PRACTICAL ISSUES IN THE APPLICATION OF DIRECT METAL LASER SINTERING

D. M. Jacobson* and G. Bennett*
*Centre for Rapid Design and Manufacture, Buckinghamshire Chilterns University College, High Wycombe, Buckinghamshire, HP11 2JZ, U.K.

Abstract

Direct Metal Laser Sintering (DMLS) was introduced to meet the objective of producing metal parts directly from CAD data. CRDM has accumulated six years of experience in applying this technique, mostly to prototyping parts for evaluation. For some applications, such as blow moulds, porosity generated in DMLS has proved to be beneficial, but for others a concession on tolerances or finish are necessary and/or complementary operations are required, which add to manufacturing time and cost. This paper examines such issues through some well chosen examples of parts to demonstrate both the strengths and weaknesses of the DMLS process.

Introduction

The development of the Direct Metal Layer Sintering technique for producing metal parts with complex geometry directly from CAD data has raised expectations for considerable financial savings and greatly reducing manufacturing times.

There are two essential variants of DMLS, powder bed and powder deposition. In the powder deposition approach, an alloy is melted and deposited layer-by-layer. While the powder deposition route is more amenable to functional grading through the addition of multiple materials to the build, deposition rates tend to be somewhat slow.

In powder bed technologies, a laser or another heat source melts, sinters or bonds a layer of powdered metal; see **Fig. 1**. This approach has the advantages of fast build rates and the ability, within limits, for builds to be self supporting, but it tends to restrict the composition to a single alloy.

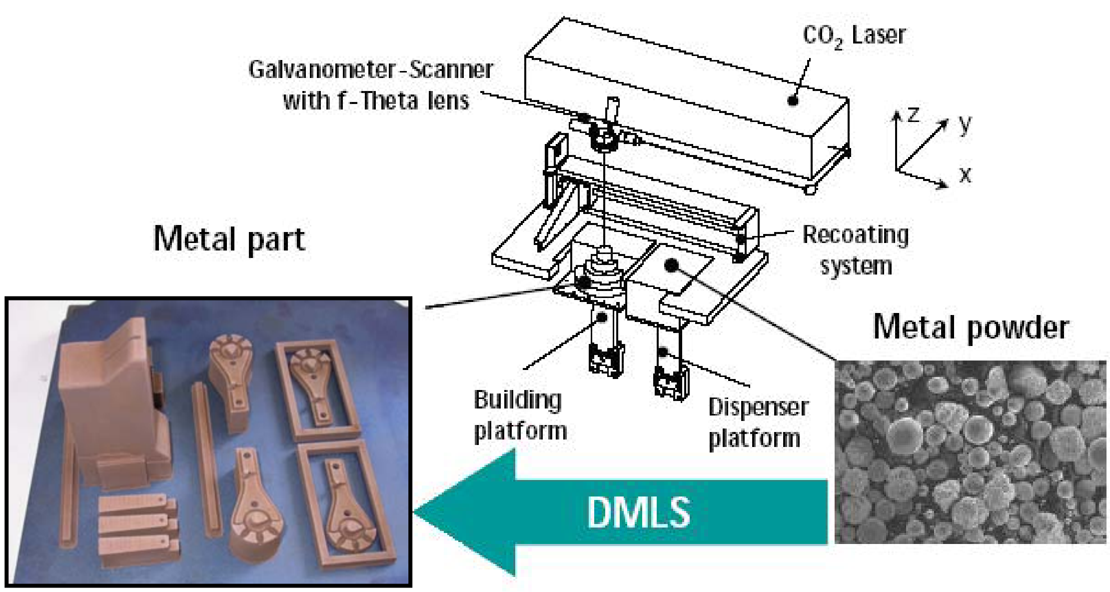

Figure 1: Basic features of the powder bed DMLS process.

CRDM, based at the Buckinghamshire Chilterns University College applies DMLS processing to rapid manufacturing as part of its services to UK industry. It employs a powder bed-based EOSINT M250 Xtended machine for different applications, but focusing on mould tool parts. Builds are generated in 20 μm layers, using a 250 W CO_2 laser to sinter together the layers, which are evenly delivered by the recoating arm. The end result is a component which can be 98% dense and have a reasonable surface finish, with features to a repeatable accuracy of within ±50 μm.

CRDM now routinely produces mould tool parts for industrial clients, such as the set of inserts for an electronic housing for an automotive application, shown in **Fig. 2**. These parts were built in DirectMetal 20 (a fine copper-based "bronze" material suitable for laser sintering in 20 μm layers) on a steel base (the "build platform"). The parts are mounted on offsetting support structures, and also included with the parts are orienting bars and frames to help correctly fix the cutting angle for the EDM wire eroder.

