Applications of AM

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Chapter 6
Applications of AM

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6.1 AM in Tool Making Application

Application of AM in toolmaking can be historically considered as a second wave of AM application (so-called Rapid Tooling). Although AM processes are mainly considered as a process for final production, their potential can be used for making tools for conventional production processes (e.g. injection moulding of polymers). Processes of design and production of complex tools such as moulds for injection moulding of polymers are typically the bottlenecks in development and production process of final products and strongly influence their time-to-market.

One of the trends at the market is shifting from mass to custom production which requires more flexibility in tool production processes. Therefore, the main objectives of AM in toolmaking application is to reduce lead-time required to make the tools, as well as to improve the efficiency of the tools (shortening the production cycle time and improvement of parts produced in the tools).

At the end of 20th and in the beginning of twenty-first century there was a lot of excitement about AM application for toolmaking, but requirements for the tools for serial or mass production (e.g. for injection moulding) and AM possibilities are not in accordance. AM in toolmaking applications is exposed to very strict demands because of common processing parameters for such tools (e.g. pressures, temperatures, impact loads, abrasion, etc.) which must be wear resistant, with very narrow dimensional tolerances and with high surface quality.

Injection mould inserts have to fulfil combination of three main requirements:

- strength ≥ 500 N/mm^2

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- dimensional accuracy ≥ 0.01 mm
- surface roughness (R_a) ≥ 1 µm.

At the moment, the mentioned requirements (especially the last two ones) have not been achieved on the market of the AM equipment and materials. However, all the companies in the field are continuously trying to meet these requirements. This refers especially to the speed of the manufacturing, precision of dimensions and forms, and the number of materials that can be processed by AM technologies. Also, the properties of usable materials are being continuously improved, contributing to the improved properties of final products. In this way, the differences between traditional procedures of mould production and alternative AM technologies are expected to be reduced in the future.

AM application for toolmaking can be realised in three ways:

- production of *short-run tools* (mainly polymer (soft) tools)—10–100 shots
- production of *bridge tools*—up to several 1.000 shots
- production of *hard tools*—up to several 100.000 shots.

In case of short-run tools, only a few moulded parts can be produced within such tools before moulds are worn or damaged. Example of this type of tools is silicone mould (Fig. 6.1). The main advantage of this tooling approach is that such tools can be produced within one day, the process is very simple and the costs are relatively small.

A small-batch production of a hundred to a few thousand parts can be run with so called bridge moulds (Fig. 6.2). Final number of produced moulded parts depends on applied materials (paper, metal, polymers, etc.). Bridge moulds can also be produced in relatively short time (from one day to few days), which also depends on applied materials and additive technologies. Bridge tools for injection moulding are not intended to be replacement for soft or hard tools used in mid- and high volume production. Instead, they are intended to fill the gap between soft and hard moulds as well as a substitute for 3D printed prototypes.

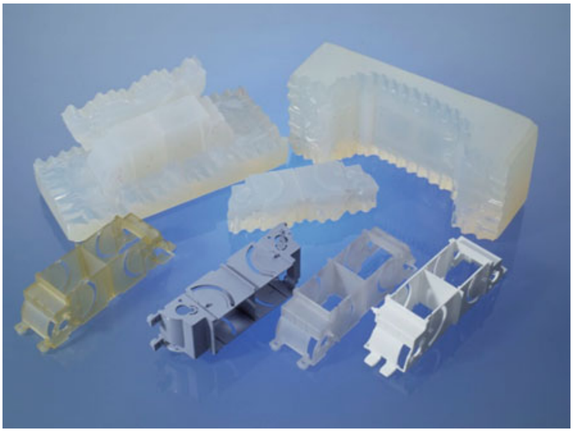


Fig. 6.1 An example of AM silicone mould: left—original 3D printed part, top—4-piece silicone mould, bottom—3 mouldings in different materials (www.scott-Am.com, Courtesy of Ronald Simmonds, photographer Giulio Coscia)

