The Precious Project: Polishing and Finishing of Additive Manufacturing (AM) Jewelry

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Introduction

The Additive Manufacturing (AM) of precious metal jewelry is slowly gaining traction in the global jewelry industry with many companies now starting to adopt or consider the technology. There are still two key areas that need to be improved in order to speed up the adoption of the technology: 1) design for AM and 2) polishing and finishing of AM jewelry. This paper explores the various polishing and finishing techniques available for precious metal AM jewelry.

Additive manufacturing of jewelry can prove to be particularly effective commercially when used to produce geometrically complex jewelry designs or personalized, individualized and customized jewelry items. These designs, by their very complex nature, can present many unique and product-specific challenges when being finished and polished. There are a number of mechanical, sometimes called mass finishing, polishing technologies now available that the jewelry manufacturer needs to consider using in combination with their AM technology while also being mindful that, like all high-end jewelry, traditional hand polishing methods will still be required to provide the desired final high-luster polish to the jewelry item.

The following information largely details the work carried out by members of the UK Technology Strategy Board (TSB) Precious Consortium[1] investigating various mass finishing techniques for AM jewelry as well as introducing new and novel finishing techniques and methodologies for AM jewelry developed since the conclusion of the project.

Additive Manufacturing of Precious Metal Jewelry

Additive manufacturing of precious metals has been proven to be a commercially viable manufacturing option worthy of some consideration when considering possible or alternative strategies for a jewelry manufacturing business. The unknown, and to a large extent unquantifiable, issue remains that of designing new products that take best advantage of the strengths of the AM process.

Complex geometries, personalization, customization and individualization, when linked to the various co-design possibilities and options, are all relatively new and unexplored/unexploited areas for the jewelry design community to discover. An applicable analogy might be "AM of precious metals is a solution waiting for the killer application/problem to be identified."

In the evolving world of AM, especially in precious metals, designers who can create jewelry that is both compelling to the consumer/customer and within the bounds of AM's manufacturing capabilities will be exceptionally valuable and much sought after. AM has the ability to be a key enabler in the production of uniquely designed high-net-worth precious metal jewelry, and companies should consider very carefully the possibilities offered by the AM process. However, these complex forms as shown in Figures 1 and 2 will also need to be finished and polished to a quality standard that the precious metal jewelry buying public has come to expect and has every right to receive in exchange for their hard-earned dollars.

(a) (b)

Figure 1 *Bi-color 18K yellow/white mesh bracelet (a) and 18K yellow bangle (b)*

Figure 2 *Platinum (Pt–Ru) hollow cuff produced in a single piece*

The Simple Theory of Polishing

Viewing a polished metal surface is mainly influenced by the elementary laws of the reflection of light. Light rays travel in parallel straight lines onto a surface and, when striking that surface, they are reflected. The rays that strike the surface are the incident rays and those leaving the surface are the reflected rays. The angle of the reflected rays is always exactly the same as that of the incident rays.

The correct scientific term for this effect is specular reflection and is specific to the mirror-like reflection of light waves from a surface. "In this process, each incident ray is reflected at the same angle to the surface normal as the incident ray, but on the opposing side of the surface normal in the plane formed by incident and reflected rays. The result is that an image reflected by the surface is reproduced in mirror-like (specular) fashion."[2]

The law of reflection states that for each incident ray the angle of incidence equals the angle of reflection, and the incident, normal, and reflected directions are coplanar (Figure 3). This behavior was first described by Hero of Alexandria (A.D. c. 10–70).[3] It may be contrasted with diffuse reflection described below in which light is scattered away from the surface in a range of directions rather than just one (Figure 4).

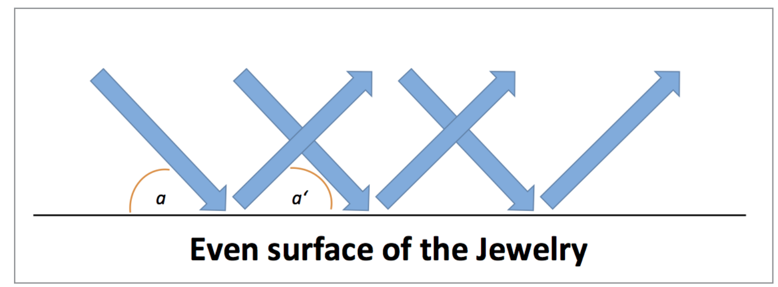

Figure 3 *Illustrates the law of reflection on a smooth, flat and polished surface. The light striking it is reflected back towards the viewer, who sees a polished surface because all the light beams arrive at the eye at the same time.*

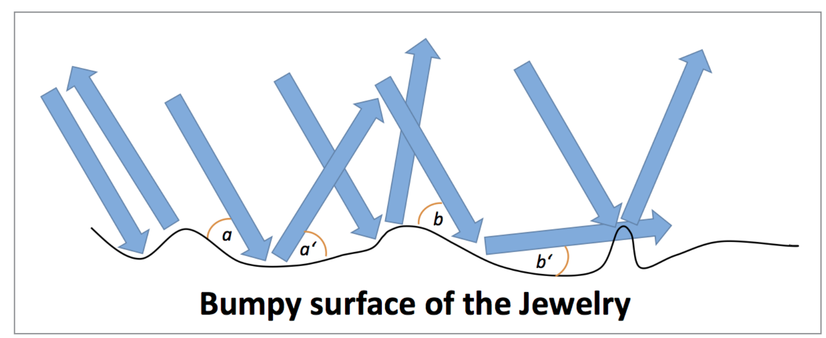

Figure 4 *Illustrates the law of diffusion on a series of ridges. The reflected light is widely scattered and could be considered typical of the surface produced by the AM process.*

The smaller the surface from which the rays are reflected, the better the viewer's perception of how well polished it is. However, if the area being viewed consists of uneven, rough surfaces tilted at various angles (as typically found on the surface of an as-built AM jewelry item), the parallel incident rays become scattered when reflected from the surface. When observed, such surfaces do not appear bright or polished. This is known as a diffuse reflection that reflects the light in a broad range of directions. A good example of this is a surface printed from a powder such as plaster or ceramic materials, which reflects light diffusely with great efficiency.