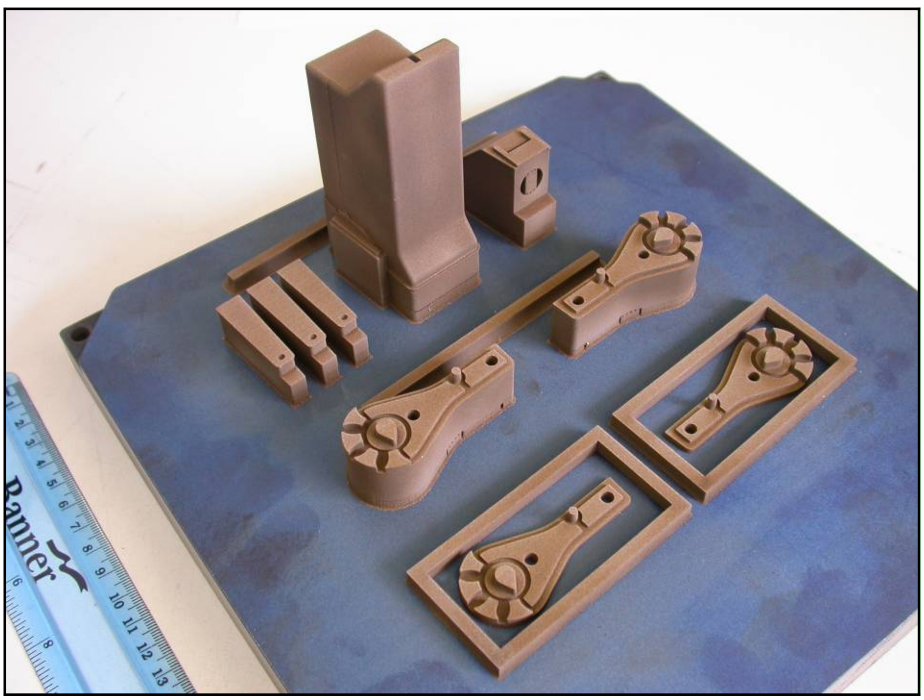

Figure 2: Mould tool inserts for an electronic housing as produced by the powder bed DMLS process in EOS DirectMetal 20, shown on the steel build platform.

EOS has more recently introduced the EOSINT M270 machine, which is equipped with a 200 W Yb-fibre laser which has a variable focus and can finely focus a short wavelength laser beam to a diameter of 100 μm (0.004 in). The use of a short wavelength ensures high absorption of energy into the metal powder, so that build speed is optimised. Recent improvements include a gas-tight working area and full melting of the metal layers for DirectSteel H20 and other new materials developed for EOS DMLS machines, and a progressive reduction of the particle size, currently at 20 μm.

Although the arrival of the DMLS technique has generated considerable interest in manufacturing industry, the take-up of DMLS machines has been slower than might be expected. Most manufacturers of metal parts, including toolmakers, have found that there is insufficient value in rapid tooling to cause them to change from their established manufacturing processes. It has mostly found favour for the production of complex metal parts, which milling and other subtractive methods cannot easily address. Through its growing experience with the DMLS in manufacturing contexts, CRDM appreciates both the advantages and limitations of its EOS machine.

Materials used by CRDM

DirectMetal (see above) builds parts relatively quickly and is favoured for producing tool parts, such as those shown above, for that very reason. With the introduction of the finer DirectMetal 20 powder, surface finish has been greatly improved, but it may still be necessary to carry out additional machining operations (CNC or EDM) to achieve finely contoured detail. DirectMetal mould tools are considerably weaker than those of machined tool steel so that pressure from plastic fill in injection moulding operations can burst the mould tool. Therefore they are often reinforced either using buttressing or steel collars on mould cavity blocks. Another means of reinforcement is to include part of the steel baseplate with the mould tool. **Fig. 3** shows a mould insert ready for wire erosion around it, perpendicular to the baseplate. The frame around the inserts shown on the left have been added to fix the two directions mutually perpendicular to the EDM cutting direction.