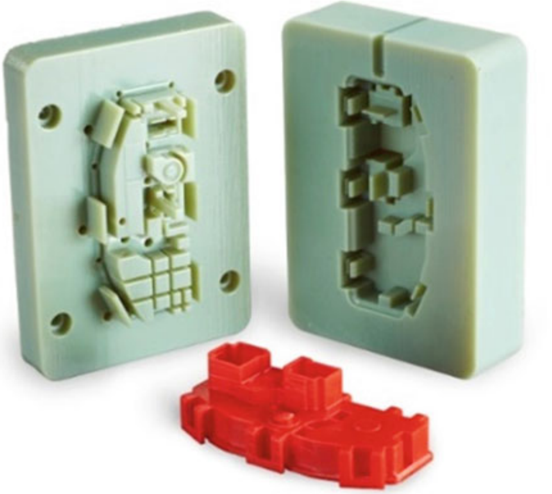


Fig. 6.2 An example of AM PolyJet (bridge) mould (Courtesy of Stratasys)

Finally, with *hard moulds* (Fig. 6.3) it is possible to produce up to a few hundred thousand moulded parts. Their durability is similar to the conventional moulds. They require much more time and expenses for production, compared to the soft and bridge moulds.

Figure 6.4 shows relations of moulds produced with *PolyJet* technology and moulds produced with classic technologies from common mould materials and AM technologies for production of metal bridge/hard moulds. It has to be stressed that A and B processed materials (e.g. unreinforced polyolefines) are far less aggressive, and C and D groups are more aggressive materials regarding mould cavity wall wearing (e.g. reinforced polymers).

Fig. 6.3 An examle of AM hard mould (Courtesy of SIRRIS)

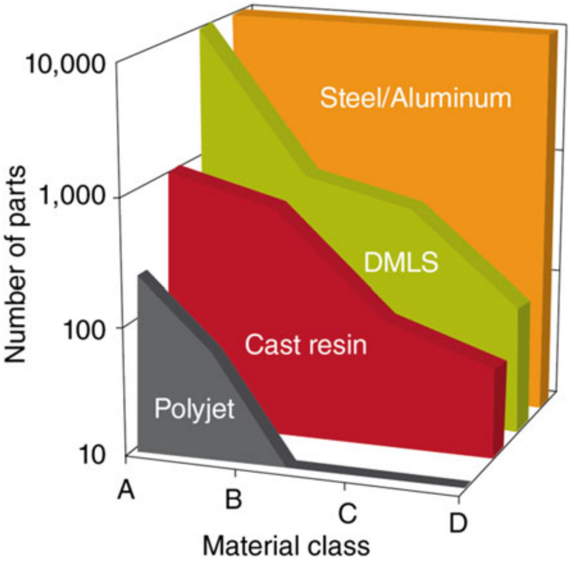


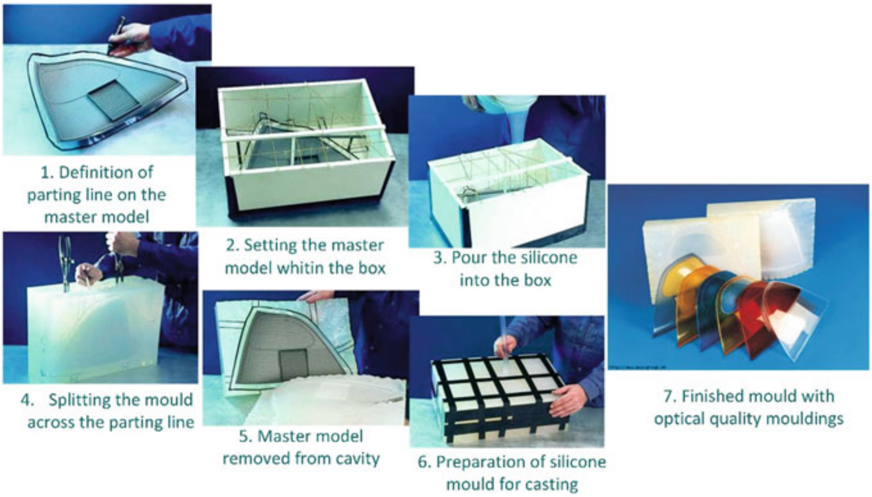
Fig. 6.4 Anticipated number of produced parts depending on the type of the mould and material class (Courtesy of Stratasys)

6.1.1 AM Silicone Short-Run Moulds

Silicone short-run moulds can be considered as AM moulds when master models (patterns) are produced with one of the AM technologies. Generally, the process consists of three main steps: master model making (AM), master model preparation for casting (definition of mould parting plane, definition of mould runner system, etc.) and silicone casting around master model for production one- or two-piece moulds. After the silicone casting and curing, silicone block is removed from the frame, master model is removed from the mould cavity and the mould is prepared for casting materials such are ABS, polyurethanes or polyamides into the mould cavity (Fig. 6.5) (Fig. 6.6).