Most materials can give some specular reflection, provided their surface can be polished to eliminate irregularities comparable with the light wavelength (a fraction of a micrometer). Depending on the material and its surface roughness, reflection may be mostly specular, mostly diffuse, or anywhere between. For an AM surface to become well-polished, it typically needs to be reduced to below the level of its deepest "pit mark" or such marks or minute depressions will remain and mar the look of the final finish. This is typically achieved starting with various bead- and sand-blasting methods followed by mechanical mass finishing. The quality of the outer surface produced by AM technology, therefore, becomes a major influencing factor in the quality of the final surface produced. This can be achieved by fine tuning the various manufacturing parameters of the AM technology and its source powders and is potentially a large area of research that needs to be reported separately.

There are two basic mechanisms by which a surface becomes smoothed and polished:

1. Removing surface material by use of abrasives or electrolytic/chemical polishing
2. Flattening and smoothing the surface by mechanical working (burnishing)

Abrasive removal of material is achieved when the surface is contacted by hard, abrasive media particles that move, or are moved, over the surface and metal is sloughed off, leaving behind a series of scratches the depths of which are determined by the size of the abrasive particles used. The use of successively finer abrasives, one after the other, enables a smoother or lower surface roughness to be obtained. In burnishing, the smoother surface is obtained by plastic deformation of the surface layer through mechanical means that typically involves hammering or frictional contact by a harder material such as steel or plastic/porcelain parts that come in a wide variety of shapes and sizes. Polishing or brightening of a surface can only occur in those areas of the jewelry piece that can be accessed by the polishing or burnishing mediums being used.

Larger media will not be able to access deep or small recesses, so time and care has to be taken assessing which type and size of media to use and for how long because there eventually comes a transition point at which there is only loss of surface material and/or surface detail. The user needs to carefully consider not mixing varying sizes, surface finishes and shapes during these processes as there is potential for excessive material losses due to some workpieces having reached their optimal surface finish while others may not have yet achieved theirs due to the variability described.

Independent of the equipment and media employed, the time taken to achieve the best surface finish will also, as previously indicated, be influenced by the surface condition of the workpiece at the start of the polishing process. Frequent and well-documented testing is the best way to discover the optimal conditions for the particular workpieces being polished, media used, ratios of jewelry to media, processing times, and liquids added. All can adversely affect the final result if improperly applied.

Finishing or mechanical polishing technologies have been used in various industries for many decades. Mechanical polishing is generally considered to be the smoothing of a surface using mechanical tools and abrasives. Mechanical polishing is generally performed in steps with progressively finer polishing mediums and abrasives until a desired degree of smoothness is achieved as a result of the abrasive friction between the workpieces and the media. Its principal use has been to deburr and polish workpieces by using a surface abrasive or polishing agent. Single-barrel tumblers, hexagonal drums, vibrators and disc-finishing machines are traditionally used for mechanical polishing and all are described below.

As with most industrial processes, mechanical polishing can, of course, have its shortcomings.

- There are almost always limitations on the complexity of surfaces that can be processed.
- Abrasives can penetrate the metal structure if the technology is not used correctly.
- Many of the typical media materials and chemicals traditionally used in mechanical polishing can have harmful effects on the operator and/or environment if not handled correctly.
- It can be a time- and resource-intensive technology, often requiring multiple stage/operator interventions and changes of media and fluids and often carried out in multiple units of the plant.
- Process control can prove to be complex, requiring a high level of operator experience, knowledge and understanding of both the mechanical and chemical nuances of the various process options available.

Polishing and the Santa Fe Symposium®

Polishing has been the subject of any number of previous Santa Fe Symposia papers and presentations, all of which are worthy of a review for the reader if you wish to have a deep understanding of the various nuances of polishing precious metal AM jewelry. All of these earlier papers and many others were reviewed in the preparation of this paper.

In 2001 Martin Moser of Otec gave an excellent explanation of the intricacies of the various mechanical polishing options available at the time.[4] He followed this with a further paper in 2003 on the same subject.[5] In 2002[6] and 2003[7] Steven Alviti of Bel Air Finishing published two excellent papers covering the use of steel ball burnishing on the surface of cast jewelry.

In 2008 Klaus Wiesner and Markus Schmidtke took us to the next stage and introduced us to the theories and principles of using rotating instruments and manual polishing,[8] which are equally as important to the finishing of AM jewelry as mechanical mass finishing. In 2009 Dr. Alexander Verdooren of Rio Grande brought us one of the more influential papers that had direct implications for those of us exploring and researching the polishing of AM jewelry.[9] Frank Cooper, co-author of this paper, also briefly touched on the subject of polishing AM jewelry in his 2012 paper entitled “Sintering and Additive Manufacturing: The New Paradigm for the Jewelry Manufacturer.”[10]

Polishing and Finishing of AM Jewelry

There are a number of mechanical polishing (sometimes called mass finishing) technologies that the jewelry manufacturer might wish to consider using in conjunction with AM while also keeping in mind that, as with all high-value precious metal jewelry, traditional hand polishing methods will still be required to provide the final high luster to the jewelry item. Mass finishing technologies are based on the correct application of pressure and speed of the workpiece and media to the jewelry item being polished. The higher the pressure exerted by the media on the jewelry and the faster the media flows across the jewelry parts, the faster the desired finishing results can be achieved when matched with the correct media type.

