

Industry 4.0 & precious metal mass customisation.

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Statement regarding copyright

Declaration Statement: Simon Evans

I certify that this is all my own work and that all other sources of information, data, images etc. have been acknowledged and referenced This work has not been previously accepted in substance for any other degree and is not being concurrently submitted in candidature for any other degree:

Signed:

Simon Evans

Date:22/02/2023

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Abstract

The current work analyses the production of Jewellery through four distinct systems for small batch, & bespoke, precious metal manufacture. Additive manufacture (AM) assisted lost wax investment casting (IVC), Selective Laser Melting (SLM), & Electron Beam Melting (EBM). Implicit modelling was employed to create a re-useable workflow for mass customisation of a simple jewellery artefact, using Triply Periodic Minimal Surfaces (TPMS). Material Jet Printing (MJP) was employed to create the wax prototypes for design iterations, and the subsequent models for IVC. Casts in silver925 were produced. A single silver SLM sample was created on the EOS-M100 system. 6 Titanium Prints were created on the EBM system. Results indicate that Polymer-AM, IVC & TPMS mass customisation are a credible pathway for lightweighting, mass customisation, with good surface resolution, with minimal surface intervention through post processing automation. SLM is a novel system that could be employed for TPMS mass customisation; however, the surface resolution is not equal to or better than Polymer AM & IVC. EBM surface resolution was out of scope of this project to prepare & polish samples. Improving surface quality of SLM parts is a barrier to industry adoption. For part production, matching the correct system, with the optimised build, material alloy & laser parameters, including accessing systems with optimised wavelengths for reflective materials, is paramount to the widespread industry implementation of this technology. Automation & optimisation of support structures is linked to the efficiency of post-production processes.

Aim

To observe whether Triply Period Minimal Structures (TPMS) can be used for mass-customisation, & light weighting production of precious metal geometric designs using implicit modelling, for additive manufacture of precious metal alloys, through selective laser melting (SLM) powder bed fusion (PBF).

Objectives

Literature review of current & future manufacturing methods of jewellery with a focus on SLM manufacture.

Identify & construct precious metal alloy builds of customisable & complex gyroid rings & compare builds of four systems.

- Proposed I4.0 System: Parametric & Implicit Modelling, SLM-PBF,
 - Alpha Laser: AL3d-Metal SLM
 - EOS: M-100 SLM
 - ARCAM: Q10 EBM
- Jewellery Industry Standard: Parametric Modelling, Polymer-AM & IVC

Evaluate the builds against the industry standards.

- Surface roughness
- Alloys
- Porosity
- Microstructure
- Mechanical properties
- Economic argument

Give guidance on suitability of SLM for jewellery manufacture

List of abbreviations used, including symbols and units of measure

3MF	3D manufacturing file
AM	Additive Manufacture
B-Rep	Boundary representation
BJP	Binder Jet Printing
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CNC	Computer Numerical Control
DfAM	Design for Additive Manufacture
DLP	Direct Light Processing
GD	Generative Design
HIP	Hot Isostatic Pressing
IVC	Investment Casting
MJP	Material Jet Printing
PBF	Powder Bed Fusion
PGM	Platinum Group Metals
RP	Rapid Prototyping
SLA	Stereolithography Printing
SLM	Selective Laser Melting
SJM	Smart Jewellery Manufacture
STL	Stereolithography
TPMS	Triply Period Minimal Surface
TO	Topology optimisation

Units

Ct	Carat
g	Gram
nm	nanometre
µm	Micrometre

Introduction

Naturally occurring gold alloys with silver as the main impurity, have been adopted by all ancient civilisations, too soft for weapons, but prized for its unreactive nature, scarcity, & malleability. By 500BC Egyptian civilisation had mastered the art of alloying gold (Corti, 2021). Silver deposits also date back to around 500BC, in Turkey, extracted from lead-silver ores used by Sumerian craftsmen (The Silver Institute, 2022) & Platinum group metals were exploited by Europe around the 16th Century from South America (Corti, 2021).

As of 2022, there has been an increase of jewellery manufactures & a decrease in jewellery wholesalers in the UK, indicative of a transition to bespoke & personalised offerings, with the global jewellery market, estimated to rise to 292 billion by 2025 (Smith, 2022).

There are 1425 UK jewellery manufacturers as of 2022, most jewellery manufactures in the UK are small with 1170 having four or less employees (Statista, 2022). Companies such as Weston Beamor who specialises in Polymer Additive Manufacture (AM) and lost wax investment casting (IVC) & Cookson gold who operate & maintain 8 EOS precious metal SLM systems, both members of the Heimerle & Meule group, support the Jewellery manufacturing community by operating a bureau for precious metal fabrication (Weston beamor, 2023), (Cooksongold Additive Manufacturing, 2023).

Jewellery design, and wax carving, are labour intensive & requiring a high level of skill. CAD & 3D printing can be employed to fabricate complex mathematical patterns, fractals, and natural structures. These can be modified for mass customisation, more efficiently against traditional design & manufacture methods (Fatma et. al., 2022). Digital assets created by CAD are enabled by AM, with no increased time, or cost penalty, for increasing the complexity of a build (3D Systems, 2020).

Design customisation includes consumer inputs, what they value; where the products are only manufactured when the idea has been co-created, validated & signed off (Tidd & Bessant, 2021). AM supports customised products, agile to changes in market demand & adds value from reducing production time from concept to creation & supports design innovation. AM supports just in time manufacture of made to order jewellery products (Cooper, 2016).

A study of customer perceptions of AM jewellery by Soares (2022) showed technologically optimistic participants who had purchased AM jewellery showed a willingness to pay a higher price for customised jewellery, however the opposite trend was noted, for consumers unfamiliar with previously purchased AM printed jewellery, noting the perceived risks & increased technology cost.

Consumers have different demands & customisation according to their specific tastes. CAD & prototyping can provide quick visualisations & prototype iterations for validation in a real-world context (Fatma et. Al., 2022). Designers who harness the creative innovations through AM's manufacturing capabilities will be valued from a design standpoint (Fletcher & Cooper, 2018).

Many materials can be 3d printed, such as polymers, ceramics & metals (Vaezi, Drescher and Seitz, 2020). Jewellery designers create from an array of materials including metal alloys such as silver, gold, platinum, palladium & non-precious alloys, such as titanium (Korium et al., 2021), precious & semi-precious gemstones & with the increasing societal adoption of technology, the process is supported by CAD software, rapid prototyping & AM (Rajili, Olander and Warell, 2014).

Investment casting is well embedded in our manufacturing culture, dating back approximately 6000years (Corti, 2021). However, investment casting has limitations, such as the alloys it can

process, requires excess material, energy intensive & has multiple process stages (Salonitis et al., 2016).



Figure 1: industry embedded polymer-AM & lost wax investment casting (3Dsystems, 2021.)

Precious metal sintering technologies allows new design possibilities, & supports flexible production of consumer personalisation & bespoke pieces. It also supports optimising existing processes, and creating new business models to exploit economics of product evolution, decreased production time & reducing work in progress, by creating products as needed (Cooper, 2016).

The consumption of material is intrinsic with the production cost of additive, formative, & subtractive manufacture. Improving the energy efficiency & material consumption aligns with the UN's sustainable development goals (United Nations, 2015).

Scalable AM technology for precious metal fabrication, such as SLM or Binder jet printing (BJP) are capable of highly accurate products & reduced materials through light weighting at the design stage (Korium et al., 2021).

TPMS builds are geometries of increasing complexity & require increased computing power to calculate & modify. Traditional modelling software for Jewellery CAD is reaching its limit. Implicit modelling re-useable workflows compute complex geometries, replaced with a simple mathematical equation (nTopology, 2021).

The literature review will give an overview of current Jewellery manufacture practices of parametric CAD, CAM, RP, IVC and the evolution for direct-metal AM through industry 4.0 technologies, Implicit modelling, simulation, SLM, & emerging fabrication technologies. It will also explore material alloys, defects that can occur from these systems, & applicable post build processes. Design rules & applications are also considered.

CAD software

Traditional modelling

Constructive solid geometry (CSG): is where primitive object surfaces are approximated using polygons, which can be intersected, added or subtracted. (Laidlaw, Trumbore and Hughes, 1986).

B-Rep modelling: all objects are represented by their boundaries, where the software uses a number of connected surface elements which define the boundaries of vertices, edges and faces, using points, curves and surfaces (Asghari, 2013). Non-uniform rational B-spline (NURBS) surfaces contained in CAD, with their compact representation, manipulation ease, & ability to produce smooth surfaces (Yan et al., 2021). Explicit surfaces, such as polygon meshes, consist of triangles, or quadrilaterals, where the surface points are explicitly stored in their surface representations (Yan et al., 2021).

'Porous Microstructure Generator': is a voxel-based software. Using algorithms, it generates 3D structures of porous materials in voxels built on small squares. These can be exported into simulation software, for evaluation of porous structures (Niblett, et al., 2022).

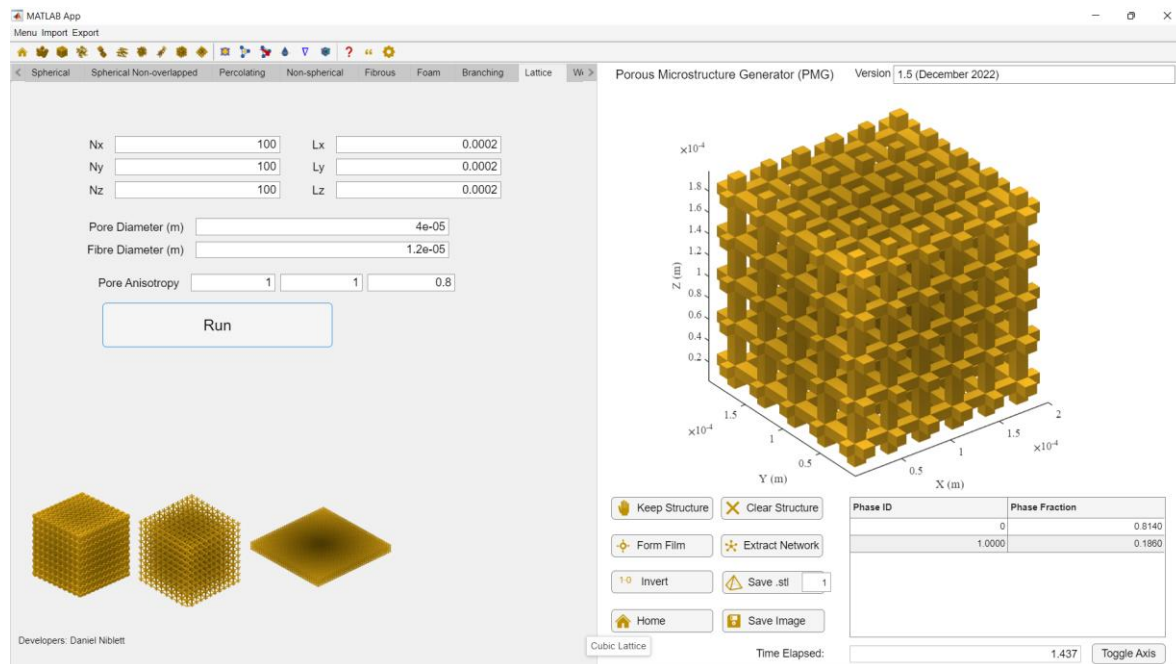


Figure 2: Porous Microstructure Generator (Niblett, et al., 2022).

Current industry embedded modelling software is reaching the computing limits for organic structures & complex shapes. For example, B-rep modelling has many tools which calculate new edges, from the intersection of faces. Complex geometries including organic, porous, & lattice structures are not well represented by B-Rep modelling (nTopology, 2019). Complex applications in traditional CAD software's are limited by computational power, incorrect model formation, or can produce models with large file sizes, that cannot efficiently integrate into the workflow (nTopology, 2019).

Rhino is a common CAD software for multiple-end uses, with many functions through translating NURBS curves, surfaces, solids, point clouds, & meshes, however Rhino itself is not parametric. Grasshopper is a plug in For Rhino for parametric design, with an interface for visual programming. In

the software, you can arrange & connect items, & also write scripts (McNeel, 2023). A Smart Jewellery Manufacture system was demonstrated by Bertacchini et al., (2021) using parametric design software, visual programming, for generative design & prototype iteration, and an algorithm for automation of laborious & repetitive operations. Automated operations included: optimisation of the .STL for print, loading parameters for print, & prototype design iterations. This was executed via a Form Labs SLA printer, with C# scripts written for production ecosystem communication.

3Design is a jewellery specific parametric design tool, created independently of Rhino, with over 5000 users worldwide. 3Design is built upon, B-rep, NURBS, CSG, and has add in tools for rendering, organic modelling, & a jewellery module (3Design 2021).

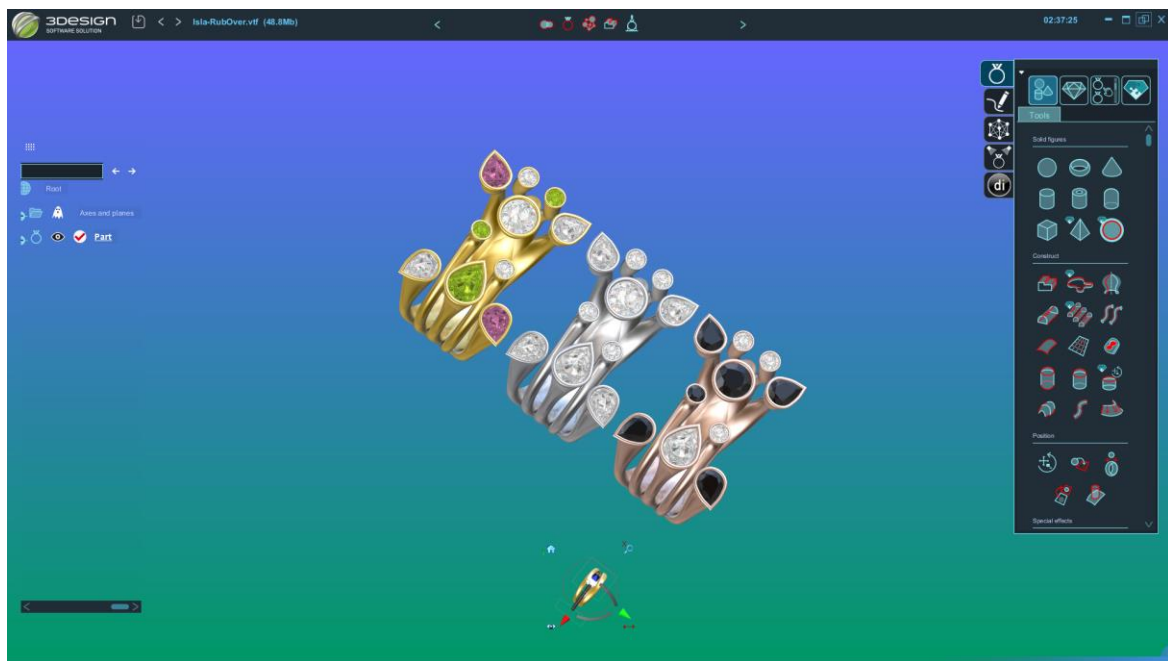


Figure 3: 3design software screenshot; Mass customisation of materials for three dress rings (Evans, 2023).

Generative design (GD)

Parametric design, an iterative process, creating designs based on the input parameters of materials & constraints, using algorithms, and parameters to automate & explore design solutions (Oh, 2019). Evolutionary based, GD can be defined as the development of a system that evolves with autonomy. It can be leveraged for end goals such as part light-weighting for improved performance, & sustainability objectives (nTopology, 2022). GD tools for light weighting include lattice structures, TPMS, & topology optimisation (Vaneker, et al., 2020).

Topology optimisation is parametrically varied, & assessed, by defining parameters including design space, loading, optimisation targets manufacturing constraints, which influence the optimised design (Oh, 2019). Material in low stress areas can be eliminated in iterative simulations, reducing weight, but retain a high stiffness, optimised for the required load conditions (Vaneker, et al., 2020).

Implicit modelling

There are algorithmic limitations in obtaining the optimal trade-off for porous structures for manufacturing & its application (Feng et al., 2022). Implicit modelling uses a simplified mathematical solution, for complex operations, such as offsets, fillets & boolean operations, and are easily calculated in real time, ideal for adoption into generative design workflows. nTopology is powered by an implicit modelling engine, where complex CAD models are created by a single mathematical equation, for quick design iterations, with the potential to reduce design bottlenecks (nTopology, 2021).

nTopology can be incorporated into the workflow for:

- Reusable workflows for Implicit modelling for lattice, TPMS, Voronoi & topology optimisation.
- Reusable workflows for simulation of mechanical tests.
- Automation of design & experiments.
- Reusable workflows for production estimation (i.e., manufacture time, material, cost.)

Triply periodic minimal surfaces (TPMS)

TPMS are lattice vectors of three, containing minimum surfaces, defined as “surfaces of zero mean curvature,” therefore hyperbolic in shape (Yan et al., 2021). TPMS have a minimal surface of a crystalline structure, and are triply periodic, repeated in the 3rd dimension (Yan et al., 2021). TPMS surfaces are smooth, interconnected, with uniformity in their pores (Feng et al., 2022) & a high stiffness to weight ratio (nTopology, 2021). Generative design can replace solid constructs with infills such as TPMS structures, that result in light weighting designs, whilst reducing material consumption. This makes TPMS suitable for AM. TPMS types include Schwarz Diamond, Schwarz Primitive, Schoen Gyroid, Neovius’ surface, Split-P, & Lipnoid (Yan et al., 2021).

AM process steps as outlined by Vaneker, et al., (2020).

A multitude of CAD software can be utilised to define the desired 3D geometry. The model file is then exported, such as an .STL, a format commonly accepted by AM systems, in which it approximates the geometry using triangles. Other formats, such as 3MF files can be utilised for more complex multi-material parts, which can contain model, material & production information (3MF Consortium, 2022). During the build preparation stage, software defines the build envelope, resolution & the model's location & orientation. The build preparation software includes build parameters, & slices the geometric data to give the AM system it's instructions to print. The build process is autonomous between insertion of a build plate & its subsequent removal. Post-processing of the build, excess material & support structures are removed. The final stage is quality inspection & part validation.

Rapid Prototyping (RP)

Rapid prototyping allows for quick iterations & validations of designs, & can improve the quality and quantity of production by automating repetitive tasks, allowing the designer more time for exploration of materials, design & creation (Fatma et. Al., 2022).

Over the past 20 years, Polymer-AM coupled with lost wax IVC, has streamlined the design process, reduced a new products time to market, reduced material & labour cost, and improved the offerings on quality, customisation & personalisation of jewellery manufacture (Cooper 2016).

Several technologies exist for Jewellery prototype & are suitable for lost wax IVC, including Photopolymer based Direct light Processing (DLP), Material Jet Printing (MJP), and the original Stereolithography (SLA), Ink jetting systems, such as Drop on Demand (DoD), & Extrusion based Fused deposition modelling (FDM) (Nagarajan et al., 2019). Two popular techniques for jewellery manufacture are MJP & DLP, coupled with IVC.

Material Jet Printing (MJP)

MJP consecutively layers a liquid photoreactive polymer material via a printhead onto a build platform, with ultra violet light curing the material. Structures are calculated, automated, & printed to support the build. It is an accurate & repeatable process, with a high resolution of up to 0.013 mm, allowing for fine details & smooth parts (AMFG, 2018). MJP has a high accuracy of deposition of material, reducing waste. It also allows for multiple part prints, but MJP is currently limited to mostly polymers and waxes (Loughborough University, 2019).

Direct Light Processing (DLP)

Holo AM (2023) discussed the technology behind the optical processing technique DLP. A DLP chipset contains a 'micro-opto-electromechanical' system, known as a digital micromirror device, which contain a microscopic array of up to 2million independent mirrors, that can be turned off or on. A high-resolution light image is projected at a photocurable polymer. For MJP & DLP cross-linking bonds are created during the curing phase, where photopolymers contain a polymer-precursor compound, photo initiators react to light, hardening the material (Gojzewski et al., 2020).

Investment casting (IVC)

It is widely understood that metal casting is a formative process, embedded in multiple civilisations cultures since 4000 BC. Casting parameter & alloy selection, allows microstructural & dimensional control over the manufactured items. Already embedded in the Jewellery manufacture industry, Polymer-AM & IVC manipulates the design freedom of AM, reduced cost & adaptive nature of investment casting (Al-Ketan, Singh & Karathanasopoulos, 2023). Lost wax IVC is used for alloys of silver, gold, palladium & platinum, within the jewellery manufacture industry. Models can be created from wax injected into a pre-existing mould, or AM of a resin or wax model, for prototype iteration or lost wax investment casting (Ferreira et al., 2012), (Al-Ketan, Singh & Karathanasopoulos, 2023).

As outlined by Klotz et al. (2019) A wax tree is created, consisting of a wax feed & the wax models of the required parts to cast. An investment powder, such as gypsum, or silica is packed in the can containing the tree. The can is heated to burnout the wax tree & fuse the investment powder, creating a negative space. The alloyed material is melted at the temperature required for the specific material alloy, centrifuged & poured. The investment is removed accessing the cast parts, which subsequently are detached from the precious metal tree. The excess sprues and miscast pieces can be re-used or refined.



Figure 4: Lost wax investment casting stages of TPMS constructs (Al-Ketan, Singh & Karathanasopoulos, 2023).

Complex geometries are not always suitable for investment cast & complex pieces may require multiple moulds & time intensive set up, where production time & number of steps from design to manufacture is greater than direct metal manufacture by SLM, with multiple phases identified for production bottlenecks (Ferreira et. Al., 2012).

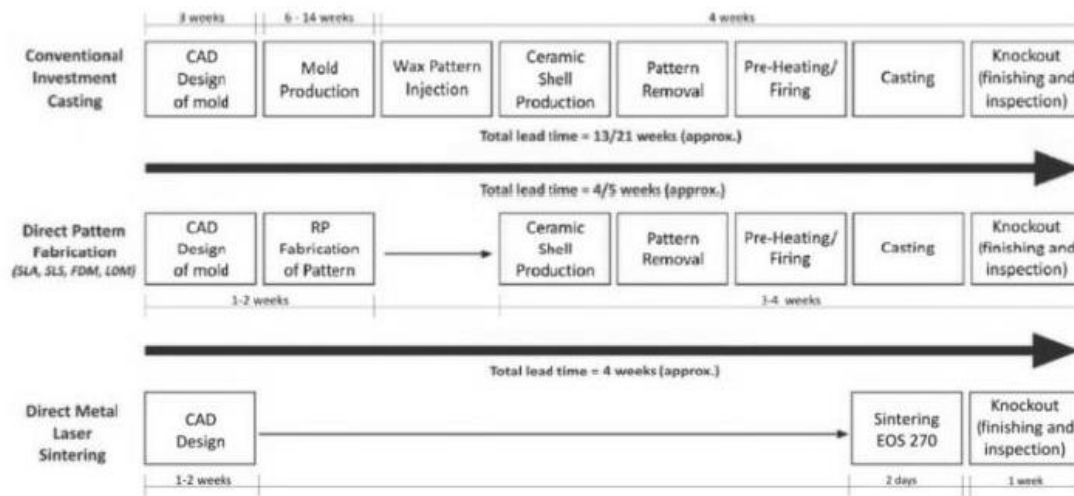


Figure 5: (Ferreira et al., 2012) Shows the comparable timeframes of three distinct jewellery production systems.

For polymer-AM & IVC, refining of material alloys requires more production steps & requires more material for the casting tree (Ferreira et. Al., 2012). Platinum casting requires higher energy, compared with silver & gold alloys, & can react against the crucible. Platinum can tarnish, oxidise, & incorporate up to 5% casting shrinkage & porosity (Houghton & Greer 2021). However, the right alloy & process can improve viability as demonstrated by Klotz et. al., (2019) with Platinum alloys explored, and Platinum950 Cobalt50 chosen for its excellent flow of molten material, with complete infilling of the cast test grid.

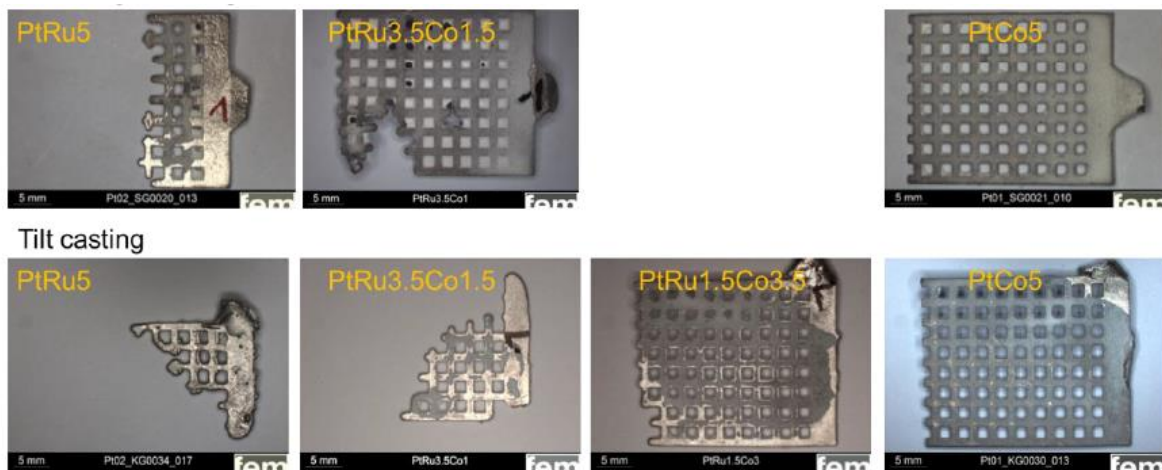


Figure 6: Platinum alloy & effect on sub alloy addition on centrifugal casting (Klotz et al., 2019.)

Selective Laser Melting (SLM)

SLM can be employed to fabricate direct-metal production of precious metal jewellery, without the need for polymer-AM (Cooper, 2016). Most commercial SLM systems use a galvo-mirror, deflecting a single spot, continuous wave or pulsed wave, infra-red fibre laser with power of up to 1000W (Zavala-Arredondo et al., 2017). SLM is a laser powder bed fusion process, for the AM of components and tools, from digital CAD files. There are fewer production steps when compared to hand made or investment cast process, with no complex tooling or associated costs for low-volume productions. (Ferreira et. Al., 2012).

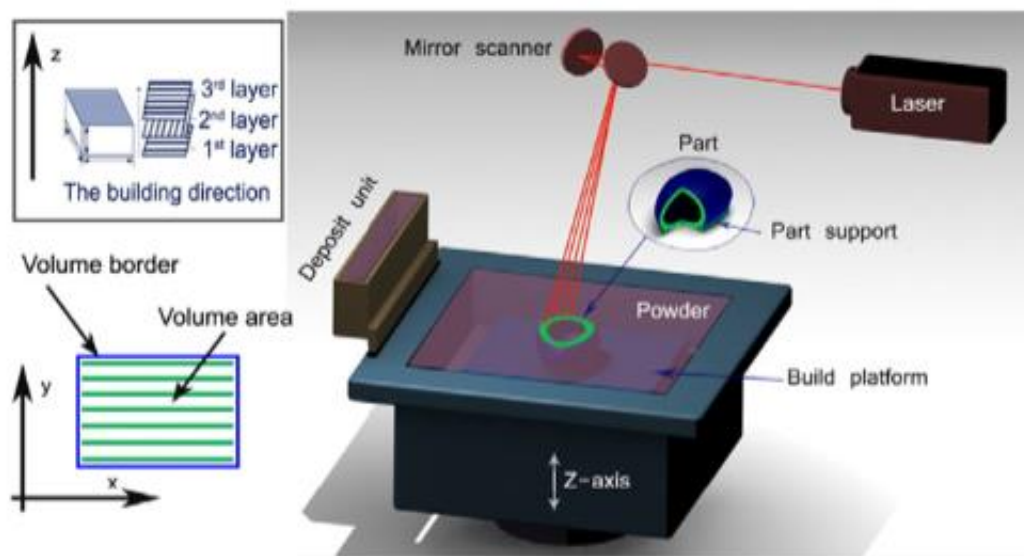


Figure 7: SLM schematic (Fischer et al., 2016).

SLM systems control the atmosphere by purging inert gas, such as Argon, Nitrogen or Helium, with a need for an even flow to reduce oxygen to the environment, preventing oxidation, which would influence the laser & material interactions. A lack of oxidation improves the desired mechanical properties of the part (Korium et al., 2021). Laser & material parameters, such as laser power, beam diameter, hatch distance, scan strategy, & thickness of the layer, influence the SLM process (Nagarajan et al., 2019). Changing the hatch distance changes the morphology of the surface, combined with scanning speed & surface depth, is important for thin walls & delicate features (Yadroitsev and Smurov, 2011). Parameters can be optimised to create high density, quality parts (Korium et al., 2021). During the solidification AM phase of SLM, unique microstructures can be observed and controlled, due to the localising of high thermal gradients, and quick rates of cooling (Hooper 2018). SLM has the ability to control the micro-structure, to produce parts with desirable mechanical properties (Popov et al., 2021). Microstructure, surface finish, porosity, residual stress, mechanical properties, & feature resolution are all controllable output characteristics of an SLM build (Nagarajan et al., 2019).

