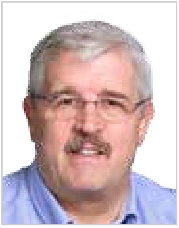

DMLM Supports: Are They the Jewelry Industry's New Sprue, Riser and Gate Feed?

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Introduction

For many years now, we—as simple bench jewelers, silversmiths, jewelry designers and casting technicians—have had an almost morbid fascination with comprehending the science behind the technicalities and practicalities of the black art (*black art/skill: a mysterious skill that is difficult to master or describe*), that is, the casting sprue, the riser, the gate feed, the effects of turbulence in molten metals at high temperatures, solidification rates, shrinkage and gas porosity, to name but a very few of the curses that can befall us during the casting process. Then, we as an industry decide to introduce a totally new, and almost alien to many, technology into the mix, Direct Metal Laser Melting, with what appears at an initial and superficial glance to be its very own set of black arts. This study aims to examine the DMLM equivalent of the casting sprue, the support structure, and lay out in simple, practical terms that designing for and building jewelry with DMLM really holds nothing for us to fear or that it is not nearly as dauntingly complex as it might first appear!

Support Structures

Support structures are required in most, if not all, laser-powered, metal-based additive manufacturing (AM) processes, and there are a number of divergent reasons for their presence. To build complex geometries with overhanging and undercut surfaces, support structures are required to assist in controling defects such as curling, sagging, cracks, shrinkage and/or other deformations of the part being built. These defects may be caused by the typical thermal stresses of the DMLM process, occasionally by overheating, or most commonly by being dragged over and disturbed by the screed applying the next layer of powder. But supports are principally required because the powder bed surrounding the melt pool created by the laser is not sufficient to support the liquid metal in place. Other functions of supports are bonding the part to the build plate and providing a thermally conductive connection between the part and the build plate to rapidly and effectively dissipate heat from the melt zone.

The needs discussed above must be balanced with the cost when considering the design and placement of support structures. Supports can be solid, hollow or even cellular structures that are removed after the build/print cycle has been completed. Thus, they can potentially represent a considerable waste in terms of expensive precious metal material, energy consumption and the time required for their creation, placement, construction and eventual removal. From a cost standpoint, supports should have as low a volume as possible, using the minimal amount of valuable materials, and be relatively easy to remove. These contradictory needs of strength and conductivity verses cost to build and remove make automated solutions for creating supports very challenging. Some of the software programs and strategies that are applied for this process will be examined closely in this study.

Support structures and their placement also have an important role in the developing 'design rules' that are now being more widely understood and applied when designing for the DMLM AM processes. Additive manufacturing processes do not totally eliminate design constraints; they are just different when compared to the more conventional manufacturing processes. For example, while we don't need to worry about draft angles, AM processes have their own limitations. We require at least a basic understanding of how part orientation can improve part accuracy and surface finish as well as reduce the production time and volume of support structures required for building a part.[1,2] There have also been extensive studies into the automatic creation of cellular-like support structures. One of these, conducted by Ahmed Hussein et al., describes these structures thus: "… these periodic lattice structures could assist in reducing the time and material volumes needed for building support structures. The volume fraction defines the relative solid volume that is inside the generated support. The lower the volume fraction is, the more open the support structure will be. If the value of volume fraction is very low, it may result in loss of connectivity between adjacent cells in the support; very high values may result in closed support volume."[3] For your reference, a very detailed analysis of support structure theory and development can be found in the paper by M. Cloots et al.,[4] but it is not the intention of the author to delve too deeply into the design rules conundrum here[5] (that's one for a future Santa Fe Symposium®). You can find excellent and relevant design rules information on both the Manufacturing The Future website[6] and Cooksongold's E-Manufacturing portal,[7] from which their recommended design guidelines can be downloaded as pdf files.

Software

Many of the earliest studies and research into support structures used in the various industrial AM technologies, particularly those used in stereolithography[8] (SLA) and Fused Deposition Modelling[9] (FDM), have concentrated on the non-metallic processes. These support structures and their creation software programs[10,11] then went on to form the basis for the development of the support structures used in the various DMLM processes. Foremost among these software programs was that offered by Materialise called Magics (and in particular its support generation module[12]), which was to go on to become the industry standard in the eyes of many. Materialise also supplies the Mimics and AutoFab softwares and there are one or two other software options such as Fabbify, but this whole area of development is extremely fluid at the moment. As a side note, AutoFab is published by Marcam Engineering, which was recently purchased by Materialise. This company is now busily absorbing the AutoFab functionality and algorithms into the Magics suite of softwares.

All of the jewelry-applicable DMLM technologies currently on the market are supplied with an integral support generation package, but this is rarely, if ever, a stand-alone package and most often part of the full operating suite of software required to efficiently operate the particular DMLM technology being used by the jeweler. Each module of the software is normally interlinked and interdependent on the other. For instance, within the operating software supplied by ES Technology (Concept Laser Mlab), Cooksongold in partnership with EOS (Precious M 080) and Realizer (SLM 50), there is a Magics support-generating module that has been custom adapted for each of these machines.

Practical Examples of Software Being Deployed

Let us now take a detailed look at how the Concept Laser Mlab customized Magics software module looks and functions. The screenshot images in Figures 1-20 are courtesy of ES Technology.

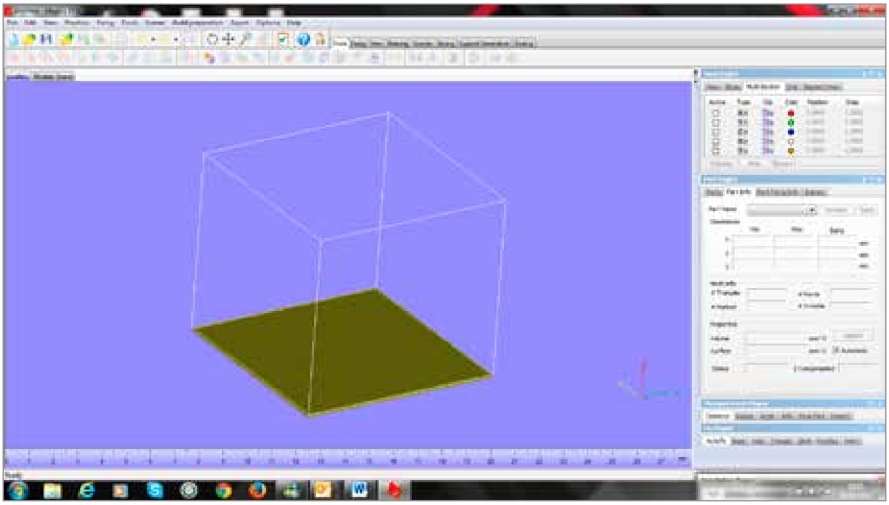

***Figure 1** The standard Mlab build envelope of 90mm x 90mm x 80mm is pre-programmed into the software. The green area represents the 90mm x 90mm build plate area, and the Z axis is set to zero.*