Figure 5 *Complex jewelry AM forms requiring mechanical polishing options*

Disc Finishing

Centrifugal disc finishing (CF), sometimes known as a High Energy Disc, is a mass finishing process developed for the surface treatment of metal items and is particularly applicable to precious metals. The process is carried out in a bowl-like container, open at the top and the bottom, and consists of a turntable-like disc separated from the container wall by a small gap. During operation, the jewelry and the grinding or polishing media in which it is immersed rotate at a high speed, creating a toroidal, abrasive polishing effect. The contact between the jewelry pieces and the medium generates a very intense finishing effect, which is up to 20 times more efficient than can be achieved with more conventional systems like vibratory finishers. Centrifugal disc finishing can be a wet or dry process or a combination of both and might be carried out in single or multiple drum options.

Figure 6 *Typical centrifugal disc (CF) finishing equipment*

When powered up, the disc’s rotational or centrifugal forces cause the entire mass (media and workpieces) within the chamber to rise quickly upwards and outwards. The walls of the processing chamber are usually ridged in order to effectively slow down the mass, in effect “braking” it, turning it over upon itself to tumble down and inward back towards the center of the disc to begin the process again. The process takes the shape of a vortex of parts and media. If this is a wet process, there is also a constant feed and drain of water dosed with brightening chemicals. The centrifugal force developed by the disc also adds weight to the parts and media. The result is a highly aggressive parts-finishing energy output. Depending upon the size of the machine (smaller machines require higher speeds than larger ones), this action will take place at anywhere from 60 to 250 rpm or more. In many machines, the rpm speed is variable, allowing the operator to vary processing forces from one part or process to the next, while maintaining the optimal “toroidal shape” of the finishing mass.

If you have researched CF at all, you will have heard various theories concerning the spinner/chamber gap. If one surface is going to rotate and the other remains stationary, something has to give way to not cause friction between the disc and the process chamber wall. What “gives” is a very small space between the rotating disc and the upper (above the disc) process chamber. This gap normally begins at a width of 10–20 thousandths of an inch (0.25–0.50 mm) or even less. With use, and unfortunately misuse, the gap tends to erode and widen slowly throughout the machine's life. Eventually, this can cause considerable trouble such as media or small parts lodging in the gap, causing jamming and damage or even complete machine failure. If you are consider purchasing a CF system, pay attention to gap design and the manufacturer's ability to renew, replace or adjust this to avoid trouble in the first place.

Drag Finishing (DF)

In drag-finishing (DF), which is a variant of CF, the jewelry is mounted on special workpiece holders. These are dragged or, more correctly, pulled in a circular motion (think of a fairground Wurlitzer motion with smaller spinning spindles inside the larger circular spinning motion) at high speed through a container filled with appropriate grinding or polishing media. The motion creates high-contact pressures between the workpieces and the media, producing excellent results in a very short time in the form of high-precision rounding of the edges or a high-luster finish. The main characteristic of drag finishing is that the parts are all individually mounted onto the workstations of the carousel, thus giving impingement-free mass finishing. Drag finishing is also an exclusively dry polishing process rather than being used for deburring. Depending on the machine size, the carousel can be equipped with 4 to 12 workstations. Each workstation may be loaded with one or multiple parts. Compared with conventional mass finishing systems where the parts are free-floating in the media, in drag finishing systems, the parts—being individually attached to the workstations—can never touch during the finishing process. This prevents part-on-part contact and, therefore, nicking or marring of the finished surface. DF is also generally found to be an even quicker polishing process than CF because not only is the media being spun round the bowl at high speed but the workpieces are also turning at high speed within that toroidal vortex of polishing media. Figure 7 shows two images of drag-finishing equipment.

Figure 7 *Drag finishing (DF) finishing equipment*

Stream Finishing (SF)

Stream finishing (SF), also referred to as immersion polishing, is a fairly new concept and a variant of DF. It features short processing times and can be easily automated, if necessary, using variants of the auto-tool changing found on many CNC technologies. In trials of precious metal jewelry items, it has shown excellent reliability and repeatability. It can produce a first-class, near-mirror finish in the right circumstances. In Figure 8 we have a DF spinning disc and chamber set up with the part to be polished held in a drill chuck and rotated in the toroidal vortex of media. The process was developed for and still is most often used to deburr newly machined drill bits but has been cleverly adapted into the jewelry polishing process for AM parts.

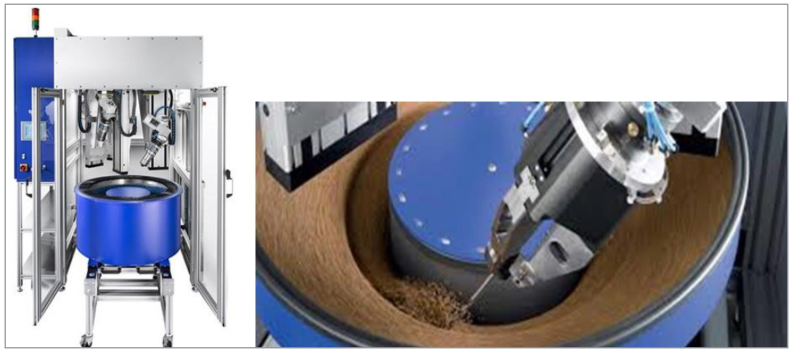

Figure 8 *Stream finishing equipment*

Figure 9 Precious project 18K yellow gold "Orbis" being stream finished

An example of a difficult geometry being mechanically finished is shown in Figure 9. This is an 18K yellow-gold piece. Stream finishing is the preferred polishing process, which will be a combination of mechanical and hand/mop (buffing wheel) polishing. The progression of the polishing process on the piece is shown in Figures 10–12.