Powder morphology such as shape & size, and chemical composition affect material flow & thermal conductivity (Yadroitsev and Smurov, 2011). Particle size & distribution has a direct effect on the flow of powder, its application & spread, and ultimately its performance, where finer particles can attain a higher resolution (Lawyer, 2023). SLM Systems typically spreads a layer of spherical atomised metal,

on the powder bed up to 50µm in depth, where the integrated laser accurately fuses, producing the part layer by subsequent layer (EOS, 2023). SLM systems typically operate in a powder particle size range of 20–50µm & support a layer thickness of 20 -100µm. To increase the feature resolution, the diameter of the laser beam, the layer thickness, and the particle size, are main factors that need to be modified, (Nagarajan et al., 2019).

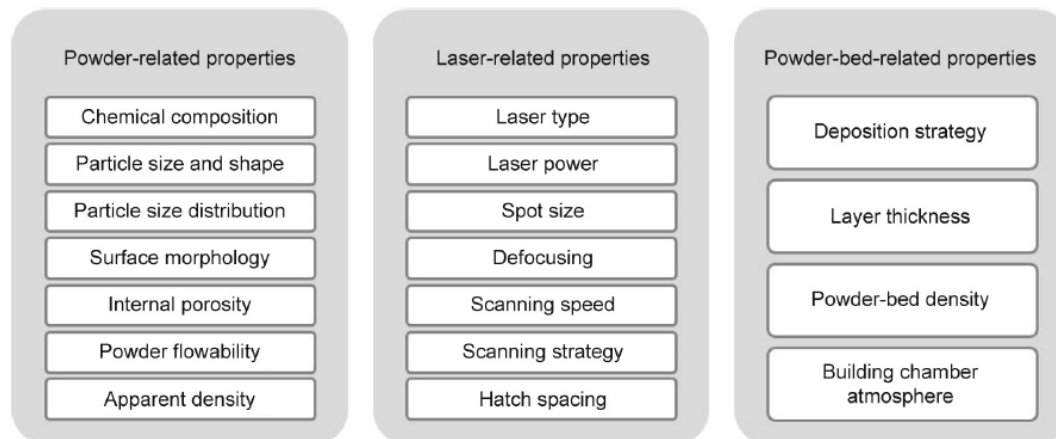


Figure 8: SLM process parameters that influence the build (Nagarajan et al., 2019).

Commercial SLM systems have the potential be modified for a microscale resolution of 15µm, minimum surface roughness of 1µm, & part density of up to 99.3%. Modifications would include, optimising the optical system, powder recoating, and powder dispensing units (Nagarajan et al., 2019). Large build chambers could be cost prohibitive for precious metal fabrication, due to the large capital cost of the powder bed, along with a technological capital cost for equipment & training (Ferreira et. Al., 2012).

Infra-Red laser 1030-1070nm

Neodymium is a common lasing ion, yttrium aluminium garnet and glass (Nd:YAG) with a wavelength off the visible spectrum at 1064nm (Corner, 2020). It is commonly accepted that most commercial fibre lasers are in the infra-red spectrum, with few visible-wavelength lasers additive manufacturing machine AM systems in industry; in an article by Schlett (2023) lasers for SLM systems for reflective materials were discussed. 1KW ytterbium fibre lasers can process highly reflective material, however frequency-doubled ytterbium lasers in the visible spectrum of 515-530-nm range are more suited to process reflective materials. Shorter wavelengths are more readily absorbed over the longer wavelengths of infra-red. The infra-red laser requires increased power for fusion, up to 10× higher than a blue laser (Schlett, 2023). 1% microalloying of elements into the alloy can be efficiently processed using infra-red laser, as the thermal and electrical conductivity decreases approximately 10%, using semiconductors, such as germanium. Surface treatments can also reduce reflectivity (Klotz, Tiberto and Held, 2017). Increasing the power is a common theme to achieve fusion, however if the power is too high, the material may fuse, but the melt-pool can be destabilised, negatively affecting surface roughness, from increased spatter & material vaporisation (Alsaddah et al., 2021).

Diode lasers tuned to shorter wave lengths 808nm, have potential for fusion at as little as 5w, and a possible scalable solution as diodes are low cost, compared to fibre lasers and less energy intensive (Alsaddah et al., 2021) however they would still require an SLM for the outline for high resolute parts.

Silver reflectivity of 98.8% laser wavelengths at 650 nm (Xiong et. al., 2019).

Green Laser 515nm

Shorter wavelengths, such as 515nm, are more readily absorbed into the reflective powder beds, where the longer wavelengths of infra-red lasers, are reflected away, leading to a less stable melt-pool, affecting the surface roughness, creating more spatter & increased porosity (Zavala-Arredondo et al., 2017). Green wavelengths create a more stable melt pool, with less spatter, greater density & improved surface resolution. While limited in the market penetration, commercial systems currently include TRUMPF 515-nm green disk lasers in its SLM systems (Trumpf, 2023). Green lasers processing pure copper have an absorption of approximately 40%, compared with less than 5% of infra-red lasers (Papastathopoulos, 2021).

Blue Laser 450nm

Nuburu is a commercial laser developer for blue lasers integrated into AM systems. Reflective metals, such as gold & copper absorbs blue light up to 65% compared with 5% infra-red, leading to a more controlled system melt (Nuburu, 2023).

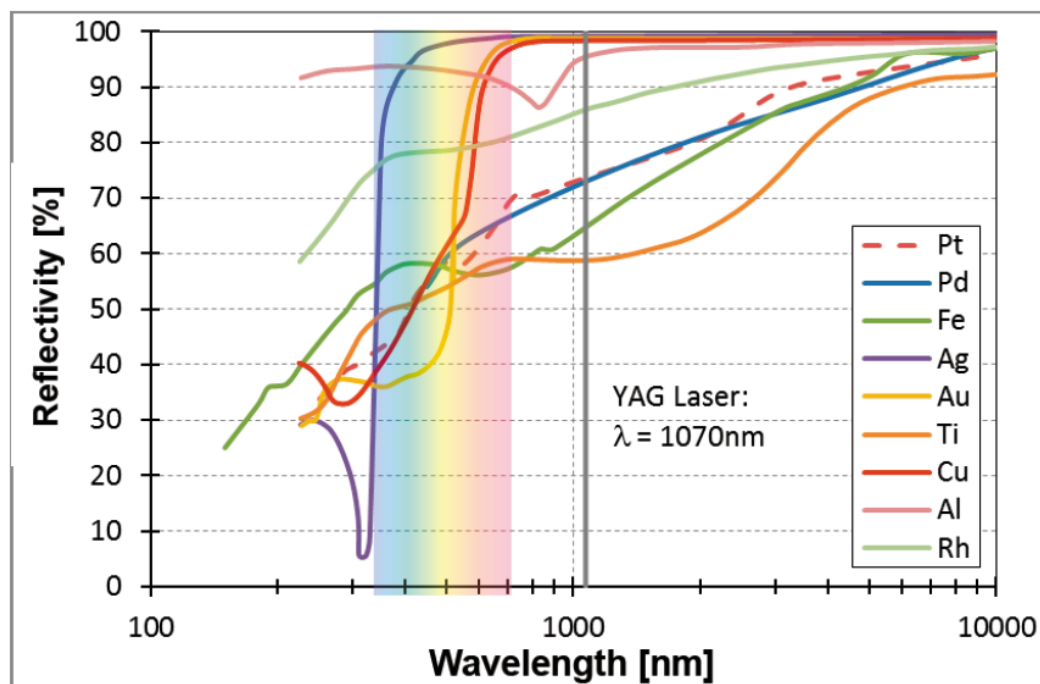


Figure 9: Reflectivity; with a focus on precious metals (Klotz, Tiberto, & Held, 2016).

Industry common Nd:YAG lasers, of the precious metals, platinum & palladium have better processing reflectivity of 60-70%. SLM of gold, copper & silver have near total reflectivity. SLM of titanium absorbs over 50%. The absorption of all precious metals would improve in the blue spectrum (Klotz, Tiberto, & Held, 2016.) For Electron Beam Melting, absorption is in the range of 65-85% for most materials, (GE additive, n.d.).

Silver (Ag)

Silver reflects 70% of the laser energy when utilising Nd:YAG fibre laser with a wavelength of 1070 nm. The high reflectivity can cause damage to the laser, & surface roughness is a post processing challenge (Gebhardt et al. 2012). For silver processing a 400w Industry standard fibre laser with a 1060–1100 nm wavelength was demonstrated by Robinson et al. (2022) to show the feasibility of processing high purity silver (99.9%). They achieved a 97% part density, at slower scan speeds, but noted all parts contained porosity (Robinson, Stanford and Arjunan, 2020). SLM Jewellery alloys of silver & gold have nearly total reflective & high thermal conductivity, and so requires specialised parameters, & alloy additions, influenced by the material's high reflectivity and high thermal conductivity, (Gebhardt et al. 2012). Due to its antimicrobial properties, 97%-part density, of pure gas atomised silver powder (99.9%) was SLM to form geometrically complex, self-supported, bone scaffolds as demonstrated by Arjunan et al. (2020). However pure silver is typically much softer and so a solution of silver (925) and copper is normally used to aid strength alloys for jewellery manufacture (Corti, 2021).

Gold (Au)

One of the earliest AM processing of gold, Khan and Dickens, (2010) demonstrated the SLM of pure gold (99.9%). The powder was 24µm, mean spherical morphology, & gas atomised. A 50w ytterbium doped, continuous wave fibre laser (1070nm-1090nm wavelength) was used to fuse the material. 50W power & 65mm/s scan speed optimal parameters were identified, & gold cubes were manufactured. Porosity between the layers was due to low power not fully fusing the powder. As pure gold is highly reflective around 85% is reflected in the infrared range, this could account for the poor fusion & higher laser power, optimising parameters or increasing the absorption with lower wavelengths could increase fusion. Micro alloying with semiconductor germanium, or silicon, improved microstructure & the SLM behaviour, allowing an optimised laser power which improved the surface roughness, 30% reduction in texture, of an 18ct gold build, whilst reducing notable porosity (Zito et al., 2014), highlighting a potential for a reduction in finishing time & reduction in lost material. Semiconductors lower thermal conductivity, allowing a more efficient laser power use. (Zito et al., 2014). Micro alloying with semiconductor elements Silicon or Germanium in gold samples reduces the thermal conductivity of the SLM process, helping to stabilise the melt pool (Carlotto, et, al., 2015).

PGM's (Pt, Pd,)

Platinum & Palladium 60-70% reflectivity Industry wide use Nd:YAG lasers wavelength of 1064 nm. High purity platinum alloys (Pt950) have a thermal conductivity less than traditional gold alloys (Carlotto, et, al., 2015).

Copper (Cu)

Pure copper has similar metallurgic properties to gold, in commercial SLM systems requires 400-1000w for fabrication due to infra-red laser reflection and thermal conductivity (Qu et al., 2021). Qu et al., (2021) utilised a laser system with a 25 µm laser spot size, 5–25 µm powder, & 10µm layer thickness. Relative density of 99.6% was achieved using a laser power of 200 W, scan speed of 600 mm/s, & 0.05mm hatch distance. Optimising the parameters & hardware allowed micro-SLM production comparable to commercial SLM's.

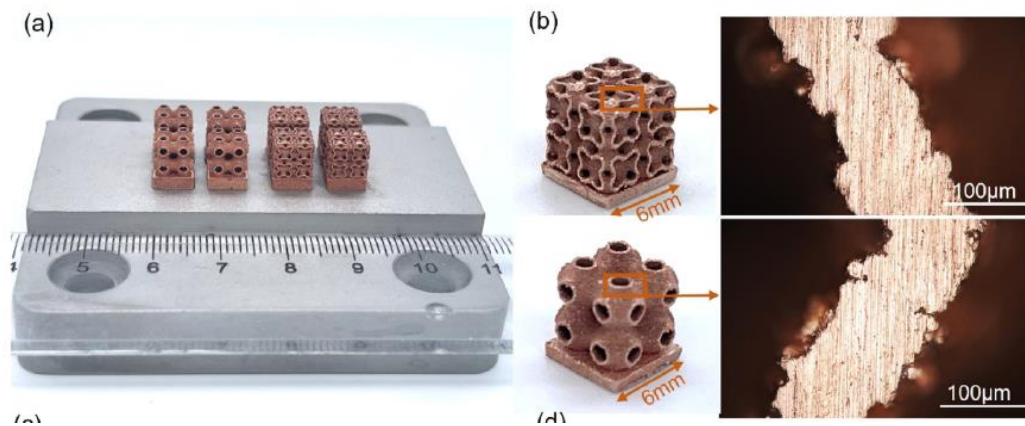


Figure 10: Copper TPMS SLM samples (Qu et al., 2021).

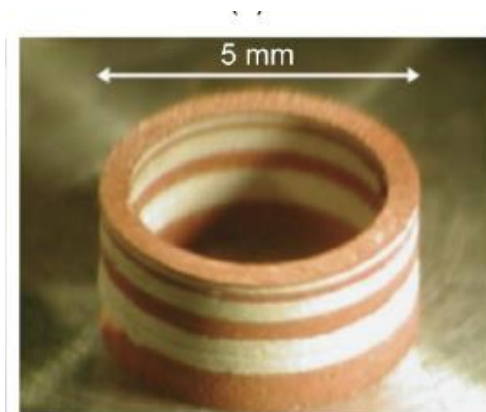


Figure 11: Micro-SLM multilayer of copper & Silver (Nagarajan et al., 2019).

Titanium (Ti)

Carter et al., (2022) explored powder adhesion & roughness in titanium SLM. They found surface roughness decreased with increasing scan speed and decreasing laser power. At low energy parameters, the roughness increased due to destabilisation of the melt pool.

Electron Beam Melting (EBM)

Electron Beam melting uses a high-powered electron gun, with up to 3.5Kw of power, to melt the powdered feedstock (Zavala-Arredondo et al., 2017). EBM systems operate under a vacuum. The dissipation of energy is prevented so the electron beam is efficiently passed to the part (Galati, Minetola and Rizza, 2019). The electron gun deflects by magnetism, with processing speeds greater than a galvo scanning system contained in most SLM printers, & the electron beam can split into multiple spots (Zavala-Arredondo et al., 2017).

Parameters influence part roughness, such as reducing scan speed, increase beam current, & build height, negatively impact the surface texture. Improving surface roughness by adjusting process parameters is limited for EBM (Galati, Minetola and Rizza, 2019).

EBM is a high temperature process, with mechanical properties similar to work hardened constructs (GE additive, n.d.). Surface roughness is a major limitation of EBM, greater than SLM, where SLM is considered the more stable technology (Zavala-Arredondo et al., 2017). EBM has applications for mass production of titanium parts for medical & aerospace industries (Galati, Minetola and Rizza, 2019).

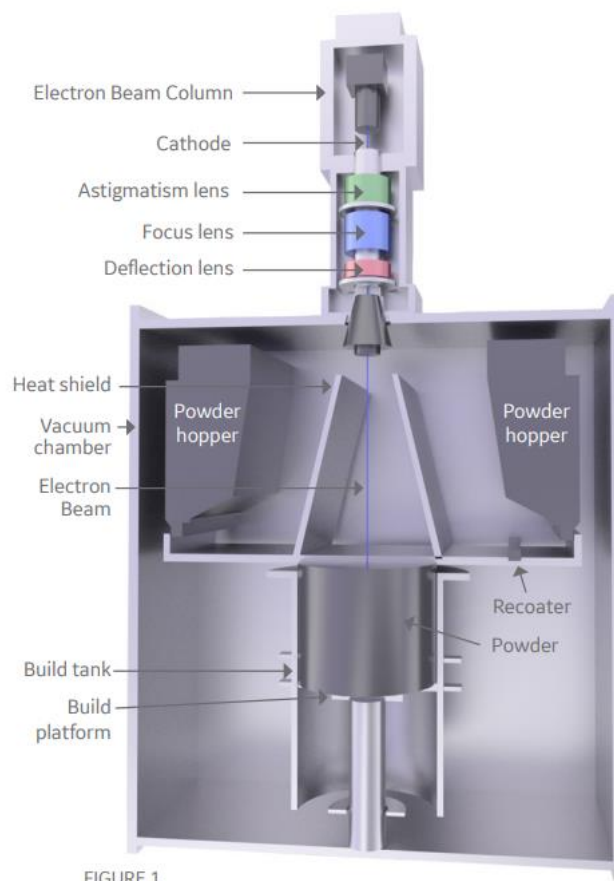


Figure 12: Schematic of the EBM system (GE additive, n.d.).

Binder Jet Printing & Pureform

Pureform uses DLP photopolymers that contain metal powder. The DLP projects the layer image & cures the metal powder & photopolymer solution, uniformly distributing the metal powder in each thin layer. These parts are then sintered in a furnace for a low ash burn out of the binder, and fuse the metal powder into a solid part (HoloAM, 2023). Pureform differs to Binder Jet Printing (BJP) in that BJP sprays an adhesive onto a powder bed, rather than using light to photo cure a polymer. The de-binding phase & sintering phase remain unchanged (Vaneke, et al., 2020). Binder Jetting has excellent surface resolution, however suffers from non-linear shrinkage & lower part densities than SLM (Vaezi, Drescher and Seitz, 2020). Desktop Metal produces BJP systems that can process silver, gold, copper & titanium alloys (Desktop Metal, 2022).

Diamond Centre Wales collaborations with Holo using pureform has produced high resolution parts with good surface resolution in pure copper components (Metal Additive Manufacturing, 2021). Environmental aspects should be considered of the de-binding & post-sintering phase in a furnace. Part shrinkage must also be calculated, and the theoretical density is less than SLM, due to de-binding & sintering stages (Vaezi, Drescher and Seitz, 2020.) PureForm Micro-AM produces parts with features <50 μm , (HoloAM, 2023). Pureform was considered, due to not needing support structures & excellent surface resolution, but materials are still in the development phase for precious metals.

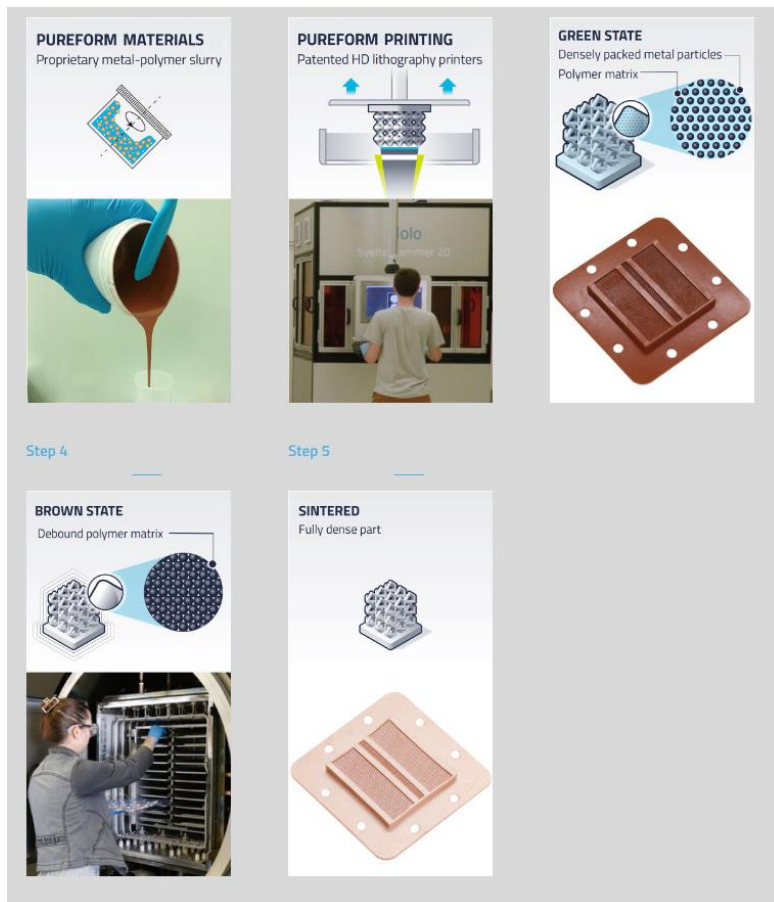


Figure 13: Holo AM process steps (Holo AM, 2021).

Simulation

Simulation is required in many aspects of the AM process for informing the accuracy & repeatability of the complex & numerous associated variables (Fraunhofer, 2022). Variables for an SLM system, as earlier outlined by Nagarajan et al., (2019) are material, laser & powder bed. Coupled with material alloy composition, the complexity of the build interactions, it is unfeasible to be able to use a trial & error system. Simulation can work towards optimising the multiple interlinked processes of AM (Johnson et al., 2020). Simulation can be employed to observe the physics of a process, or simulate the physics of a manufacturable part for material testing (Fraunhofer, 2022).

Simulation of the Process

Fraunhofer (2022) demonstrated the combination of simulation methods to map the entire process of laser powder bed fusion, as no part works in isolation. Fraunhofer simulated how the powder particles melted to simulate the laser interaction and heat conduction, & simulated the surface tension that causes the melt to flow, & employed cellular automaton to estimate the microstructure produced of the material. This combination of simulations creates an ecosystem of real-time-modelling of the process.

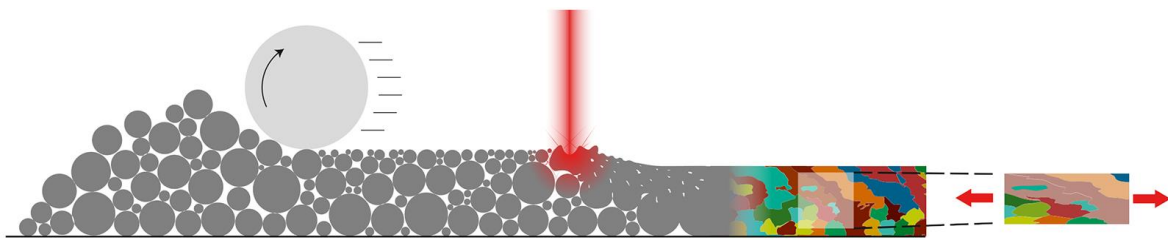


Figure 14: SLM process simulation; powder to the mechanical properties (Fraunhofer, 2022).

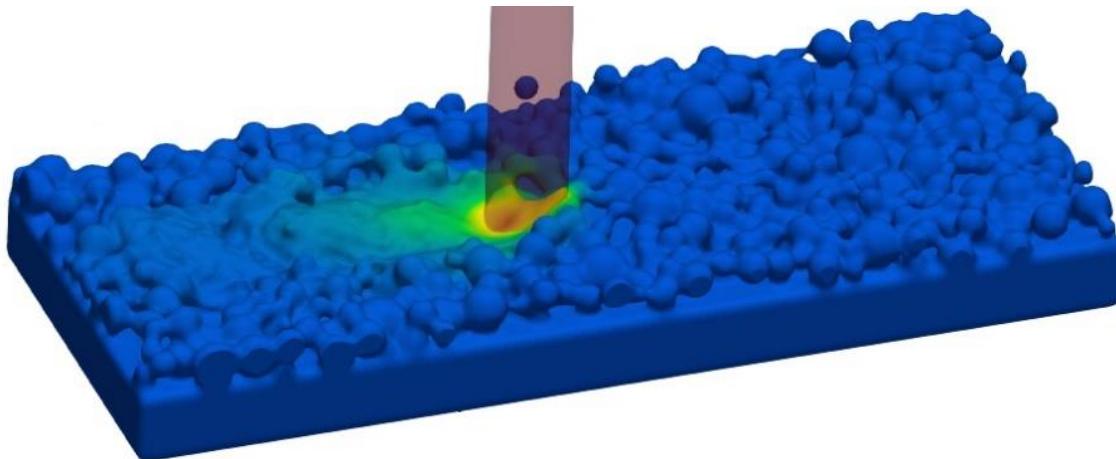


Figure 15: Laser & powder bed simulation process (Fraunhofer, 2022).

Alloy Simulation

For a tailored alloy production, design algorithms are required, influenced by scientific developments, proprietary software, and increased computing power can be leveraged to predict millions of different alloy simulations (Corti, 2021). As investigated by Johnson et al., (2020) machine learning can be exploited to predict an alloy through data collected, reducing the time and cost to production. as a material is manufactured on the build, it is influenced by the thermal, chemical & mechanical

changes the material experiences. In-situ monitoring of the melt-pool & build, with feedback, and control is a technology that can respond to issues in real-time, whilst collecting data. It can inform on how to influence the desired microstructure, or to limit the production of defects. Data is produced through computational modelling & in-situ monitoring. Machine learning adds to the production of data. All of this data can be used to model & simulate the AM process & alloy requirements (Johnson et al., 2020).

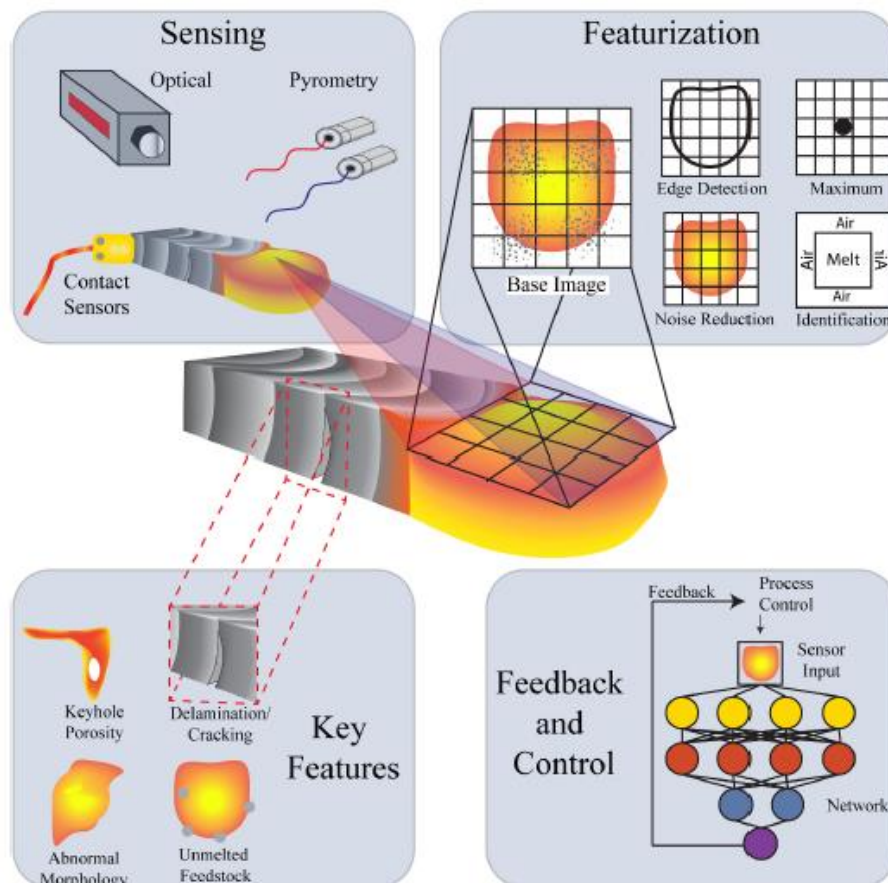


Figure 16: In-situ monitoring of the melt pool to detect defects, part accuracy, & incorporate feedback controls (Johnson et al., 2020).

Simulation of mechanical tests

Finite element simulation can be employed for material characterisation tests, such as tensile or compression (Fraunhofer, 2022). There are gaps in literature as most research is on uniform TPMS (Feng et al., 2022). Limitations of simulated compression tests with nTopology is that whilst the design is a non-conformity shape, so the test simulation would be on a uniform TPMS structure compared against a solid construct. The Simulation material is also pure silver, gold & platinum. However, there are several known alloys that have been developed for additive, subtractive & formative processes & may differ between suppliers. Simulation is only as good as the data inputted, & so the exact alloys, & process, would need to be determined & modelled to ensure simulation accuracy.

Critical Rare materials (CRM's)

CRM's have great economic importance for manufacture, and include PGM's, such as Platinum & Palladium, where additive manufacture can efficiently use these materials, through reduced materials needed for builds, and efficiently re-atomising supports, and re-using spent powders (Popov et al., 2021).

Supply chain issues can manifest with CRM's, especially bottlenecks of material availability & monopoly of producing countries, for example, the platinum production in South Africa accounts for over 80% of the worlds primary production, threatened by blackouts & political instability (Thethwayo, 2018). The demand for CRM's is driven by industrial use of platinum, includes fuel cells & catalysts, palladium is used in desalination & catalysts, silver is used in solder as opposed to lead, as per the WEEE directive, & required for RFID tags, & titanium is required in desalination plants & medical implants (Resilience for the future: The UK's critical minerals strategy, 2022).