In case of two-piece silicone mould (Fig. 6.7), two-step process is applied. In first step, lower half of the box is filled with modelling clay and silicone is poured into the upper half of the box creating the first half of the mould. After silicone curing, the box is rotated 180°, the clay is removed from the box, parting plain is coated with separation agent and the process is repeated to create the second half of the mould.

In case of the production of more complex mould geometry, within a silicone mould, different metallic or polymeric inserts can be used. Those inserts can be a good replacement for thinner silicone mould parts, and they can prolong mould durability.



1. Definition of parting line on the master model

2. Setting the master model whitin the box

3. Pour the silicone into the box

4. Splitting the mould across the parting line

5. Master model removed from cavity

6. Preparation of silicone mould for casting

7. Finished mould with optical quality mouldings

Fig. 6.5 Production process of one-piece silicone mould (www.scott-Am.com, Courtesy of Ronald Simmonds, photographer Giulio Coscia)

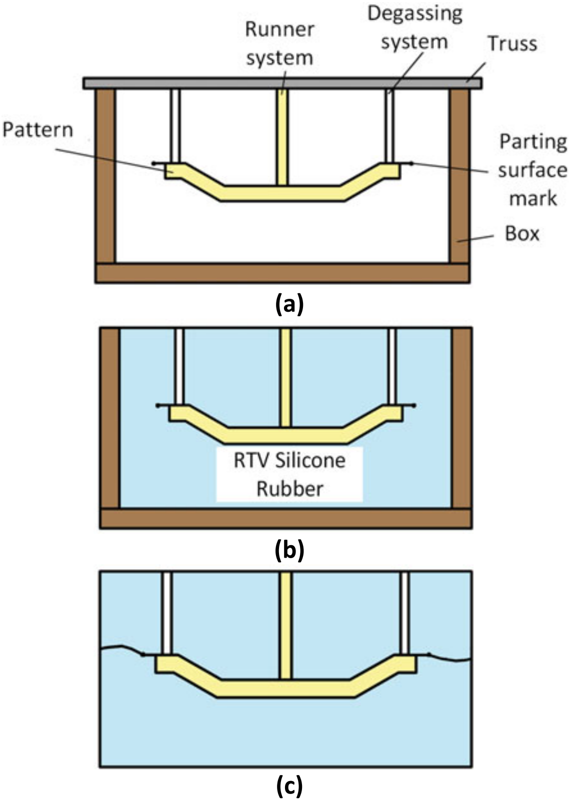


Fig. 6.6 Production process of one-piece silicone mould: **a** setting the master model, runner systems and degassing system, **b** pouring the silicon into the box, **c** finished silicone mould (Courtesy of Andreas Gebhardt)

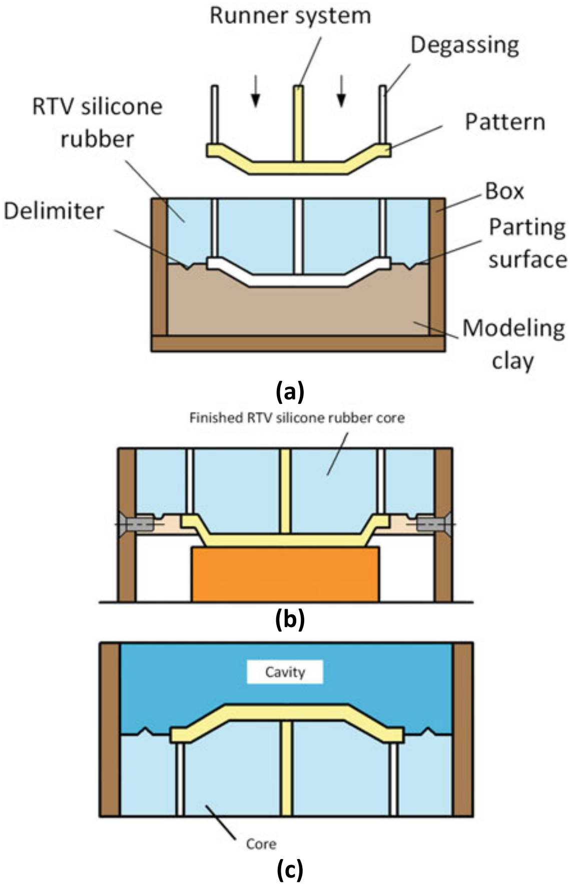


Fig. 6.7 Production process of two-piece silicone mould: **a** setting the master model, runner systems and modelling clay system, **b** ouring the silicon into the box (core production), **c** box rotation, pouring silicone into the box (cavity production)—finish (Courtesy of Andreas Gebhardt)