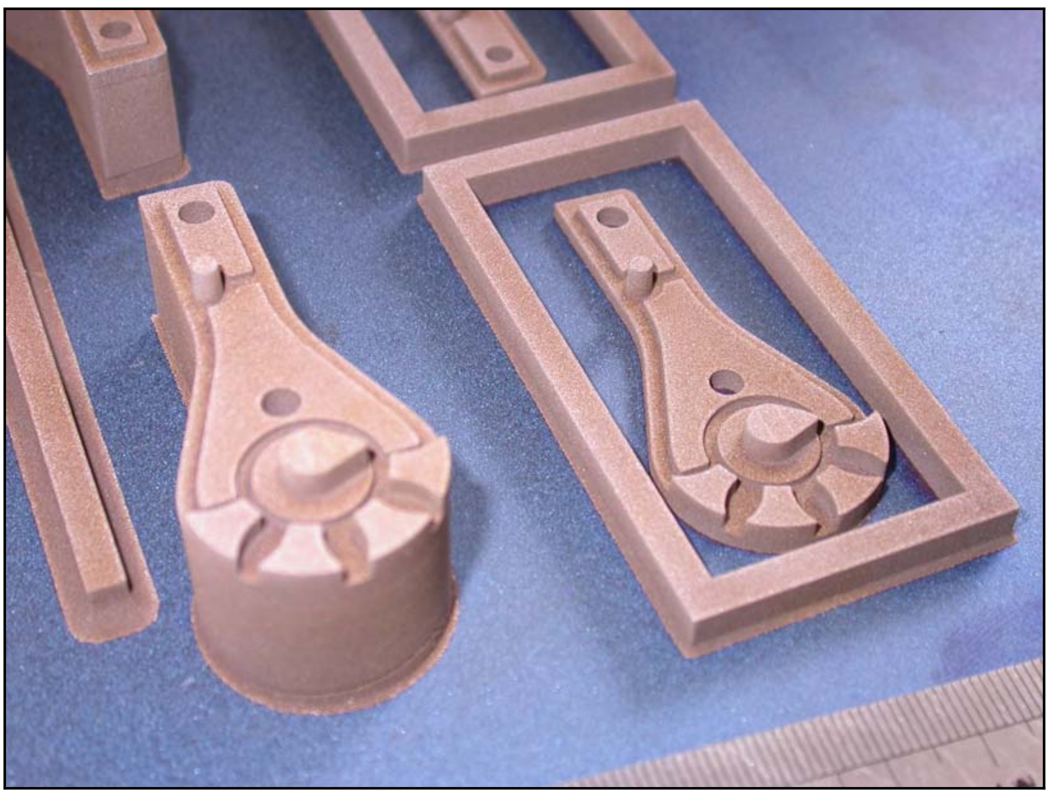

Figure 3: Close-up view of mould tool inserts shown in Figure 2. Those parts on the right were to be machined by EDM to leave a backing of the steel build platform for mechanical reinforcement.

DirectMetal tools also suffer from significantly higher wear rates during service life in injection moulding than those made of tool steel. It may be possible to reduce wear by chemically treating the tools to change the composition close to surfaces so as to harden them, but this has not been tried. The present limitations of DirectMetal 20 restrict its use in mould tools to small production runs (typically < 10,000 parts).

DirectSteel 20 is a fine grained mixture of iron (> 70%), nickel and copper-phosphorus powders, capable of producing parts with fine detail and superior mechanical properties than DirectMetal 20. Thus, the tensile strength of laser sintered parts in DirectSteel 20 can be up to 600 MPa, as compared with 400 MPa for DirectMetal, Young's Modulus is 130 GPa (80 GPa for DirectMetal) and hardness is 225 HV (115 HV for DirectMetal). In consequence, parts of DirectSteel 20 used for moulds are more durable. However, there is also a downside. Parts in DirectSteel are slower to build, because the powder needs to be heated to a higher temperature and to do so, the laser scan speed needs to be reduced by up to 50%, depending on the scan strategy used. They have a higher surface roughness and more finishing work is required to achieve smooth surfaces. Moreover, parts built in DirectSteel 20 are more highly stressed, which results in a more pronounced bimetallic bow of the built parts on the building platform. This also reduces options with regard to support structures, which need to be sufficiently strong to avoid premature failure. In particular, it has been found that the tooth-like support structures that can be used for DirectMetal parts tend not to be sufficiently strong to suit builds in DirectSteel.

Problems and limitations of EOS DMLS Systems

Size of parts is limited by that of the powder bed in the machine, i.e. 250 x 250 x 180 mm, and this limits the size of parts that can be built.

Stress that develops between the steel plate (that constitutes the building platform) and the DMLS part results in a development of a bow in the part. If the part is subsequently stress relieved on the steel platform so as to straighten the base, a bow will develop towards the upper surface of the latter that tends to be significant for large parts. Therefore, stress relief of the built part has to be avoided in order not to generate geometrical distortion, but then the strength of the part is compromised.

Because the part is built up from powder, there is an inevitable degree of surface roughness (typically between 4.5 and 6.3 Ra, or 33 to 36 VDI for 20 μm layer builds in DirectMetal) – different on vertical and horizontal surfaces. A set cosmetic finish can be achieved with additional machining, including EDMing. It may also be possible to modify the as-sintered surface roughness by chemical treatment, but this has not been tried in a systematic fashion.

The sintering process will also result in a degree of porosity, which can be controlled and largely removed by using a finer powder and by raising the power of the laser so as to increase the proportion of the powder that melts, up to complete melting. Porosity is often detrimental, as for example in water-cooled parts, because the porosity can generate leakage paths. A "core" build strategy to create a porous bulk of material is generally used for DirectSteel and DirectMetal in order to speed up building, and only the surface regions are made fully dense by a "skin" build strategy, that essentially involves total melting of the outer layer. "Core" build rates are typically 4 mm^3/s to produce a 98.5% density, whereas "skin" build involving full melting to give 100% density is at only half that rate.

As with many RP machines, the EOS machine makes little use of feedback to provide accurate monitoring and controlling of the build process during operation. In earlier models of the machines, builds have failed for no apparent reason, which the lack of appropriate feedback has made difficult to resolve. For example, many types of error could occur during the building process but go unregistered and hence no corrective steps are taken by the machine; such errors include short-fill recoatings, etc. We believe that if EOS machines came equipped with more comprehensive feedback, most users would be willing to pay more for the machine, especially as, in most operations lead-times are critical. For example, 3 days lost in project which has to be delivered in 2 weeks is usually unrecoverable. EOS claims that customers are sensitive to additional costs, although an EOS M270 unit is priced in the region of $500,000. However, it has been noticed that, with each new model, EOS DMLS machines are becoming progressively more reliable.

