Santa Maria del Fiore Cupola construction tools: a non-invasive characterization using portable XRF

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Santa Maria del Fiore Cupola construction tools: a non-invasive characterization using portable XRF

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***Abstract* – The construction of the Santa Maria del Fiore Cupola, also known as Brunelleschi's Cupola, was one of the most challenging and revolutionary projects of the Renaissance, specifically from the technical point of view. The Cupola, whose construction was completed in 1436, more that 100 years after the beginning of the Cathedral building, is one of the greatest architecture masterworks. Its construction was possible only thanks to the revolutionary ideas and innovations of Brunelleschi's project. New tools and machines were designed in order to overcome the technical difficulties of the project. Some of these tools, property of the 'Opera di Santa Maria del Fiore' and preserved in the Museo dell'Opera del Duomo in Florence, were never analysed. This paper presents the performed investigation and the preliminary obtained results related to XRF measurements. These can be of great interest in order to define the origin of these historical tools and their production technologies.**

I. INTRODUCTION

The construction of the Santa Maria del Fiore Cupola (Dome) in Florence (Italy) was one of the most innovative projects of the Renaissance. This unique masterpiece, built by Filippo Brunelleschi, was innovative and challenging under many aspects. As a matter of fact, *Maestro* Brunelleschi was the only one capable of completing the Cathedral project, after the Cupola remained unfinished for 50 years.

The construction of Santa Maria del Fiore cathedral started in 1296, thanks to the project of the Italian architect Arnolfo di Cambio and it took more than 100 years to complete the works that lead to the construction of the cathedral main body, leaving the facade and the cupola unfinished [1]. The incomplete church contrasted with the reputation that Florence had in the 14^{th} century, as one of the most important European cities. The project aimed to attract people and pilgrims and to show the importance of the city itself, by the construction of the cathedral with the biggest cupola in the world [1, 2, 3].

Only in 1420, after a long competition between many architects, Filippo Brunelleschi was able to convince the commission with his project, even if his work was surrounded by scepticism until the completion of the Cupola, 17 years later [2, 3, 4].

The Cupola construction project had to face many challenges; the major one was its size. The support structures necessary to build it with regular techniques would have been so large that they would have collapsed under their own weight. Indeed, Brunelleschi, as many artists in the Renaissance, looked back to the Roman best practices. As a matter of fact, he studied many Roman constructions, with particular attention to the Pantheon in Rome (AD 118). Notwithstanding, Brunelleschi was able to deduct, modify and adapt some ancient techniques to this absolutely innovative project [1, 2, 5, 6]. Among the Roman best practices that were used in the Pantheon project and that the *Maestro* modified for the Duomo project, it is worth to notice:

- the use of concrete [7], that inspired him to use lighter bricks combined with fast setting mortar, since the concrete formula was lost [2];
- the use of centering, that was not possible for this project, considering the Cupola height and dimensions, but lead him to build the dome directly

Fig. 1. Hystorical tools displayed in the Museo dell'Opera del Duomo. From the left: pincers, turnbuckles, three-legged lewis, pulleys.

on the drum, keeping the structure stable in all the construction phases [1];

- the insertion of spiral shaped spines of vertical oriented bricks ("a spina di pesce") was the key to make the cupola self-supporting while in construction;
- the Pantheon foundational base: Brunelleschi designed a drum, that was 9 m high and that could support the dome weight;
- the use of external stepped-rings for the dome support was interpreted to create a double-walled dome;
- the use of lighter concrete at higher height, that was translated in the thickness reduction of all the elements used in the construction [5];
- the oculus in the roof center became the conjunction between the two dome shells [8];
- the use of scaffoldings, that was not possible and that was substituted by the use of suspended platforms that could be moved as the construction proceeded [7];
- the production of materials on site was an unfeasible strategy, because of the great amount of supplies that the construction required in order to deliver the project without further interruptions [2];
- the Roman construction engines, that inspired the architect to design specific machines and tools to lift and transport the building materials [1, 3].

Machines and tools were a real breakthrough for the realization of the project, because they allowed to save time and reduce the overall cost. Actually, loads and stones handling constituted a major issue for the Cupola construction. The design of these truly innovative tools and machines by Filippo Brunelleschi is part of the technical novelties conceived thanks to this project. Drawings of these tools were realized by Taccola, Francesco di Giorgio, Bonaccorso Ghiberti (grandson of Lorenzo Ghiberti, co-chief architect of the Cupola), Giuliano da Sangallo [1] and Leonardo da Vinci in many sheets of the Codex Atlanticus [10]. Nowadays some pieces of this equipment, that are part of the Opera di Santa Maria del Fiore collection, are displayed in the Museo dell'Opera del Duomo, in Florence. The museum collection is composed of more than 750 artefacts presenting the history of the city and among them also objects like the pulleys, turnbuckles, pincers, winches and ropes used in the dome construction and maintenance are displayed.