Figure 10 An 18K yellow-gold "Ojo" design being stream finished (SF)

Figure 11 After 30 minutes (left), one hour (center) of stream finishing and after hand polishing (right)

Fletcher

Figure 12 Finished 18K yellow-gold "Ojos"

Tumbling or Barreling

With this long-established, low-tech technology and one often used in the jewelry industry workshop, the jewelry to be polished is allowed to drop under the force of gravity within the polishing media. The down side of the process is that the workpiece being polished is only being actioned during half of the rotational cycle. While the media is "climbing" back up ready to "tumble" back down under gravity, the workpiece is not being rubbed/polished by the polishing media. The most common kinds of media used in these systems are steel shot and/or pins. Tumbling or barreling is probably better described as a burnishing process rather than a pure metal-removal polishing process.

The standard barrel system's efficiency to deburr or polish depends on the ability of the parts and media to slide down a slope created by gravity. If the slope is broken up by too much speed, the parts may become airborne, causing part damage and/or the barrel system to become ineffective. Too slow of a speed does not hurt the parts but makes the cycle time longer. When faster speeds are desirable, there should be a greater quantity of water and chemical compound in the barrel (if a wet process) to give more cohesion to the mass. This will also soften or buffer the impact or hammering effect of the media on the parts. If the barrel is turning too fast, the desired sliding action can be adversely affected. The slide of the workload depends on the diameter of the barrel, the rpm of the barrel, the height of the load level and the height of the water level. With a 60% load level and a water level one inch below load level, the greatest slide is obtained at about 150 surface feet per minute (SFPM). At the beginning of the tumbling cycle, a low SFPM will avoid the rolling over of some burrs. The SFPM can be raised after ten or fifteen minutes. A low SFPM will also help protect delicate parts. Too much SFPM could cause the load to fly around in the barrel and create impinging and pitting.

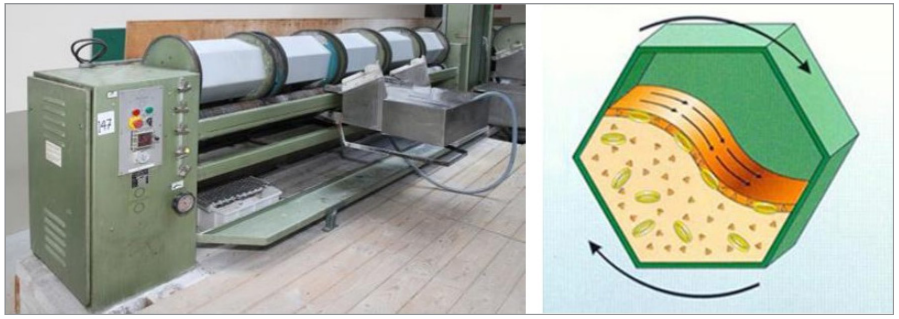

Figure 13 *Typical tumbling barrel machine and a schematic of its tumbling action (Source of the schematic: Dr. Ing. Manfrid Dreher GmbH & Co. KG)*

Centrifugal Tumbling

Sometimes known as planetary tumbling, this is a high-energy and high-speed deburring/polishing process using a planetary barreling system. It is typically used when other, more basic technologies do not reach requirements on speed and finish. Unlike the tumbling process, in this technology the workpiece is continually abraded and worked by the polishing media during all parts of its revolutionary processing.

Figure 14 *Centrifugal tumbling machine and a schematic of its high-speed planetary revolving action (Source of the schematic: Dr. Ing. Manfrid Dreher GmbH & Co. KG)*

Vibratory Bowl Finishers

Vibratory processes are specifically designed to be used when high-quality luster finishes are required. The polishing media in the bowl is usually either plastic or ceramic. The media normally has aluminum oxide or other abrasives imbedded within it. As the media is turning in the machine, the matrix material is slowly wearing down and exposing new abrasives on the surface of the media. As

the media goes back and forth across the part, it deburrs it. At the same time, water and compound (soap) are being circulated through the machine to keep the surface of the media clean. If the water is not kept clean or no compound is used, the media becomes glazed over and its ability to deburr is greatly reduced. Thus, it is important to clean the water in your machine often and use the right compound for the best results.

Vibratory tumblers have an action that is caused by an eccentric, rotating weight shaking the tub in a circular path, during which the entire load is lifted up at an angle and then dropped. As the load is falling (but not actually airborne), the tub returns to an upward position, applying an upward and angular force that causes a shearing action where the parts and media rub against each other. Since the load is moving as a unit, very fragile jewelry is quite safe in the vibrator as there is no tearing action or unequal forces that tend to bend and distort parts. Despite the apparent rubbing action of particles against parts, studies have shown that the primary mechanism of material removal in vibratory finishing is erosion caused by the relatively normal impacts of particles on parts. These impacts occur at the same frequency as the vibration and at impact velocities of less than 1 m/s.

Figure 15 *Various types of vibratory bowl finishers*

The Time to Process AM Jewelry

The various mechanical polishing techniques as described above have been proven to effectively and speedily reduce the amount of time and effort required to bring a piece of 18K AM jewelry to a suitable surface finish that effectively minimizes the amount of time and effort required to achieve a good-quality, high-luster finish. The results of this research and measurement are shown in Figures 16 and 17.