Build quality and machine performance is critically dependant on the operation of the recoater arm. The motion of the recoater arm can result in non-uniform distribution of the metal powder and distorted parts being built. Care has to be taken to ensure that the long edge of the recoater arm is not parallel to any long edges of the parts being built. If such alignment does occur, the arm can 'bump' over the edge which causes a vibration in the build volume and, due to the high density of the metal powder, this can lead to powder settlement which prevents even recoating on subsequent sweeps. The solution to this problem has been to build the parts such that there is always an angle of more than 5^o between any long edge and the recoater arm. If this cannot be done, supporting skis or slopping edges can be used to try to reduce the 'bump' effect. Structures on either side of the part can also be useful in preventing the recoater arm from knocking it over during build, especially if it has a small footprint. Newer machines have sturdier recoater arms and also an inbuilt flow feed to minimise dead areas, which have reduced problems arising from that source.

Geometrical precision obtainable for parts built using the EOS metal DMLS process is ± 50 microns, in addition to which there is a cumulative scaling error towards the corners of the build volume.

Advantages of the EOS DMLS Process

The EOS DMLS process has all of the normal advantages of a rapid prototyping process in so far as very little machine set-up time is needed, sharp internal corners and difficult geometric features are easy to produce, machine minding is minimal and parts are made to a high degree of accuracy.

CRDM has found the EOS DMLS system especially effective for building tooling inserts for small parts (< 25 x 25 x 25 mm^3) with complex geometries, i.e. parts which would normally require extensive milling and electro-discharge machining to produce. Builds can be accomplished within a working day, compared with several days for conventional machining.

Porosity can be advantageous for some applications, e.g. blow moulding tools where the porosity permits evolved gases to escape. CRDM frequently designs a measure of porosity into its tools in order to reduce injection mould cycle times and injection pressures Porosity can also be useful for the manufacture of tools with no ejection, where compressed air is used to 'blow' the part off the tool. This reduces tool manufacturing time and also production cycle times.

An example from CRDM's activities is an animal face mask mould tool, where it was necessary to avoid the use of ejector pins, because they would have produced protrusions and edges that would have interfered with the fitting of the mask; see **Figs. 4** to **6**. The injection moulded face masks, produced in a thermoplastic elastomer, were blown off the mould tool by blowing compressed air through the mould tool, and this approach avoided the need for ejector pins and resulted in entirely smooth items.

Figure 4: DMLS Injection mould tool with animal facemask in thermoplastic elastomer.

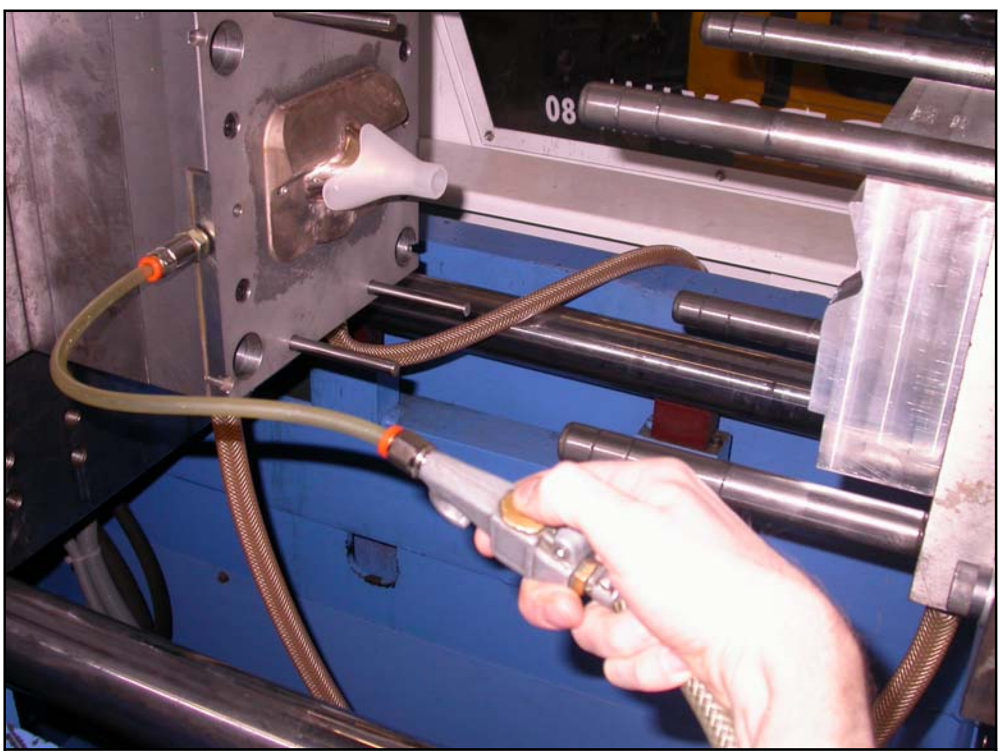

Figure 5: Moulded animal facemask being blown off the DMLS tool by compressed air blown through the porous tool.

Figure 6: Injection moulded animal facemask separated from the tooling.