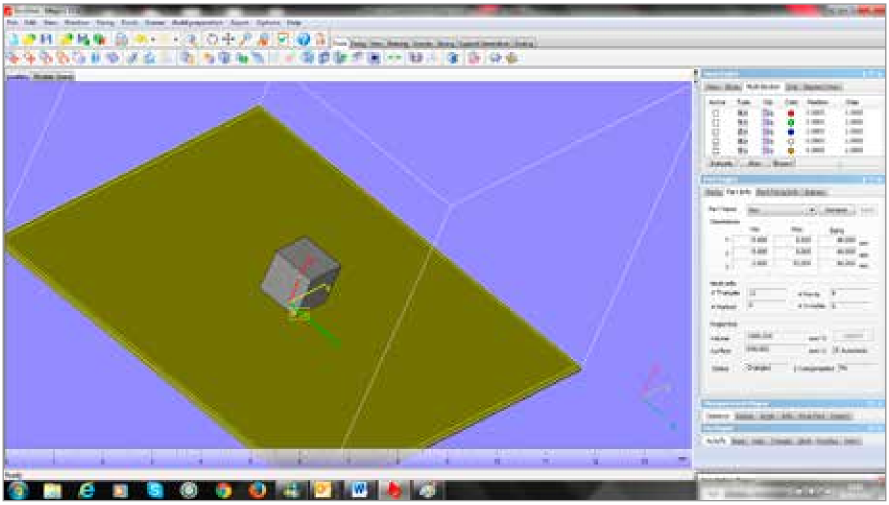

Figure 2 *The STL file of the 3D CAD model is then imported.*

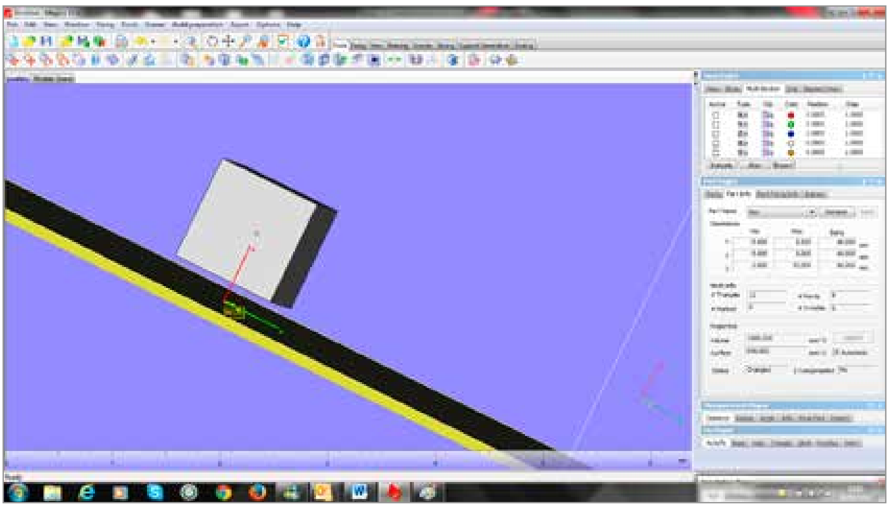

Figure 3 *The model is positioned 2mm above the build plate plane. This allows the supports to be created in the gap between the bottom of the CAD model and the Z axis zero build plate line.*

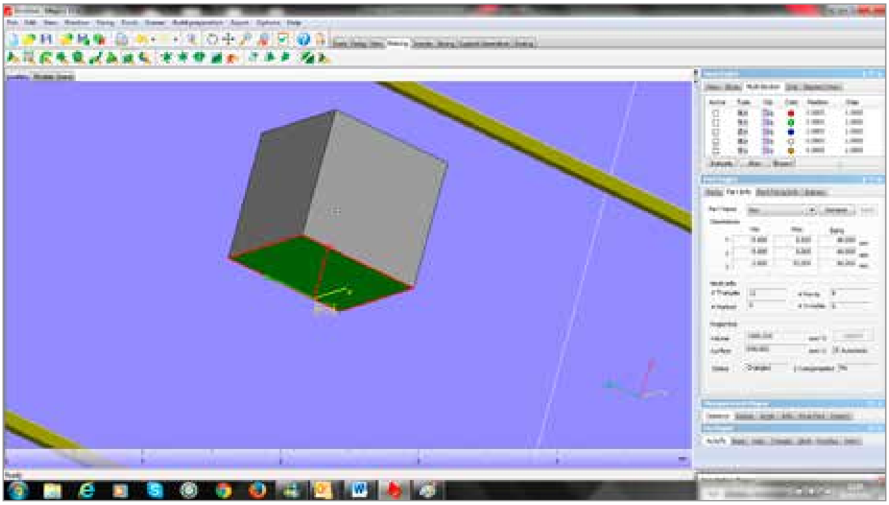

***Figure 4** The downward facing areas that are to be supported are identified and indicated as the green plane.*

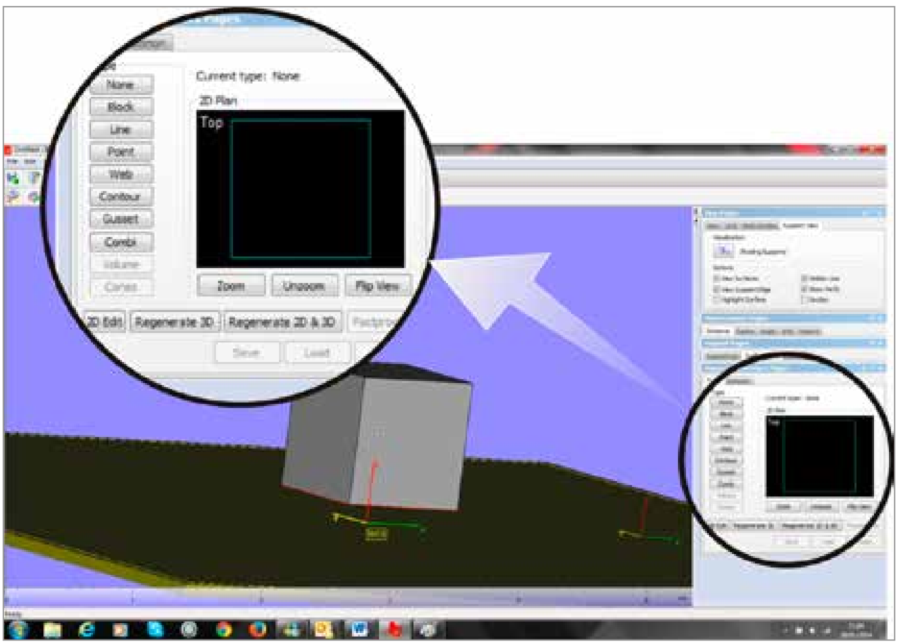

***Figure 5** Any one of a range of support types such as conical points or blocks, etc. can be selected from the drop down menu on the right side of the screen.*