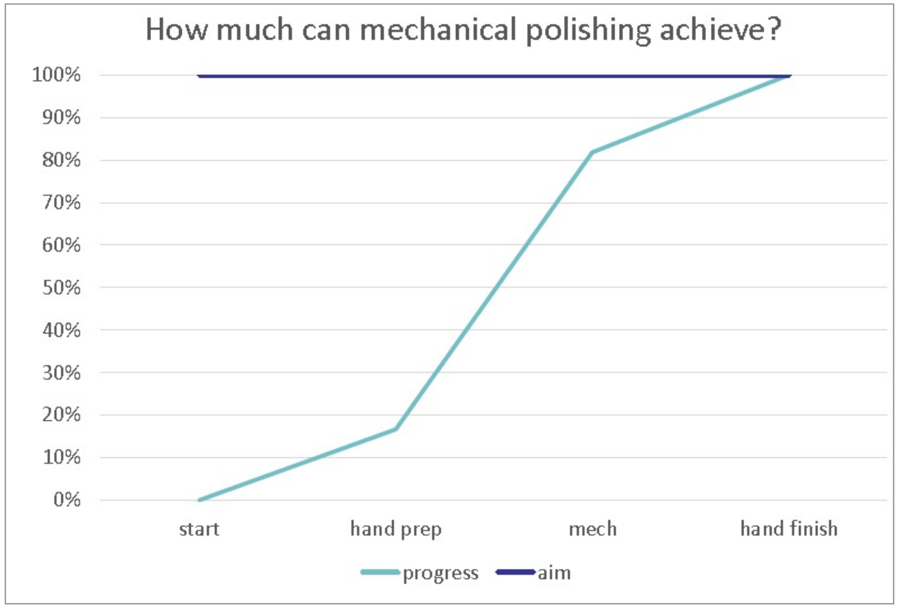

Figure 16 *Mechanical finishing/polishing versus hand finishing/polishing*

Figure 17 gives a good indication of the process times for the various polishing technologies examined during our trials on the Precious project jewelry demonstrator pieces. The time scale used is in processing hours.

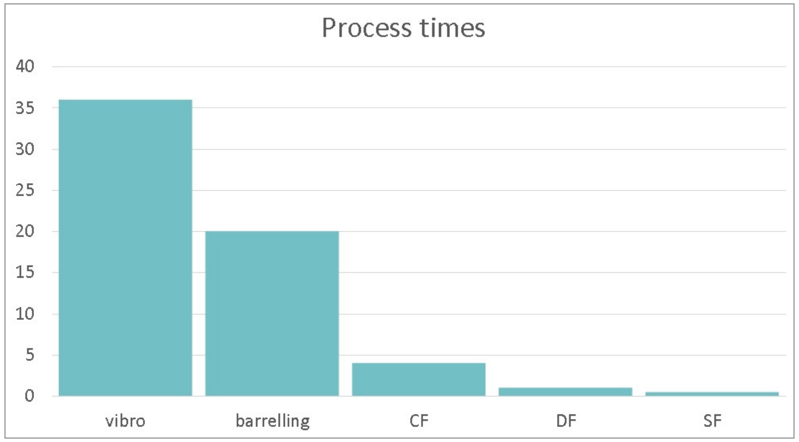

Figure 17 *Comparison of process times*

New Polishing and Finishing Techniques

Since completion of the Precious project, a number of newer and novel, some still even experimental, polishing technologies have also been considered, are under investigation and are described in the following pages.

Laser Polishing[11]

In laser polishing the laser melts the metal on the surface, causing the metal to flow from the peaks to the valleys. This smoothing effect is due to surface tension of metal in its liquid phase. Material is not removed; rather, it is relocated while molten (see the schematic in Figure 18). The laser beam is guided over the surface in contour-aligned patterns. The innovation in laser polishing results from the fundamentally different active principle (re-melting) compared to conventional grinding and polishing (abrasion and removal). For the laser polishing of metals, it should be noted that diode-pumped solid-state lasers are normally recommended.

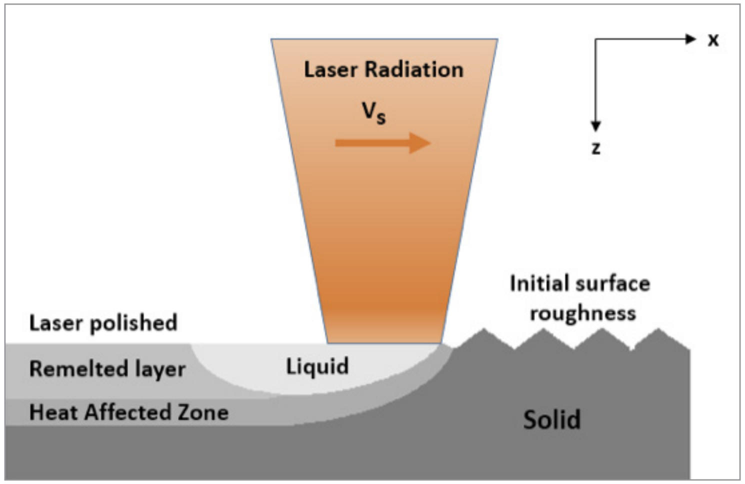

Figure 18 *Basic principle of polishing with laser radiation*

A relatively new laser polishing technique being researched at the School of Jewellery for use on AM jewelry consists of using traditional jewelry-workshop laser welding equipment on a relatively low power and pulse setting to effectively melt/polish the surface of the piece. This technique works well on difficult-to-access surfaces, which are often very difficult to clean up either mechanically or manually. The laser welder was able to keep the structure of these areas intact while giving the piece a brightened, polished finish. Care is needed to ensure the welds overlap.