Refining Platinum requires corrosive acidic solutions production a leaching solution. (Heinrich, Laag, & Copponnex, 2019). SLM has the potentially to efficiently use materials & increase material recycling rate. Recycling Platinum can lead towards a circular economy, rather than relying on material mining of Platinum, traditionally high impact on environment & resource consumption. Biohydrometallurgy or selective chemical dissolution could be a future option to reduce energy & waste, with a high platinum recovery, however the technology readiness level is low & not currently embedded in the supply chain (Granados-Fernández et al., 2021).

The Government projection is a fourfold increase of CRMs for clean energy technologies by 2040 (Resilience for the future: The UK's critical minerals strategy, 2022) increasing pressure to access & efficiently use these materials

Jewellery alloys

Table II Relevant Hallmarking Standards for Precious Metals (40)		
Base precious metal	Hallmark	Minimum weight fraction
Gold	14 karat	58.5%
	18 karat	75.0%
Platinum	850Pt	85.0%
	900Pt	90.0%
	950Pt	95.0%
Palladium	500Pd	50.0%
	950Pd	95.0%
Silver	Sterling/925	92.5%
	Britannia/958	95.8%

Figure 17: Common Purity for hallmarking standards (Houghton and Greer, 2020).

Silver 925 (92.5%) dominates traditional Jewellery production, traditionally sub alloyed with Copper, Zinc, Gold or Platinum. Micro-alloyed with Germanium (1.1%) added to avoid subsurface copper oxidation resulting in fire-stain, an undesirable dark patch formation, where the germanium bonds with the copper, forming an intermetallic phase, a protective germanium oxide layer (Corti, 2021).

Gold 9ct & 18ct (75%, 37.5%) purity dominates traditional UK & European Jewellery production. Gold colour is dependent on alloying metals, such as palladium or silver for white, copper for red, & cadmium for green hues (Corti, 2021).

High purity golds are prized in the far East & Middle East. Micro alloying with Titanium (1%) significantly improves the strength, whilst keeping the deep yellow colour, that can't be obtained with lower carat golds (Corti, 2021).

Platinum 950 (95%) purity dominates traditional Jewellery production. Platinum Cobalt alloy for jewellery casting is popular due to its material flow, low oxidation & optimal mechanical properties (Frye and Fischer-Buehner, 2011).

Titanium is not considered a precious metal, but one of the most widely researched SLM materials (Fxigor, 2023) & is widely used within the Jewellery industry as an alternative precious material, which can be anodised, changing the colour of the titanium through electrolytic oxidation process, which thickens the oxide layer of Titanium (Kahar, et. al., 2020). Whilst jewellery is generally valued for its high lustre, with no imperfections, rough titanium is advantageous for stimulation of bone growth & fusion (Taniguchi, et. Al., 2015). Titanium builds are included for a comparison of a widely researched & industry embedded material.

Mechanical Properties.

A core innovation of SLM can be realised through material optimisation and process improvement (Forno, Actis Grande and Fais, 2015). Tensile test, & compressive tests can be used evaluate SLM mechanical performance (Arjunan et al., 2020). Alloys are crafted for their process, with desired properties for casting, deoxidation, ductility, hardness, scratch resistance, tarnish resistance, fabrication working, and more recently, for SLM (Corti, 2021). Arjunan et al., (2020) used physical compression tests of pure bone scaffold prototypes to determine the optimal SLM parameters.

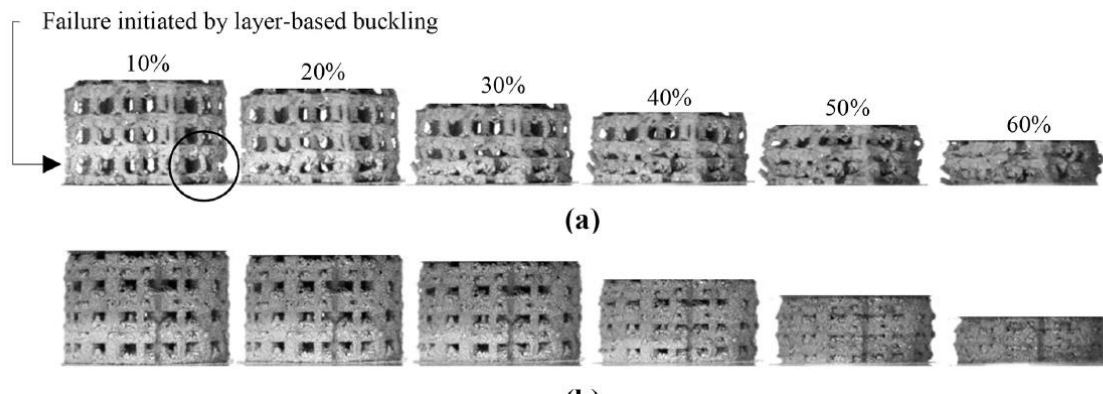


Figure 18: Physical compression tests of pure silver lattice scaffold prototypes (Arjunan et al., 2020)

An alloy's structure refers to its crystalline arrangement at the atomic scale, grain orientation & morphology when viewed through the mesoscale (Johnson et al., 2020). Microstructure describes the phases, grain morphologies, roughness, and defects such as porosity, influencing the material properties (Johnson et al., 2020). Precious metal alloys are polycrystalline, their atom arrangement in a regular periodic lattice (Houghton and Greer, 2020).

Due to simplicity, hardness tests, such as Vickers, is a commonly accessible test in the jewellery industry (Forno, Actis Grande and Fais, 2015). Minimum hardness of 100 HV for jewellery manufactured alloys is required, where widely used jewellery alloys, with 150–200 HV still mark & dent with ease. (Houghton and Greer, 2021). High hardness & scratch resistance are desired mechanical properties for jewellery manufacture. In traditional Jewellery manufacture of crystalline alloys, they are usually alloyed, thermally treated & mechanically processed to achieve these properties up to 300 HV (Houghton and Greer, 2020). Lustre of precious metal is intrinsic with the alloys ability to withstand tarnishing & oxidation, which can degrade the mechanical properties (Houghton and Greer, 2021).

A study by Heinrich, Laag, & Copponnex, (2019) explored new jewellery manufacture alloys suitable for AM production. Rh50Pt50 (Rhodium & Platinum) with a tensile strength of 2000MPa & hardness up to 350Hv was achieved by hot rolling & a 99.95% density achieving 100% density with Hot Isostatic Pressing (HIP.) It is a luxury alloy, expensive to process & refine & a high associated production & material costs.

The microstructures of SLM materials follow an ordered pattern & lower grain size compared to cast materials. Through grain refinement of the micro-structure, SLM can increase silvers material hardness up to 200% (148.9 HV SLM, 45HV Cast) with a density up to 96.7% (Xiong et al., 2019). In general terms, the harder the material, the easier it is to achieve a specular lustre, an important characteristic for the jewellery industry (Forno, Actis Grande and Fais, 2015). It is worth noting that

legacy platinum constructs were hand formed, through bending, forming, & hammering, deforming the crystal lattice, however most current platinum jewellery offerings are cast, and so do not benefit from work hardening (Klotz and Fryé, 2019). Platinum alloys containing micro alloys of Gallium, or Indium, increased hardness and strength significantly, whilst also facilitating increased fusion of the material during laser melting (Klotz and Fryé, 2019). Another way of improving hardness was the inclusion of alloys containing nanodiamonds, sintering with 18ct yellow gold improved the hardness (180-220HV), producing dense parts, unaffected by porosity in the final polishing stage (Forno, Actis Grande and Fais, 2015).

In an interview with Fryé (2022) Cast platinum ruthenium (Pr950 Ru50) alloys were compared against SLM production, where it was observed, an increase in strength and resilience, where the grain size is significantly smaller, by the way material is formed under a laser. All printed parts had porosity, no sample reached 100% density, but hot isostatic treatment was applied to mitigate the porosity formation. It was observed mechanical properties of SLM Pt-Ru were greater than IVC, where the yield strength was 93% higher in the AM part than the cast, but ductility remained unchanged (Platinum Innovations ABC, 2022).

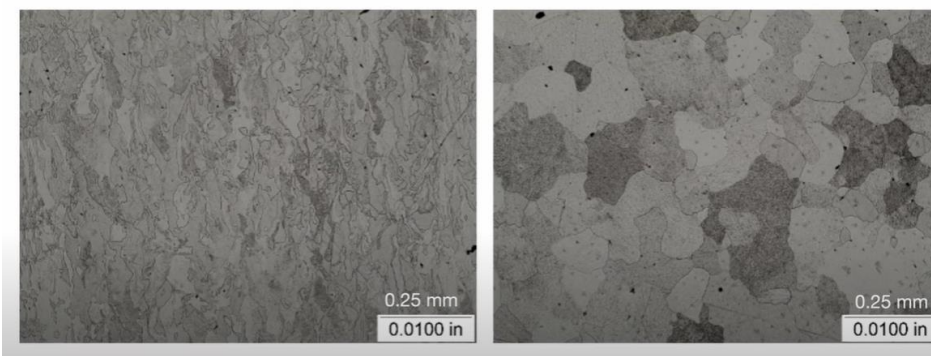


Figure 19: Smaller grain size created using SLM (left) when compared to IVC (Right) (Platinum Innovations ABC, 2022).

Bulk Metallic Glass

Developments in cast bulk metallic glass (BMG) have an amorphous, non-crystalline structure, and can be thermoplastic formed, containing precious metals to obtain a hardness exceeding 300 HV, without the application of post processing activities (Houghton and Greer, 2020). BMG's properties include increased strength & hardness, increased elastic strain limit, with little to no shrinkage during casting. BMG's have excellent manufacturing capability through casting and deformations which can produce intricate geometries (Corti 2021). 18ct gold alloys are possible, however 950 Platinum is more difficult due to the higher purity of Platinum required for UK hallmarking (Houghton and Greer, 2020). Low cast temperatures, superior mechanical properties & glass lustre are attractive for the jewellery industry, but use of Nickel in the BMG alloy, an unfamiliar industry technique, & high capital cost would need to be addressed (Houghton and Greer, 2020). AM of amorphous powders offers new possibilities for non-crystalline components & parts, where rapid cooling enables amorphous solidification, post-melt (Trumpf, 2020). 'The absence of dislocation-mediated plastic deformation means that BMGs can reach much higher elastic strains than crystalline metals and can approach the theoretical strength' (Houghton and Greer, 2021).

Defects of Cast & SLM parts

To date, most platinum jewellery is cast & creates porosity, & is traditionally soft & easily deformed (Corti, 2021). Defects that affect lost wax casting include, sub surface porosity, porosity under the anchor sprue, cracking, large internal voids, & loss of detail (Fryé and Fischer-Buehner, 2011). Porosity can be recognised as a manufacturing defect, where solid constructs for formative processes aim for 0% porosity. Porous structures are common in nature, such as bone, coral & honeycomb (Feng, et al., 2022.)

CNC machining is a subtractive methodology, removing material from a dense blank, with minimal production defects, & generally metal prototypes are machined with much smaller tolerances. Subtractive methodologies, such as CNC, are not best suited for these complex geometries such as TPMS. The application of TPMS structures can be superior to their conventional solid parts. (Feng et al., 2022).

Whilst AM increases design freedom and complexity, there are certain metallurgical defects that can also occur from the process of laser melting and the solidification phase, including hot cracking, unfused powder, porosity & oxidation (Al-Ketan, Singh and Karathanasopoulos, 2023).

High reflectivity, thermal dissipation & material oxidation increase part surface roughness (Robinson et al., 2022). Defects are likely to originate when the temperature field of the melt pool is not optimal (Hooper, 2018) so increasing the power for fusion of reflective materials likely to increase defects. Defects ultimately negatively impact the profit margin through failed pieces, lost material & increased workshop labour to correct, as well as impacting on the mechanical properties through excess soldering, or working of material (Fryé and Fischer-Buehner, 2011).

Korium et al, (2021) observed the surface of silver SLM samples exhibited an increase in porosity, when compared to gold & titanium printed samples, due to internal stresses between the print layers, a result of the silver alloys large co-efficient of thermal expansion. Porosity can be attribute to keyhole or blowhole, where there is trapped gas, or porosity from a lack of fusion (Robinson, Stanford and Arjunan, 2020), where Un-melted material during SLM, can attribute to porosity forming (Arjunan et al., 2020). Lower Ambient pressure can minimise keyhole porosity formation. (Wang et al., 2022). Laser scanning can help reduce porosity formation, as the speed increases, the porosity size decreases significantly in relation. (Wang et al., 2022).

Robinson et. al., (2021) SLM of high purity silver alloy had porosity attributing to 2.78% which could be improved by optimising process parameters & packing density. Subsequently optimising parameters was shown to increase part density, reduce defects such as porosity, and improve build success rate. (Robinson, Stanford and Arjunan, 2020).

X-ray nanotomography (X-ray nCT, or Micro Ct.) can be utilised for non-destructive porosity analysis in complex AM parts (Arjunan et al., 2020). It can also be used to detect internal micro-voids & unspent investment or metal powder (Al-Ketan, Singh & Karathanasopoulos, 2023).

Hot Isostatic Pressing (HIP) can be employed to close up micro-porosity (Fryé and Fischer-Buehner, 2011). Porosity formation affects the mechanical properties, decreasing ultimate tensile strength, and responsible for fatigue failure, and fracture strength (Wang et al., 2022).

Observing Surface texture

Studying surface texture improves our understanding of the capabilities of AM, with a gap in the literature between part performance and surface texture. Surface texture characterisation, where information is collected from complex topography from measurement parameters. Profile texture measurements are widely embedded in industry, however due to the nature of the contact stylus, this method cannot capture the entire 3d structure, compounded by complex structures, such as TPMS. (Townsend et al., 2016).

2D imaging, primarily SEM and optical microscopy, are used for qualitative surface investigation, with traditionally limitations of quantitative information in the sample height. (Townsend et al., 2016). SEM can be utilised to observe the microstructure & surface porosity of samples & utilised to determine surface peaks and valleys to determine the mean surface roughness (Arjunan et al., 2020).

Scanning Electron microscopy (SEM) was considered for this project, but is limited due to access to system & training. Traditionally you would have to choose between depth of field and resolution & SEM could provide that. However, there are now optical microscopes that can take images with small micro steps and composite an image to create an image with depth of field & the required resolution, & automate surface roughness measurements from line or area (Keyence, 2019).

Gwyddion is an opensource software for the analysis of height fields. It is employed to determine the Ra & Rq values of the samples. 3D focus stacked imaging from an optical microscope, exporting the data samples into Gwyddion, can analyse roughness analysis (Nečas & Klapetek, 2012).

Ra measurements quantify the surface resolution of a line (Keyence, 2023). the 'arithmetic mean of the absolute ordinate values within a sampling length' (Townsend et al., 2016). Rz measurements quantifies the surface height, where Rz & Ra together to represent the surface conditions & explains anomalies of peaks (Keyence, 2019). Sa measurements quantify the surface resolution of a quadrant area, rather than a line measurement (Keyence, 2019).

X-ray computed tomography extracts surface from volumetric data & can access all areas of complex geometries, such as TPMS, which is not available from surface probes, or surface investigation (Townsend et al., 2016).

Post Processing

In a study by Al-Ketan, Singh & Karathanasopoulos, (2023) Polymer-AM IVC & SLM were compared. The cast samples were smooth and specular, whilst the SLM samples were granular & perceived to be rougher in formation. Manufacturing efficiency comes from production of optimised design, build, laser & material parameters, whilst reducing material and post-processing activities (Halonen, 2020).

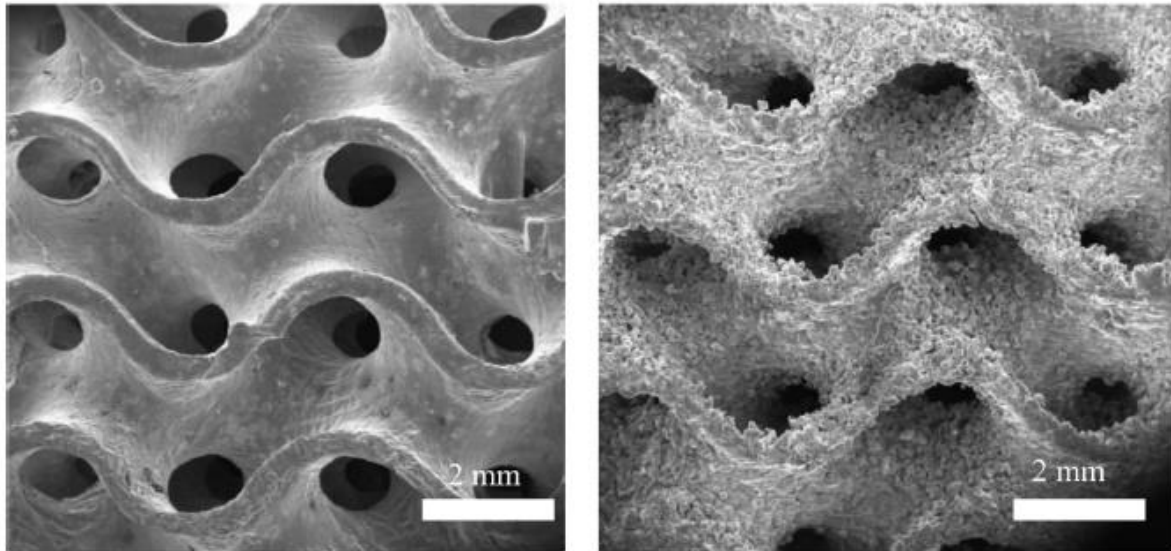


Figure 20: SEM of the AM & IVC (Left) SLM (Right) of Aluminium alloy (AlSi10Mg) (Al-Ketan, Singh & Karathanasopoulos, 2023).

Producing parts with minimal supports & reducing the need for post processing is desirable for manufacture of near net shape parts. Support removal & post processing is labour intensive & material loss has an associated cost. Post processing can lead to crack initiation. Internal supports can be inaccessible, or difficult to remove (Robinson et al., 2022).

Mechanical working can be employed to smooth the surface, or by removing surface material using abrasives, chemicals, or electrolytic polishing (Fletcher & Cooper, 2018). Mechanical polishing and electropolishing can automate the polishing stage & reduce surface roughness, (Robinson et al., 2022) prior to hand finishing high value jewellery (Cooper, 2016).

In the Precious Project, an Innovate UK funded project led by Fletcher & Cooper (2018), summarised the main technologies for automation of finishing in the jewellery manufacturing industry. Mechanical polishing has limitations on surface complexity & abrasives can penetrate the surface, a complex process with materials & chemicals, requiring multiple-stages. There are also environmental & operator implications of chemicals involved, such as particulates generated by deburring, grinding & polishing. Laser polishing, electropolishing, & plasma electro polishing can be utilised as an environmentally greener process, for the preparation of highly specular surfaces & complex geometries.

A post production phase, HIP could be employed as it is effective at removing porosity & optimising the desired microstructure (Corti, 2021).

Design Rules

SLM facilitates greater design freedom, & complex designs are economically manufactured (Ferreira et. Al., 2012), (Cooper, 2016). The technical knowledge required to design for SLM, operation of technology, & post processing activities, coupled with the drivers of economic, societal & environmental, are required to educate potential users & consumers of the opportunities & limitations, for successful industry adoption, requiring a long-term plan & capital expenditure on system, powder & training (Tidd & Bessant, 2021).

Design rules developed by Cooksongold (2016) for laser bed fusion, for their EOS M-80 precious metal system included: guidance on undercuts, hollowed sections, multiple links or the most delicate, intricate & complex shapes, to be built using SLM. All in-one-builds, include chains, meshes and hinges are built using SLM. Supports are used to orientate the links, with a gap $>0.5\text{mm}$, and removed post build for a free-flowing chain. Hollow parts with, or without, TPMS infills, & wall thickness $>0.5\text{mm}$, are built with a 0.5mm powder drain hole, plugged post build. The build, along with a wall thickness of at least 0.5mm . 0.25mm resolution details support delicate & complex builds.

Supports are needed to ensure structural stability during SLM production, usually required for builds with features 45° from the build plate, & strategically placed supports to manipulate thermal management of the part during melting (Cooper, 2016). Supports that cannot be removed from geometrically complex items, affect the finished weight, & functionality of a part. Support free printing would decrease print time & increase material efficiency, & reducing post production time of support removal & finishing. This is where BJP has the advantage over SLM (Orye, 2022). SLM practices that minimise or eliminate their need for supports would be advantageous for economic & environmental gains.

There are consideration of design & build parameter constraints & the material needed for creation. In a study by Ferreira et. Al., (2012) an SLM support structure was required constituting 30% of the build weight, and the lost-wax process required 60% of the build weight to effectively cast. Further reductions could be created by using a TPMS workflow, changing solid supports to TPMS structures, such as gyroids (nTopology, 2021).

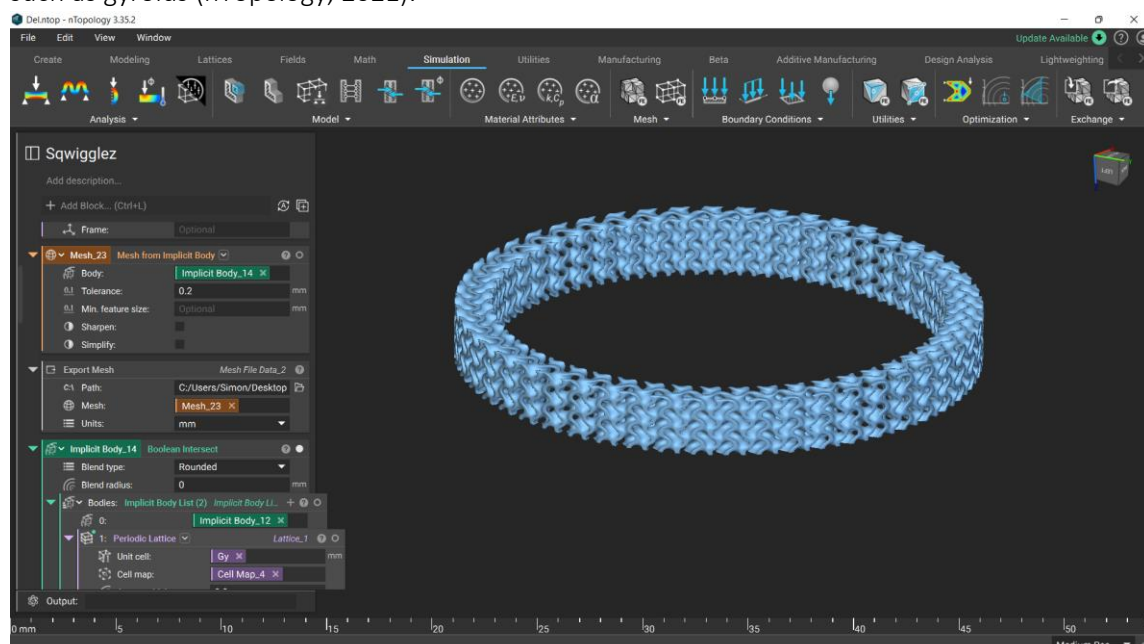


Figure 21: nTopology software screenshot; Creation of a Gyroid TPMS support (Evans, 2023).

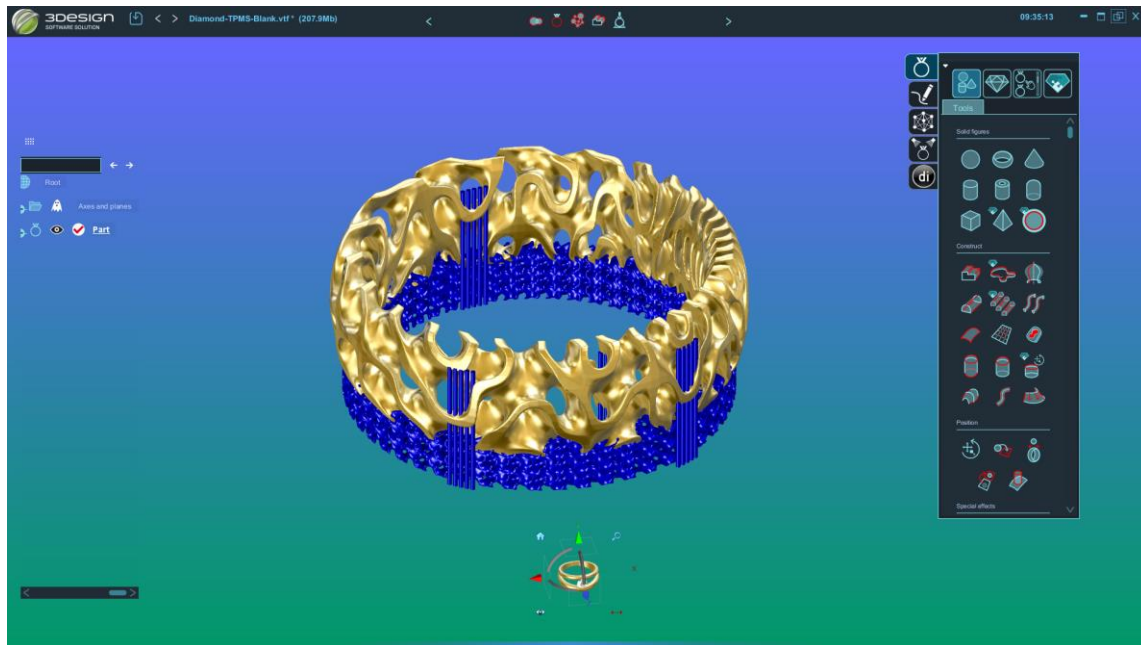


Figure 22: 3design software screenshot; Diamond TPMS ring, Gyroid TPMS supports (Blue), and support pillars (Blue) for print on SLM (Evans, 2023).

Design innovations, & previous builds

EOS M-80 complex build

Isla Cocos, exploited SLM design rules by (Evans, 2020) in silver alloy (Ag925) utilising SLM, EOS M-80. The collection contains SLM design innovations of encasing heat sensitive pearls, taking advantage of the material fusion, with localised generated heat from the laser (DCW, 2021). Hollow computational generation of the voronoi micro details was unsuitable to be cast. Fully customisable using parametric design, & material combinations (Evans, 2020). There was a perceived surface roughness for the silver SLM compared to IVC, however it was noted there was a reduction in porosity, which greatly reduced the labour time to laser infill with silver wire, & re-finish, & there was a reduction in sub-surface oxidation, (Evans & James, 2023).



Figure 23: Keyshot rendering; Isla Cocos SLM innovations (Evans, 2020).



Figure 24: Isla Cocos SLM build at Cooksongold EOS M-80 (Watts & Hill, 2021).

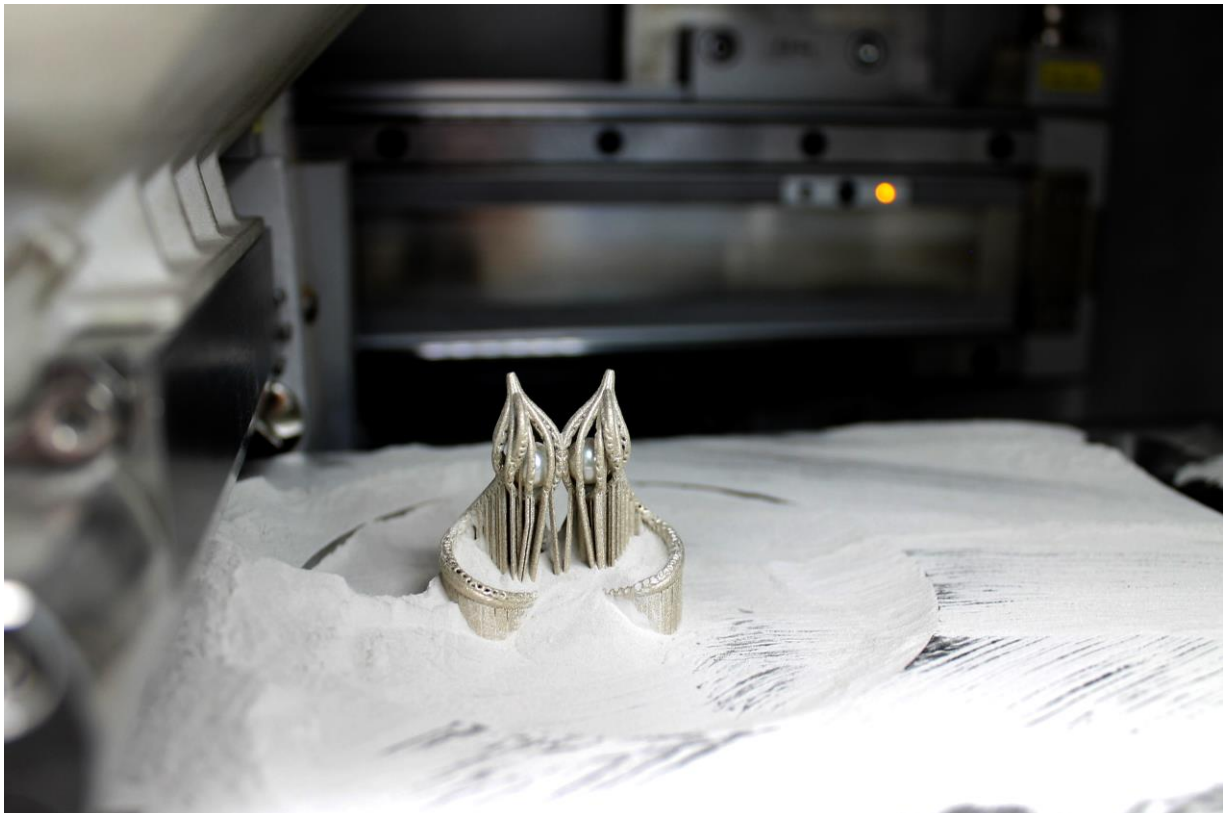


Figure 25: Isla Cocos SLM finished Build (Watts & Hill, 2021).