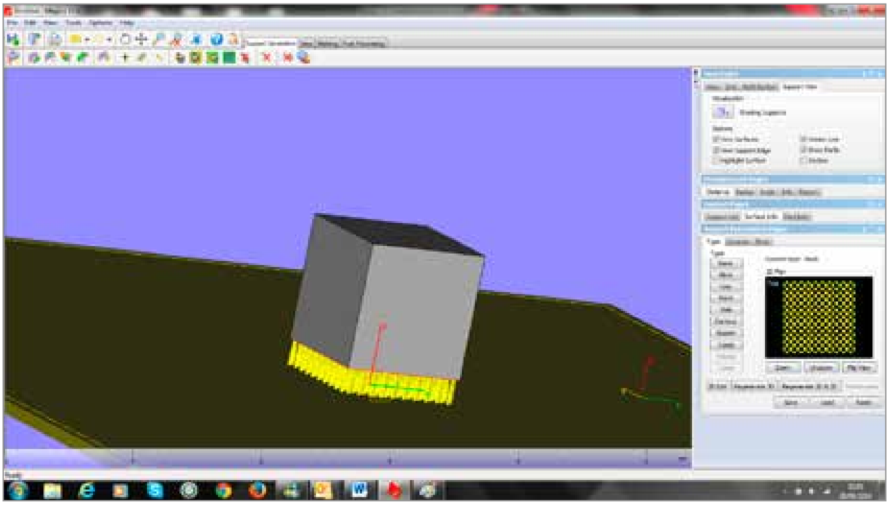

Figure 6 *Here the block option has been selected, which uses predefined support struts, in this case 0.7mm x 0.7mm cross struts, identified in yellow.*

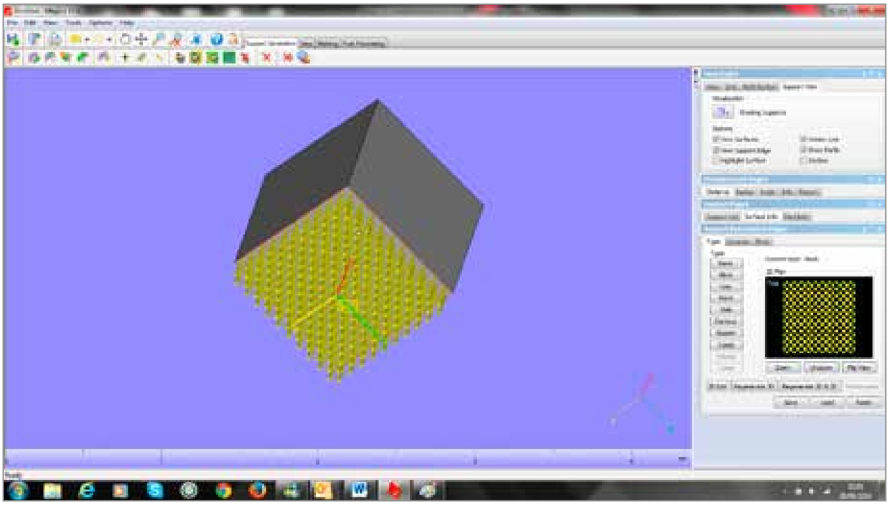

Figure 7 *This process is easy, just one click, and the software decides on the number of support struts necessary, then quickly and automatically generates them and covers the entire area of the pre-selected plane.*

The software has automatically placed the supports at what it calculates to be the optimum positions to maximize support of the object to be built. This is where orientation of the item becomes crucial; making the wrong choice can result in far more supports being built than are really necessary. Having to remove unnecessary supports and their resultant witness marks adds to cost and therefore should be avoided. (The process of removing DMLM supports and their witness is similar to removing feed sprues and their witness from a cast piece of jewelry.) The software offers the flexibility of allowing the operator to manually delete supports to optimize the quantity of supports used.

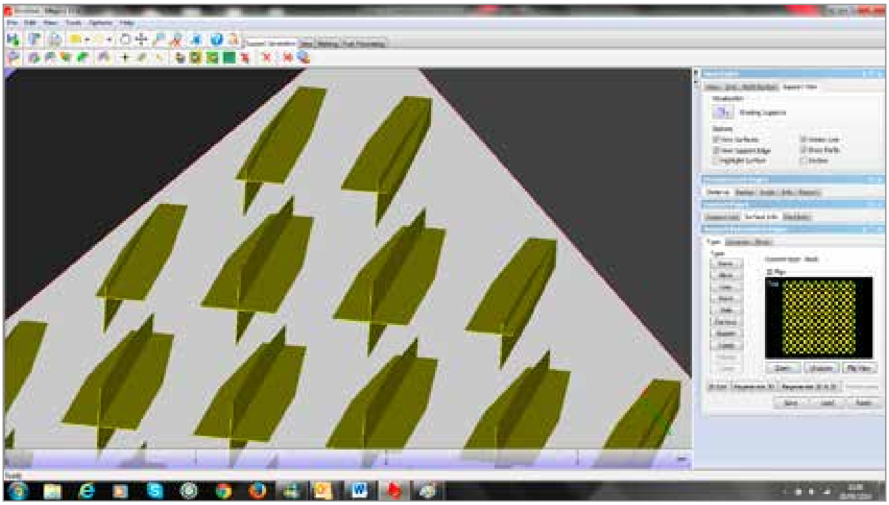

Figure 8 A close-up view of the support struts, which can be changed in size and spacing, and stored within the software to suit individual applications

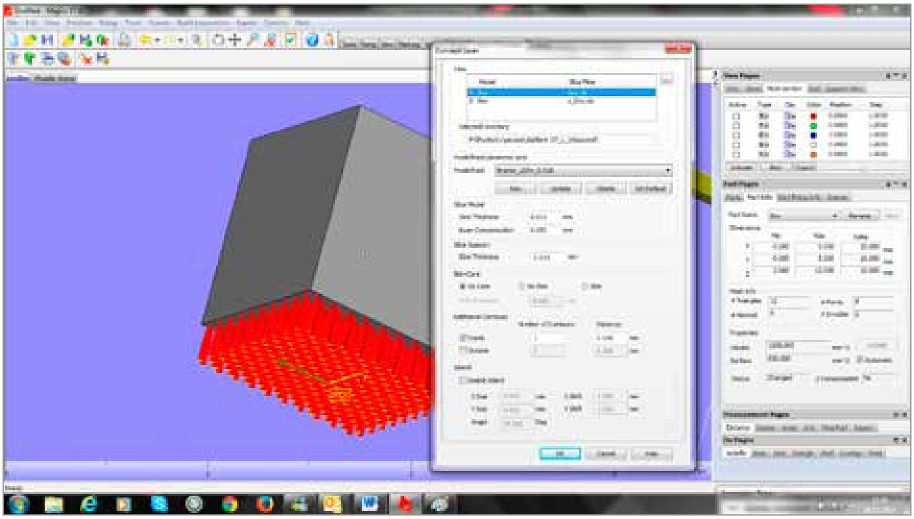

Figure 9 This is the point at which the material, slicing layers and laser path strategy are defined by the slicing module within the software.