6.1.2 AM PolyJet Bridge Moulds

PolyJet and *PolyJet Matrix* processes enable application of more than hundred different materials based on acrylic resins, which can mimic the properties range of the materials from elastic to rigid. For manufacturing bridge moulds, mould materials have to be strong enough (tensile, flexural, compressive and bending strength), tough, and resistant to high temperatures in order to maintain mould cavity dimensions. Four materials can be selected as the most appropriate for the *PolyJet* bridge mould manufacturing: *RGD 525* (white high-temperature material), *RGD 5160-DM*, *RGD 5161-DM* and *Digital ABS plus* (ABS-like green materials). Table 6.1 shows some basic mechanical and thermal properties of those materials.

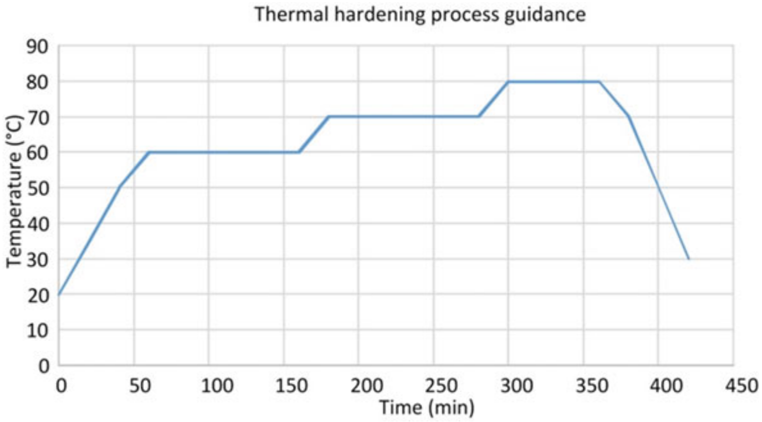


Fig. 6.8 Process of ABS-like mould insert hardening (Courtesy of Stratasys)

Table 6.1 Properties of PolyJet materials suitable for mould production

Property/(unit)	RGD 525	RGD 5160-DM RGD 5161-DM	Digital ABS plus
Tensile strength/(MPa)	70–80	55–60	55–60
Tensile modulus/(MPa)	3200–3500	2600–3000	2600–3000
Flexural strength/(MPa)	110–130	65–75	65–75
Flexural modulus/(MPa)	3100–3500	1700–2200	1700–2200
Izod impact strength/(J/m)	14–16	65–80	90–115
Heat deflection temperature/(°C)	63–67	58–68	58–68
Heat deflection temperature (after hardening)/(°C)	75–80	92–95	92–95

Material RGD 525 is the strongest material, but its toughness is 5–7 times lower compared to the other materials. RGD-5160-DM material is suitable for production of details with wall thickness down to 1.5 mm, while RGD-5161-DM for wall thickness down to 1.0 mm. If high impact resistance and shock absorption are requested, Digital ABS plus is the most appropriate. By hardening process in furnace (), heat deflection temperature can be increased for all materials up to 30%. Increasing the heat deflection temperature is very important for mould inserts for injection moulding, where mould material is heated in cycles as hot polymer melt fills the mould cavity (Fig. 6.8).

6.2 Design Rules for Bridge PolyJet Moulds

In design of bridge *PolyJet* moulds it is possible to apply basic guidelines for design of classic moulds for injection moulding. Nevertheless, because of specific properties *of PolyJet* materials for production of bridge moulds, it is necessary to make some modifications in design concept. This is necessary because of compensation of mechanical, thermal and dimensional characteristics of such plastic moulds. Some of the basic rules for design of *PolyJet* bridge moulds are:

- increase the draft angles for easier moulded part ejection (Fig. 6.9),

- add minimal radius at all sharp edges,
- in case of inserting 3D printed mould into classic mould base, add at least 0.2 mm in height at back face to enable better mould closing and avoiding of flush (Fig. 6.10),