Pureform Holo.

As precious metals have not been validated for the Pureform process, a pure copper sample (99.9%) was trailed on the system to demonstrate the design innovations of support free, hollow, geometrically complex parts, with fine features (Aghababaie, 2021). Refinements of the design from the initial CAD drawing were the removal of the shank, as this had no design value being manufactured through this process. It could easily be investment cast. The incorporation of a flat base under the part to attach the build plate. Unsupported Features; the highlighted spheres in the hollow head were re-orientated & anchored with material. The sphere diameter was required to be less than 2mm, to support the de-binding process & post sintering phase (Aghababaie, 2021).

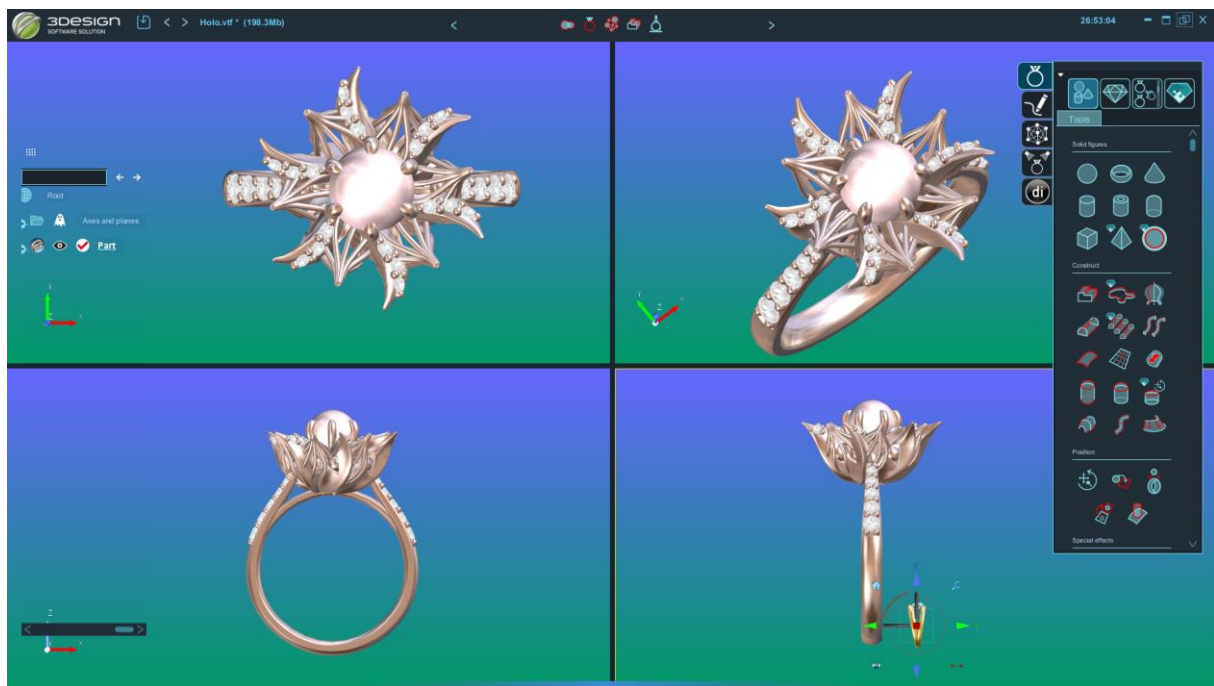


Figure 26: 3design software screenshot; Holo AM design innovations experiment (Evans, 2023).

Holo

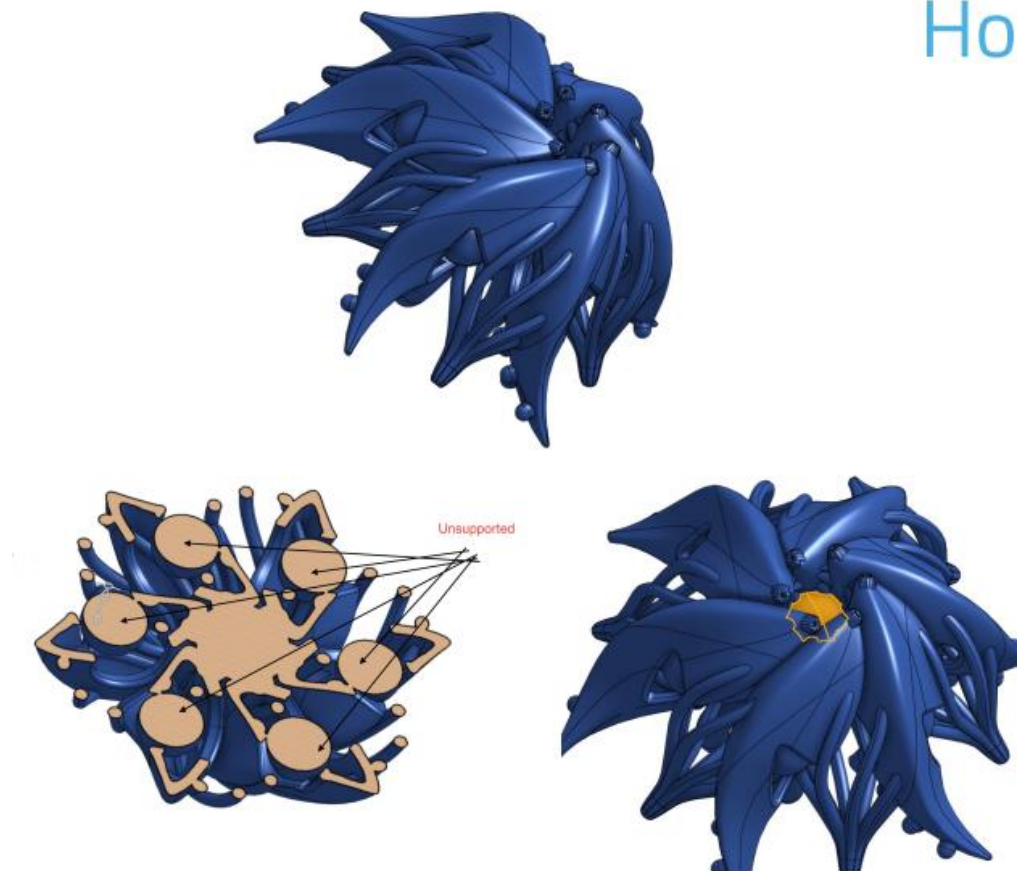


Figure 27: Holo amendments for copper trial Halo ring (Aghababaie, 2021).



Figure 28: Keyshot Render of Holo ring & subsequent pure copper trial part (Metal Additive Manufacturing, 2021).

Evolving the business model

SLM & Implicit modelling can support jewellery manufactures core, adjacent & transformational aspects of a company's innovation strategy as outlined by Naji & Tuff (2015). Stasis or incremental innovation of the product, could include increasing speed of production, efficient use of materials, reducing the number of process stages, implanting environmentally greener processes, & reducing the geographical barriers (Vaneke, et al., 2020). Although hallmarking would still need to be carried out at an Assay, or Sub-Assay, office (Assay office, 2022). 0Product evolution, where new products are created from access to new design rules & new material alloys & their optimised mechanical properties (Cooper, 2016). Supply chain evolution, where there is a reduction in the number of stages compared with investment casting, and production can be easily localised due to the size & reduction in phases. New material alloys and powders, so a system and raw powder can produce the necessary on demand sub-assemblies. CAD files, rendering, augmented reality & reusable work flows replace expensive pre-fabricated stock. (Vaneke, et al., 2020). Business model evolution where there is new product development & an evolved supply chain working together. Circular economic models could be applied to increase product durability, upgrading, repair, and optimised recycling systems, for material reclamation, product disassembly & product remanufacturing (Atasu, Dumas and Van Wassenhove, 2021).



Figure 29: Vaneke, et al., (2020) framework for the use of AM to evolve the business model.

However, there is an unknown cost for technology & alloy powder production access may be the reason why there is not successful industry wide adoption (Platinum Innovations ABC, 2022). Environmental and economic objectives have inherent challenges for the evolving business landscape. Environmentally aware consumers drive supply chains towards implementing, & achieving, sustainable development goal (Heydari, Govindan and Basiri, 2020). There is a need for a qualification plan for SLM processes, materials & parts to the industry standards, (ATSM, ISO) with process risk assessment to identify, document & mitigate failure modes, such as substandard mechanical properties of a part, or powder contamination (Gopalakrishnan, 2023).

Methodological review

The researcher's objective was to observe whether implicit modelling could be harnessed for the production of precious metal alloy, complex geometric designs, through AM of Ag925 SLM & compared with industry standard lost wax IVC. Methodological triangulation was employed, where more than one method to study a certain phenomenon, was used to increase the reliability & accuracy of the research (Noble and Heale, 2019). Peer reviewed Journals including, IEEE, Elsevier, & Science Direct, and select system manufacturers websites with a date range of 2010 to 2023, were considered to support the literature review. Communications with Industry partners, most notably AIM, Birmingham School of Jewellery, Centre for Batch Manufacture, Diamond Centre Wales, Weston Beamor & Cookson gold.

Part Fabrication

Using parametric modelling 3Design & implicit modelling software nTopology, a blended approach of qualitative & quantitative analysis of parts for constructed precious metal alloy builds, of customisable TPMS rings were compared for builds of the four identified systems.

Proposed I4.0 System: Parametric & Implicit Modelling, SLM-PBF,

- | | |
|-----------------------|-----|
| 1. Alpha AL3d-Metal | SLM |
| 2. EOS M-100 | SLM |
| 3. Arcam Q10 Titanium | EBM |

Benchmark against embedded industry practice:

4. Jewellery Industry Standard: Parametric & Implicit Modelling, Polymer-AM & IVC

Access to AM systems were considered a limitation, due to operator training & access, however processes were discussed & documented through images, videos & subsequent physical parts produced (Appendix 5.)

Method for part creation

- Implicit model created & exported
- Prototype iteration by MJP ProJet 2500w system
- System Setup (Model validated, Supports created, build slices & file creation.)
- Production on each system:
 - 1) 3 *EBM ARCAM titanium (TPMS Gyroid, Split-P & Diamond)
 - 2) 3 *Polymer-AM by MJP & IVC silver cast (TPMS Diamond)
 - 3) 1 *SLM EOS-M100 Silver (TPMS Diamond)
 - 4) 3 *SLM Alpha Silver (TPMS Diamond)
- Part removal
- Support removal
- Post processing

Economic argument

- Weight estimation/Post Build/Post process (g)
- Metal prices from WB (£)
- Costs for Fabrication from each system provider (£)

- Time for support removal (H)
- Time post processing & polishing (H)

Weight & manufacture time of solid constructs VS TPMS.

Qualitative research methods of observations

- Successful Build/cast (Compare to digital file)
- Comments on Support generation & removal
- Oxidation
- Surface Roughness
- Post processing observations
- Porosity

Optical Microscope

Surface resolution quantification.

Six line positions are measured upon each surface to determine Ra & Rz values.

A quadrant of the sample is measured on the test surface to determine Sa & Sz values.

VHX 7000 4K High Accuracy digital

Located at SPECIFIC, courtesy of AIM.

Light Microscope VHX7000 has a twenty-fold depth-of-field compared to conventional microscopes, & wide magnification range & a stepper motor of 1µm increments. A stepper motor & image processing is used to capture a series of images, composited into a single focused image. Traditionally light microscopes were unable to capture depth of field images, and so SEM was employed (Keyence, 2023).

Building the TPMS court section band model.

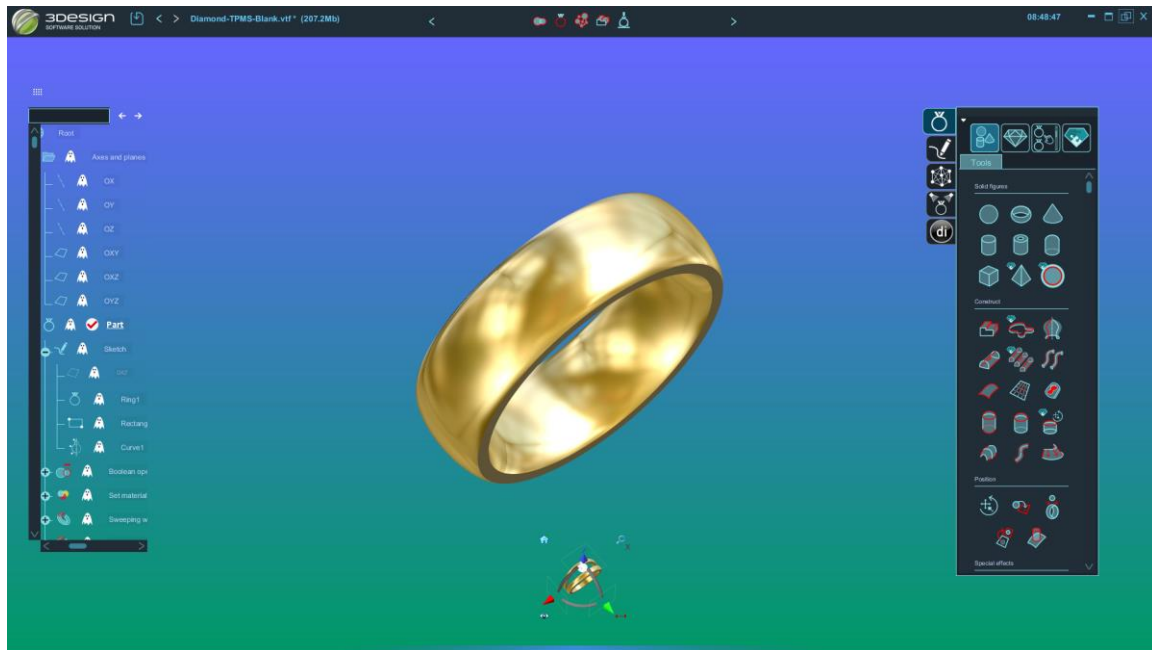


Figure 30: 3design software screenshot (Evans, 2023).

3Design is a parametric modelling software. Once parameters are modified, the geometries are automatically reconstructed (3Design, 2021). A basic court section ring was modelled in 3Design, a of diameter 20.76mm, & court section with a width 8mm & depth 3mm. Using the finger size & court section curves, the ring was modelled as a solid, then exported as an .OBJ rather than an .STL to avoid triangulation of the file.

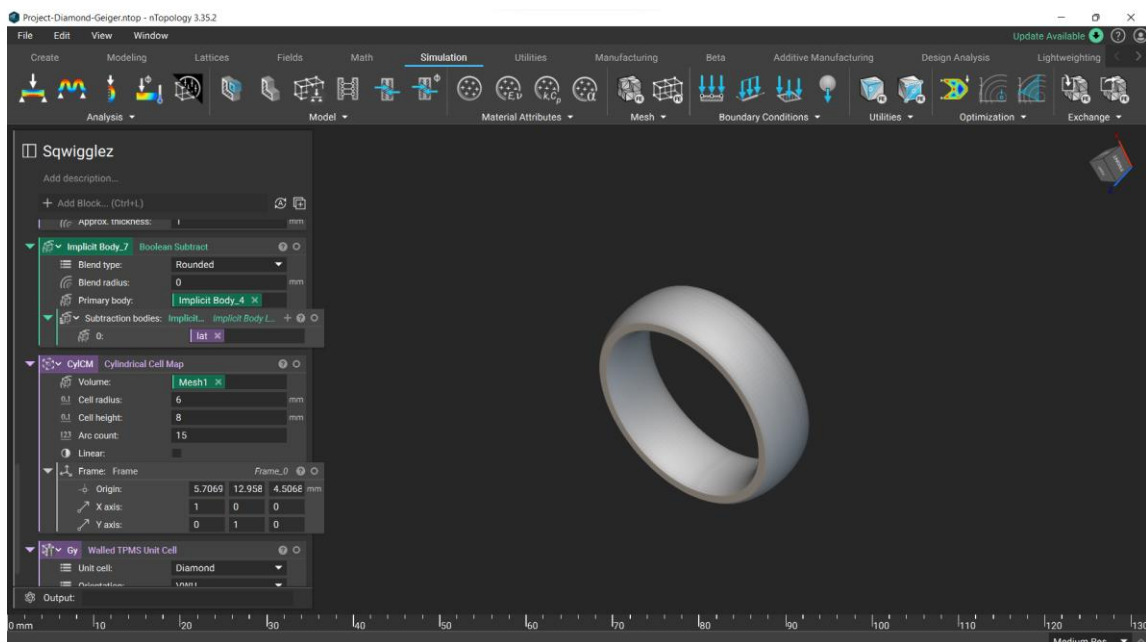


Figure 31: nTopology software screenshot; Import of mesh ring, & conversion to implicit model (Evans, 2023).

TPMS structures are expressed with precision, using mathematical functions. Manipulating parameter functions can influence the parameters of porosity or the specific surface area (Feng et al., 2022). TPMS structures were chosen & offset to provide aesthetically pleasing designs for custom jewellery production. To explore TPMS structures three customisable workflows in nTopology were created using Diamond, Gyroid & Split-P unit cells. The court section band .OBJ model was imported into nTopology, & converted into a mesh. The mesh is highlighted and converted to an implicit surface. Creation of a unit Cell, for this project we will use interchangeable TPMS structures of Gyroid, Diamond & Split-P, with a focus on Diamond TPMS for fabrication, with a cell thickness of 0.4mm.

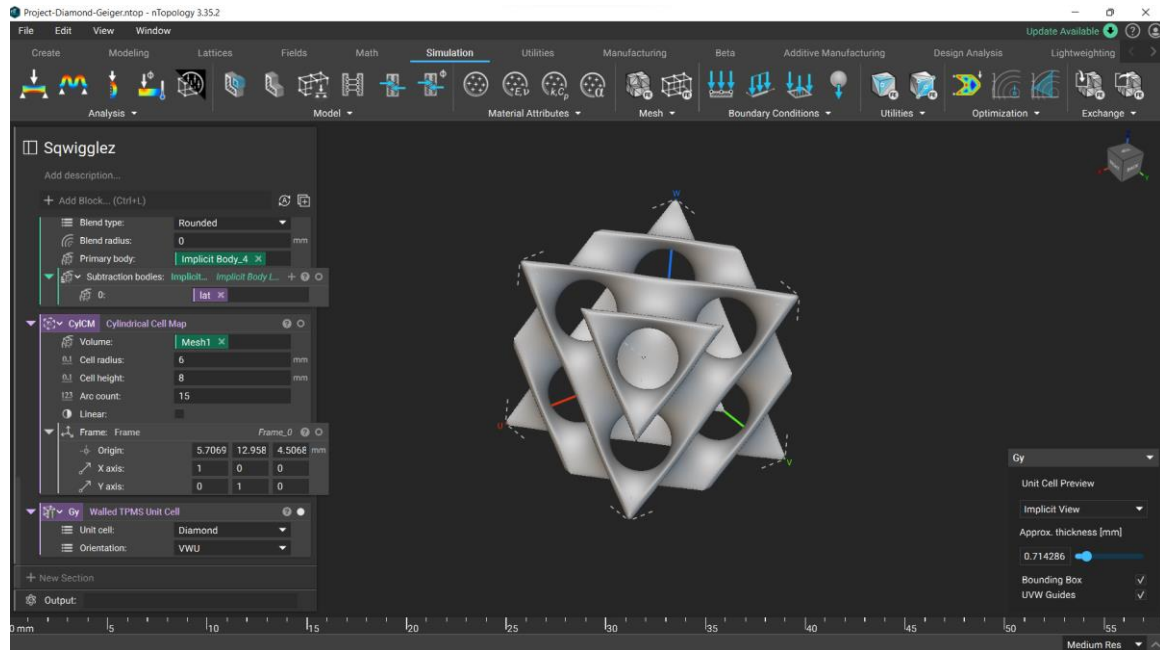


Figure 32: nTopology software screenshot; TPMS Diamond Cell (Evans, 2023).

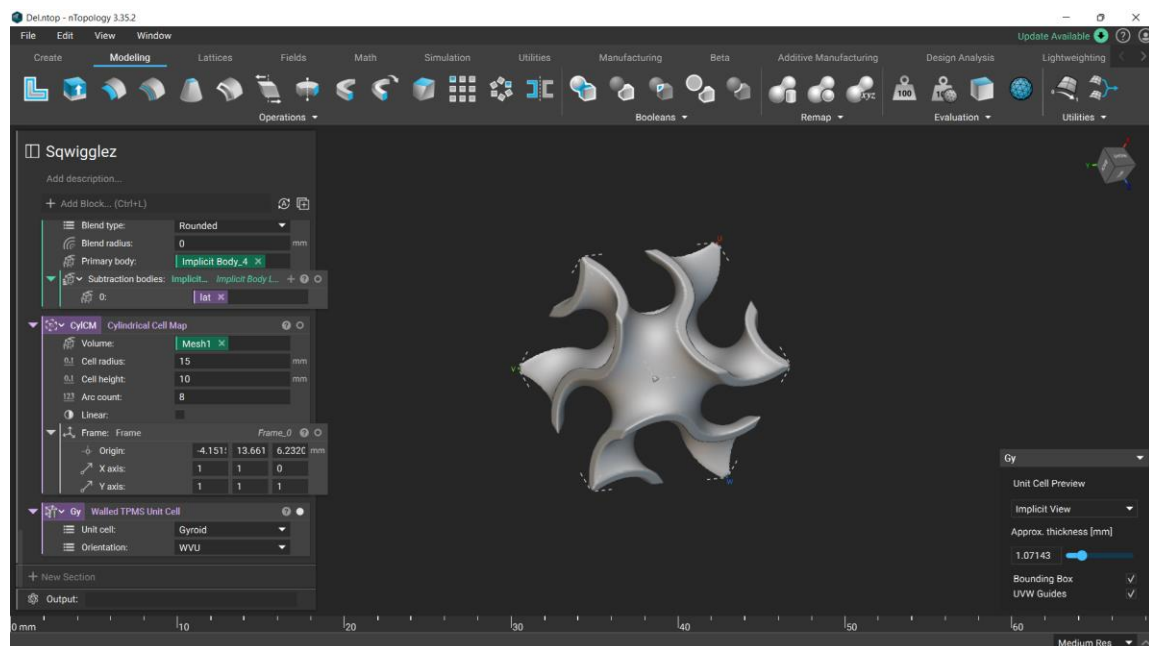


Figure 33: nTopology software screenshot; TPMS Gyroid Cell (Evans, 2023).

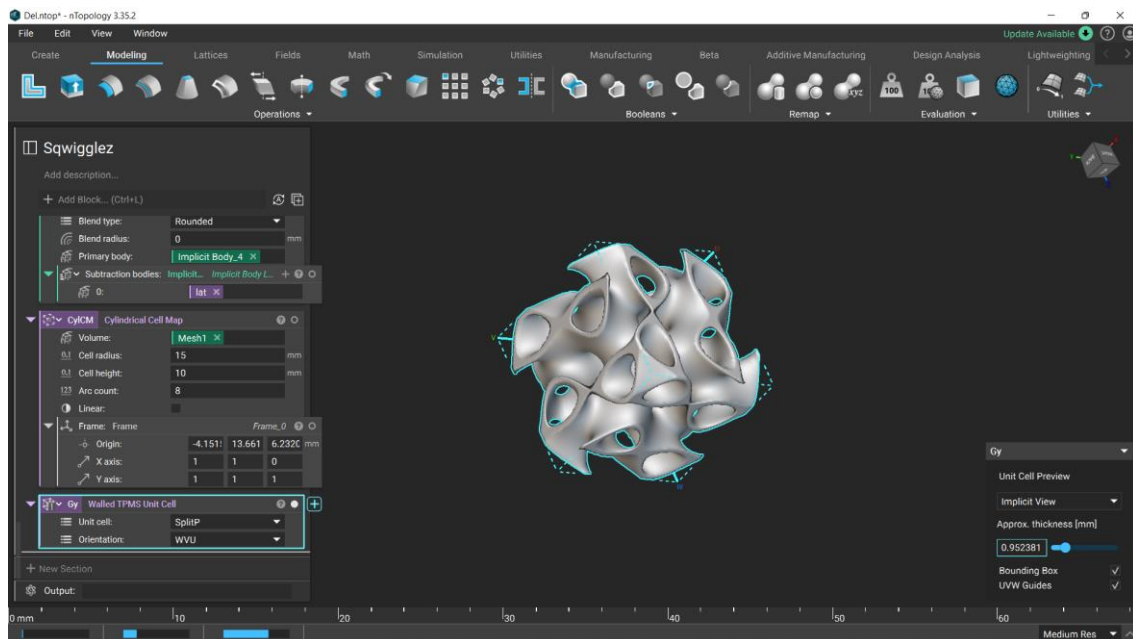


Figure 34: nTopology software screenshot; TPMS Split-P Cell (Evans, 2023).

Cylindrical Cell map is created with full control over radius, section number, height & depth. In this case it has been offset to enhance the intricacies of the pattern of non-conformity, for the court ring.

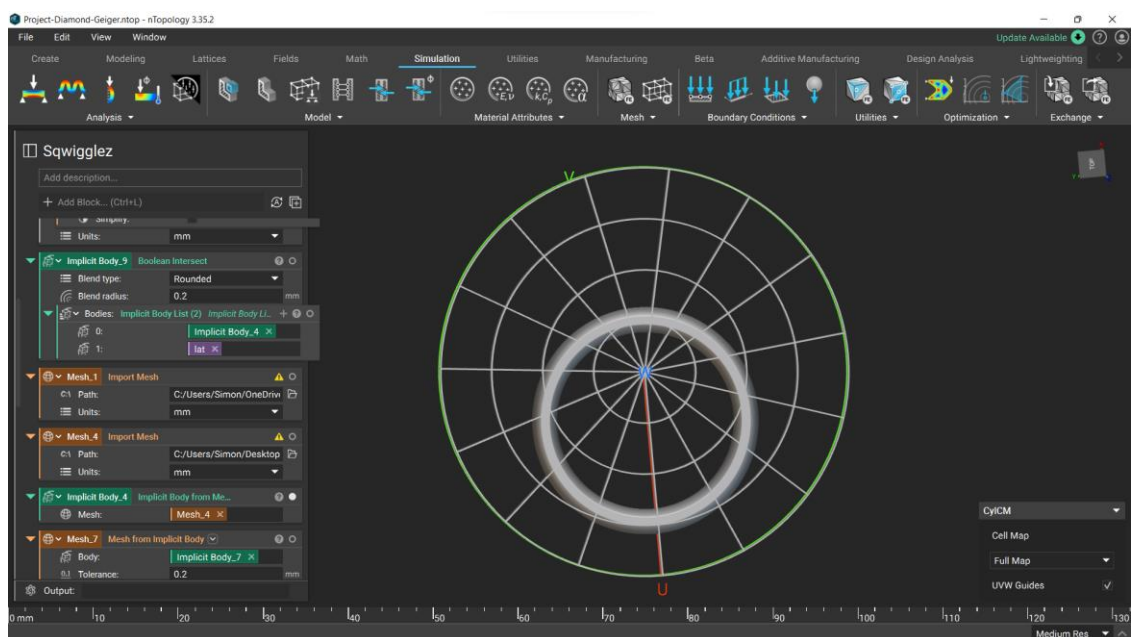


Figure 35: nTopology software screenshot; Cylindrical cell map (Evans, 2023).