The software offers the operator options to export the file to the machine's operating software as two conjoined slice files, which allow for an optimized build strategy to be selected with a lower laser power setting used for building the support structures than the main body of the item. This means less wasteful energy consumption and support structures that are eventually much easier to break away.

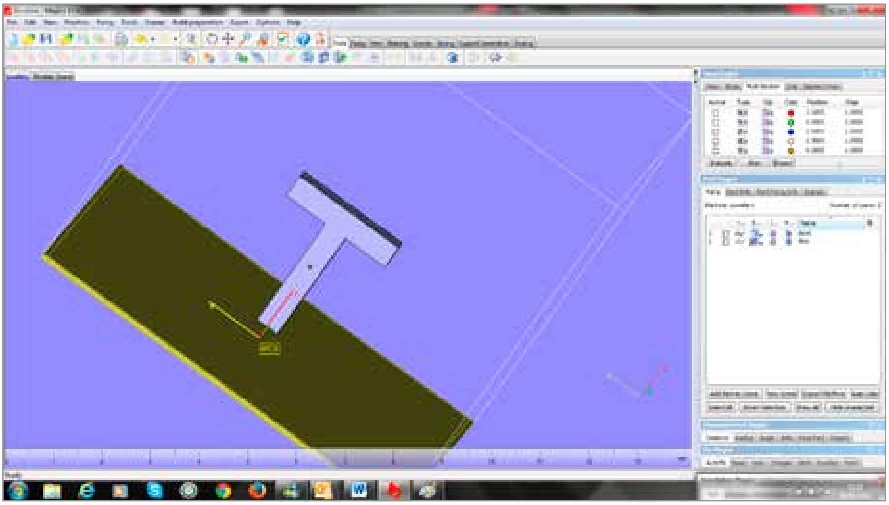

Figure 10 *If a model has overhanging features, they will clearly need to be supported from the build plate.*

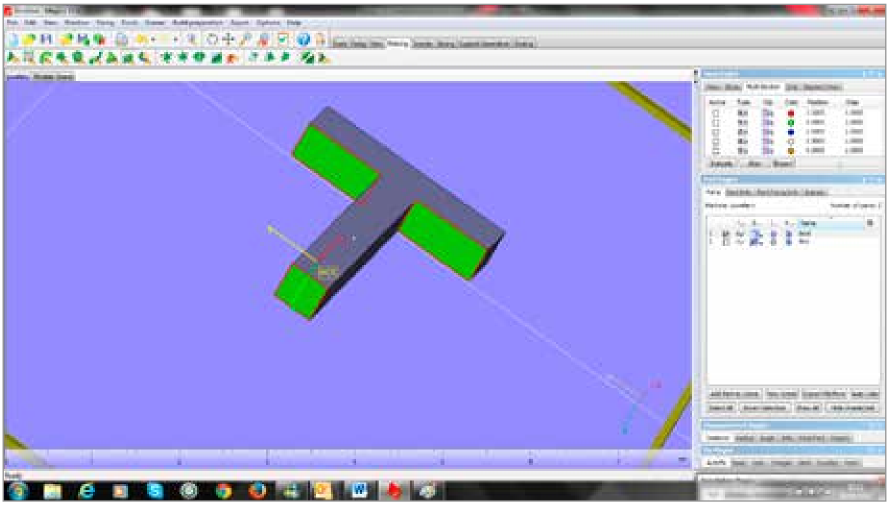

Figure 11 *The area where support may be required has been identified and highlighted in green.*