The wires on the pendant in Figure 19 were all approximately 1 mm thick when they were manufactured. Had they been significantly thicker or square, this technique would not be as suitable. Settings used and suitable for a ROFIN laser welder were 220V, 4.5ms, 0.70-0.90 mm, 3.9Hz and Shape 13.

***Figure 19** Pendant by Andrew Cowley, student at Birmingham City University, laser polished on a ROFIN laser welder*

Electropolishing

Electropolishing is an electro-chemical material-removal process for metallic workpieces using an external source of electric current. It is used to polish, passivate and deburr surfaces. During this process, material is removed from the workpiece (anode), which is immersed in an electrolyte that is chemically and especially suited to the particular metal being polished, thereby considerably reducing the surface roughness. The advantages of electropolishing are a metallically pure surface with no noticeable effect on crystalline structure. Electropolishing is an electro-chemical process in which metal is removed to obtain a smooth, highly reflective surface. Thus, electropolishing is the reverse of electroplating. Electropolishing of metals is carried out in an electrolytic cell that consists of three component parts: an electrolyte and two electrodes (a cathode and an anode).

The electrolyte is usually a solution of water or other solvent in which metallic ions are dissolved. When driven by an external voltage applied to the electrodes, the electrolyte carries the metallic ions that flow to and from the electrodes, where reduction/oxidation reactions can take place. An electrolytic cell can only dissolve more noble metals into solution when applying an external potential (i.e., voltage) of the correct polarity and large enough magnitude. Electropolishing of metals has been around for almost one hundred years. However, its use on jewelry has been either limited or potentially dangerous. There have been a number of patents describing silver electropolishing. Most of these patents require the use of cyanides and/or thiocyanates. In addition, in order to achieve satisfactory results, these processes require a tight control and thus monitoring of the electrolyte chemistry.

Conventional electropolishing has its main limitation in the uneven removal of metal. More metal is depleted from the high protrusions and sharp edges (the points with the highest current density) than from the valleys and flat areas. For jewelry items this is a problem, since edges and corners get rounded, and the finished piece deviates from its original design. This is true as well for electroplating; in this case, metal is deposited more on high areas and sharp edges. The electropolishing of sterling silver is depicted in Figure 20. The item to be polished is in the anode position in the electrolytic cell. Silver and copper ions pass from the piece into solution and travel through the electrolyte. Silver and copper are finally deposited on the cathode as silver and copper oxides. Figure 20 shows an electropolishing unit.