The next step is to use unit Cell & cylindrical cell Map to create a solid Periodic lattice

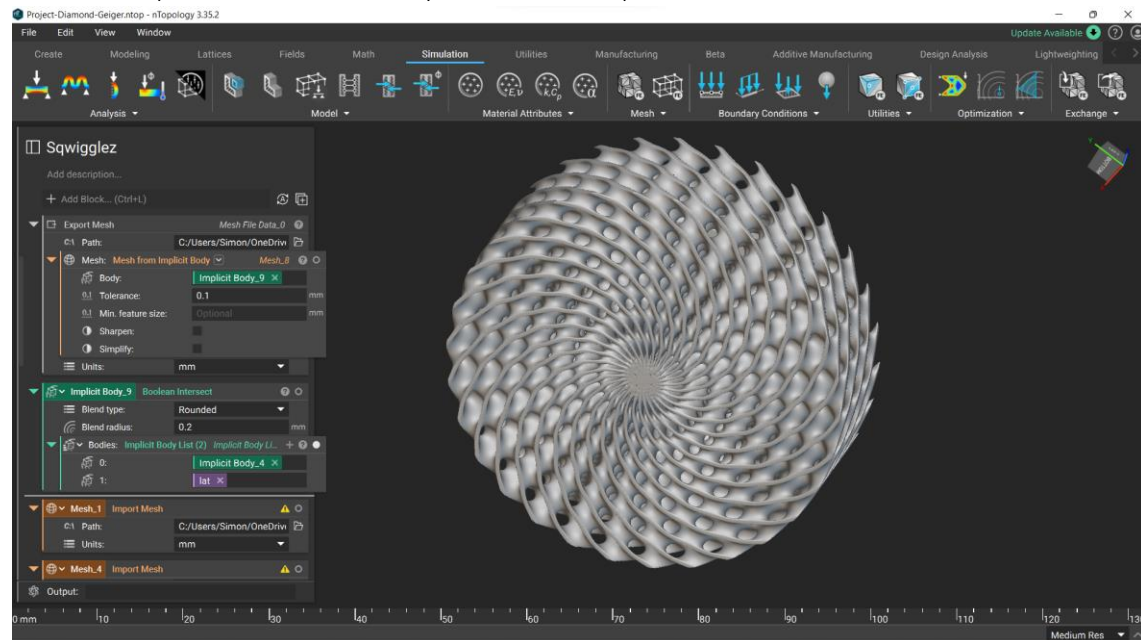


Figure 36: nTopology software screenshot; Creation of a Periodic Lattice (Evans, 2023).

The Simple court implicit model is boolean Intersected against the TPMS periodic lattice.; Using a cylindrical cell map and changing the orientation & depth of the unit cell & cylindrical map results in lots of user-controlled design changes.

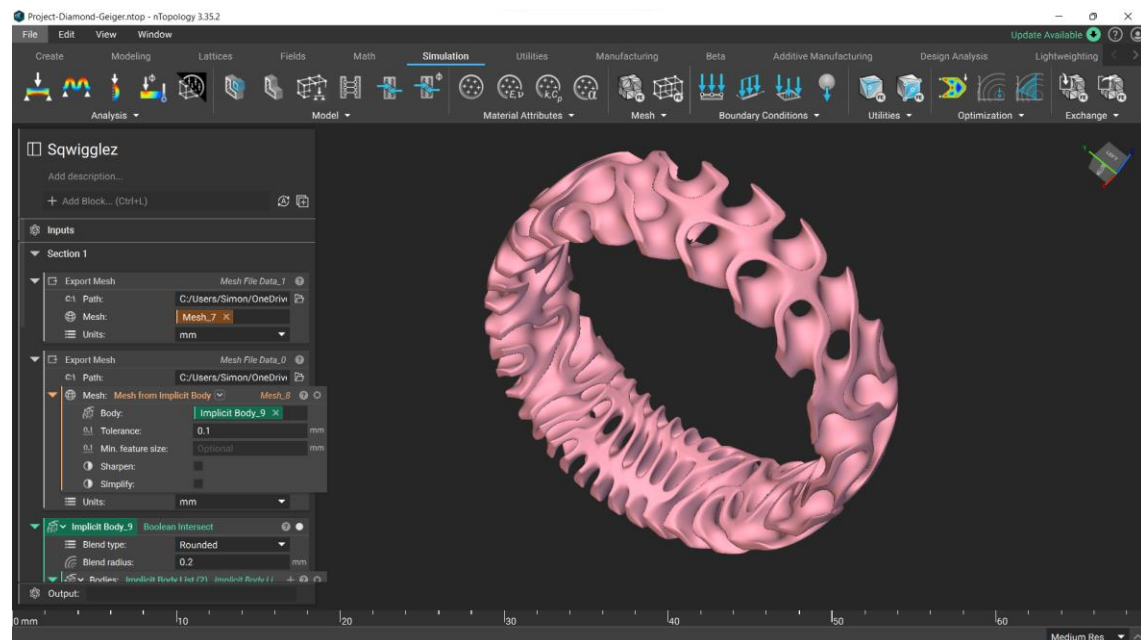


Figure 37: nTopology software screenshot; Intersection of the periodic lattice (Evans, 2023).

Design iterations happen in real time & are automatically re-exported to the instructed file location. TPMS structures can also be utilised to create the support structures for the build, reducing the material needed for ancillary supports, & easier access of spent powder through TPMS porous nature (nTopology, 2021).

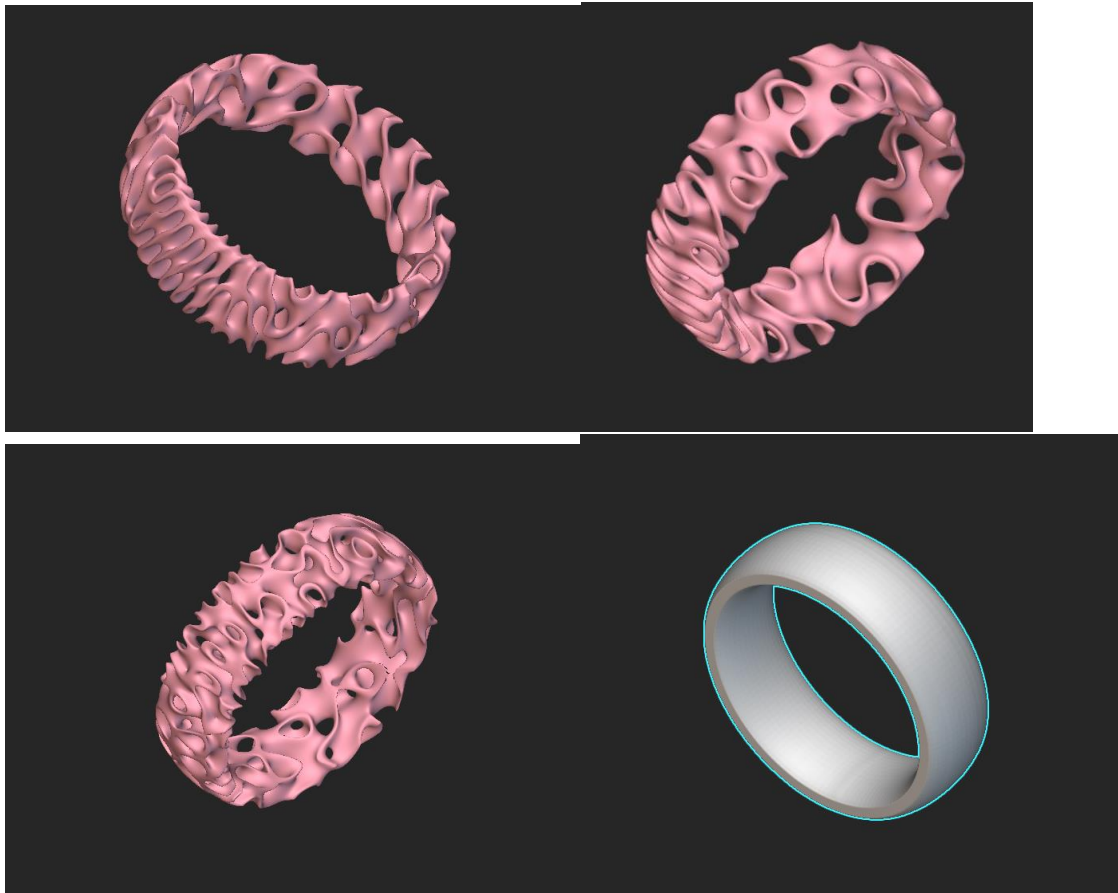


Figure 38: TPMS examples of mass customisation by changing the unit cell, Diamond, Gyroid & Split-P (Evans, 2022).

Prototype iteration @DCW



Figure 39: 3Dsystems ProJet 2500W (Evans, 2023).

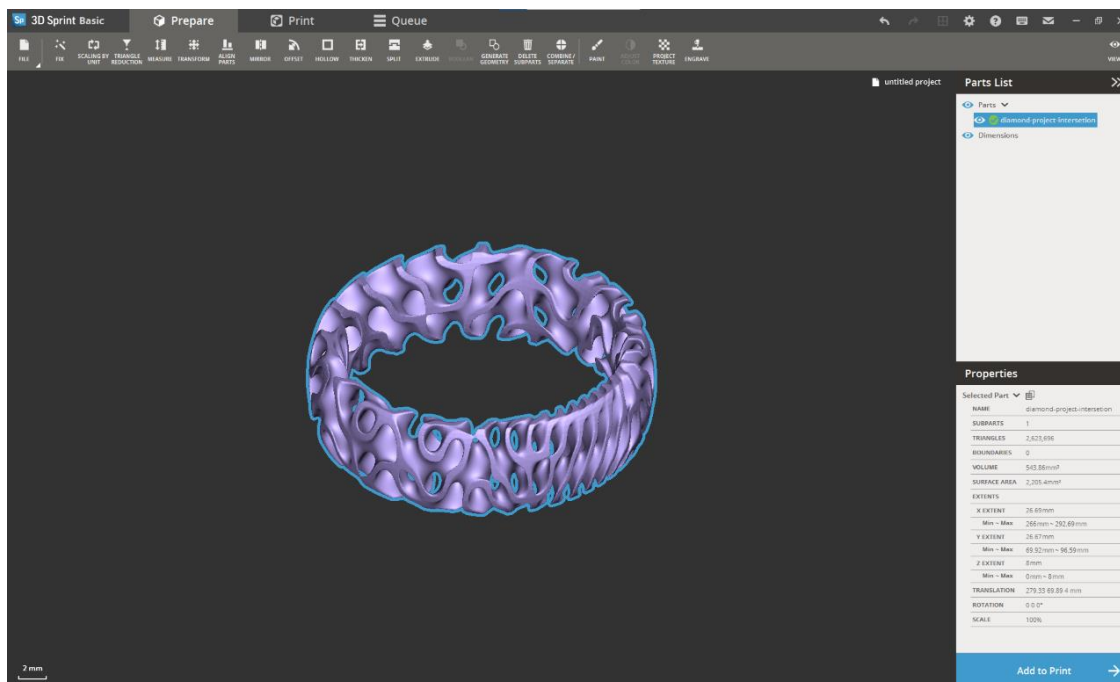


Figure 40: 3Dsystems ProJet plate construction for 3DSprint software (Evans, 2023).

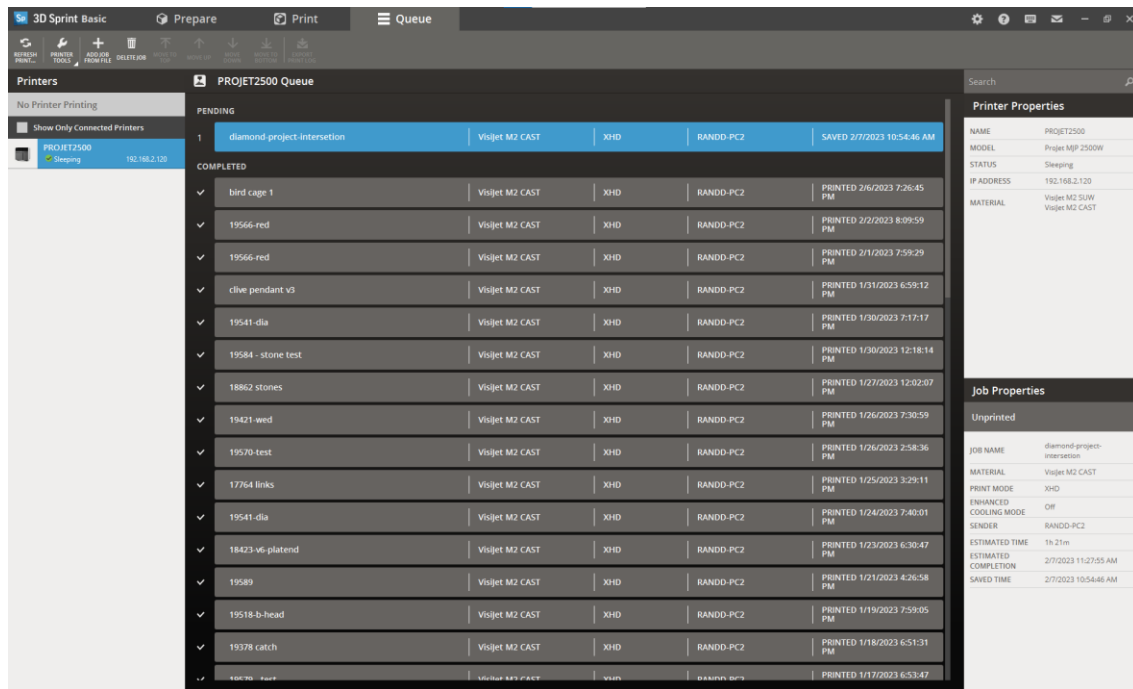


Figure 41: 3Dsystems ProJet build file queued for print (Evans, 2023).

To create the prototypes the MJP process was employed, utilising a ProJet 2500W & VisiJet M2 cast 100% wax content (3dsystems, 2017). The TPMS OBJ. Model files for Diamond, Gyroid & Split-P were imported into the proprietary 3dsprint software, used to automate file repair & ensure compatibility of the file for print, converting to a .STL. The software automates support generation, & creates the build file by creating file slices, & exported to a print file. Once the file has printed, the build plate is placed on a heated tray, to melt the support connecting layer, and removal of the builds from the plate. Dissolution of support structures, is enabled, by placement in an isopropanol heated bath between 36-45°C. Wax is suited for IVC as it has little to no ash content during the burn off phase for defective free casting, which provides an increased surface quality that reduces finishing time & removal of excess precious metals (Klotz, et. al., 2019).



Figure 42: Diamond, Gyroid & Split-P wax samples, suitable for RP & IVC (Evans, 2022).

Lost wax Investment cast builds @ Weston Beamor

Following the same methodology for the prototype iterations, but using a red wax improved formula, increased the model durability & economic savings, eliminating the time and costs of fragile models breaking (3dsystems 2021). Purple Waxes are brittle especially when left in Isopropanol. Red wax is an improvement for strength & casting for prototype iteration & casting. Consumers who view these wax iterations would be better seeing a resin model, as they have improved strength. Red wax is less brittle when dried out with Isopropanol, where intricate TPMS waxes have an increased survival rate of the multiple phases, from print, dewaxing, attachment to the wax tree sprue & casting (Gucci, 2022).



Figure 43: Red MJP wax builds of TPMS Diamond ring (Gucci, 2022.)

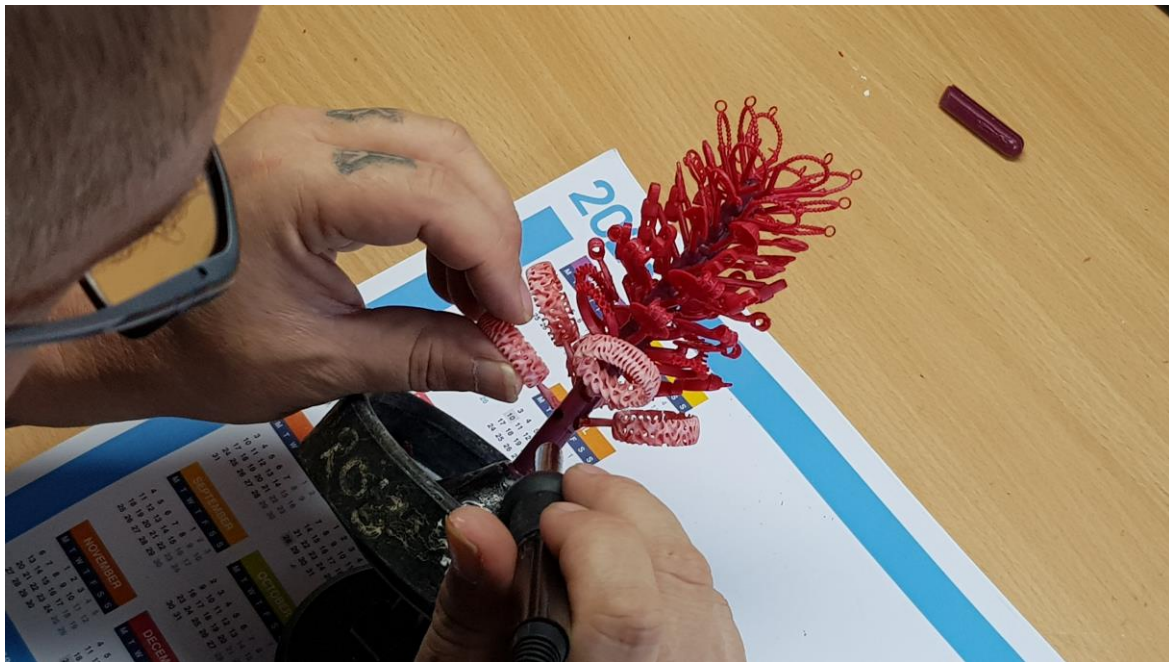


Figure 44: TPMS Diamond ring samples added to a wax tree for lost wax investment casting (Gucci, 2022.)

For the cast silver system, a silica-based investment powder was utilised, with an over pressure casting machine, under a vacuum, where gravity pushes, and the vacuum pulls material into the investment can. The silver alloy composition is Ag: 92.65% Cu: 7.33% P: 0.02%. (Gucci, 2022.)



Figure 45: Silver samples post cast, & removal from tree with wire cutters (Gucci, 2022.)



Figure 46: Silver Sample support removal, post production with 800 & 1200 grit paper, magnetic polishing & hand Polishing with polishing compound (Evans, 2023.)

SLM EOS M-100

SLM print Via the EOS M100 at Cooksongold, with proprietary information for EOS systems & Cooksongold powders. Materialise Magics was used to automate the production of supports, & simulate the build to optimise production through reduction of failure (Watts & Hill, 2022). Layer by Layer of gas atomised silver powder fused with a fibre laser on a build plate. On completion of the build, the excess powder is removed & recycled & the build plate removed from system. The Part is chiselled from the plate at the supports, subsequently the supports are removed from the part, ready for preparation & polishing for a high lustre.

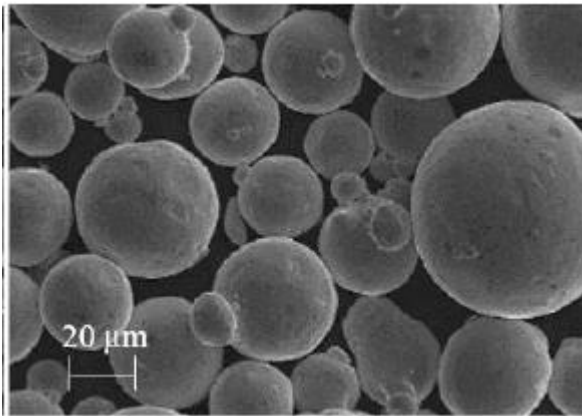


Figure 47: Example of gas atomised silver powder under SEM (Robinson, et al., 2022.)

The Cooksongold powder composition literature (Appendix 3) indicates 93.3% Silver content gas atomised <40µm spherical powder used for the EOS M-100 trial (Appendix 3). In previous work with Diamond Centre Wales, the powder was sent for elemental analysis as the powder was trialed with Holo's Pureform process, for its use in metal DLP technology & post sintered. However, there was issues with 100% fusion, and so the powder was sent for analysis.

Tests	Results/Units
Ag	93.7%
Cu	4.40%
Fe	0.001%
In	1.30%
O	0.044%
Pd	0.004%
Si	0.22%
Sn	0.17%
Zn	0.14%

Figure 48: Elemental analysis of Cooksongold gas silver gas atomised powder (Aghababaie, 2021).

The addition of Indium could be attributed to strengthening the alloy. Platinum alloys containing micro alloy of Gallium, or Indium, increased hardness and strength significantly (Klotz and Fryé, 2019).

While the use of micro-alloying of semi-conductors is used for SLM of reflective materials, Indium, present in the silver gas atomised powder tailored for the SLM process, was not suitable for the Pureform process, a type of Binder Jet Printing, where in the post print sintering phase, a high density was un-achievable, due to the inclusion of indium produces surface oxide (Aghababaie, 2021) highlighting the importance of tailoring the right alloy for the process.

EOS M-100 System Specifications

Laser Power	200w
Build Envelope xyz	100x100x95mm
Laser type	Yb Fibre Laser
Scanning speed	7 m/s
Focus diameter	40 μ m
Notable Powders	Precious metals (Silver, gold, Platinum & Titanium.)

System & Material database EOS M-100 (Senvol, 2020.)



Figure 49: EOS M-100 system (Watts & Hill, 2022.)

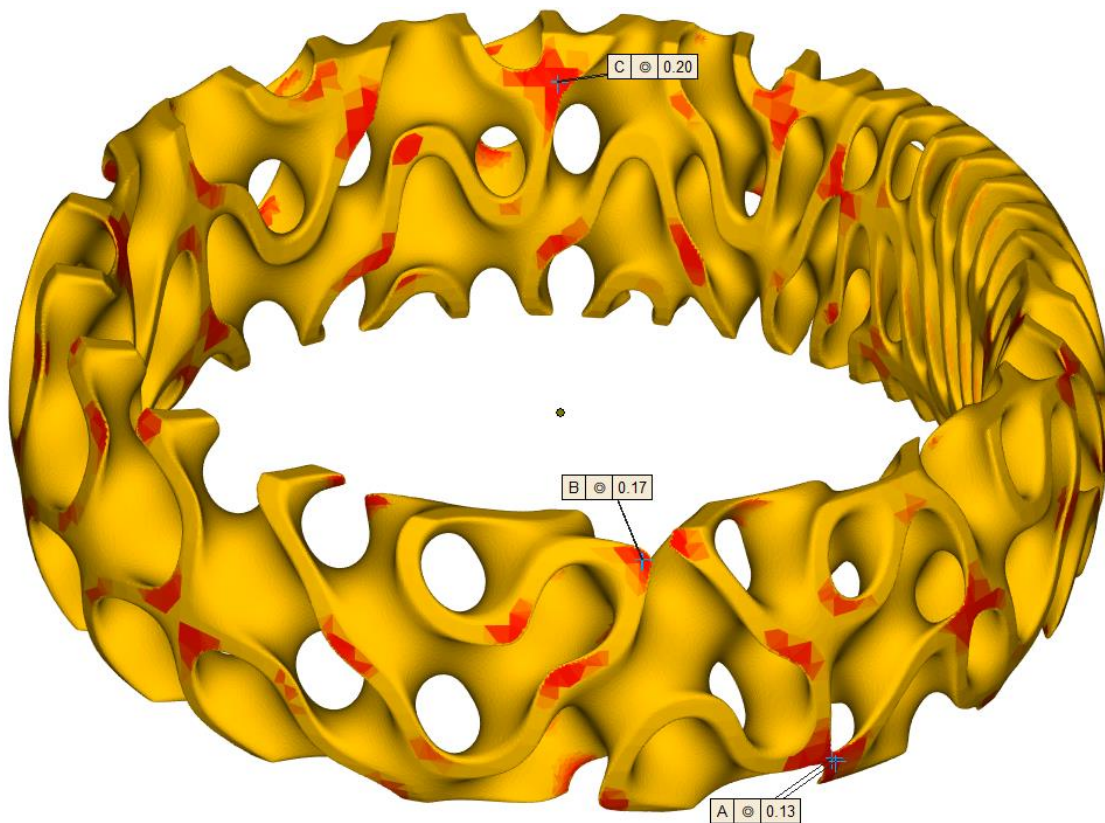
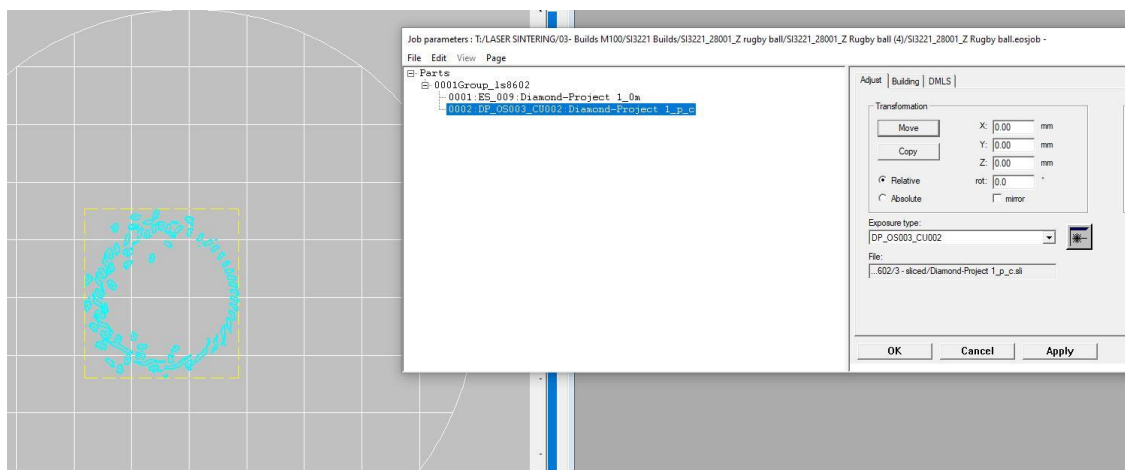


Figure 50: Materialise magics build tolerance warning (Watts & Hill, 2022.)

Materialise Magics Part analysis of TPMS diamond wedding band, where the red areas indicate a thickness of below <0.3mm (Watts & Hill, 2022.) Cooksongold design guidelines state to try and achieve a minimum of 0.25mm-0.5mm for fine features (Cooksongold, 2016.)



EOS Figure 51: M-100 build layer (Watts & Hill, 2022.)

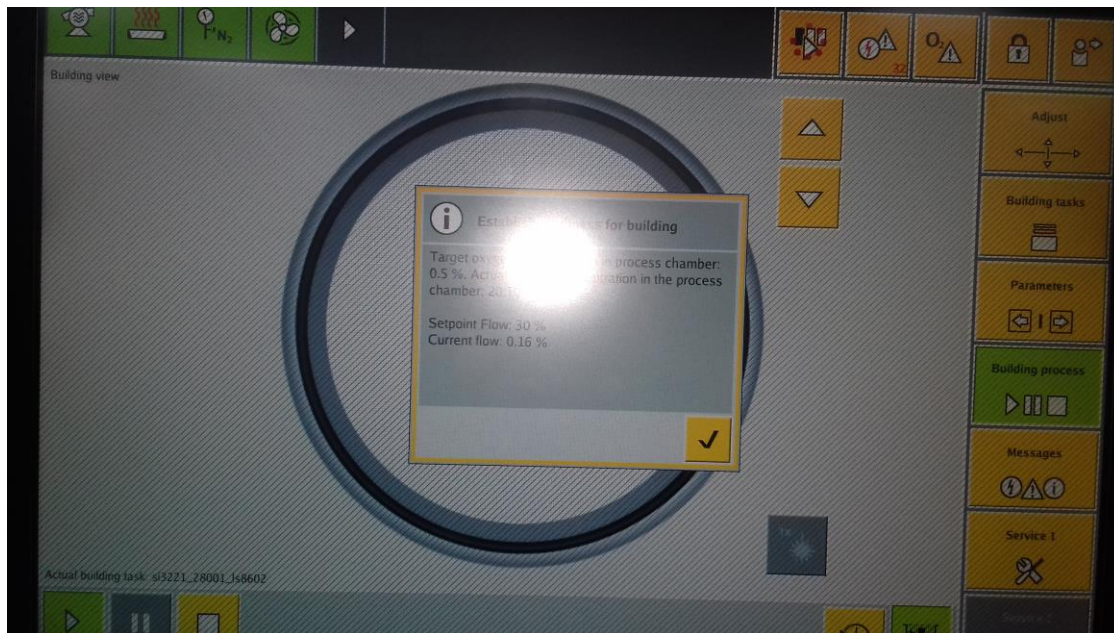


Figure 52: EOS M-100 build process window (Watts & Hill, 2022.)



53: EOS M-100 build plate (Watts & Hill, 2022.)