- add minimal radius at all sharp edges,
- in 3D printing of core pin, height/width aspect ratio of 3:1 is recommended (for larger aspect ratios it is recommended to use exchangeable metallic pins),
- for making holes, minimal diameter is 0.8 mm,
- classic side, film, tab and ring gates are recommended in mould gate design (avoid tunnel and pin gates) (Fig. 6.11),

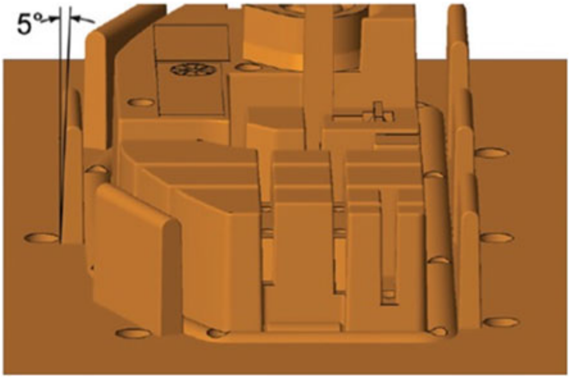


Fig. 6.9 Increased draft angles (Courtesy of Stratasys)

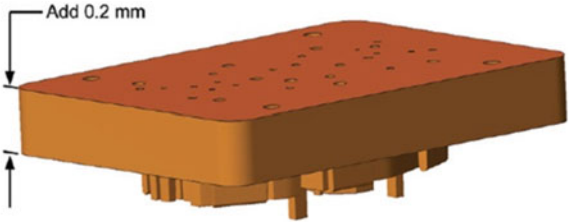


Fig. 6.10 Extension of the back face of the core/cavity (Courtesy of Stratasys)

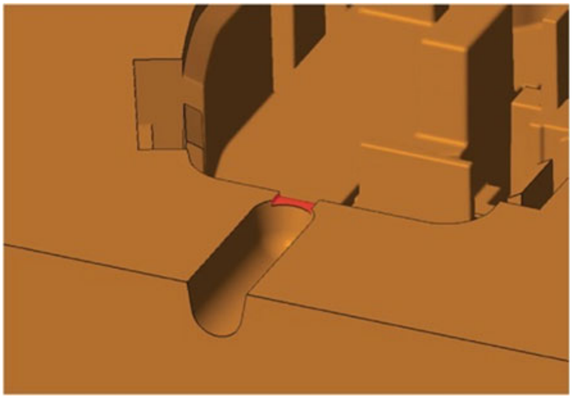


Fig. 6.11 Typical bridge mould side gate (Courtesy of Stratasys)

- gate dimensions have to be 2–3 times larger than gate dimensions in classic steel moulds,
- gate thickness has to be equal or larger than maximal moulded part wall thickness,
- metallic sprue has to be built in the plastic mould, in order to avoid direct contact of the plastic mould with hot injection moulding machine nozzle,
- classic ejector pins that are not placed on distance smaller than 3 mm from mould cavity edge have to be built in (otherwise, the mould can be damaged) (Fig. 6.12),

- decrease the ejector holes diameters by 0.2–0.3 mm and adjust them while mounting the ejector in the mould insert with classic machining,
- complex mould cavity geometry has to be split into multiple mould inserts (Fig. 6.13), in order to achieve appropriate mould cavity venting through tolerances in inserts contact,

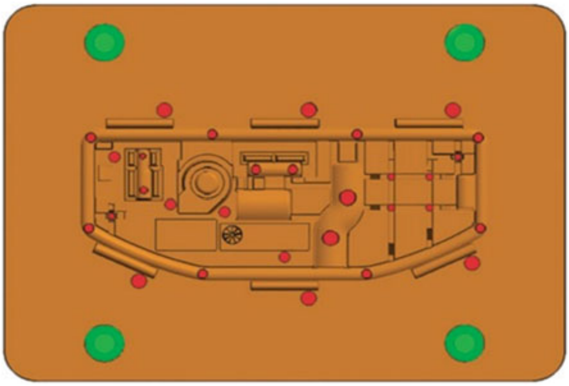


Fig. 6.12 Moulded part ejection system (Courtesy of Stratasys)

