Applications of Additive Manufacturing Technology for the Aesthetic Restoration of Ceramic Artefacts: The First Stages of the Research

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KEYWORDS

Additive manufacturing · Aesthetic restoration · Ceramic · 3D printing · Conservation

INTRODUCTION

Aesthetic restoration treatment, as part of conservation procedure, aims to improve the legibility of an artefact's form, respecting simultaneously its authenticity and history. Traditional aesthetic treatments include re-modelling missing parts with either moulding or casting methods, and reassembly. However, these methods can be time consuming, and if the object is too fragile, could not be appropriate. The end result of aesthetic restoration depends, on a great extent, upon the skills of the conservators. Whilst creative input from the conservator can be invaluable, it may introduce a significant subjective aspect to the process. Advances in technological methods, such as additive manufacturing technology, can complement traditional aesthetic restoration to produce results that may be more objective, particularly in terms of repeatability. They may also provide new solutions in restoration and reassembly of missing parts, improving and advancing the aesthetic restoration treatments overall. This research will apply, test, and evaluate current additive manufacturing technologies and their suitability for aesthetic restoration of ceramic artefacts by recreating missing parts and, where possible, reassembling them. Additionally, the additive manufacturing materials employed will be tested and evaluated, taking into consideration all those factors required of traditional fill materials: reversibility and re-treatability, strength, density, durability, shrinkage, thermal expansion, and long-lasting performance. Finally, the processes will be evaluated regarding their aesthetic outcomes, the time and cost involved, and other implications for object conservation.

This abstract presents the first stages of research: an initial review of restoration principles and additive manufacturing technology; a discussion of a sample of ceramic artefacts from the Greek-Roman and Chinese collections of the British Museum, and from the archaeological collection of University College London (UCL), which are used as case studies; the methodology that has been followed for capturing the ceramic artefacts; and the methodology that will be followed for digitally restoring them, selecting the additive manufacturing materials, and recreating the missing parts.

TRADITIONAL RESTORATION OF CERAMIC ARTEFACTS

Traditional restoration treatments include reconstruction of fragments, replacement of missing parts, and finally, colour retouching. When joining fragments, it is important that the optimum adhesive is chosen. The selection of an adhesive depends on the composition of clay, as well as the size and condition of the object. Mostly, synthetic resins are used as adhesives. For replacing lost fragments, synthetic materials are also used, be they malleable or in fluid form. Thermal expansion of the filling material must be considered, and detachable fills are often the preferred choice. Fills need to adhere to the original, have the appropriate strength and density, maintain reversibility, and allow for adjustments by dyes or pigments for the colour retouch (Buys and Oakley 1993; Λαμπρόπουλος 2004).

The most common fill materials for ceramics are epoxy resins, acrylic resins, and calcium-containing compounds. Plaster of Paris ($CaSO_4 \cdot \frac{1}{2}H_2O$) is the most common calcium-based material. It has similar porosity and weight (2.32 g/cm^3) to lower-fired archaeological ceramics (2.4 - 2.6 g/cm^3). It has also been tested in various temperatures (35 °C to -5 °C), proving that its workability, reversibility, and coefficient of thermal expansion is similar to those properties of ceramic bodies, and more so then when compared to other synthetic fillers such as acrylic, epoxy, and polyester resins (Buys and Oakley 1993; Λαμπρόπουλος 2004). However, it cannot be used for ceramics kept outside because it dissolves easily in rain water (the solubility of gypsum is 0.241 g in 100 ml of water). Another downside to plaster is that when solubilized, soluble sulphates can penetrate a ceramic's pores, which, under specific temperature and humidity fluctuations, can cause crystallisation/re-crystallisation and damage the ceramic object (Plenderleith and Werner 1971; Λαμπρόπουλος 2004).