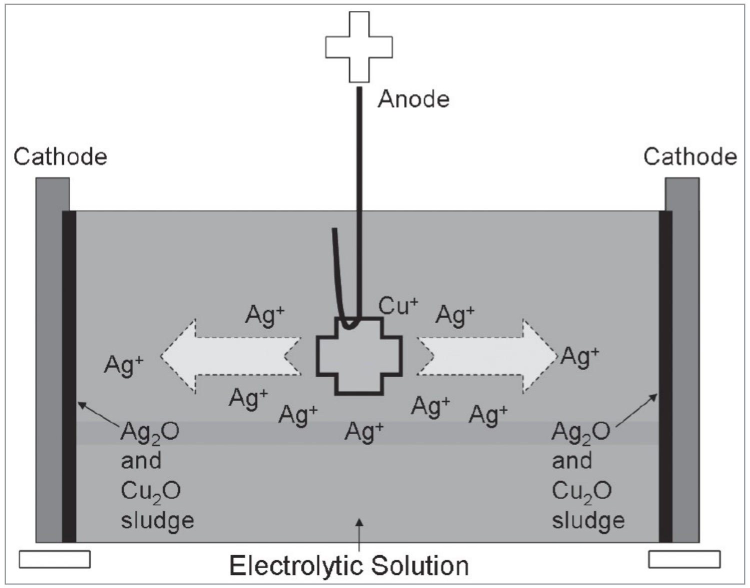

***Figure 20** Schematic: electropolishing of sterling silver*

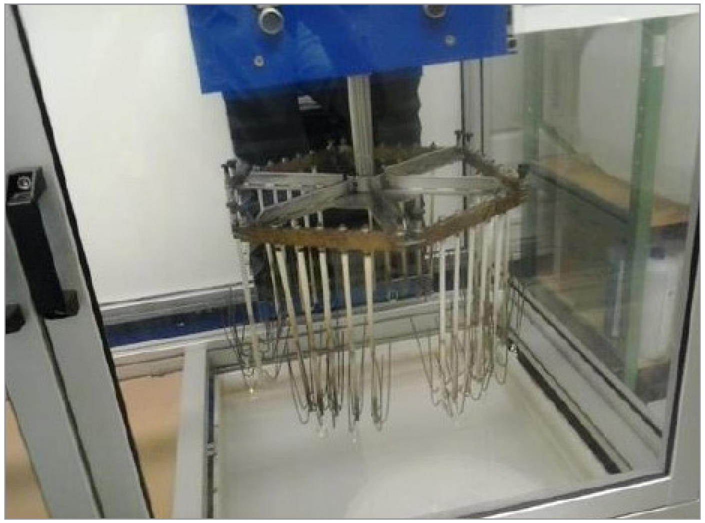

***Figure 21** An electropolishing unit*

Electro-Mechanical Finishing

The electro-mechanical finishing (EMF) process was first described by Marc Robinson in his 2008 Santa Fe Symposium® paper[12] and further refined by Alexander Verdooren in 2009.[9] The workpieces to be processed are hung on racks of titanium hooks. These racks move on a pendulum motion inside an electrolytic solution and non-abrasive plastic media. The media is made of PVC lentil-shaped particles that are about 3 mm in diameter and 1.6 mm in height. The machine has a power setting that controls the voltage with a maximum value of 10 volts, which represents the most aggressive process action. The voltage can be stepped down one volt at a time to slow the process to get improved surface quality. The electrolytic solution varies but can be a mixture of de-ionized water and mineral oil that is pre-mixed with a surfactant. Close to the anode (the jewelry) the water/oil emulsion becomes unstable. This happens because the negatively charged surfactant is pulled out from the emulsion in the anode vicinity. Without the surfactant there is no emulsion and, thus, water and oil separate. This generates the formation of a viscous oily anodic layer that acts as a barrier to the electrolytic process due to its high resistance. This isolating barrier protects the piece from constant metal depletion. When the work is moved through the non-abrasive plastic media, the media disturbs this barrier at random points. Removal of metal will occur by contact between the plastic media and the work in the areas where the isolating barrier has been disrupted or thinned out.

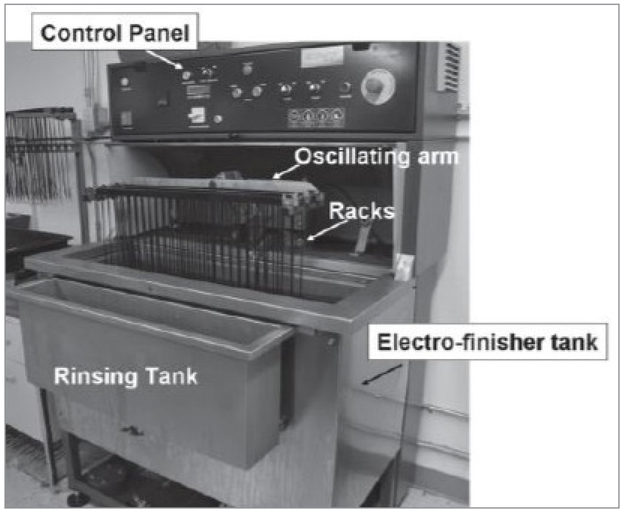

Figure 22 *An electro-mechanical finishing unit*

More recently, EMF small workshop-scale systems (example in Figure 23) have been released that perform both a grinding and polishing process for gold, silver and even brass alloys. The system uses a unique electrolytic solution which, when electricity passes through it, forms a gel-like coating over the surface of a metal piece. The liquid also contains thousands of tiny plastic particles which, when the system is powered up, are rotationally brushed against the surface of the metal (schematic of the process in Figure 24). When one of these particles hits the surface of the metal, the gel coating is dislodged temporarily, allowing the electro-polishing reaction to take place before the gel re-forms over the surface. As the plastic particles measure only 0.20 mm in diameter, they cannot reach into the deeper "valley" parts of the metal's surface until the "peaks" have been eroded back, creating a smooth, uniformly polished surface shine.

Figure 23 *Small workshop-scale EMF system*

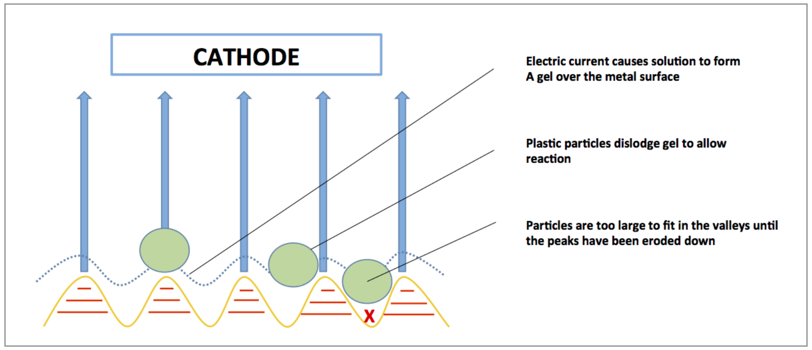

Figure 24 *Illustration of the EMF process creating a smooth, uniformly polished surface*

This type of EMF system can process various pieces at the same time in one fully automated step on a small-volume basis. The polishing action reaches every corner of the piece, enabling it to process articulated pieces such as necklaces, or interior walls which cannot be accessed mechanically. Pieces can be processed without removing embedded gems, which will not be affected and will maintain their original properties. The dielectric parts are also unaffected by the process. As can sometimes be seen in mechanical processes, this technique does not round edges and can penetrate all dead zones big enough to allow the plastic particles to access. The process achieves a high-standard polish quality with minimal removal of material as shown in Figure 25. The material that is removed is deposited on the cathode, from where it can be recovered. Importantly, no environmentally harmful materials are used during the process.

Figure 25 *Results of the workshop EMF process after 15 minutes*

Plasma Electrolytic Polishing

What is Plasma?

Plasma technology is based on a relatively simple physical principle. When supplied with energy, matter changes state: solids become liquidus and liquids become gaseous. If even more energy is supplied to a gas, it is ionized and transformed into energy-rich plasma, the fourth state of matter.