Enhancements achieved at CRDM

CRDM has been exploring ways of reducing build times by, for example, producing tools with metal inserts in place. Support strategies for parts being built are recognised as often critical in achieving built parts and with regard to economics of the operation. It is often found advantageous to redesign the part, so long as this does not impact on its functionality, to best accommodate the DMLS process. An example where it has been possible to considerably reduce support structures is a waveguide, illustrated in this presentation. In this case, a bulky and complex series of support structures was obviated by simplifying the exterior stepped profile of the waveguide horn by a 45° conical profile which was capable of being self supporting during build in a powder-bed DMLS operation. **Fig. 7** shows the original design provided by the customer, while **Fig. 8** is the 3D CAD drawing showing the same part encased with the necessary concentric support structures for building in a powder bed DMLS system. **Fig. 9** shows the external profile modification which enabled most of the support structures to be dispensed with, without detrimentally affecting functionality of the part. **Fig. 10** shows a suitably redesigned waveguide part.

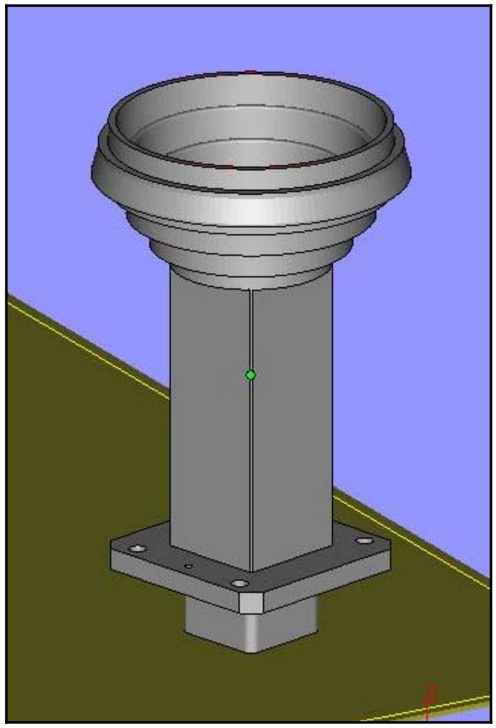

Figure 7: 3D CAD design of original waveguide part provided by the customer.

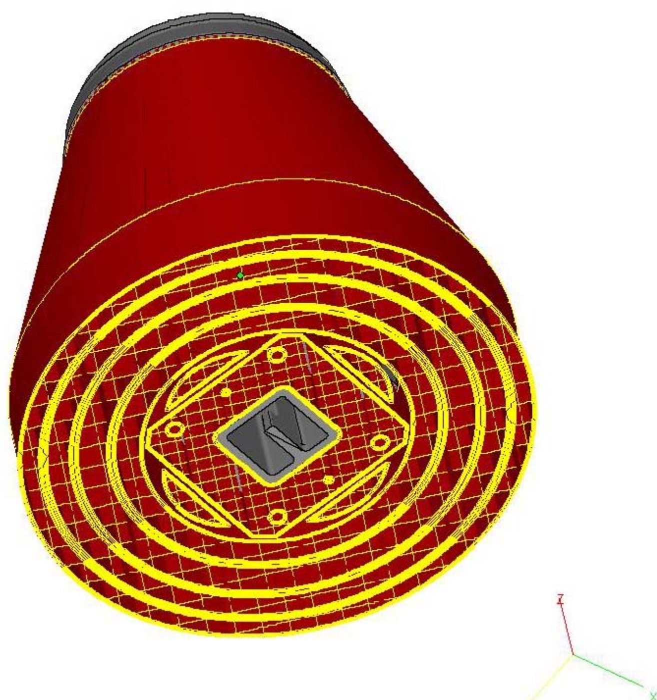

Figure 8: 3D CAD drawing of the part and enclosing support structures that would have been required to build the waveguide part, as originally designed.

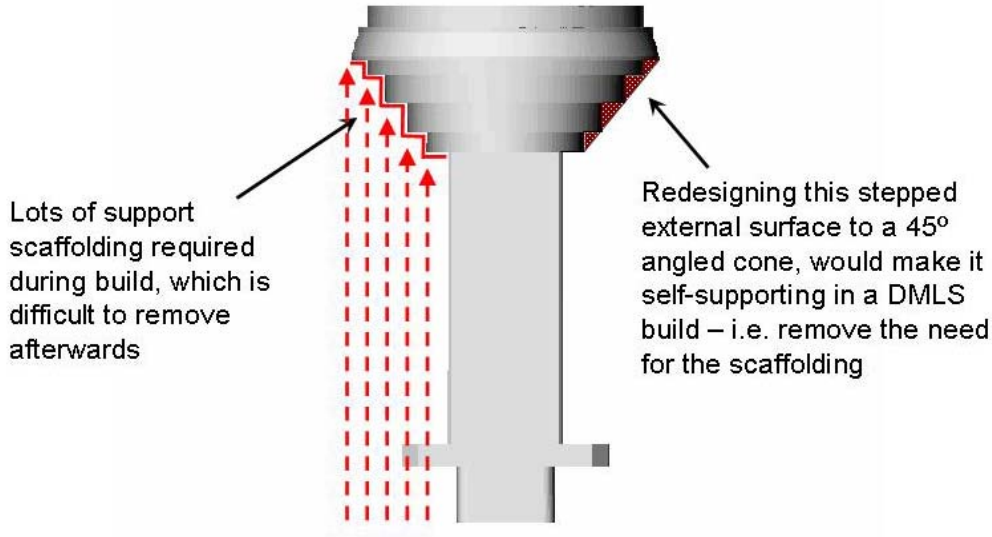

Figure 9: Drawing of the waveguide part showing the modification to the external surface of the horn which enabled most of the support structures shown in Figure 9 to be dispensed with.