During centuries, these unique objects received limited attention, probably underestimating their value. Actually, artefacts characterization can help curators in finding the best conservation strategies [9]. Moreover, many of these tools can give important information on the materials used in the construction site and on the production routes typical of the Renaissance. Some indications can derive from their visual appearance, but in many cases the procedure is complex and requires analytical investigations. This research project aims to study these historical tools stored in the Museum with a non-invasive approach in order to understand which materials were used and to have insights on the production techniques employed for the tools that realized the largest Cupola in the world.

Thus, an in-situ and non-destructive measurement campaign was carried out. Specifically, X-ray fluorescence analyses were performed on the objects and the obtained preliminary results are presented in this paper.

II. MATERIALS AND METHODS

A. *The hystorical tools*

This study investigated the alloy composition of different tools, currently exhibited in the Museo dell'Opera del Duomo. Aim of the investigation is to determine whether this tools could date back to Brunelleschi's yard, deriving possible new hypothesis from the materials constituting the objects and thus the corresponding production techniques. They include pulleys, turnbuckles, pincers and a three-legged lewis; a photograph of some of the analysed tools is shown in Figure 1. Pulleys were generally used to lift loads and stones from ground floor to one of the platforms where laborers were working. The other tools were specifically intended for precise locating of stones in the building structure. Turnbuckles substituted steel rods for the stone positioning, reducing the risk of chipping them during this operation. Moreover, they had unique efficacy when the project required to locate heavy blocks in specific positions, moving steadily. Pincers were used to clamp and move stones between different levels of the building site, while the principle of the lewis is to realize a clearance in the stone in order to insert in succession the three parts and then lift the load.

B. *X-Ray Fluorescence*

In order to investigate the constituent materials of the tools employed in the Cupola construction, portable X-Rays Fluorescence Spectroscopy (p-XRF) was exploited. XRF is frequently used coupled with Raman spectroscopy [11] and Photogrammetry [12] for in situ survey of artefacts collections, and thanks to its portability, non-invasiveness and non-destructiveness, it is particularly suitable for this project. As a matter of fact, these historical tools are stored and displayed in the Museo dell'Opera del Duomo and they can not be moved outside the building or damaged. Thus, p-XRF meets all the requirements to study them.

Measurements were performed by means of a Bruker Tracer 5i analyzer. This instrument can be used both as standalone or connected to a personal computer. In both the cases it is possible to monitor the acquired spectra and the measurement settings. The analyser is equipped with a 20 mm^2 silicon drift detector and a Rhodium (Rh) anode. It is provided with an inner filter wheel, that allows to select the proper filter depending on the elements that have to be analysed. In this case, the Ti-Al filter was chosen in order to reduce the presence of peaks related to Rh and Pd, always present and due to the instrument itself, and to enhance those of S and Cl, as commonly done during the analysis of high atomic number alloys. Analyses were carried out using voltage and current values of 40 kV and 40 μA respectively, with the 3 mm collimator. Data were processed by means of the Artax Spectra (8.0.0.476) software. In particular, elemental interference (pile up and escape peaks) and background were corrected and Bayesian deconvolution was performed in order to obtain the net counts rate for each element.

III. RESULTS AND DISCUSSION

In this study, results from the XRF analyses performed in a preliminary measurement campaign are presented. Specifically, the aim was to carry out a survey of the materials used for the realization of the different tools in order to better clarify the production routes of this equipment. Thus, different points of analysis were chosen for each object so as to obtain a general overview of the involved alloys.

Specifically, great interest was arisen from threaded parts because in the 15^{th} century, during the Dome construction, technologies did not allow to produce the nut-screw in iron either by casting or by cutting operations. Actually, techniques which allowed to reach the iron melting temperature were available only from the 17^{th} century. So these analyses can also give an additional evidence of the authenticity of the tools, dating back to Brunelleschi time.

XRF measurements allowed to identify iron-based alloys as the most frequent material constituting the tools. The appearance of the surface suggests that the objects were produced by hammering, so as to give the material its final shape and to strengthen it by plastic deformation. As an example, Fig. 2 shows the spectrum acquired on one of the pincers. The two main peaks at 6.40 keV and 7.03 keV can be attributed to iron, which is the main constituent of the material; then, other elements like zinc, lead and copper were identified. Other minor peaks were attributed to potassium, calcium and aluminum and can possibly be related to environmental contamination.

Between all analyzed objects, a remarkable example is then represented by the turnbuckle. As can be seen from Fig. 1, it is composed by different parts, namely the central screw, the nut, the hook and two connecting rods. Results showed that lead-bronze was employed in the realization of the nut, while the remaining parts were made of steel. The spectrum acquired analyzing the nut is shown in Fig. 3. The main constituents of the piece are copper, zinc, lead and tin related to peaks at 8.04 keV, 8.63 keV, 10.54 keV and 25.27 keV respectively. Additional alloying elements are then manganese, iron and nickel, while calcium can be related to surface contamination.