Plasma electrolytic polishing (PEP) is another potential polishing process currently being explored and researched by Frank Cooper's team at the School of Jewelry's Centre for Digital Design and Manufacturing (DDM) with a partner university in the UK. Plasma electrolytic polishing is an innovative surface treatment that has been found to result in surfaces that are very smooth and have a high-polish appearance. See the illustration in Figure 26 showing the process. Although it has many advantages compared to electropolishing, very few accessible scholarly articles have been published in the field of PEP to date (and mainly of stainless steel and titanium workpieces). The DDM team has been reviewing some recently released literature describing plasma electrolytic polishing in the field of polishing copper and its alloys. Transferring PEP to other metals and typical AM geometries requires an adaption of the experimental conditions. To overcome this challenge, a systematic experimental methodology is being discussed with other potential university research partners. Several parameters, such as electrolyte composition and voltages, are also to be investigated. PEP is considered to be an electropolishing process but one which operates at comparatively very high temperatures and at high voltages while also using environmentally friendly non-acid electrolytes.

The Technical Explanation of Plasma Electrolytic Polishing (PEP)

Matthias Cornelsen et al., in an article on the MDPI website explains plasma electrolytic polishing (or electrolytic plasma polishing , EPP) as follows:[13]

> "In the case of plasma polishing, ecologically harmless aqueous salt solutions are used as the electrolyte, with significantly higher voltages in the range of 180 V to 320 V. The anodically polarized workpiece to be processed has a much smaller surface area than the cathodically polarized basin, and thus represents the active electrode. As a result of the applied DC voltage, a current flows through the electrically conductive electrolyte. According to Joule's law the resulting heat energy W is a product of the current I (squared), the electrical resistance R and the time t ($W = I^2Rt$).
>
> "Due to the different area ratios, the current density at the active electrode is higher, therefore a higher heat generation effect takes place, according to Joule's law. Due to this heat energy, an insulating gas layer is created between the workpiece surface and the electrolyte. The gas layer causes an interruption of the current flow between the anode and the cathode. By means of the applied DC voltage it results in an ionization of the gas layer. Various physical mechanisms...lead to the material removal of the anodically polarized workpiece caused by plasma discharges in the gas in the form of thin current streams (streamers). As shown [below], the first plasma discharges are heat and remove the profile peaks of the metal workpieces surface. Each plasma discharge during the polishing process results in the same energy being released, which leads to the same quantity of ablated material from the surface... so as the peak is gradually reduced, the cross-section increases, which means the removal height automatically decreases."[13]

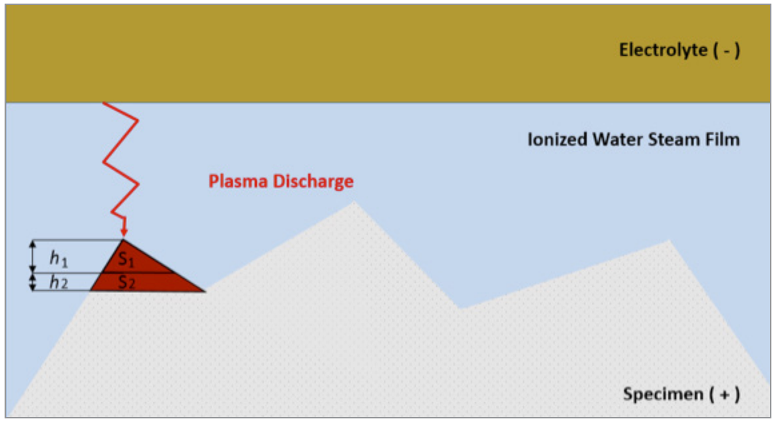

Figure 26 *Schematic of electrolytic plasma polishing (EPP)*[13]

Conclusion

What advantages could the use of the various mechanical and electrolytic polishing options discussed here bring to those companies considering adopting a stream of AM jewelry into their business model? The work carried out identifying suitable polishing and finishing processes identified above sets out to address three major points:

1. Can mechanical polishing help to reduce the amount of hand finishing and polishing AM jewelry might require?
2. What sort of process times can be achieved by the various mechanical polishing options available for polishing AM jewelry?
3. Will mechanical and/or electrolytic polishing reach those difficult-to-reach parts of jewelry?

One of the key selling points for jewelry designers and manufacturers considering adopting the use of precious metal additive manufacturing for jewelry is the freedom it gives them to explore using previously unheard of geometric complexity in their jewelry designs along with the various customization, personalization and individualization options also available to them. However, these options bring with them their own unique problems and issues when it comes to finishing and polishing these types of infinitely variable jewelry items because there is little to no uniformity or repeatability required, or even being sought, through adoption of these design options. Therefore, the various and suitable mechanical polishing options that might be adopted will need to be equally as flexible and adaptable as possible, given the various constraints of the different technologies discussed in this paper.

The minimum size of any apertures through which the polishing medium might need to flow will need to be known and understood to allow the correct particle size of media to be used. Knowing this will most probably lead to the adoption of simply just using the smallest media available without understanding the effect this might have on the possible longer time it will take to bring a workpiece to the required level of polished surface. Please note: The various mechanical and electrolytic options being discussed here do not bring the workpiece to its final desired, high-luster finished condition. This will still need to be done using traditional and manual polishing methods using down buffs and polishing rouge and all applied by the skilled hands of an experienced polisher.

While there can be no doubt that introducing mechanical polishing options to the finishing of AM jewelry will certainly reduce the amount of hand finishing/polishing required, obtaining the optimum reduction in processing time will require the identification and adoption of the most suitable mechanical finishing option, always assuming that option is available to the user. There is also little doubt that having access to electrolytic polishing options could prove to be a far more attractive proposition to those companies opting for the more geometrically complex possibilities of AM jewelry, which are liable to have difficult-to-access multiple inner surfaces requiring polishing. However, many of these process are either still in the experimental stage or at the very early stages of commercialization and will require equally exhaustive researching and testing before being adopted into the business.

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