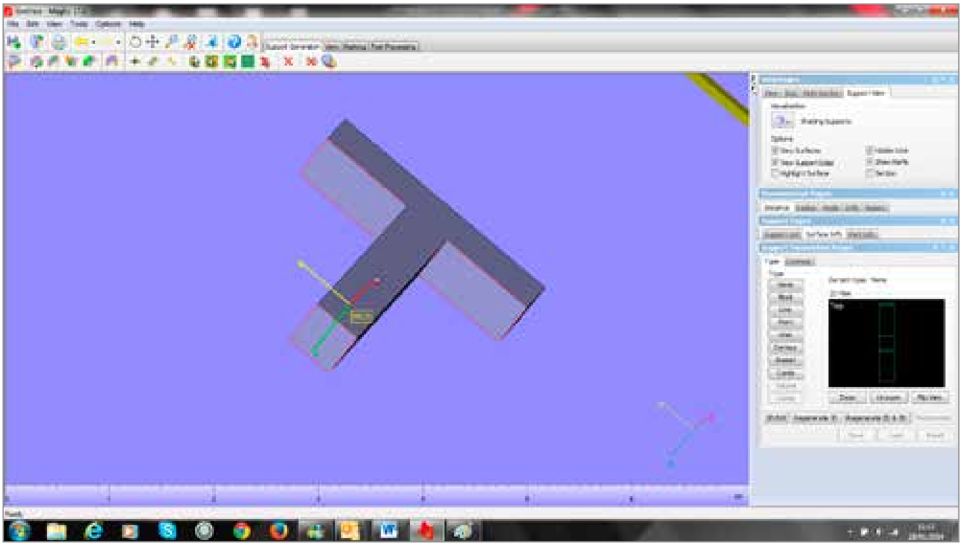

***Figure 12** The block support option is selected again.*

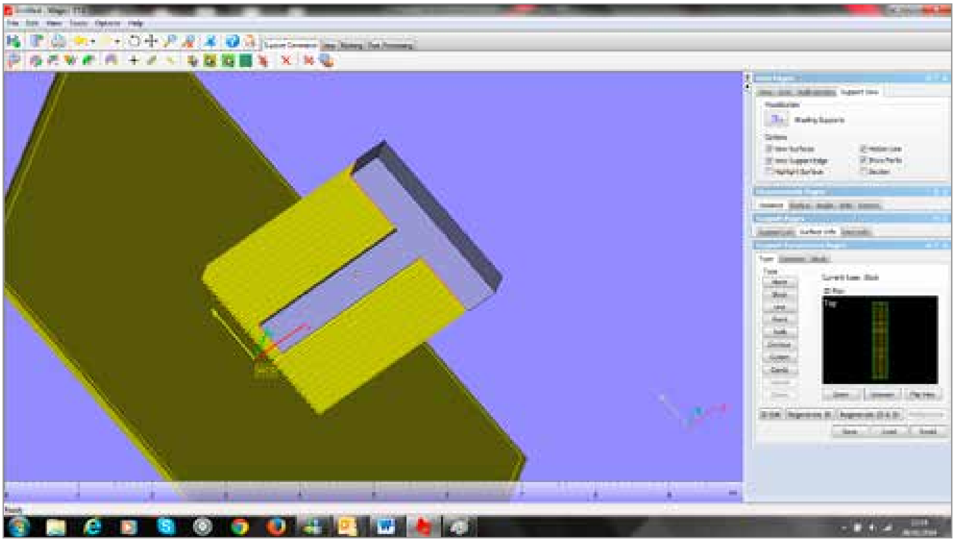

***Figure 13** The supports are automatically created by the software and attached to the highlighted areas of the part and the build plate.*

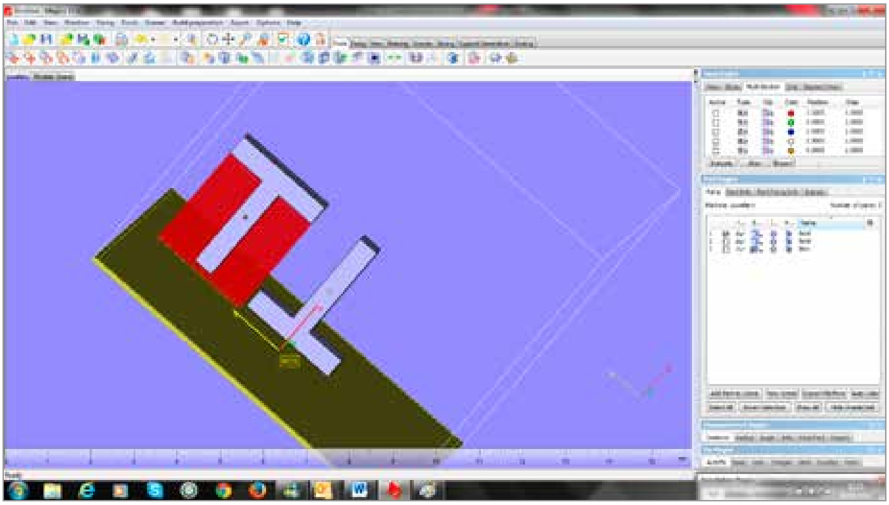

***Figure 14** Are there alternatives? In this example, we created a second model and turned it upside down.*

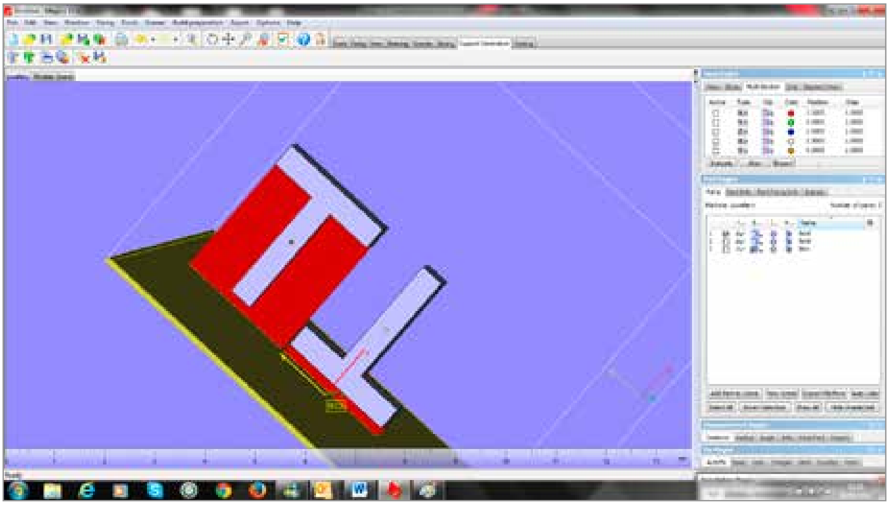

***Figure 15** The software has automatically created the optimum number of supports under the second model, as shown here, and so greatly reduced the quantity and volume of supports required.*

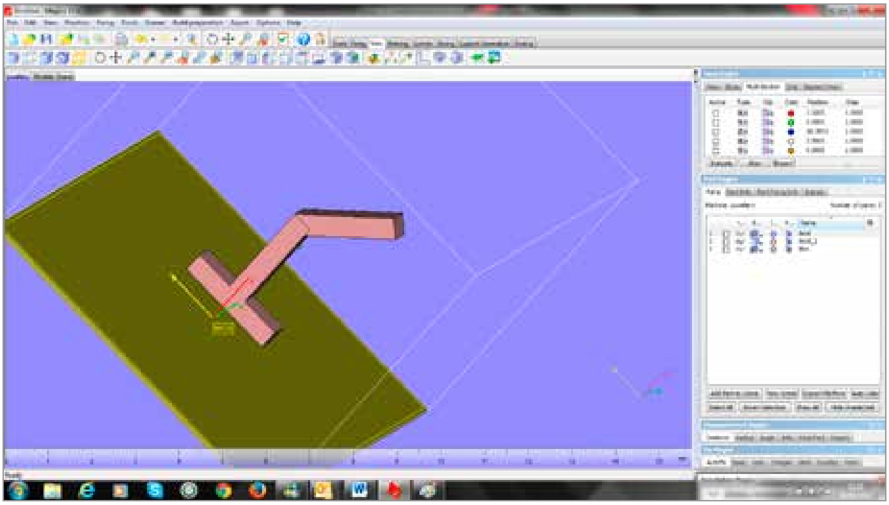

Figure 16 *If an overhanging feature is about 45 degrees or more to the base, it does not require supports. The software automatically identifies this element as self-supporting and does not apply supports to it.*

An important factor to keep in mind when using automatically generated supports placement and deciding on the eventual orientation of the part is the effect the powder refilling screed might have on the part as it passes across the powder bed during the powder replenishment stage of the process. It is very easy for the refilling screed to move or even completely dislodge small features of a part created in the last laser scan on the powder bed if it has not been adequately orientated and supported.

