke. Two samples from every location were examined under the microscope with magnifications ranging between 25x to 500x. Different aspects were taken into account: the lead, the solder, the fractures, the various oxidation and corrosion phenomena and the presence of trace elements.

A small representative part (approx. 5 mm) of the different samples was introduced in an epoxy resin and polished. These polished areas were shortly etched (5-10 seconds) with a solution of 4,25 p. Glycerine, 1 p. nitric acid and 1 p. acetic acid, then rinsed with water and photographed under the microscope. A second etching was carried out on the samples with a solution of 2 p. Alcohol, 0,24 p. hydrochloric acid and 0,12 p. nitric acid.

By means of a microsonde, an analysis of the different samples was also carried out. With this technique, only the samples with a concentration of lead bigger than 99 % and the trace elements with a concentration bigger than 0,1 % could be detected. Nevertheless, we can deduce their presence and estimate their concentration by careful interpretation of the pictures taken under the microscope.

These are the most relevant results from the analyses:

Altenberg, Sample 1: cross-section of a lead came with soldering joint; it seems that this joint has been soldered twice with solder of a clearly different composition. Due to the too high temperature of the soldering bar, a re-crystallisation of the internal structure has taken place. With the microsonde, a concentration of 99,8 % lead was detected in the sample. The average grain diameter is very small (16 μm).

Altenberg, Sample 2: cross-section of a came. This sample had a very normal grain structure. The very high concentration of tin (between 0,5 and 0,7 %) probably indicates that this lead is the result of re-melting an old lead-network which still had preserved tin from the soldering joints. The average grain diameter of 16 μm is, in comparison with lead produced after 1850, with a grain diameter up to 77 μm , very small. This indicates the presence of trace elements, other than tin, which could not be determined with the microsonde.

Pedralbes, Sample 1: cross-section of a came with a thick soldering joint. A particular internal structure created in the network during the casting is still visible. Along this structure, there are certain trace recognisable elements, mainly tin. The average grain diameter is 19,9 μm .

Pedralbes, Sample 2: cross-section of the leaf of a later mending lead without heart. Here there is a recognisable corrosion structure. The average grain diameter is 25,2 μm .

Conclusions

Finally I would like to briefly summarise the main results of this research (Table 1).

The most important conclusion is the better quality and greater care for all the production details in the panels in Altenberg. The reason for this is probably to be found in the much longer tradition of the German stained glass art in comparison with Spain, still noticeable nowadays. This is to be seen in the continuous care and restorations been carried out during the centuries, the re-melting of old lead-networks, which makes the panels more resistant, the reinforcement of the panels with iron bars, the aesthetic role given to the different lead-thickness, the soldering of the whole surface of the leads, the engraving of marks to easily identify the location of the panels, the flattening of the comes to eliminate irregularities, the quality of the soldering, like better joints and better the contact between the hearts and the more rounded forms of the comes, which make them more stable.

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