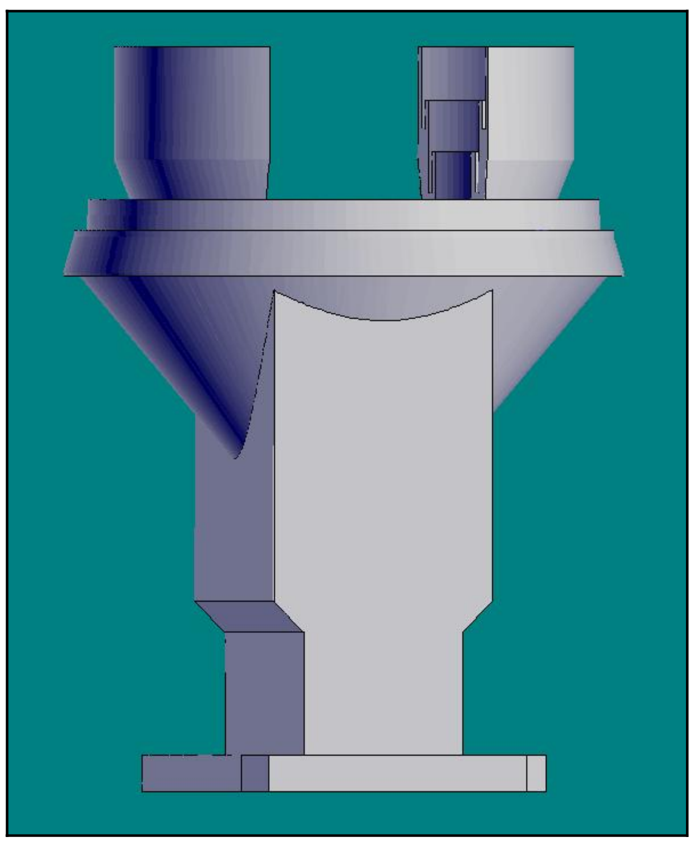

Figure10: A redesigned waveguide component to suit production in a powder bed DMLS system, without compromising its functionality.

As a further example, we shall briefly describe extrusion blow mould (EBM) tooling for a motorbike oil reservoir. In this particular tooling application, high density polytethylene is melted and extruded into a hollow tube (a parison). This parison is then captured by closing it into the cooled metal mould. Air is then blown into the parison, inflating it into the shape of the hollow container. After the moulded plastic has cooled sufficiently, the mould is opened and the polyethylene part is ejected, at the end of the process cycle.

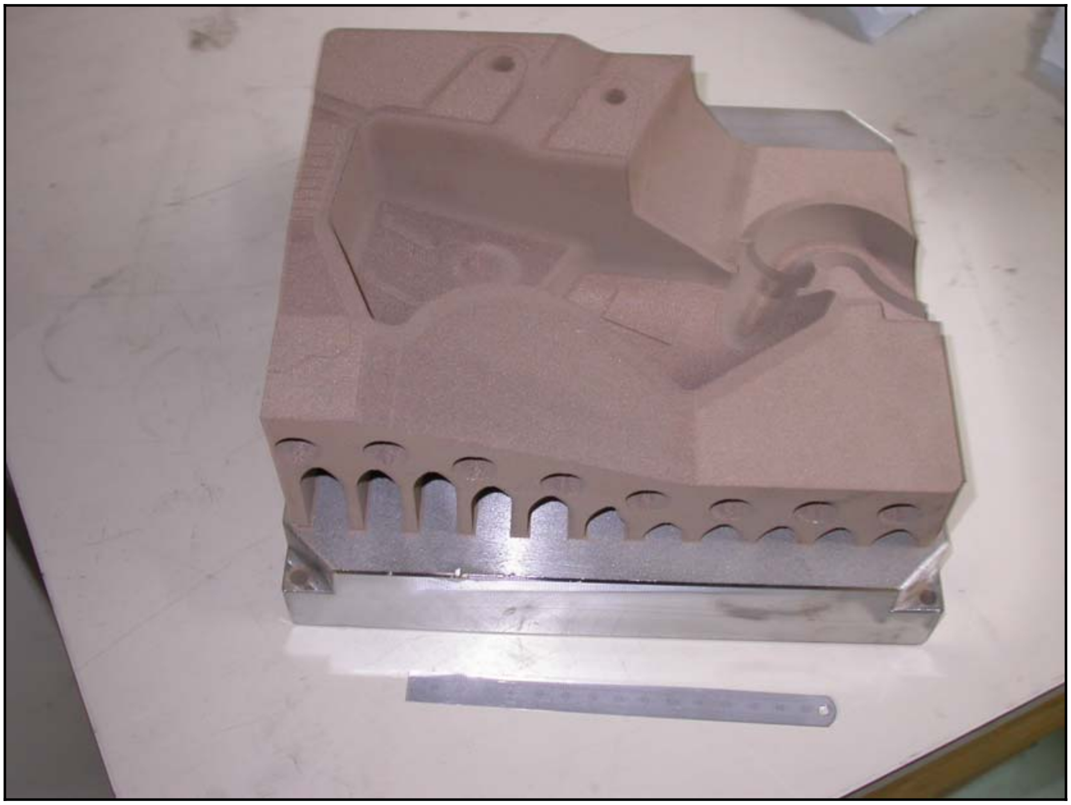

Figure 11: DMLS blow moulding tool part in DirectMetal 20, with buttressing to reduce tool weight and manufacturing time. Above the buttressing can be seen the openings to the incorporated cooling channels.