Most DMLM technologies re-coat along the X axis so the machine operator has to consider very carefully the best orientation for the object when laying out parts on the build plate. The example in Figure 17 was designed by School of Jewellery student Lucy Ryalls and built by ES Technology in the U.K. on its Concept Laser Mlab. It is a long, narrow, geometrically complex component made in silver. If a model has many complex features like this example, which also has multiple overhangs, it becomes difficult to identify and pre-assess all the areas where supports might be required.

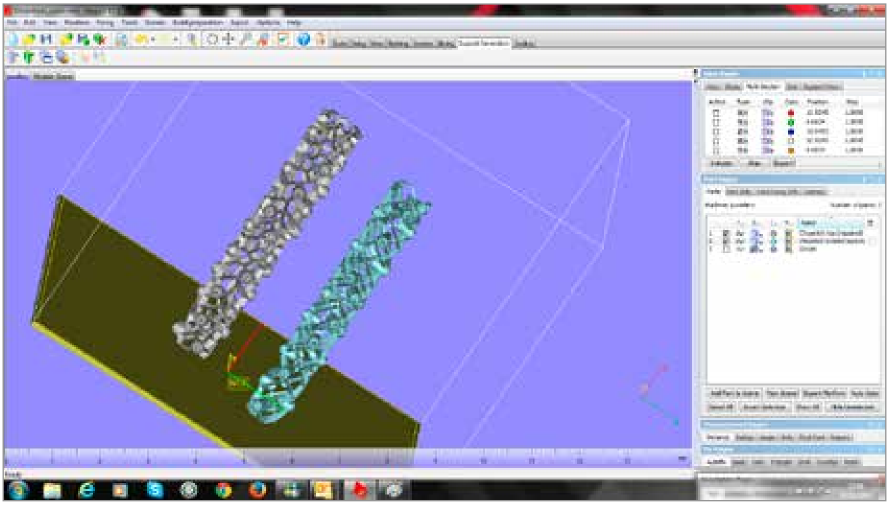

Figure 17 *Example of a long, narrow, geometrically complex component designed by School of Jewellery student Lucy Ryalls*

In Figures 18 and 19, we can see examples of various orientation options that were considered for manufacturing this particular component. The many complex areas potentially requiring support structures are automatically identified by the software. The operator then has the option of working through the file and manually selecting supports considered to be surplus to requirements while still producing a viable build.

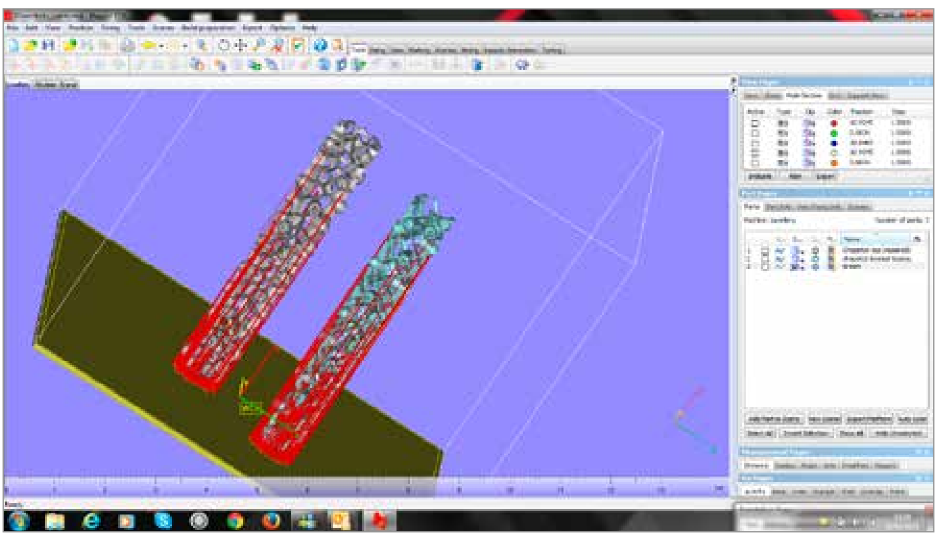

Figure 18 *One orientation option for the component in Figure 17*

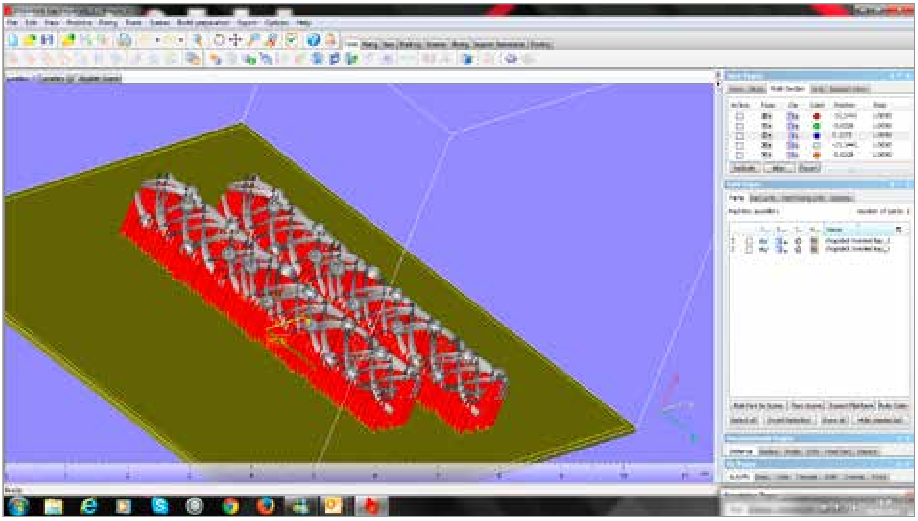

Figure 19 Another orientation option for the component in Figure 17

Choosing to rotate and re-orientate the model will have a considerable impact on the time needed to build the piece. In Figure 19 above, it has been placed horizontally and with its narrowest profile presented to the screed blade. Further refinements were considered that involved moving the pieces by a few degrees from the straight Z axis, but there was insufficient time to complete this part of the research.

Figure 20 shows the finished build in silver, and Figure 21 is the CAD rendering of her project showing variations on the design.