Figure

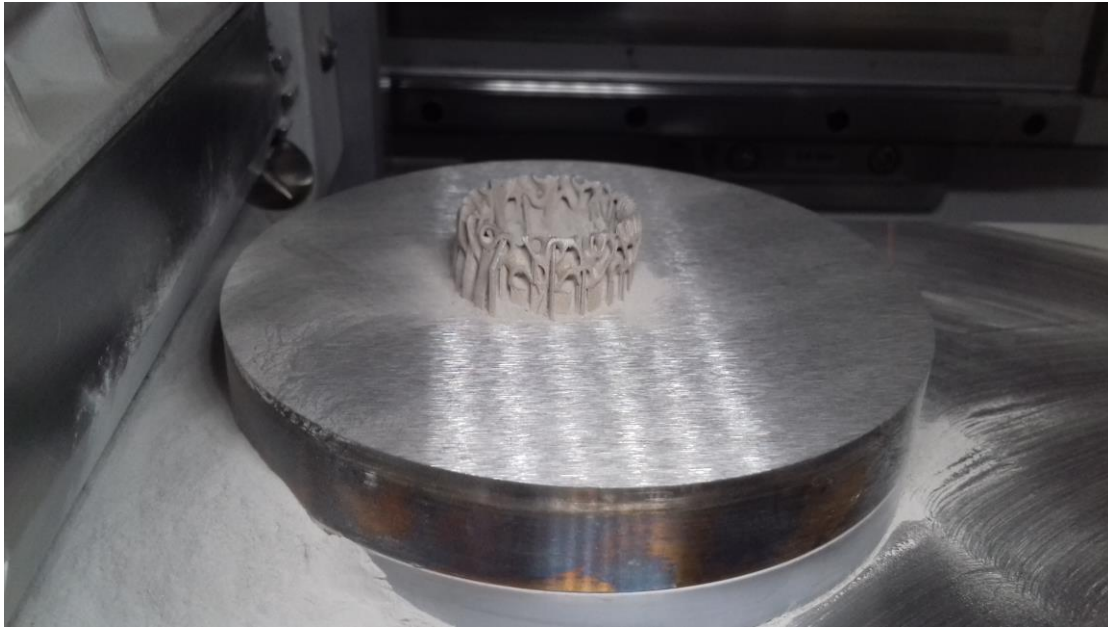


Figure 54: EOS M-100 finished build (Watts & Hill, 2022.)



Figure 55: Finished ring with support structures (Watts & Hill, 2022.)



Figure 56: Finished ring top view with support structures (Watts & Hill, 2022.)

Alpha SLM Build

AL3d is a 200 W fibre laser, 50 μm laser diameter & high beam quality. Closed powder circuit and small build chamber, for high yield powder retention & retrieval. Cartridge system reduces setup times & machine parameters set for each powder material can be amended. AL3D-OS imports & arranges 3d models from CAD data, & generates support structures. Post-build the part is placed in an unpacking station, & separated from the powder (Alpha laser, n.d.)

There are four stages to verify before production.

AL3d-Metal System Specifications

Laser Power	200w
Build Envelope xyz	50x50x50mm
Laser type	Fibre Laser 1070
Scanning speed	5 m/s
Focus diameter	50 μm
Notable Powders	Precious metals (Silver, gold, Platinum & Titanium.)

System & Material database AL3d-Metal (Senvol, 2021.)



Figure 57: Alpha Al3d-Metal system, Argon Tank & de-packing station model validation (Evans, 2023.)

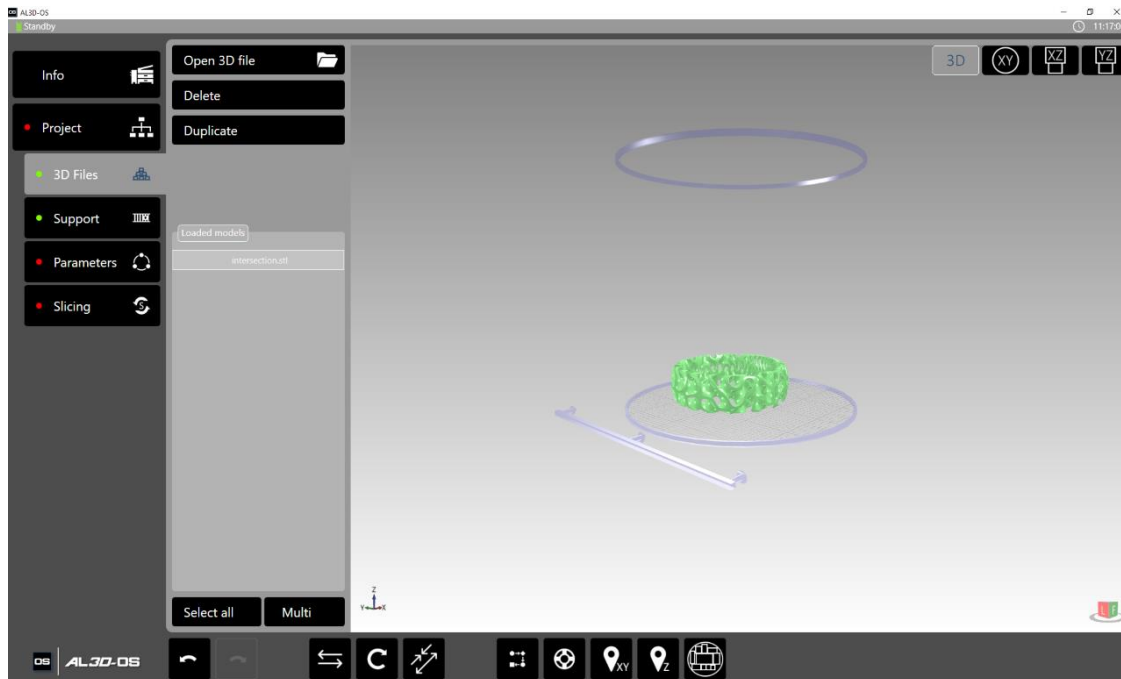


Figure 58: Alpha Al3d-Metal system; model validation (Evans, 2023.)

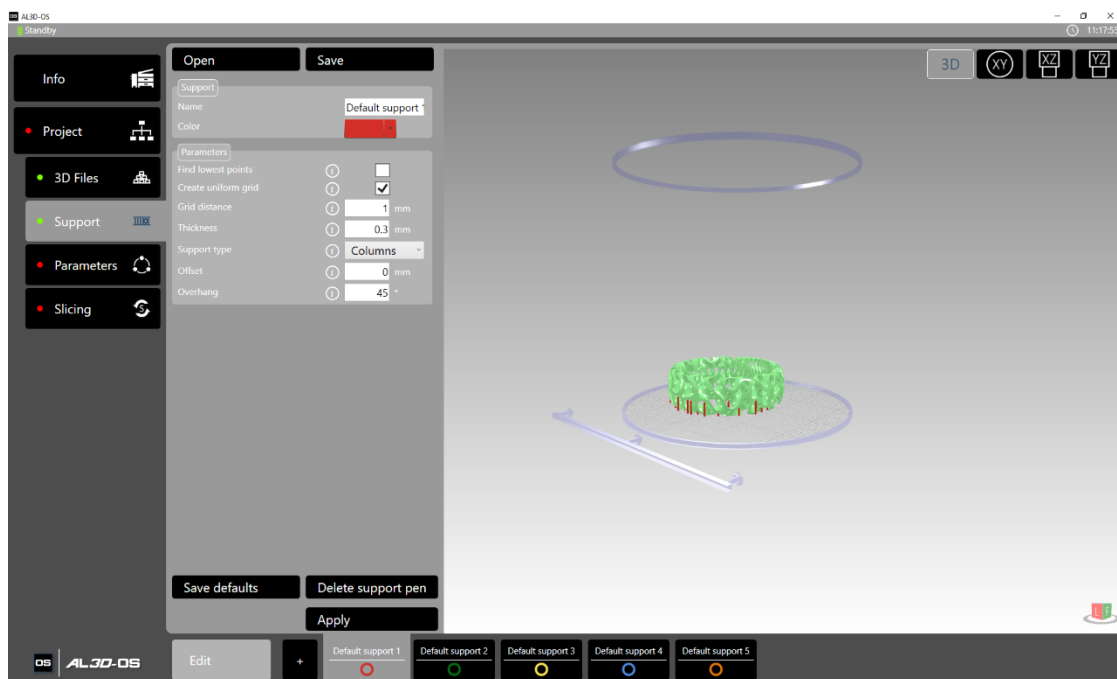


Figure 59: Alpha Al3d-Metal system; Support generation (Evans, 2023.)

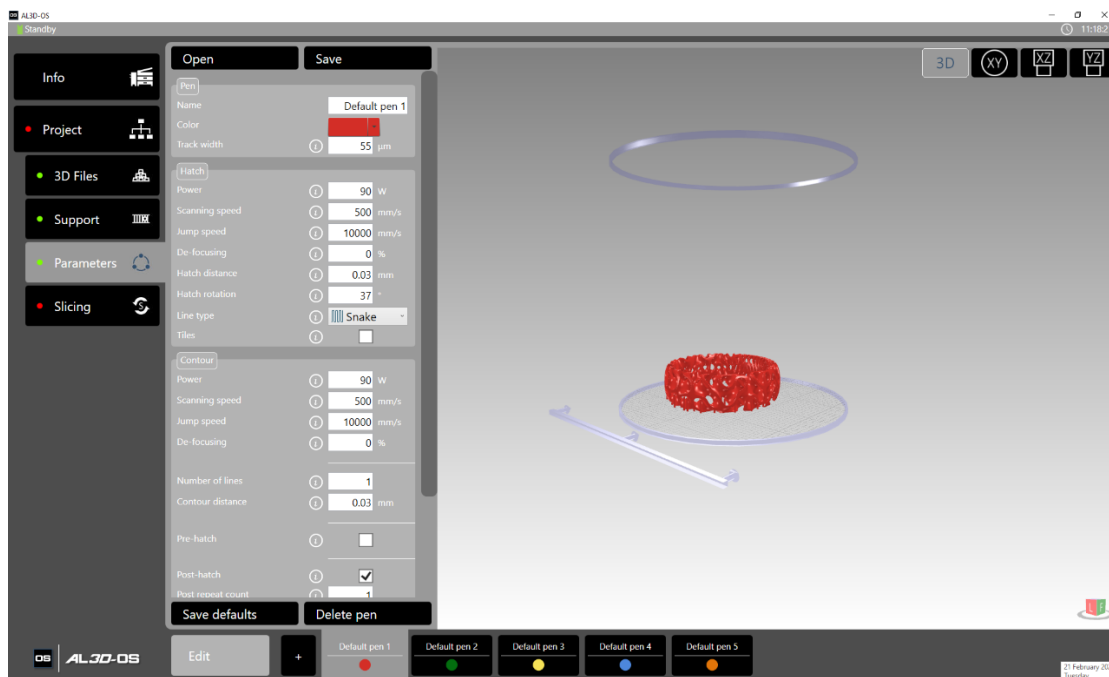


Figure 60: Alpha Al3d-Metal system; Parameter Selection (Evans, 2023.)

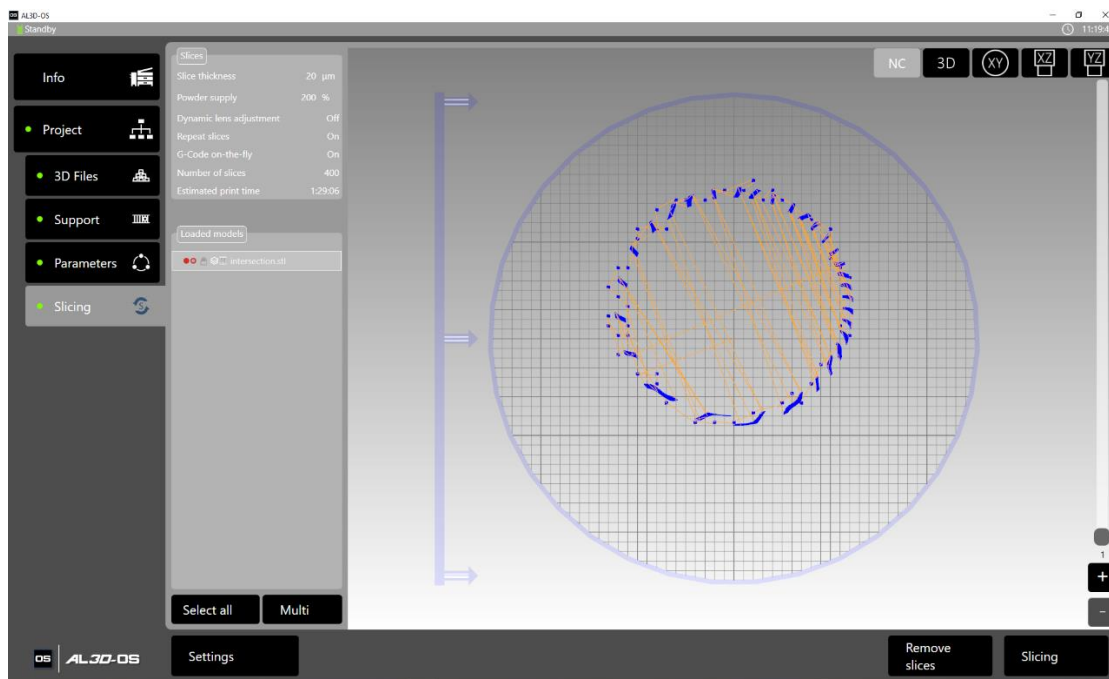


Figure 61: Alpha Al3d-Metal system; model slice validation (Evans, 2023.)

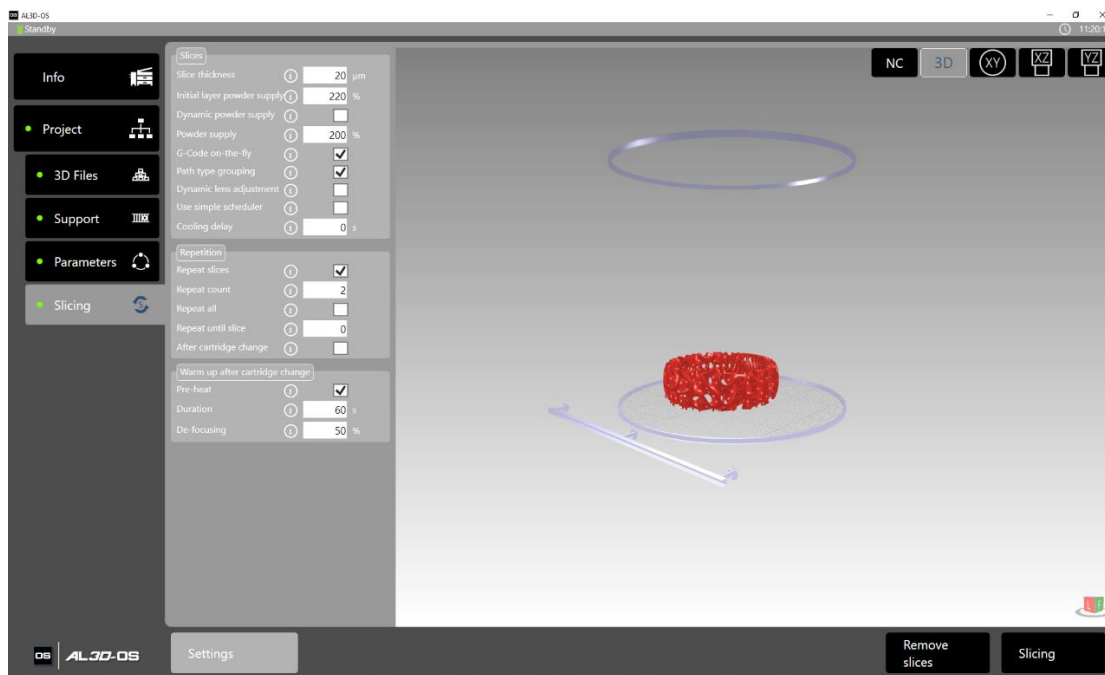


Figure 62: Alpha Al3d-Metal system; All stages Green lit; ready to print (Evans, 2023.)

No successful build on the Alpha Al3d-Metal was achieved, due to calibration plate delays & a new CPU required for the de-packing station. Embedding the Alpha system on-site at DCW was a strategic research & development partnership, where Alpha placed the technology on-site at no cost to DCW. DCW arranged for 2kg of 18ct white powder, to determine the parameters. A specific supplier had to be used, & the high cost of the powder also caused delays in obtaining the required material for processing.

Electron Beam Melting (EBM)

ARCAM Q10 located at the Centre for batch manufacture.

The main features of the ARCAM Q10, as outlined by Arora (2019,) as employing a 3KW Electron Beam Gun, vacuum insulated build chamber, fast cooling, closed powder handling, & Arcam LayerQ am™ for build verification. It is a cost-efficient manufacturing process for one off parts, and small batch manufacture. In an Arcam system each layer has a powder distribution, with two preheating stages, followed by the melting phase (Galati, Minetola and Rizza, 2019.)

Arcam Q10 System Specifications

Laser Power	3000W
Build Envelope xyz	200x200x180mm
Laser type	Electron Beam
Scanning speed	NA
Focus diameter	100 µm
Notable Powders	Titanium, Cobalt

System & Material database Al3d-Metal (Senvol, 2016.)



Figure 63: ARCAM Q10 EBM system (Davies, 2023.)

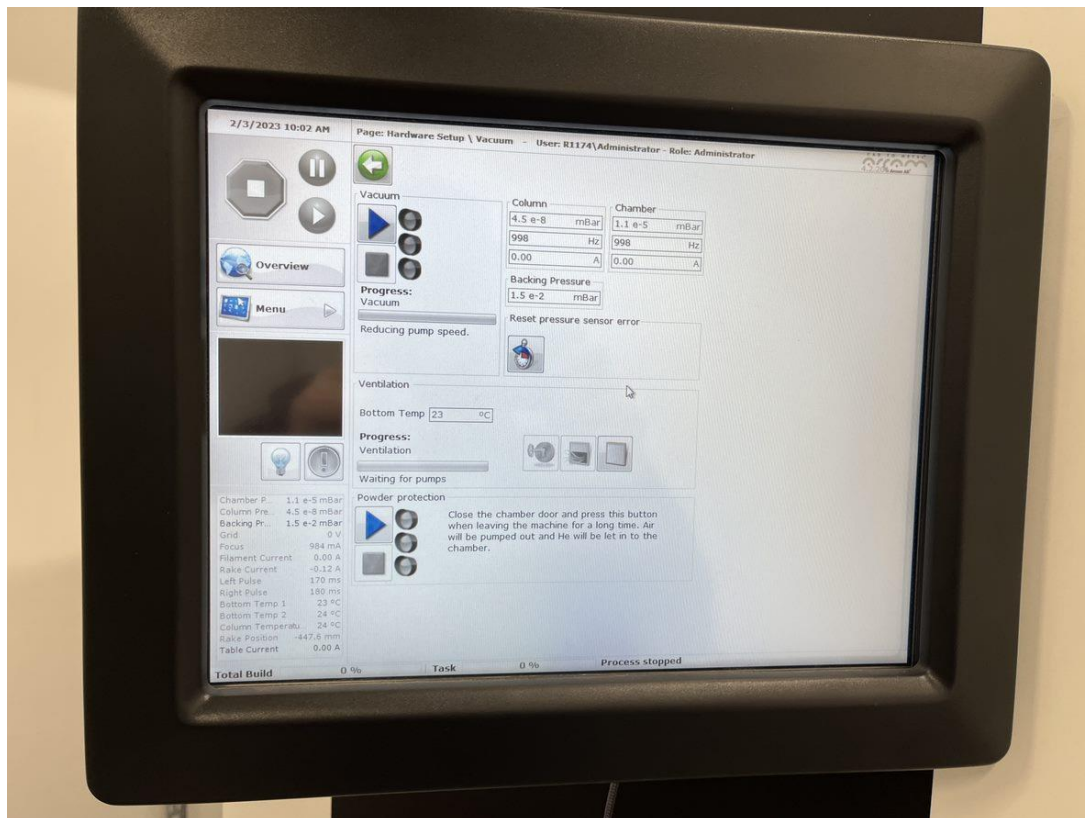


Figure 64: ARCAM Q10 EBM system interface (Davies, 2023.)

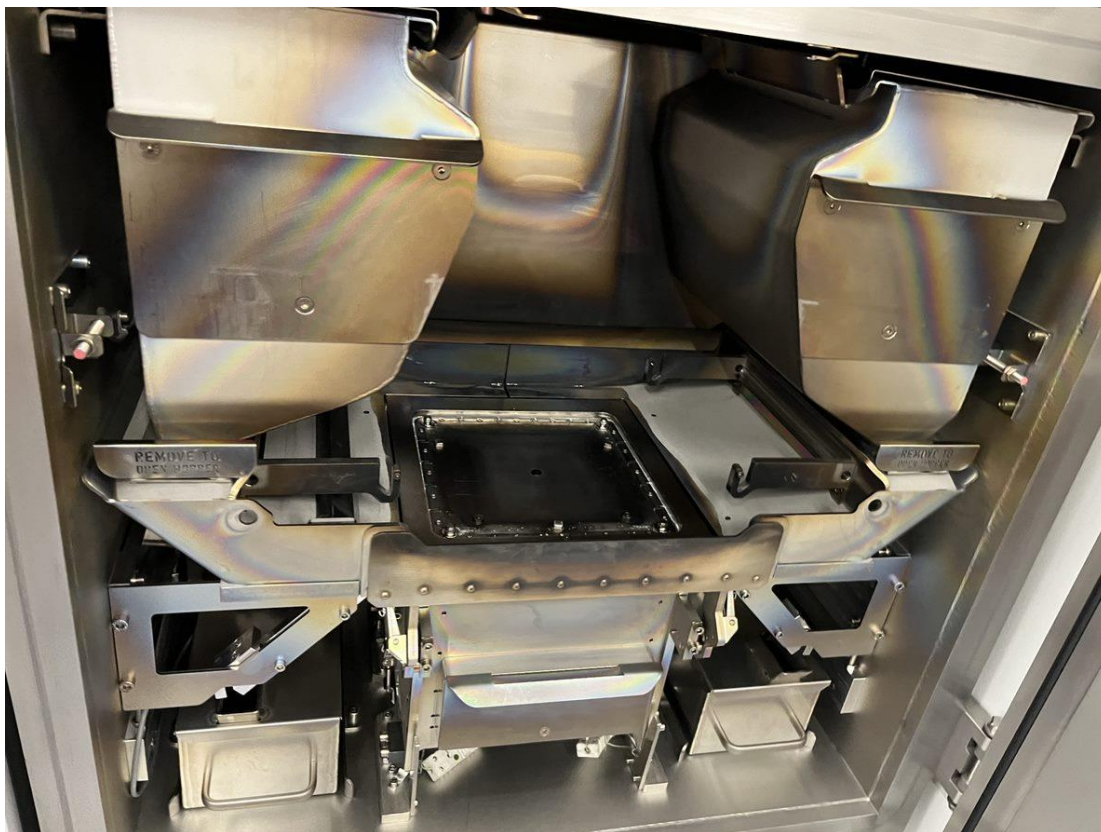


Figure 65: ARCAM Q10 EBM build chamber (Davies, 2023.)

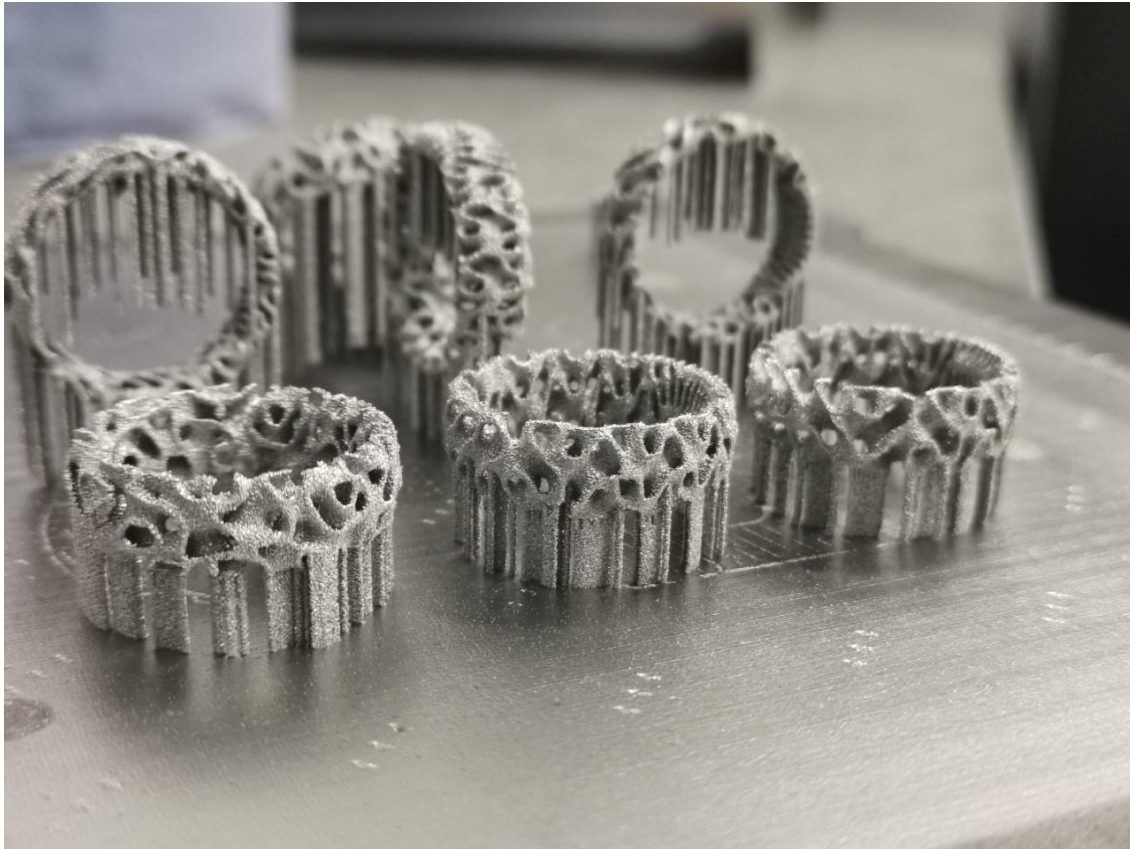


Figure 66: CBM Titanium samples (Davies, 2023.)

Discussion/Analysis of results

Polymer-AM & IVC

The use of an improved red wax suitable for fine features of TPMS led to less model breakages. Silver925 polymer-AM wax cast samples fully formed, all 6 samples, with excellent surface quality. Investment can break away, especially with fine features, such as the TPMS extremities, causing internal & surface porosity. TPMS structures are naturally self-supporting with no sharp edges, & so the design supported good material flow. Investment cast produced good results for complex geometries.

IVC perceived to be relatively smooth whiter surface. Three minutes to remove the small sprue, file & prepare the surface, & remove polymer-am lines in the cast, prepared with emery paper (grit 180 & 500 & 1200) beforehand polishing 30minutes on process refinement. Minimal work was needed to prepare the samples for automation of finishing using mechanical methods of magnetic barrelling. No notable defects or porosity were recorded. Part analysis of areas <0.3mm were not an issue on the production, further highlighting the benefits of using TPMS shapes. Scanning of the completed models showed no major loss of any features from original digital model. Cost of casting is less inexpensive compared to SLM. Half the cost was due to Polymer AM production at the casting house. A quarter of the cost was the casting house casting charge. Could be an argument made for a small desktop caster & Polymer-AM system for these specific patterns & materials.

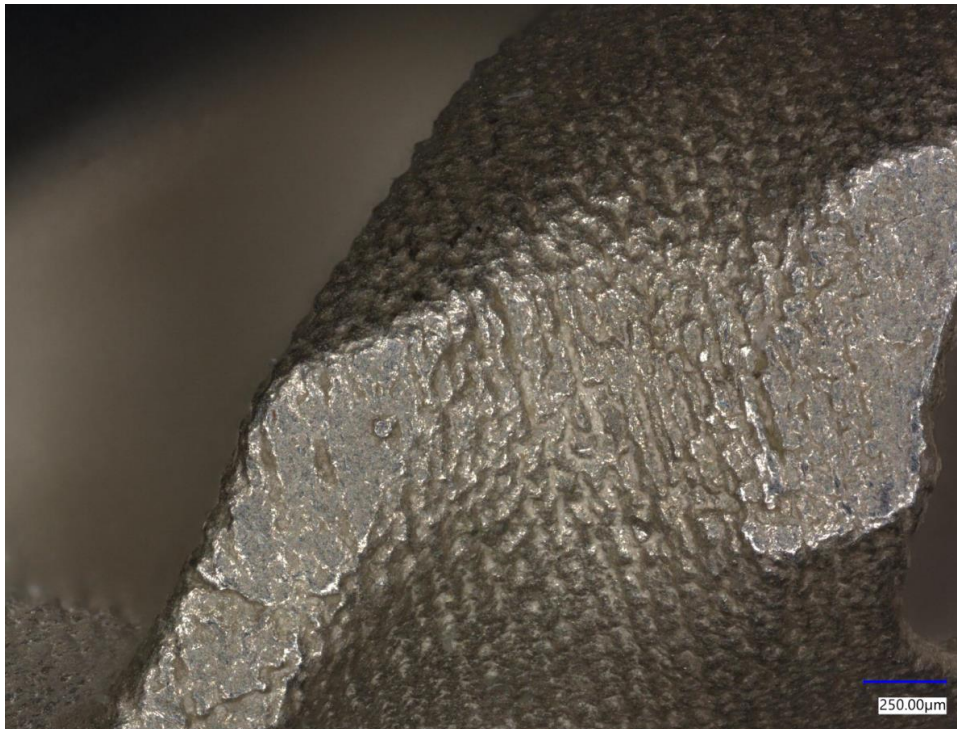


Figure 67: Optical composite image of Cast surface (Appendix 9.)