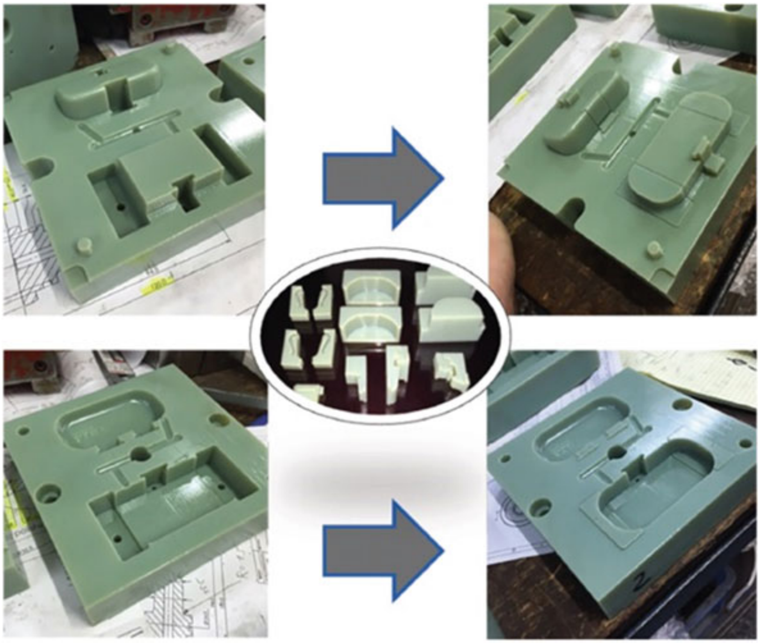


Fig. 6.13 Multiply mould inserts (Courtesy of Stratasys)

- although, because of the poor thermal conductivity of *PolyJet* materials classic mould tempering by cooling channels and water as a coolant is not efficient, it can contribute to prolongation of mould durability (expected up to 20%) (Fig. 6.14),
- more effective cooling is by blowing of compressed air on mould parting plane,

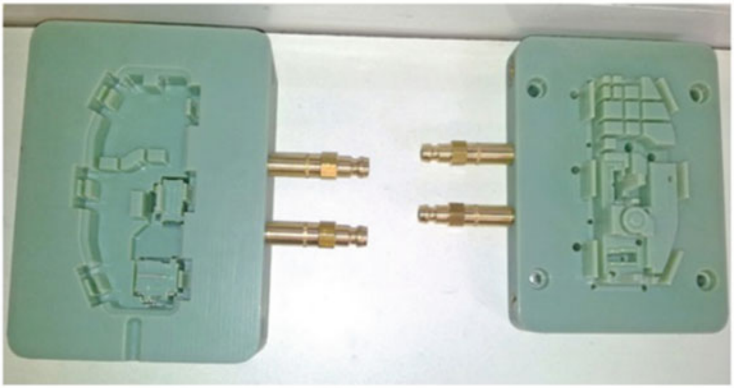


Fig. 6.14 Cooling channels plugs (Courtesy of Stratasys)

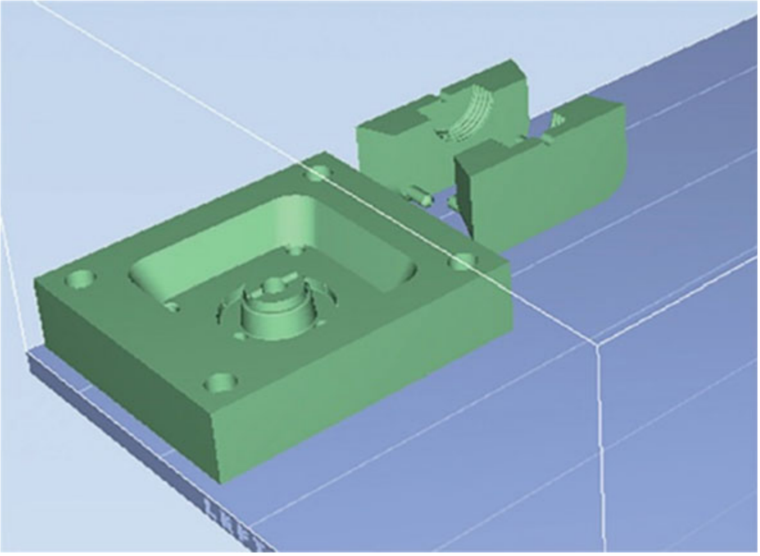


Fig. 6.15 Orientation for glossy surface without support material (Courtesy of Stratasys)

- while preparing for 3D printing, mould insert should be oriented so that mould cavity is up-oriented (glossy surface without support material), which will result in smoother mould cavity surface (Fig. 6.15),
- mould insert should be oriented on building platform with larger dimension in line of printing head moving direction (print lines) because in such orientation the material is better cured—it is exposed to the UV light longer (Fig. 6.16).