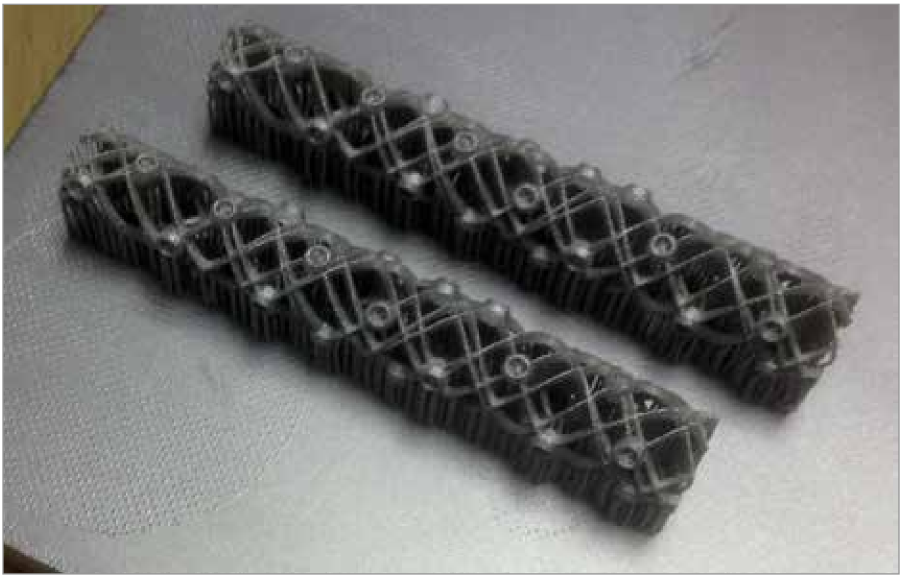

Figure 20 The final chopsticks build in silver from the Concept Mlab.

Figure 21 *Lucy Ryalls' rendered CAD image of her 'Chopsticks' for her DFI AM assignment. Image is courtesy of Lucy Ryalls.*

Practical Examples of Support Structures

Before moving on to a look at future developments and conclusions, let us take a quick look at a couple of practical examples of supports in real-time manufacturing situations. In Figure 22, silver spoons were printed on a Concept Laser Mlab and the supports generated in Magics. The large number of supports fixed to the downward-facing surfaces will require considerable work to remove the witness marks left by these supports. Building the spoons vertically would have significantly reduced the quantity of supports and offered an option to build many more of the spoons but, conversely, would have also hugely increased the build time.

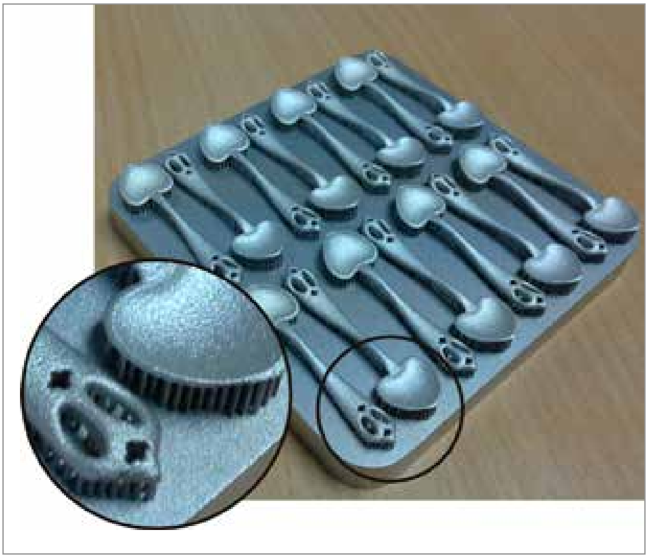

Figure 22 *Building silver spoons arranged face up requires a huge number of supports and subsequent finishing effort. Image is courtesy of ES Technology.*

The silver stone-set rings in Figure 23, again printed on the Concept Laser Mlab, show some experimental support structures generated by the AutoFab software used by Colin Cater of ES Technology. The most significant refinement shown here is how tilting the rings from the vertical has made lower sections of the build self-supporting and aided in reducing the quantity and placement of the supports required.

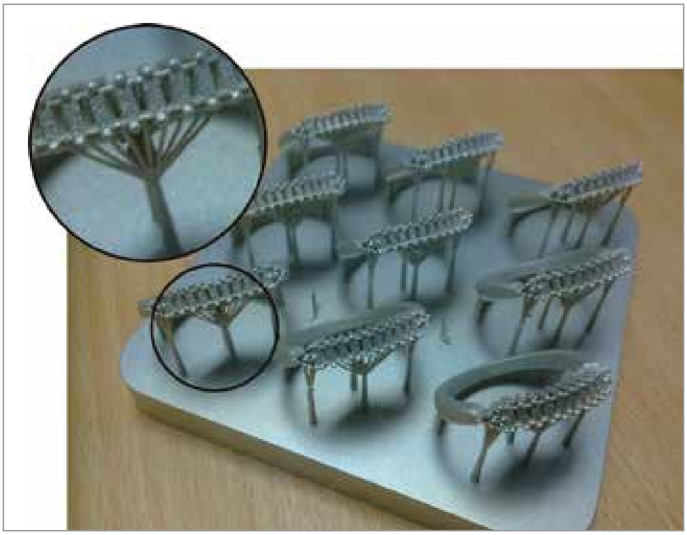

Figure 23 *Tilting the ring allows more of the ring to be self-supporting and reduces the number of supports required. Image is courtesy of ES Technology.*

In Figure 24 we see a practical example of how the Magics module supplied with the Cooksongold M 080 is used by the machine operator to employ two different support strategies, one based on the block option and one that follows the contours of the piece, to create two similarly shaped items to be printed in 18K gold. The Magics software module created for the Cooksongold M 080 is pre-set with the 80mm diameter build base of the machine, and all the necessary laser parameter settings for each alloy as well as support settings are locked down. Thus, the user has no need to experimentally discover the optimum settings required to achieve the desired results.

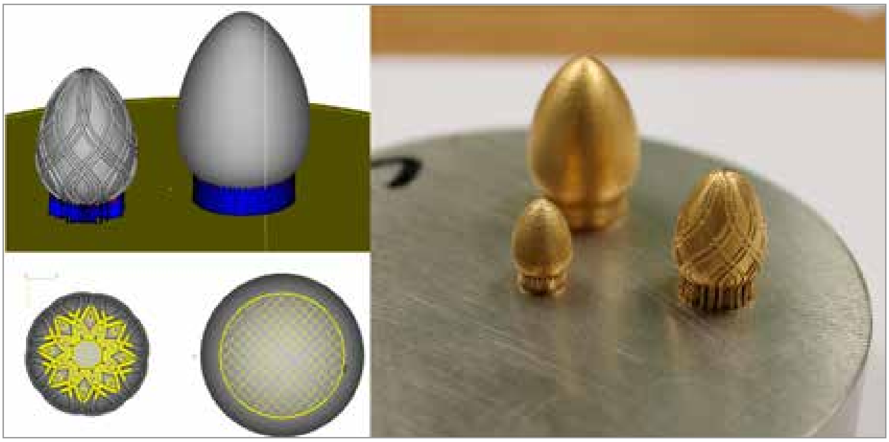

Figure 24 *The yellow lines show the points where the block-type supports generated by the software supplied with the M 080 machine would attach to the part. Image is courtesy of Cooksongold.*

Finally, let us look at a practical example of an 18K yellow-gold watch case that was developed for Hoptroff Watches. The full story behind the design and development process can be found in the Reference section,[13] and a blog about the Hoptroff journey into AM can also be found there.[14] Figure 25 illustrates the software support strategy adopted for this watch case.