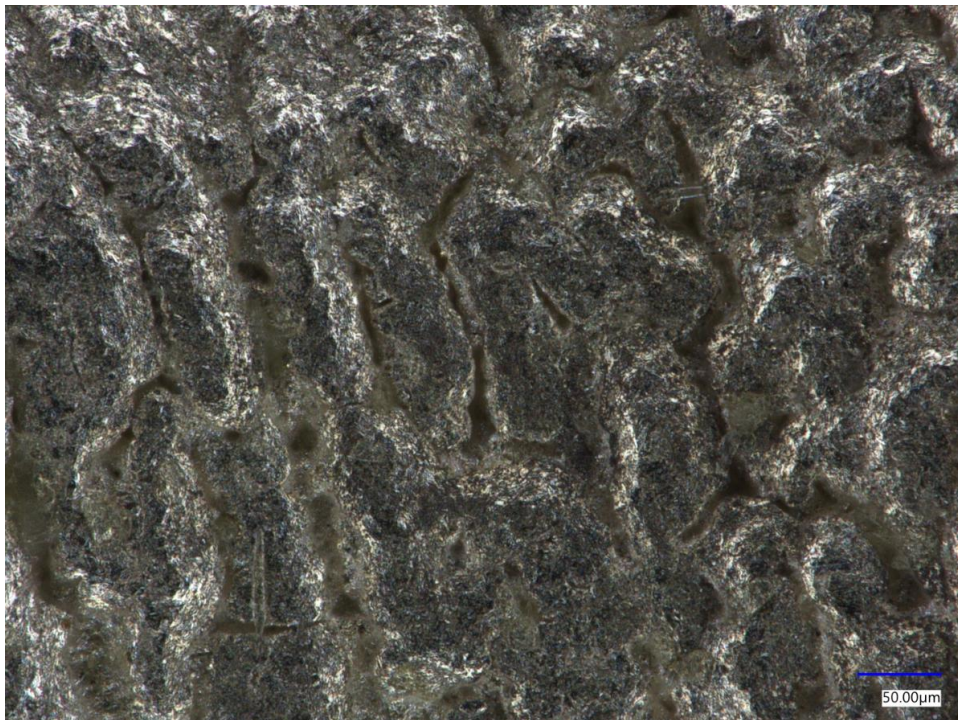


Figure 68: Optical composite image of Cast surface (Appendix 9.)

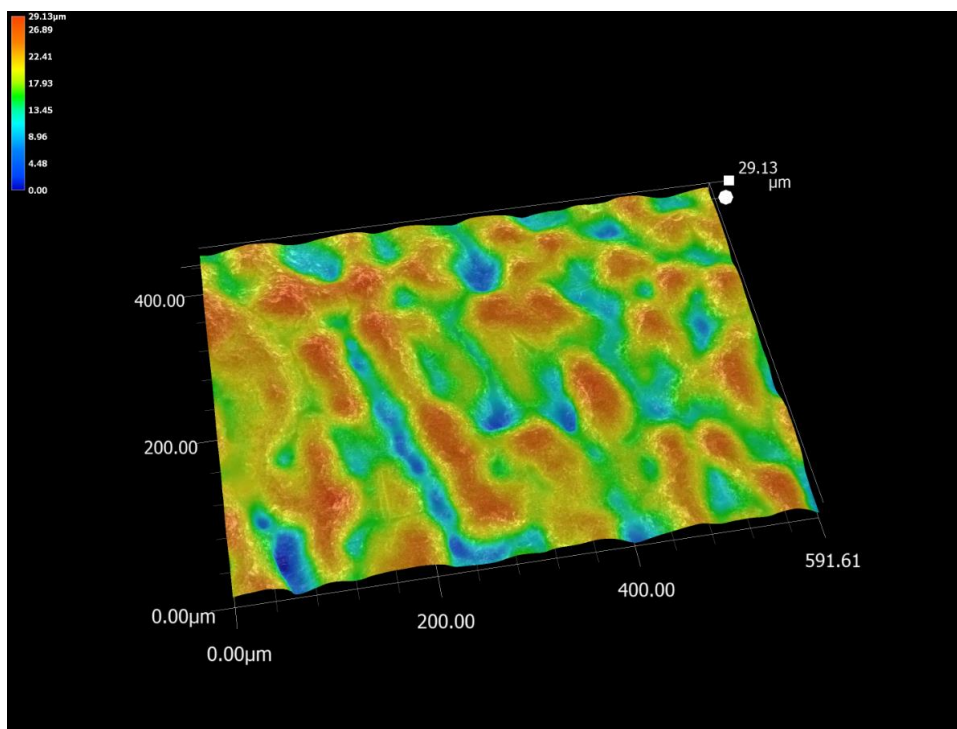


Figure 69: Height Map to flatten curved profile of sample (Appendix 9.)

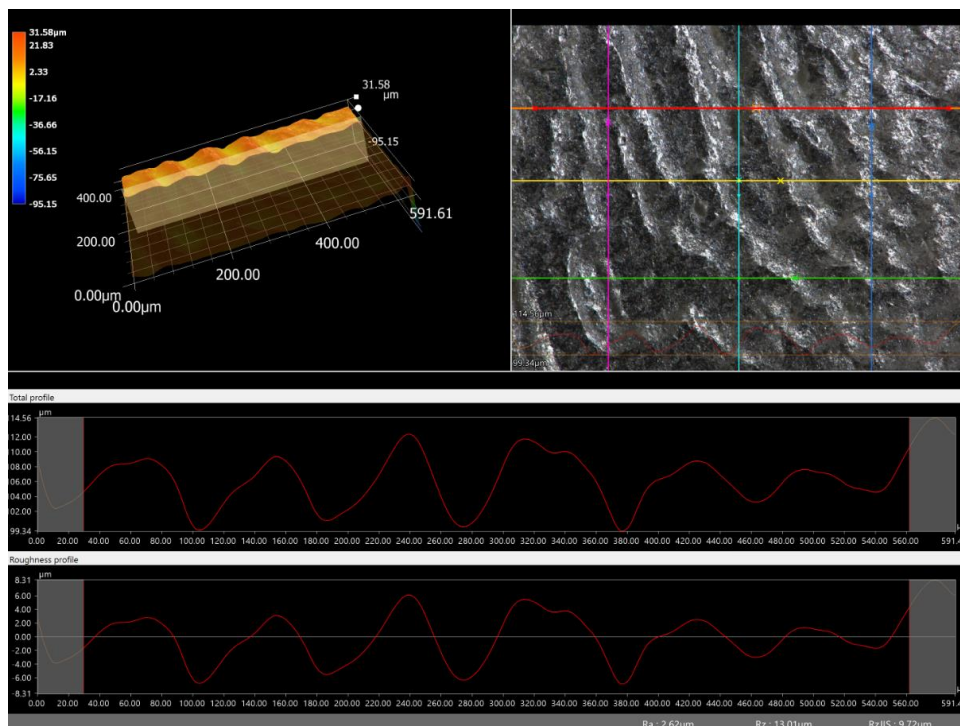


Figure 70: Line roughness analysis; To obtain Ra & Rz values at six locations (Appendix 9.)

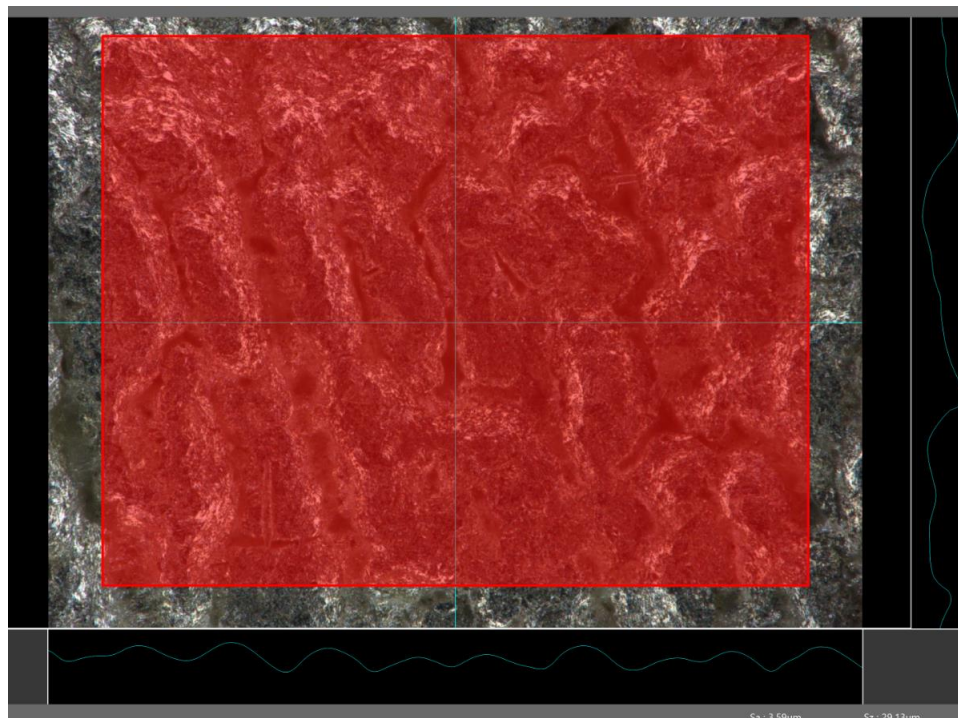


Figure 71: Quadrant roughness analysis; To obtain Sa & Sz values (Appendix 9.)

SLM

1 x silver SLM on the EOS M-100 system was successful for the precious metal print. There was no successful print on the Alpha system, for the reasons previously discussed. It was noted there was an increased Labour time for the SLM EOS-M100 parts, compared to IVC parts, due to removal of the

extra supports & surface roughness needing grinding, preparing & polishing. Removal of supports were difficult due to the support structures moving through the gyroid structures. The SLM parts are darker indicating oxidation of the parts. Quality of all builds were acceptable with a perceived roughness in the SLM compared with IVC samples. Cost to produce AM parts over SLM, there is no longer a chasm between the two.

£57.68 unit cost for the Polymer-AM & Investment cast process (Appendix 1)

£91.80 unit cost for the EOS M-100 (Appendix 2)

However, there is likely to be an Increased labour costs for increased support removal & increased surface preparation time & polish, due to the surface resolution being less than investment cast. Removal of supports was challenging due to moving through the TPMS structures.

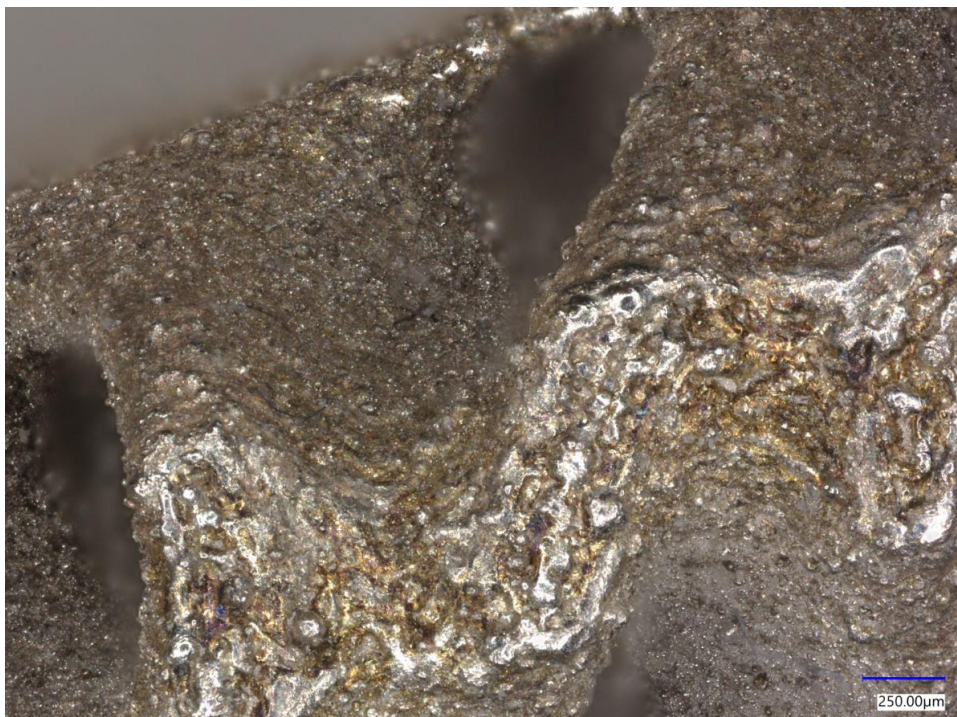


Figure 72: Optical composite image of SLM surface (Appendix 9.)

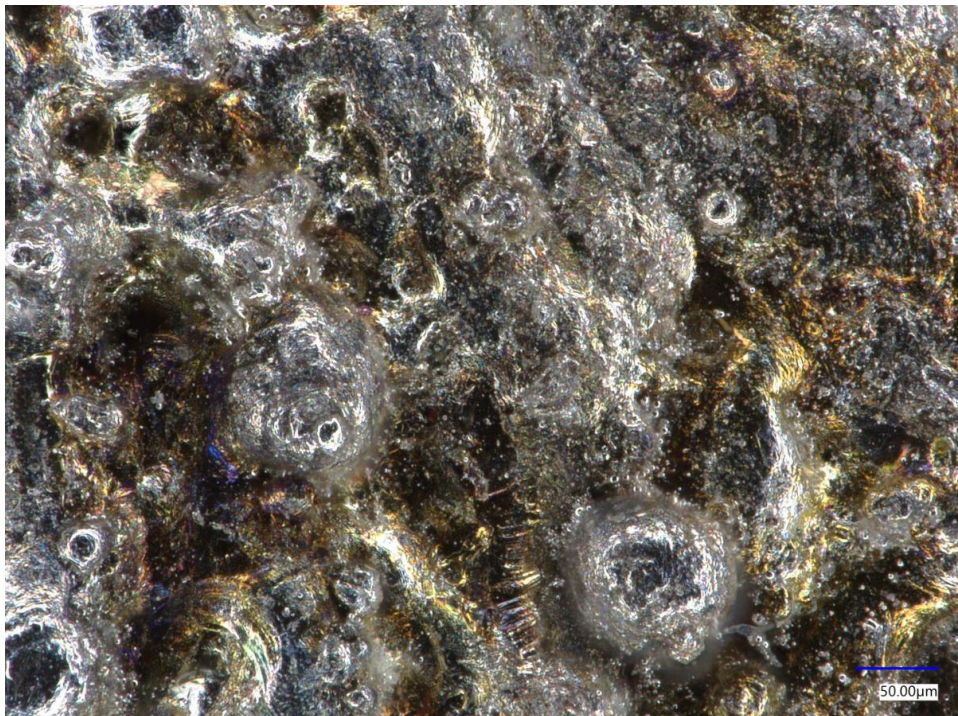


Figure 73: Optical composite image of SLM surface (Appendix 9.)

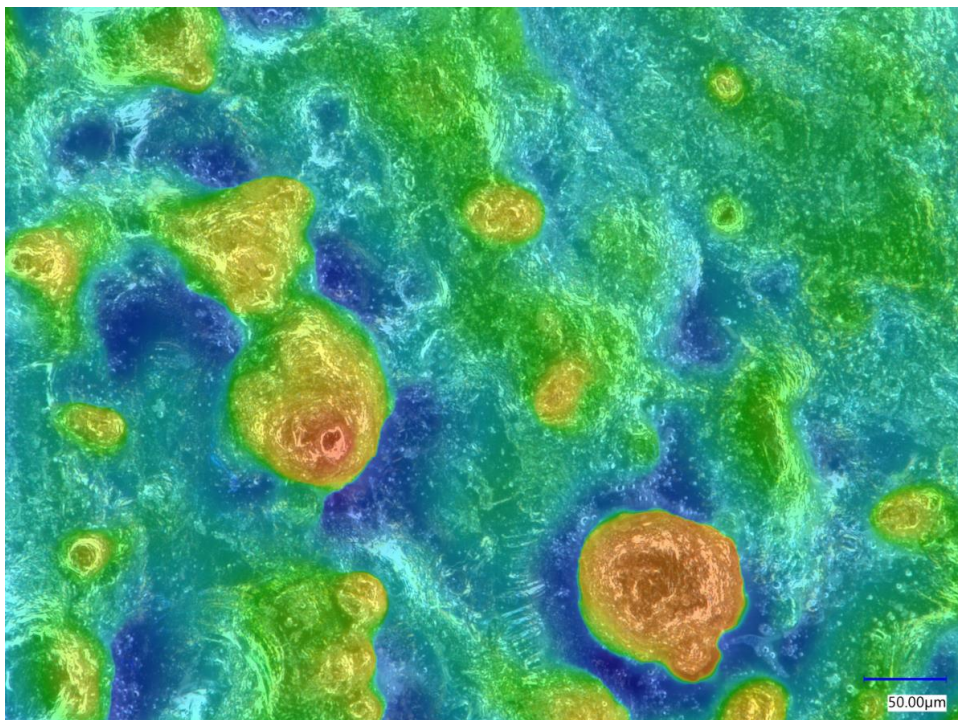


Figure 74: Height Map to flatten curved profile of sample (Appendix 9.)

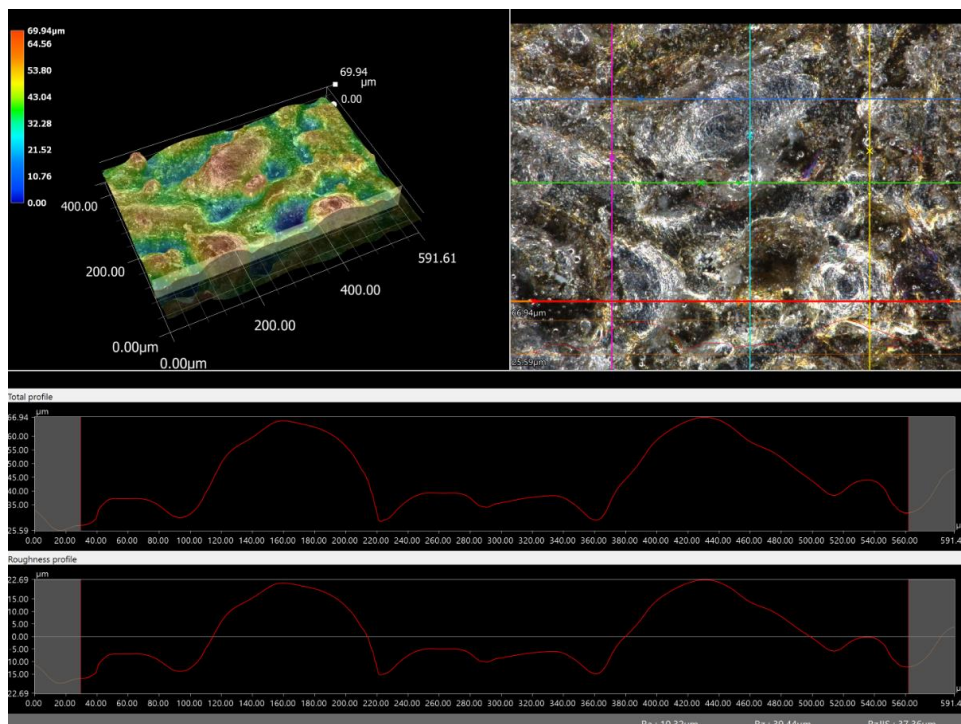


Figure 75: Line roughness analysis; To obtain Ra & Rz values at six locations (Appendix 9.)

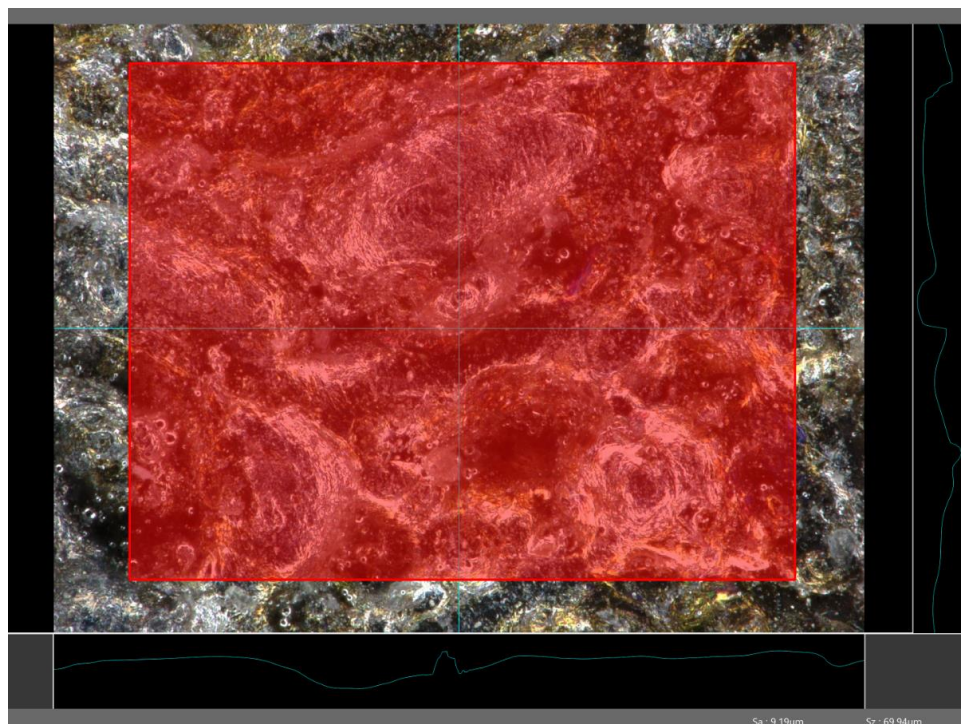


Figure 76: Quadrant roughness analysis; To obtain Sa & Sz values (Appendix 9.)

EBM

Six samples were successfully built, Diamond, Gyroid & Split-P TPMS rings, demonstrating production of mass customisable parts. Roughness of the surface is evident, with an increased surface texture compared with SLM. Surface preparation & polishing is beyond the scope of this project. Light &

strong parts were created. Manually placed support structure removal were challenging due to the shape.



Figure 77: Optical composite image of EBM surface (Appendix 9.)

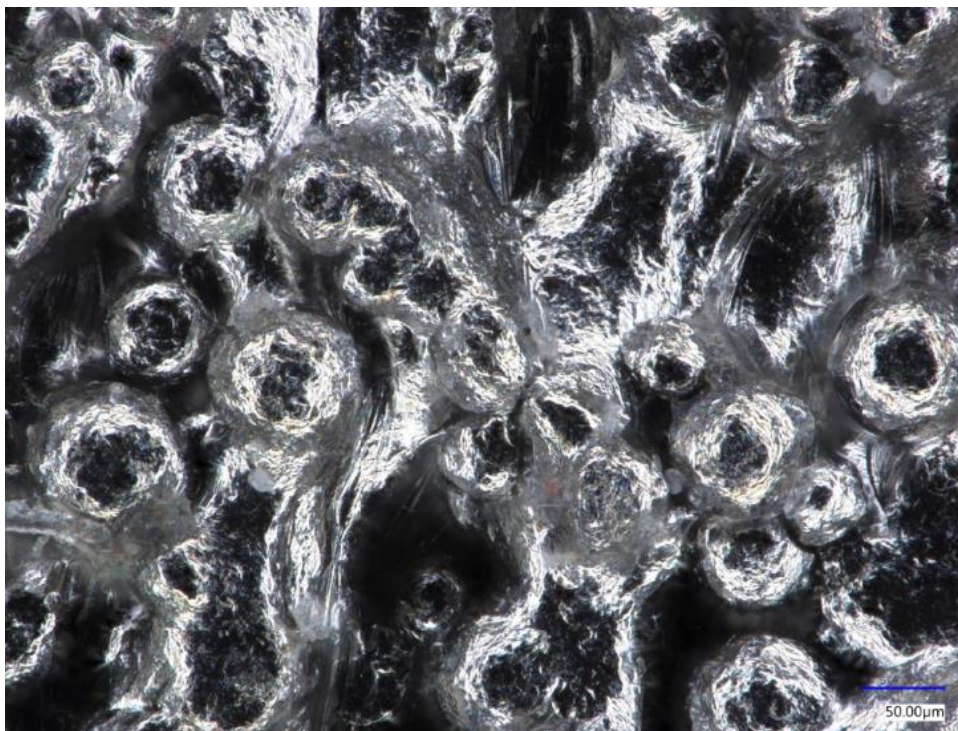


Figure 78: Optical composite image of EBM surface (Appendix 9.)

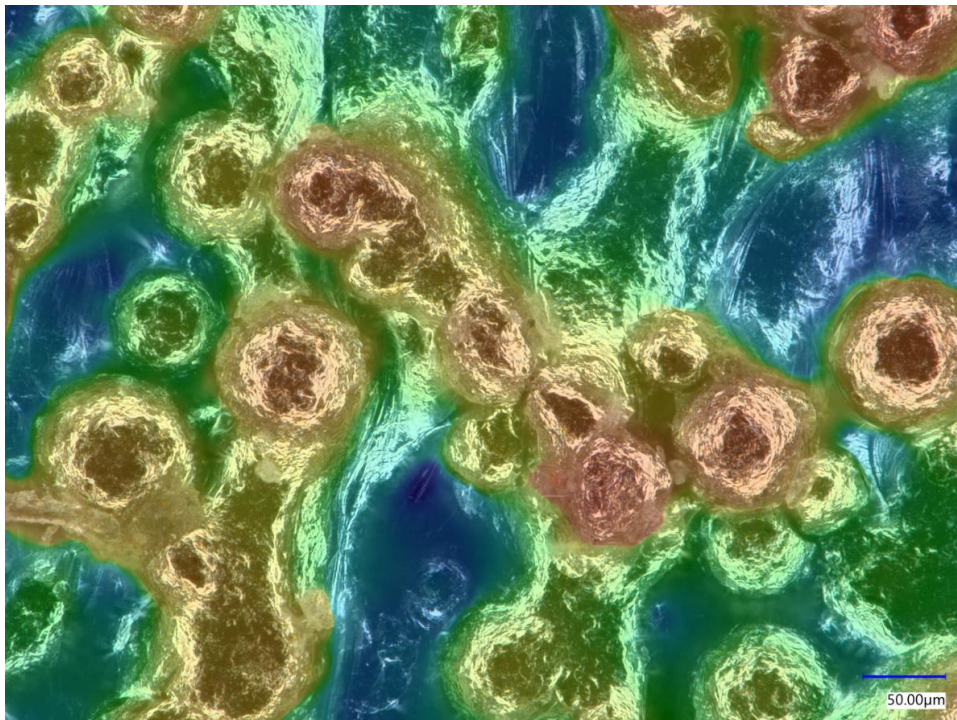


Figure 79: Height Map to flatten curved profile of sample (Appendix 9.)

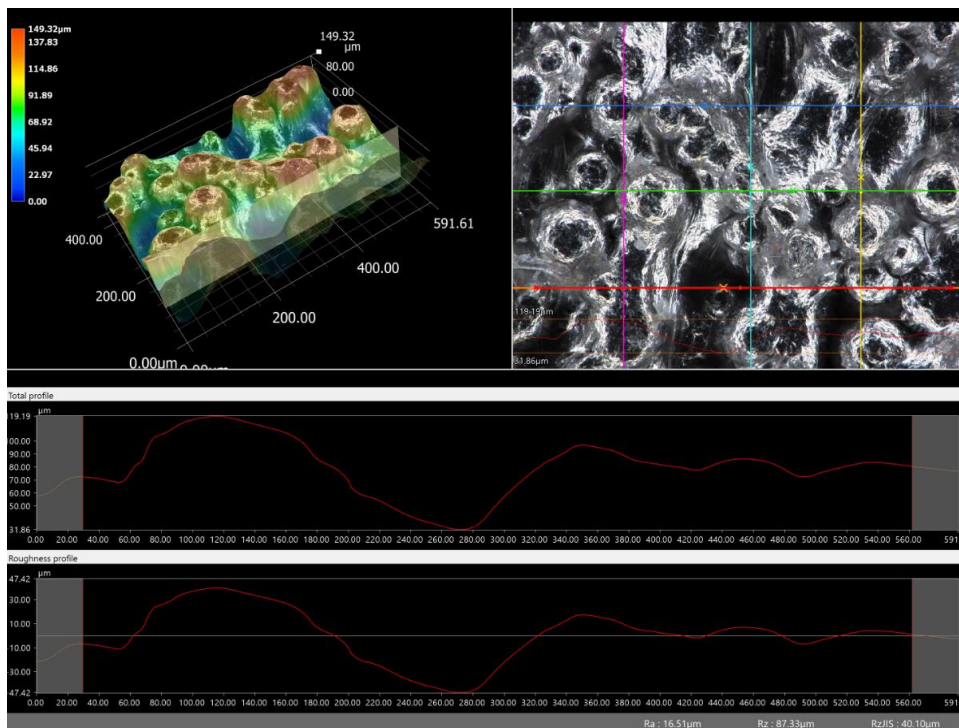


Figure 80: Line roughness analysis; To obtain Ra & Rz values at six locations (Appendix 9.)