The use of bronze for threaded parts is in good agreement with information about the processing technologies typical of the Renaissance [13]. It was employed essentially for its good machinability using steel tools, so blacksmiths could easily drill a hole in the component and then thread it. These findings support the attribution of these tools to the Brunelleschi era and give them additional significance. Actually they represent

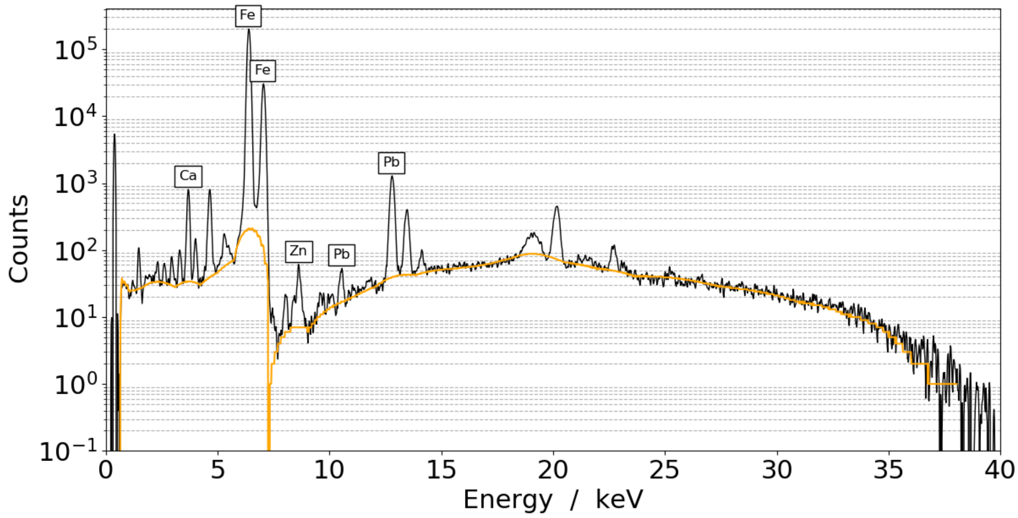

Fig. 2. XRF spectrum acquired on one of the pincers; the computed spectrum background is plotted in yellow. The identified material is an iron alloy.

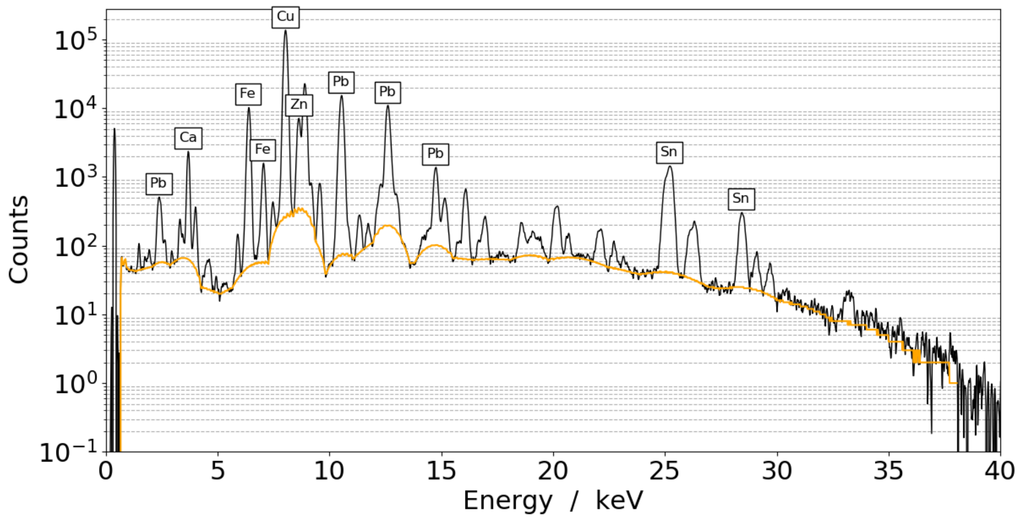

Fig. 3. XRF spectrum acquired on the turnbuckle nut; the computed spectrum background is plotted in yellow. The identified alloy is lead-bronze.

a unique opportunity for curators and researchers to better understand the forming technologies typical of the Renaissance era and figure out how the construction of the Florence Cathedral took place.

IV. CONCLUSIONS

The paper presented the results coming from the preliminary survey of the materials used for the production of the Cathedral construction tools. The analyses revealed the use of iron alloy as main constituent of the objects. Then, interesting findings were obtained on threaded parts, which were realized in lead-bronze, as expected from the traditional processing routes of the Renaissance. Future work will increase the number of points of analysis in order to investigate specific parts of the tools and will try to assess possible differences in the iron-alloy composition.

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