DMLS offered a number of important advantages for producing the blow mould tooling for this application. It was relatively easy to incorporate buttressing around the mould cavity to reduce tool weight and manufacturing time; see **Fig. 11**.

Similarly internal water cooling channels could be included at hardly any additional cost or manufacturing complexity; see **Figs. 11** to **13**. As with the previous tool, creating porous tool parts – which was readily achievable by DMLS – offered the advantage of facilitating the moulding operation. In this case air caught between the blown polyethylene part and the wall of the mould tooling could escape through the connected porosity. In the case of conventional machined tooling, the cavity surfaces have to be roughened in order to provide escape paths for the trapped air, and this involves additional work.

As mentioned earlier, the motion of the recoater arm can result in non-uniform distribution of the metal powder and distorted parts being built. The solution that has been successfully applied at CRDM is to build the part at an angle to the recoater arm.

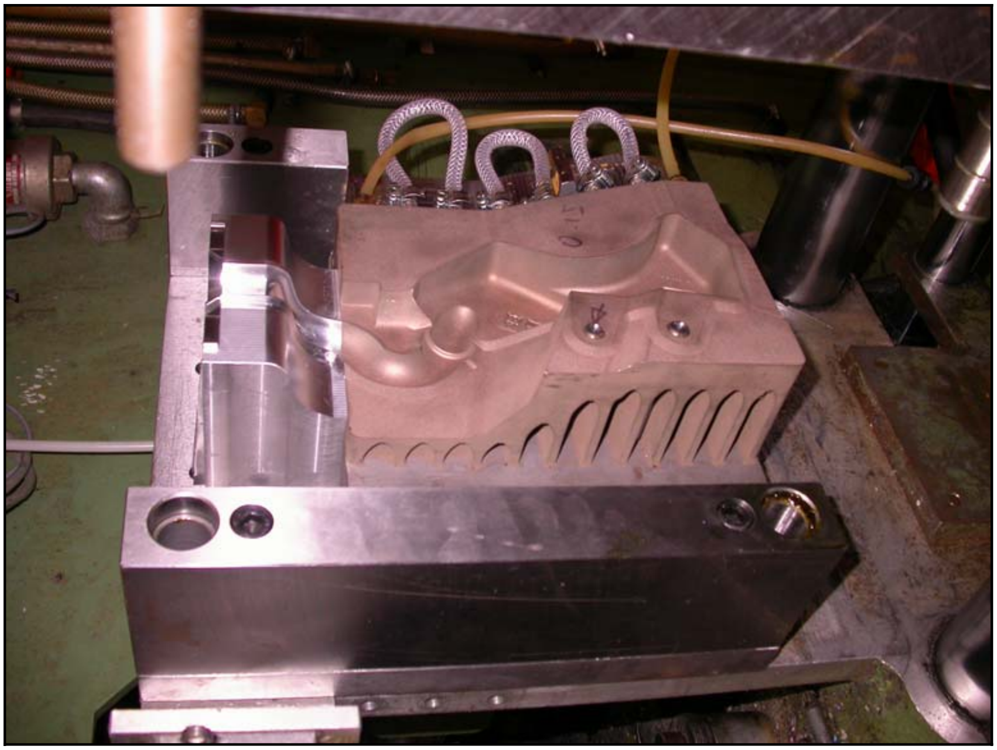

Figure 12: Mounted DMLS blow moulding tool part with water connections in place

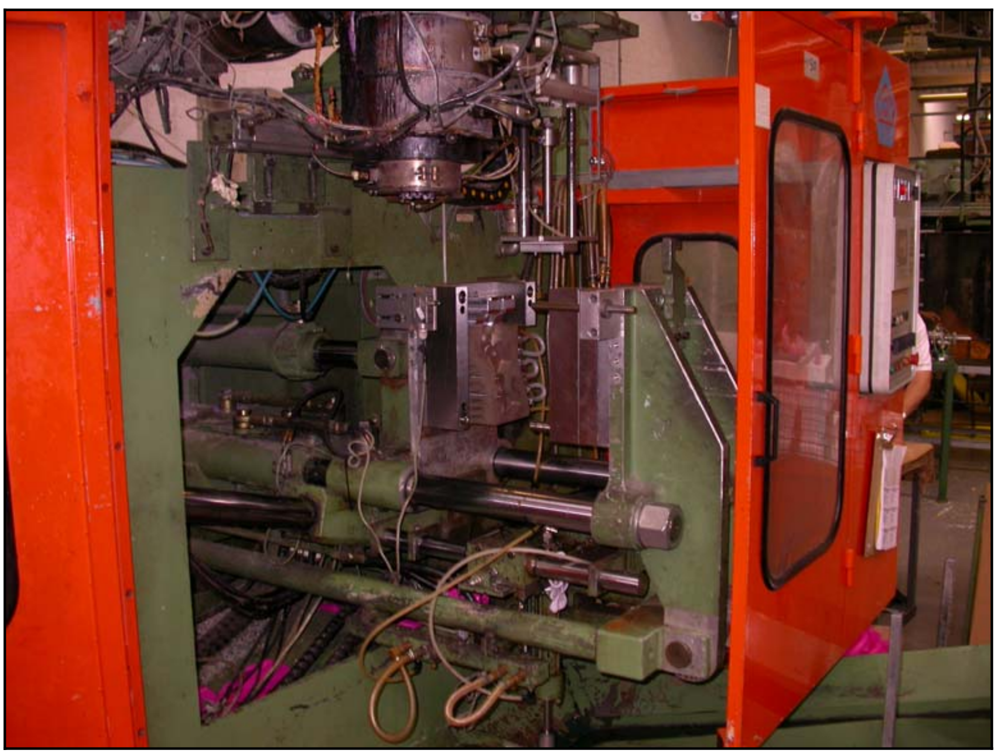

Figure 13: DMLS mould tool part in place in the blow moulding machine

Smoothness of surfaces remains a limitation, even after applying “skin” scanning strategies. Post-process polishing can be used, including vibro-finishing, involving a hybrid mechanical-chemical process. Media (chips), compounds, water and components are set in relative movement. However, this process is only suitable for large numbers of parts. It adds cost (typically $25k for the equipment) as well as additional time and cost for