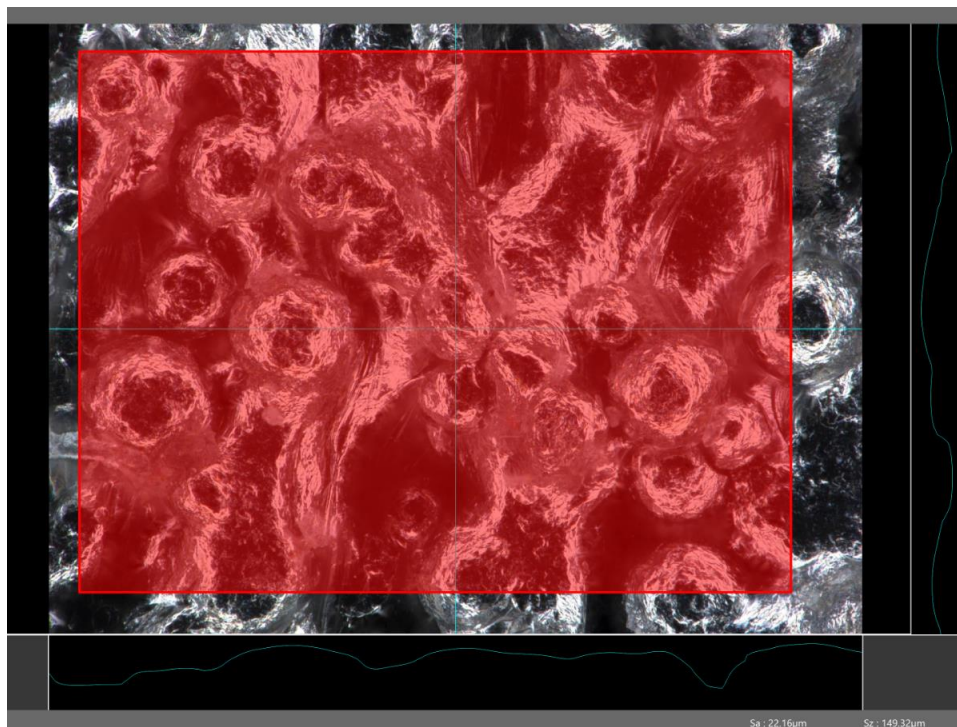


Figure 81: Quadrant roughness analysis; To obtain Sa & Sz values (Appendix 9.)

Surface Roughness

Surface roughness (Ra & Sa values) of EBM, was greater than SLM, was greater than IVC, but a decrease in porosity in SLM parts can reduce preparation & polishing times. Titanium high roughness linked to higher spot size, electron gun inaccuracies, & greater power for fusion. SLM silver sample have a higher roughness compared with IVC linked to the reflective nature of the material & the use of a laser on the infra-red spectrum. Laser energy & wavelength must be optimised for reflective materials to stabilise the melt pool, potentially reducing surface roughness comparable to IVC.

Cast			SLM			EBM		
Sa	2.72 µm		Sa	9.19 µm		Sa	22.16 µm	
Sz	24.28 µm		Sz	69.94 µm		Sz	149.32 µm	
Sa	3.59 µm		Sa	8.46 µm				
Sz	29.13 µm		Sz	78.5 µm				

Figure 82: Sa & Sz values from VHX7000 for; Cast, SLM & EBM samples (Appendix 9).

Cast			SLM			EBM		
Ra	1.86 μm		Ra	4.51 μm		Ra	20.94 μm	
Rz	8.93 μm		Rz	27.08 μm		Rz	82.28 μm	
Ra	2.53 μm		Ra	8.72 μm		Ra	23.51 μm	
Rz	16.27 μm		Rz	41.36 μm		Rz	94.41 μm	
Ra	2.85 μm		Ra	6.3 μm		Ra	9.25 μm	
Rz	16.55 μm		Rz	35.68 μm		Rz	33.79 μm	
Ra	1.33 μm		Ra	8.04 μm		Ra	25.17 μm	
Rz	6.36 μm		Rz	41.73 μm		Rz	109.78 μm	
Ra	2.43 μm		Ra	6.14 μm		Ra	20.32 μm	
Rz	16.56 μm		Rz	24.79 μm		Rz	88.71 μm	
Ra	2.62 μm		Ra	12.16 μm		Ra	16.51 μm	
Rz	13.01 μm		Rz	60.64 μm		Rz	87.33 μm	

Figure 83: Ra & Rz values from VHX7000 for; Cast, SLM & EBM samples (Appendix 9).

Business case

		Weight estimation (g)		Weight estimation (g)	
	Cost/g	Solid Band (No-TPMS)	Cost Estimation	Diamond TPMS	Cost Estimation
Silver 925	2	15.37	£100.74	5.88	£81.76
9ct 375	32.05	16.4	£595.62	6.06	£264.22
18ct 750	53.2	22.6	£1,272.32	8.38	£515.82
Platinum 950	42.93	30.16	£1,364.77	11.15	£548.67

Figure 84: Weston Beamor 14th December metal cost £/g (Appendix 4.)

The weight estimation was created by re-importing the TPMS diamond band into 3Design software & assigning the precious metal alloy. This was compared against a solid court wedding band of the same dimensions. Precious metal cost is dynamic, and a small amount of material change in weight, affects the profit margin. Material costs were obtained from Weston Beamor on the 14th December 2022. An hour of manual finishing was charged at £70/h and factored into the estimation. However, there is an assumption that complex pieces take a longer amount of time to finish, but has not been factored into this comparison. There is a business case for material savings on Silver constructs, however high value items made of Gold, or Platinum, could make substantial cost savings, whilst also providing product personalisation.

Implicit modelling supports the business case for mass customisation & lightweighting, where two rings, the boolean Intersection & the boolean subtraction, could be made from one traditionally solid ring. The weights of each ring can be manipulated by increasing, or decreasing, the TPMS cell thickness in nTopology.

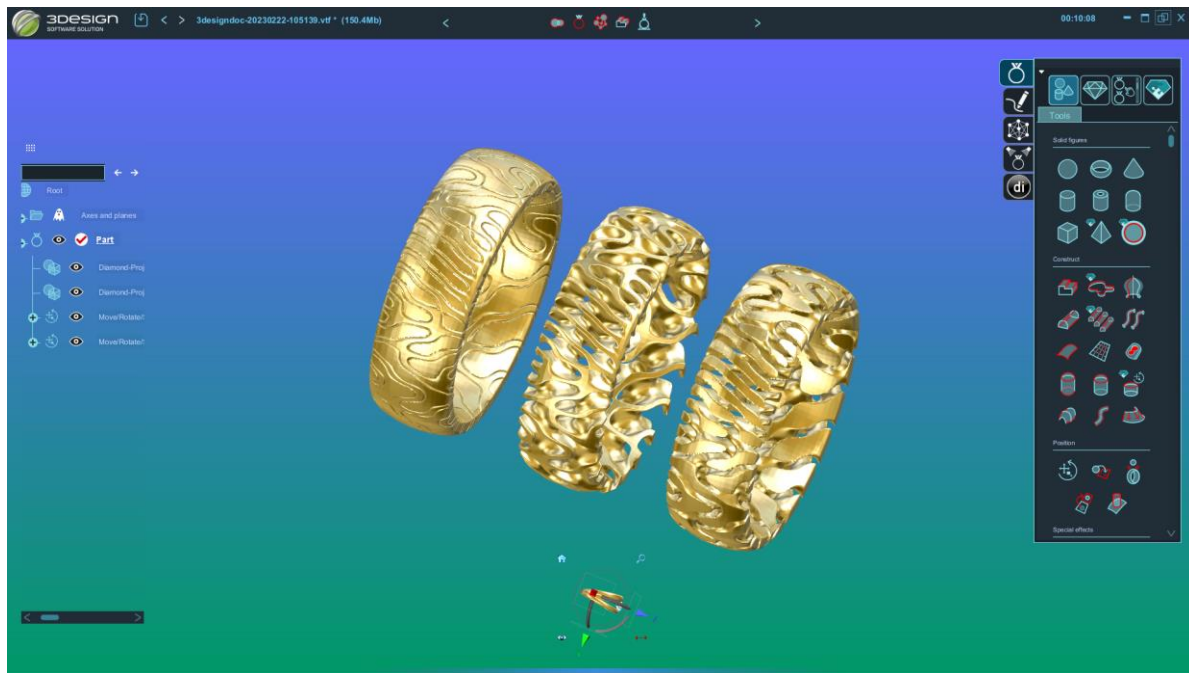


Figure 85: 3design software screenshot; From left to right: Boolean addition, Boolean intersection, Boolean Subtraction (Evans, 2023.)

Conclusions

Implicit modelling has the potential to evolve the CAD workflow & support complex geometries & mass customisation. Implicit modelling is not a replacement for traditional CAD modelling software, but can complement with re-useable workflows, that automate tasks such as lightweighting. Implicit modelling makes changes & export the results in real-time. nTopology is a complex & intelligent software, that can be used for other tasks, including simulation, design of experiments & cost analysis. Re-useable workflows can be created for design, support structure preparation, simulation of stress & strain, & cost analysis.

Implicit modelling & SLM supports efficient manufacture of material with the addition of mass customisation, for batch size of 1 capability. SLM & implicit modelling has the potential to reduce number of processes & localise production, with the removal of geographical barriers, creating a faster time to market. SLM has the potential to reduce materials for construction, reduce labour, reduce porosity, & create complex geometries & parts.

TPMS structures have a large surface area, so we could expect increased surface porosity, especially in IVC models, due to gas escaping. In large flat surfaces it is generally a problem, however early indications of no notable porosity, perhaps due to the natural self-supporting shape allowing gas to escape, and not build up. However, these TPMS structures are at the limits of what conventional investment casting can obtain. If the structures were sharp angled, enclosed or hollow parts, the nature of these could be considered un-castable with the developed industry design rules.

Light weighting through the use of TPMS structures allows for personalisation, mass customisation of products & efficient material use, & with the rising costs & accessibility of precious metals, including CRMs such as PGM's, this can alleviate some of the consumer pain points with demand for bespoke products & reduced-price points. However increased complexity will need to be tempered with efficient build & post processes to maximise labour & material efficiency.

IVC is capable of creating complex geometric shapes in precious material alloys. However, it may be more limited as complexity increases, or the addition of enclosed sections, sharper angles, or hollow sections. We think of porosity negatively, as a defect. However Implicit modelling can harness structural porous shapes as a design tool.

Industry embedded Polymer-AM coupled with IVC is a credible pathway for light weighting parts, whilst offering personalisation of precious metal constructs, for use in the jewellery manufacturing industry. For these specific samples Polymer-AM & IVC in silver 925 was the lower cost through fabrication charge, surface quality & post processing activities. Polymer-AM & IVC processes have been optimised to facilitate good castability with minimal surface intervention, post-cast. With the many processes being developed for manufacture, the key will be identifying the right tool for the manufacturing process, and then to design the piece, with that process' design rules in mind.

SLM has the potential to exploit three main factors; design methodology, environmental aspects, & improved mechanical properties, for industry wide adoption of this technology. Optimising SLM parameters & laser wavelength, as well as optimising the material alloy, has the potential to decrease the perceived surface roughness, creating parts more comparable with the results obtained from IVC. Core SLM business innovations can be made through material optimisation, and process improvement.

SLM has the potential for a reduction in waste produced & energy consumed, with less process-stages, & increased production automation. SLM systems have a high technological cost.. Bureau systems like Cooksongold, with access to 8 EOS printers & hallmarking facilities can greatly reduce product mileage, as digital model files can be uploaded, allowing companies with limited resources, access to technology with high overhead costs, that requires dedicated highly skilled workers. Improvements for the SLM process include; recycling powders, re-atomisation of supports, inefficient laser absorption, surface resolution of reflective materials, & production of micro-fine detail. SLM technology will have to decrease in system cost & complexity, to become adopted industrywide. SLM is a relatively new technology when compared with IVC. While there are plenty of areas to optimise, there is a greater chance of reaching 100% density, controlling mechanical properties, & pushing the boundaries of design on a potentially much greener process.

Surface roughness of reflective materials, can be attributed to the poor absorption, requiring excess power for fusion, destabilising the melt pool. Optimising parameters of speed & power, & tuning lasers to shorter laser wavelengths, could increase part quality, reducing post processing time. Optimising surface quality, by limiting defects, such as porosity & increasing the pack density, would also increase the efficiency of the finishing application. SLM is better placed to eliminate porosity, with a theoretical 100%-part density. Beam diameter, thermal conductivity of the material, shorter wavelength laser source & optimising the build, powder bed & laser parameters are important aspects for processing reflective materials. These should be carefully considered when assessing system specifications for desired process. Optimising SLM parameters & laser wavelength has the potential to decrease the perceived surface roughness, more comparable with results obtained from IVC.

Optimisation of supports, or adapting the designs to minimise supports needs to be considered. If nTopology is leveraged to automate mass customisation of designs, then an efficient support structure generation tool needs to be identified. Alternative technologies, such as Pureform, or Binder Jet Printing, could be employed, as they do not require supports. However, the post production phase, of de-binding & sintering adds to the environmental footprint. Part shrinkage, & lower densities, would also need to be considered.

Surface roughness & support removal on SLM silver need to be minimised & optimised as these are intrinsic to the economic value through lost material & labour. The generation of particulates would need to be regulated, through closed systems for deburring, preparation & polishing phase, could be considered. Automation of the finishing process, along with improving the surface quality of highly reflective SLM parts are intrinsic in making the process economically viable. Materials with a high economic value needs to minimise waste through failed builds, reduce support structures, efficiently process & recover the material from all phases in the build & post processes. Automation of finishing is adequate, however, electropolishing, dry air polishing, or Plasma electropolishing could be investigated for future suitability. Optimising DfAM, build, laser & material parameters, & reducing material and post-processing activities, are key to manufacturing efficiency. Lightweighting reduces the print time & material & energy needed for production, reducing the build cost. Automaton of the polishing phase can realise economic value for small batch & bespoke complex builds

IVC is an energy intense, & material inefficient process. IVC has limitations; however, it is capable of complex TPMS geometries. SLM is more costly compared to industry embedded IVC, for part production & system technology. With decarbonisation legislation, environmental aspects may be the bigger drivers than design innovations, or mechanical properties, driving industry adoption of SLM.

Opportunities of SLM & Implicit modelling for precious metal jewellery manufacture

- Implicit modelling for design iterations & mass customisation re-useable integrated workflows with real time changes & file export.
- Supports bespoke design & small batch production
- Supports light weighting of parts & support structures.
- Access to new material alloys not suitable for investment casting or forming.
- Access to new design geometries & design rules, with design freedom from casting & machining restrictions
- No large tooling costs associated with subtractive & formative methodologies
- Reduced porosity potential, with parts reaching full density.
- Material Properties can be controlled & manipulated by the laser process.
- Efficient use of precious & CRM materials & porous structures by design.
- Incremental & sustaining business improvements whilst creating new business models
- AM supports a Circular Economy
- Localises production, reducing manufacturing steps & potential reduction in product mileage.

Recommendations

With Implicit modelling, SLM optimised for a surface roughness equal to or better than investment casting, & with a post processing unit you can automate large portions of the design process for mass customisation, production & finishing.

Selection of the optimal process for the task. SLM is not a replacement technology, as investment casting can be the more economically viable option, especially where improved material properties or environmental drivers are not valued.

To consider the benefits of SLM as an environmentally greener process, with the new design rules to add value through a combination of light weighting & personalisation for consumers.

Use Implicit modelling & SLM to evolve the business model for lightweighting, mass customisation & personalisation of products, through re-useable workflows.

Use implicit modelling, polymer-AM & IVC to embed skills, and adopt SLM when resources are optimal. Cost of technology should be matched with training & finishing processes, & so companies with limited resources should consider AM for design iterations & polymer-am & IVC for production, & bureau services for SLM to test market demand before investing considerable resources.

Limitations of the study

AM is a complex subject with many interacting processes, parameters & variables. The time to explore every discerning aspect & variable was out of scope for this project. The time afforded, & cost of processing even the basic jewellery alloys of gold & platinum, was out of scope of this project. The cost of using the technology through training & system access coupled with the cost of accessible material was a limitation leading to a low number of alloys processed. Only one sample on the EOS-M100 at Cooksongold was manufactured due to cost. However, processes were discussed & documented with each operating body.

Silver 925 was investigated, however more alloys need to be built & compared. These were limited by access to machine time, proprietary laser & build parameters & printing the samples, through technology, material, & post processing costs. Access to the Alpha system was limited by mechanical & financial issues, previously discussed.

The lack of access to the Alpha SLM system meant that certain areas were not explored. Primarily the gyroid support structures to reduce the weight, and ease of placement. The Alpha system has access to parameter development, that could have been explored. The Alpha laser has a spot size of 50µm and the EOS M-100 has a spot size of 40µm. It would have been interesting to bench mark any discernible differences of a 10µm reduction between the two SLM systems.

Mechanical testing, such as compression testing with in-situ Xray to analyse the deformation between solid ring and TPMS ring to observe the resistance to deformation was a limitation. The cost, skill & access to technology was a barrier to inclusion, but could be followed up in a separate investigation, or PhD project.

There are gaps in the literature on jewellery alloys, & precious metals. Alloys differ between processes and also suppliers. Some of the information is proprietary and not available.

Simulation of the builds were limited due to access to Materialise Magics, however some preliminary work by Cooksongold highlighted areas of <0.3mm for investigation. Simulation of Compression Tests in nTopology were limited due to the TPMS shapes being non-conform, the alloys for modelling being pure metals & researchers knowledge & experience.

Further research

Areas for further research include:

Into the methods & practices of current & future mass finishing methods needed for geometric complexity. The complex design freedom afforded by SLM & Implicit modelling may be limited by part quality, but also by finishing requirements.

Societal impact of SLM through the creation of jobs & loss of jobs through the automation of tasks. The environmental implications of efficient process, and reduction of material refining, through recycling of powders, & re-atomisation of supports. The environmental implications of the atomisation process, looking at the emissions of gas & plasma atomisation of powder production.

Safety Aspects of using SLM, with a focus on closed systems & operator contact with micro-fine particulates.

Silver alloy 925 was explored due to its comparatively low cost. However, PGM & Gold alloys should be explored. Micro-alloys of semi-conductors should also be explored due to their increased fusion, through lowering the thermal absorption, & their increased material strength.

SEM or optical microscopy of manufactured parts to quantify the microstructure, focusing on the alloy used, method for production, & the parameters involved. The microstructure has a direct effect on the material properties.

Xray Ct could be used to deduce internal porosity, from a non-destructive test. It can also be used to look inside complex constructs, such as TPMS builds, for defects, unspent powder, & model validation.

Mechanical properties of the parts that have been built in this project would be interesting to investigate. Even though there are areas <0.3mm it doesn't feel weak, or bend under hand compressions for the IVC pieces, which theoretically should be weaker. It would also be interesting to bench mark against other materials, traditionally platinum is harder to cast than silver & gold. Platinum TPMS samples might not fully form due to the higher casting temperatures with Investment casting, & would need to be optimised with the receptive alloy, such as platinum Cobalt. It would also be interesting to see whether lattice cell structures would be as easy to cast compared to the interconnected smooth nature of the TPMS structures.

Investigation into BJP or Pureform as a viable alternative to SLM, & whether the reduction in part density & smoother surface resolution is suitable. Quantification of the environmental impact of BJP against SLM would be interesting to see the

Investigation into the effect of absorption of precious metals with a laser(s) that could be tuned from the visible spectrum to the infra-red range for a range of commonly assessable precious metal powders, to define build parameters & optimal wavelength for each alloy, with in-situ monitoring of the melt pool & part production.

Investigation into automation of support geometry using machine learning & in-situ monitoring and a feedback-control loop during physical builds, to inform future support generation.

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Appendix 1: Cooksongold TPMS diamond SLM Invoice

SIMON EVANS
13 PINE COURT FOREST HILLS
TLBOT GREEN
UNITED KINGDOM
CF72 8LA

PROFORMA INVOICE BI2223587

Account No. CTK729
Date (1) 20/12/22 12:16:58
Your Order No. SIMON
Our Order No. B02323951
Payment Terms CASH/CARD
Despatched By DHL Express
Raised By JHILL
Prepared By

BI2223587 76 DHL Express Tax Point Date 20/12/22
Our VAT No.GB161806221

Item	Product	Description	Qty	Weight	Rate	Value
1	SSAS8602	Sterling Silver Sintered Item Ls8602 Diamond Project	1.00	8.50GM	787.440KG 58.810EA	6.69 58.81
		Total Wgt & Qty	1.00	8.50GM		
		POSTAGE & PACKING				11.00
THIS INVOICE IS DUE FOR IMMEDIATE PAYMENT						GBP
TOTAL AMOUNT						76.50
VAT						15.30
TOTAL						91.80

Appendix 2: Weston Beamor TPMS diamond casting Invoice

JEWELLED PHOENIX
13 PINE COURT
FORREST HILLS
TALBOT GREEN, CF72 8LA
WALES

INVOICE

COPY

westonbeamor
 complete jewellery solutions

3-8 Vyse Street
 Birmingham, B18 6LT

Telephone: +44 121 678 4131
 Fax: +44 (0)121 212 4951
 Email: info@westonbeamor.co.uk
 Website: www.westonbeamor.co.uk

Document Date 21. December 2022
 Invoice No. PSI-01141292
 Quote above number in all correspondence.
 Order No. SO-01874140
 Payment Due Date 31. January 2023
 Bill-to Account No. WP0288

VAT No. GB823842232
 TAX POINT IS DOCUMENT DATE

Your Order Ref.	Description	Quantity	Unit Price	Amount	VAT Rate %
DIAMOND PROJECT 3	PROJET PROJECT	3	Each	7.41	22.23
	Silver	15.7	Grams	1.40	21.98
	DIAMOND PROJECT 3				
	Hallmark Not Required	3		0.00	0.00
DIAMOND PROJECT 3	Project Print Charge	3	Each	30.00	90.00
DIAMOND PROJECT 3	Post, Packing & Insurance	1		10.00	10.00
Total GBP Excl. VAT				144.21	
20% VAT				28.84	
Total GBP Incl. VAT				173.05	

REGISTERED

JEWELLED PHOENIX
13 PINE COURT
FORREST HILLS
TALBOT GREEN, CF72 8LA
WALES

PSI-01141292

All goods are supplied subject to our standard terms and conditions,
 a copy of which is available on request.

Sort Account
 IBAN
 SWIFT

PSI-01141292

Telephone calls may be recorded for quality and training purposes.

Appendix 3:Cookson gold powder Composition literature

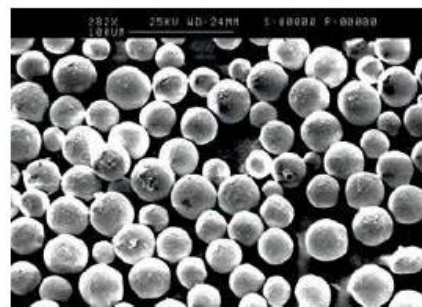
Direct Precious Metal 3D Printing Powders

Specifically developed for all 3D printing systems.

Cooksongold's gas atomised precious metal powders have been developed to ensure that the powder composition, flow characteristics and particle size distributions optimize performance in laser sintering applications. The material is rigorously tested to provide reliable and repeatable results across multiple builds, and between different batches of material.

Stocked Powders	18k 3N Yellow Gold Powder	18k 5N Red Gold Powder	18k White Gold Powder Pd	950 Pt/Ru Platinum Powder	Sterling Silver
Alloy Composition					
Product	ALNP000	ALIP000	ALZP000	AXHP000	ASRP000
Alloy ref	11889	11884	11883	00647	28001
Gold	75.10%	75.10%	75.20%		
Platinum				95.50%	
Silver	12.00%	4.50%	3.00%		93.30%
Palladium			13.90%		
Ruthenium				4.50%	
Colour	3N Yellow Gold	5N Red Gold	White Gold	Platinum	Sterling Silver
Alloy Properties					
Particle Size	< 40 micron	< 40 micron	< 40 micron	< 60 micron	< 40 micron
Density	15.5g/cm3	15.2g/cm3	16.0g/cm3	20.7g/cm3	10.3g/cm3
Melting Range	870°C–905°C	870°C–900°C	1100°C–1170°C	1780°C–1795°C	890°C–950°C
Melting Temperature					
Solidus	870°C	870°C	1100°C	1780°C	890°C
Liquids (°C)	905°C	900°C	1170°C	1795°C	950°C
Annealing Temperature					
Annealing Temp	600°C–700°C	600°C–700°C	650°C–750°C	1000°C–1100°C	500°C–600°C
Water Quench	Yes	Yes	Yes	Yes	Yes

Cooksongold can also provide Base Metal Powders – contact us for more information.



SEM Microscope: 282x magnification, 100 micron scale.

Appendix 4: Weston Beamor metal costs £/g

 Siantel James <siantel@diamondcentrewales.com>
To: Simon Evans


Wed 14/12/2022 14:37

 Reply  Forward

From: Jake Taylor <Jake.taylor@dominojewellery.com>
Sent: 14 December 2022 11:14
To: Siantel James <siantel@diamondcentrewales.com>
Subject: DOM METAL PRICES

Hello,

Please see below for this weeks metal prices;

WEDDING BANDS	
WB9Y	£32.05
WB9W	£33.98
WB9R	£33.11
WB18Y	£53.20
WB18W	£64.10
WB18R	£57.79
WBP	£42.93

Kind regards,
Jake.

Appendix 5: Cooksongold EOS M-100[Recorded build process LS8602](#)**Appendix 6: nTopology TPMS workflow**[Project-Diamond-Geiger.ntop](#)**Appendix 7: Model File exports**[Diamond-Project-Intersection.obj](#)[Diamond-Project-Subtraction.obj](#)[DE Project \(3\).stl](#)

Appendix 8: Optical Microscope specifications

Data Sheet



VHX-7000

Digital Microscope



Specifications

Model	VHX-7000	
Camera	Image receiving element	[VHX-7020 High- Performance camera] 1/1.8 inch, 3.19 megapixel CMOS Image sensor Total pixels: 2064 (H) × 1554 (V); virtual pixels: 2048 (H) × 1536 (V) [VHX-7100 Fully- Integrated] 1/1.7-inch, 12.22-megapixel CMOS Image sensor; total pixels: 4168 (H) × 3062 (V); virtual pixels: 4024 (H) × 3036 (V)
	Scanning system	Progressive
	Frame rate	[VHX-7020 High- Performance camera] 50 F/S (max.) [VHX-7100 Fully- Integrated] 30 F/S (max.)
	Resolution	Fast
		Standard
		High-resolution
		High accuracy
	High dynamic range	16-bit Intensity range through RGB data from each pixel
	Gain	Manual, Preset
	Electronic shutter	[VHX-7020 High- Performance camera] Auto, Manual, 1/60, 1/120, 1/250, 1/500, 1/1000, 1/2000, 1/5000, 1/9000, 1/19,000 [VHX-7100 Fully- Integrated] Auto, Manual, 1/30, 1/60, 1/120, 1/250, 1/500, 1/1000, 1/2000, 1/5000, 1/9000, 1/19,000
	Supercharge shutter	[VHX-7020 High- Performance camera] Can be set in 0.01 s increments from 0.02 to 16 s [VHX-7100 Fully- Integrated] Can be set in 0.01 s increments from 0.03 to 4 s
LCD monitor	White balance	Push-set, Manual, Preset (2700K, 3200K, 5600K, 9000K)
	Back-focus adjustment	Not required
	Built-in light source	Type
		Service life
	Size	Colour LCD (IPS type), 27-inch ²
	Screen size	596.736 (H) × 335.664 (V) mm
	Pixel pitch	0.1554 mm (H) × 0.1554 mm (V)
	Number of pixels	3840 (H) × 2160 (V)
	Display colours	Approx. 1.07 billion colours ³
	Brightness	350 cd/m ² (Centre 1 Point, typical)
Hard disk drive unit	Contrast ratio	1300:1 (typical)
	Viewing angle	±89° (typical, horizontal), ±89° (typical, vertical)
Storage capacity	1 TB (including 350 GB reserved system space)	
	Approx. 2.16 million Images (when 3 megapixel Images are compressed) to approx. 71.1 thousand Images (when 3 megapixel Images are not compressed)	

Appendix 9: Optical Microscope VHX-7000 images & surface measurements[Cast](#)[SLM](#)[EBM](#)