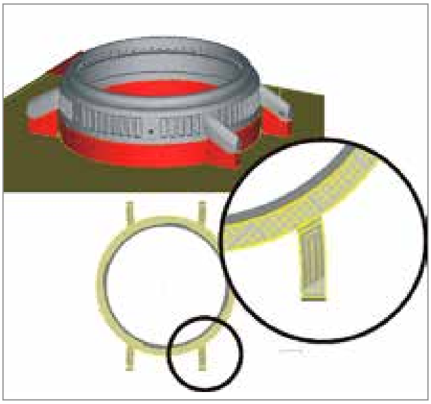

Figure 25 *The yellow lines show where the supports would be connected to the watch case. Image is courtesy of Cooksongold.*

Figure 26 shows the actual build of the Hoptroff watch case in 18K gold and indicates clearly how the support structures are positioned. Figure 27 shows the finished watch.

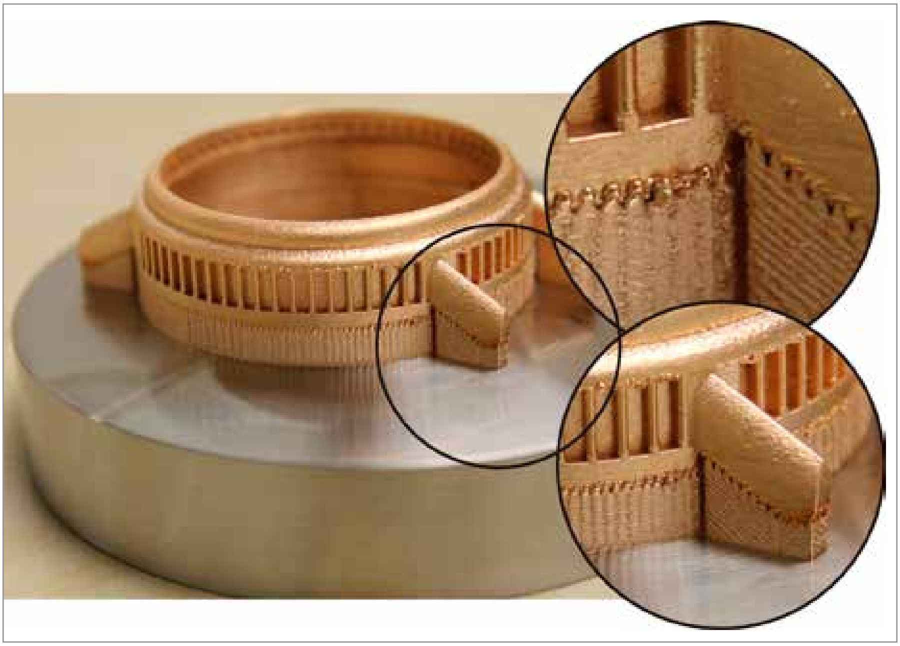

Figure 26 *Detail of the support structure in 18K gold. Image is courtesy of Cooksongold.*

Figure 27 *Here we see the finished, limited-edition watch. Image is courtesy of Hoptroff Ltd.*

Future Software Developments

In an ideal world, removing the need for supports at all would be the optimum solution but as that currently remains as nothing much more than a vague tick on a researcher's wish list, then optimizing and refining what we already understand about the needs and constraints of the powder-based DMLM process can be considered to be a good starting point. If the quantity or angle of overhanging faces can be reduced, then the powder bed can adequately support the part. The required angle is typically accepted to be 30 to 40 degrees from the vertical axis. Therefore, the part's orientation becomes crucial in determining the amount of downward-facing material that will need supporting. However, the opposing forces to these criteria are the part's height and the desired surface finish quality. Being able to use software that can automatically analyze a part with the aim of reducing the amount of support needed to build it is highly desirable as long as the as-built surface finish is not compromised, and the time to build the part does not become uneconomical by selecting an orientation that substantially increases the build height.

Delcam is developing just such a new software (not yet generally available and still in alpha and beta testing) called PartBuilder, which has a simple tools interface designed to suggest the optimum orientation required in order to reduce the area of the part needing support. It has libraries of differing support structures designed for use with specific materials and machines/technologies in order to minimize material consumption and for ease of removal. For example, PartBuilder will add special supports, described as superstructures, to support extreme overhanging features such as the cavity inside a cylinder laid on its side. These superstructures are self-supporting curved members that extend from the build base into the part, providing a base for small supports and thus reducing the amount of clean up where the bottom of the supports would have attached inside the cylinder (as seen in the ring on the upper right of Figure 28). However, the use of superstructures can have a negative trade-off of slightly increasing material usage.

PartBuilder employs, as one of its generational algorithms, a patent-pending technique from Fabbify Software GmbH that automatically generates the supporting fixtures onto the part. The results of this are contact points that are calculated very accurately by the software to identify areas needing support, taking into consideration the specific performance characteristics of the machine and build parameters.

Figure 28 *Examples of the supports created by the Delcam PartBuilder software, with the ring on the top right showing a superstructure. Image is courtesy of Delcam.*

Within the U.K. government Technology Strategy Board-funded project (Precious[15]), a consortium that includes the JICC, Cooksongold, Finishing Techniques and Delcam is working to improve, among other things, the finishing process for AM parts made of precious metals. The project aim is to reduce the hand finishing of AM precious metal parts, which today typically requires 60% hand finishing, to 20% by developing automation and mechanical processes that will do at least 80% of the work.

The removal of the support structure witness marks consumes a significant amount of the time required to achieve the requisite highly polished finish on a DMLM piece. Therefore, using PartBuilder to automatically create the support structures that provide both minimal contact and minimal material usage is intended to play a crucial role in achieving the goal of reducing finishing cost.

Conclusion

In conclusion, it is clear that the current generation of support-generating software is more than adequately able to cope with the process of positioning and generating the support structures necessary for the successful building/printing of complex geometries using DMLM. Software developers are customizing the support strategy for each of the main technology platforms, and they are constantly developing and refining it. The software developers and highly skilled manufactory-based machine operators are working together to develop the best build parameters for each material type in order to provide turnkey systems. The philosophy is to provide end users with a working system so they need not worry about the finer details of how and where to place supports or variations and adjustments to the build parameters.

Acknowledgement

I want to acknowledge the work of Colin Cater and his team at ES Technology, along with the School of Jewellery Design For Industry's cohort of students, on their AM design project and his insights into the various strategies that he and his team considered and tested in order to come up with a number of novel and optimal solutions for the students' work.

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