carrying out the polishing operation. A superior finish can be achieved, but this process is much slower than shot peening. Also, it is necessary to optimise chips and media for each job, which again is time consuming and costly. Shot peening is widely used at CRDM because it is cheap and quick. Parts are built with projecting lips along edges and corners so as to offset the rounding of these features by shot peening, as shown in **Fig. 14**.

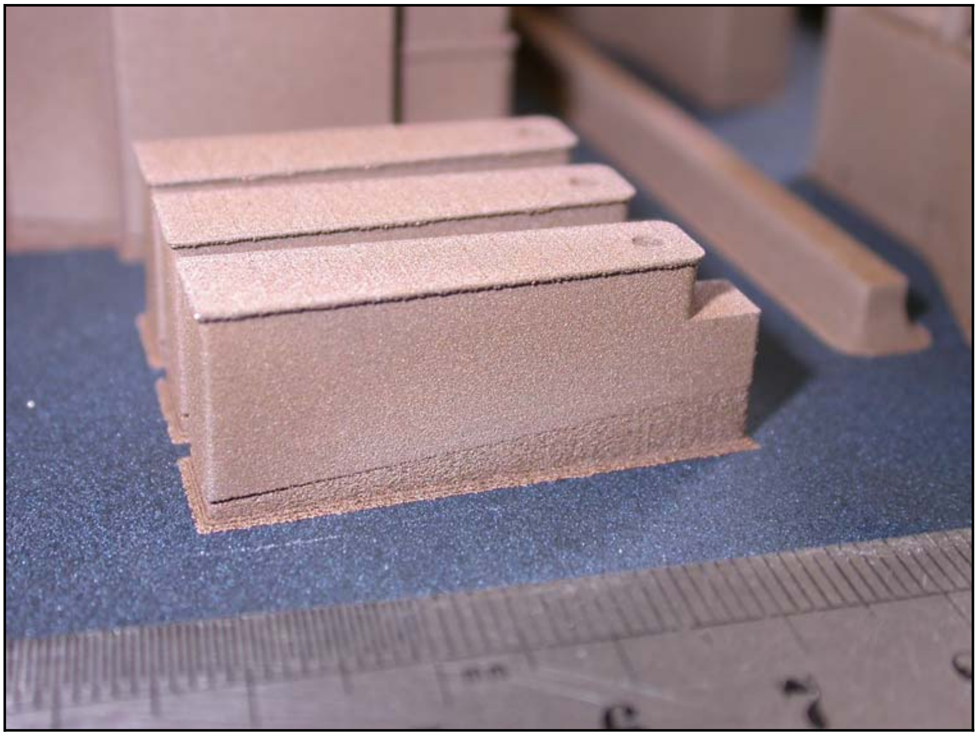

Figure 14: Mould tool inserts with projecting lips along edges and corners so as to offset the rounding of these features by shot peening.

Conclusions

Experience at CRDM in using the powder bed DMLS process for rapid tooling has demonstrated the considerable versatility of this technique. It is proving cost effective in a commercial environment, as customers appreciate the benefits that it offers – reduced lead times on orders for tools, the ability to dynamically iterate designs and also exploit special features of DMLS parts, from porosity to the ready incorporation of embedded elements, in particular cooling channels. In order to gain the most out of this powerful additive manufacturing technique, users must be discerning and critical of the claims of the equipment manufacturers and to show creativity in redesigning parts to better suit the application of the technique, without detriment to their functional requirements. On the other hand, when the capabilities of DMLS are properly appreciated and mastered, new manufacturing opportunities can be grasped and used to greatly reduce production lead times and enhance profitability.

***Acknowledgements*:** Peter Holland and Gary Wise of CRDM are thanked for sharing their considerable experience of the DMLS process with the authors.