In application of bridge *PolyJet* mould inserts, several approaches of embedding in standard mould bases or their independent application are possible. In case of smaller injection moulded parts it is possible to independently use *PolyJet* bridge moulds. Depending on the usage of manual or mechanical injection moulding machine (Fig. 6.17), it is necessary to adjust *PolyJet* moulds dimensions correspondingly.

When *PolyJet* moulds are used on mechanical injection moulding machines, it is necessary to adjust mould dimensions to the injection moulding machine clamping plates and tie bars, as well as to the rest of the mould base. Also, it is necessary to enlarge the thickness of mould plates, compared to the moulds aimed to operate with manual injection moulding machines, in order to avoid creation of cracks on the mould plates (Fig. 6.18).

In case of production of large amount of moulded parts on larger injection moulding machines, *PolyJet* mould inserts have to be embedded into a steel mould base (Fig. 6.19).

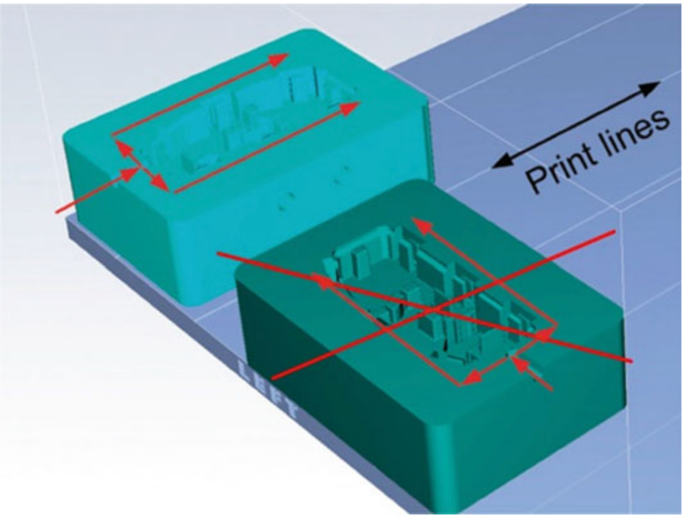
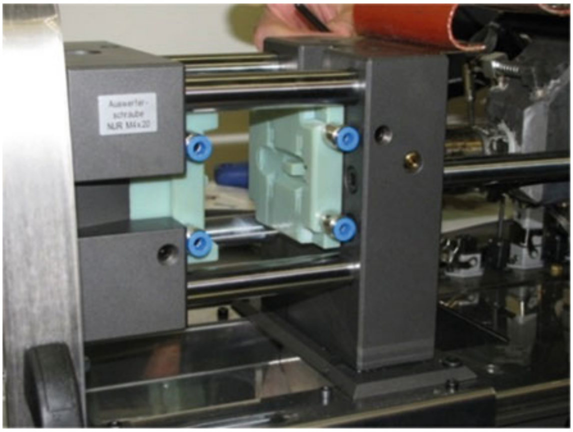


Fig. 6.16 Orientation along printing line (Courtesy of Stratasys)

Fig. 6.17 Bridge mould on injection moulding machine (Photo by Damir Godec)



6.2.1 AM (Steel) Hard Moulds

For a long-run tooling, AM hard moulds/tools are required. AM hard moulds are mainly made through direct AM processes such as PBF-LB/M (e.g. SLM) and DED. The primary concerns when making AM mould inserts for long-run tooling are surface roughness, dimensional accuracy and wear. Most of AM processes can provide only partial solutions to those requirements mainly because of higher surface roughness and lower dimensional accuracy than it is required for mould inserts.