ADDITIVE MANUFACTURING TECHNOLOGY

Additive manufacturing technology was first invented in 1983-84, when Charles "Chuck" W. Hull inspired the idea of using an ultraviolet (UV) light source for hardening polymer liquid on a tabletop coating, by using his "StereoLithography Apparatus" (SLA) machine (Balletti et al. 2017; Bandyopadhyay and Bose 2016; Hager, Golonka, and Putanowicz 2016). At the same time, he developed a way to make a connection between the digital 3D model of the CAD software and the 3D printer, by creating the STL file, named after the abbreviation of the word STereoLithography (Bandyopadhyay et al. 2016; Gibson, Rosen, and Stucker 2010).

Since then, the technology of additive manufacturing has been further developed, and new technologies have been invented. Today, the International Organization for Standardization (ISO)/American Society for Testing and Materials (ASTM) uses the most critical fundamental properties, i.e. fabrication speed and resolution, to classify the techniques into seven categories: (1) binder jetting, (2) powder bed fusion, (3) directed energy deposition, (4) material extrusion, (5) material jetting, (6) sheet lamination, and (7) vat photopolymerization (J.-Y. Lee, An, and Chua 2017; Afshar-Mohajer et al. 2015; Hofmann 2014; ASTM F2792-12a 2012).

Even though the polymer was the main material used in the 1980s when the technology was invented, today there are many different materials available, divided into four main categories (Gibson, Rosen, and Stucker 2010; Campos 2018). The first three refer to the chemical properties of the original material and are: polymers, ceramics, and metallic materials. The fourth category of composite materials refers to the combination of those original materials, with, in some cases, additions that enable them to exhibit other properties, including acting as "smart" or "4D" materials (Khoo et al. 2015; A. Y. Lee, An, and Chua 2017; Momeni et al. 2017).

Additive manufacturing technology has been used in various sectors, such as architecture, applied arts, medicine, and transportation. In cultural heritage, it has been applied for the preservation and replication of monuments and artefacts, documentation and research, museum programming, and the creation of new works of art. In the last decade, additive manufacturing technology has been applied in conservation as a restoration process. Published examples can be found from the National Museum of Slovenia (Antlej et al. 2012), the 3D ArcheoLab in Italy (Bigliardi 2014; Bigliardi et al. 2015; Anonymous 2017), and the Victoria and Albert Museum in the UK (Allen 2015).

Figure 1. *a) Human faced monster. ca. 600-700 BCE, glazed earthenware, H 31.7 cm × W 12.6 cm × D 16.2 cm. British Museum, 1912,1231.34; b) 3D digital model of the Human faced monster artefact; c) chalice. ca. 600-580 BCE, painted pottery, H 11.5 cm × Diam. 17 cm (rim). British Museum, 1965,0930.979; d) 3D digital model of the chalice*

CASE STUDY

A case study for this research is being developed using three ceramic objects from the Greek-Roman collection, three from the Chinese collection of the British Museum, and one from the archaeological collection of UCL. The objects selected from the British Museum are considered suitable due to their different manufacture properties and shapes, and range of complexity in their missing components. The conservators involved in this research have many years of experience in restoring these types of objects, and this experience is essential for better estimating the results of the additive manufacturing restoration method, regarding the time spent, and the anticipated aesthetic result. The object from the archaeological collection of UCL for this case study has not yet been chosen. A series of interviews with the collections' curators and the objects' conservators have been taken, in order to identify shared goals for conservation treatment, and the objects selected for the case study have been digitised, using the method of photogrammetry (Figure 1).

NEXT STEPS OF THE RESEARCH

The next step of this research is the digital restoration of the objects, which will be carried out according to what is gleaned from curatorial and conservation input. Then, the most suitable additive manufacturing materials will be chosen following physical testing of traditional restoration materials regarding their compression, tensile strength, hardness, flexibility, and Oddy testing, and comparable testing of a range of additive manufacturing materials. The additive manufacturing materials will be chosen to match or exceed the qualities exhibited by traditional restoration materials, whether on their own or used in combination. After the restoration treatments are complete, follow-up interviews with the curators and conservators will be undertaken to evaluate both the processes and their outcomes. Finally, an analysis will be carried out to measure the final aesthetic result for each treatment against the chosen material properties, accuracy of the printed object fragments, financial and time implications, and additional opportunities and issues introduced by use of additive manufacturing technology in comparison with traditional restoration methods.

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