Two different strategies can be applied in order to achieve required mould insert properties. First is application of common AM systems for production near-net shape

Fig. 6.18 PolyJet mould plate with cracks (Photo by Damir Godec)

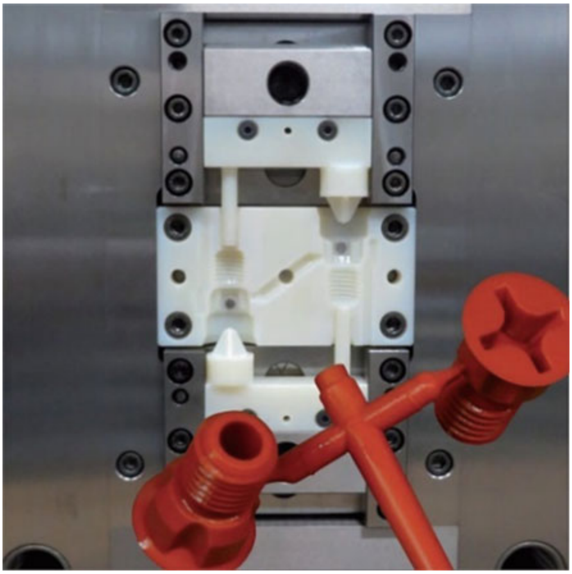


Fig. 6.19 PolyJet mould inserts embedded into steel mould block (Courtesy of Stratasys)

inserts. Achievable surface roughness of near-net shape inserts is in R_a range 12–20 μm, and with dimensional tolerances in range ±0.1 mm, which is not acceptable for the most tooling applications. Therefore, additional subtractive operations have to be applied (e.g. shot peening, milling etc.)

Second approach is application of hybrid technology which combines both AM and subtractive technologies in one machine. The example is Laser Deposition Welding (AM-DED) and milling (subtractive process) (Fig. 6.20), or PBF-LB/M (SLM) with High Speed Cutting (Fig. 6.21) presents differences in mould insert surface roughness after PBF-LB/M phase and after CNC HSC machining (Fig. 6.22).

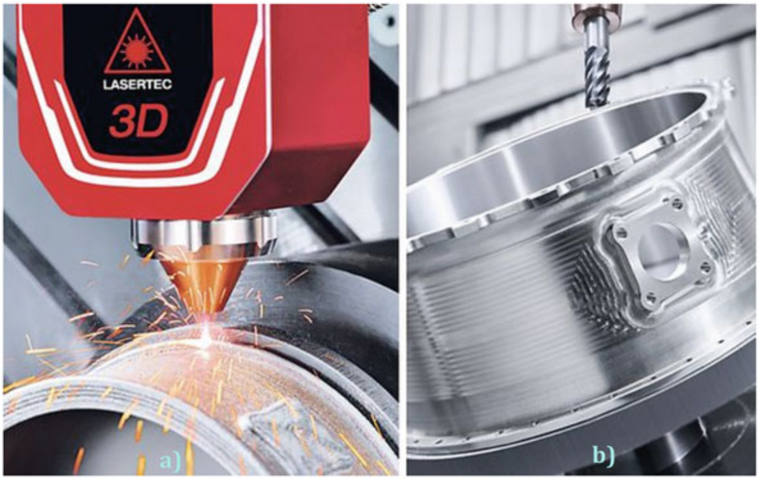


Fig. 6.20 Hybrid manufacturing process: **a** Laser Deposition Welding (DED), **b** milling (Courtesy of DMG MORI)

Fig. 6.21 Hybrid manufacturing process—PBF-LB/M (SLM) & HSC (Courtesy of Matsuura)

Because of the need for additional processing with CNC in order to achieve required dimensional accuracy and surface roughness (in both scenarios), during mould insert design phases it is necessary to predict excess material in critical areas of AM mould insert. It is also advisable to design a fixture points to AM mould

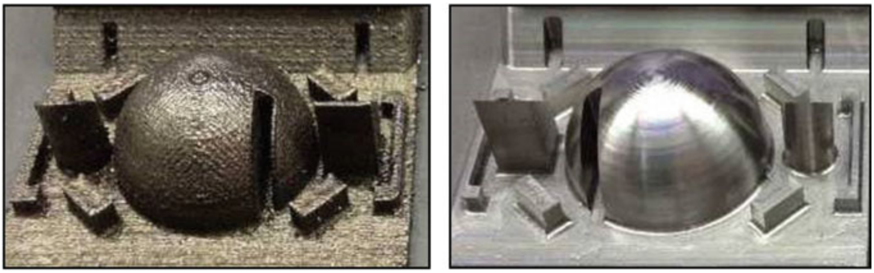


Fig. 6.22 AM mould insert—after PBF-LB/M process (left) and after HSC machining (right) (Courtesy of Matsuura)

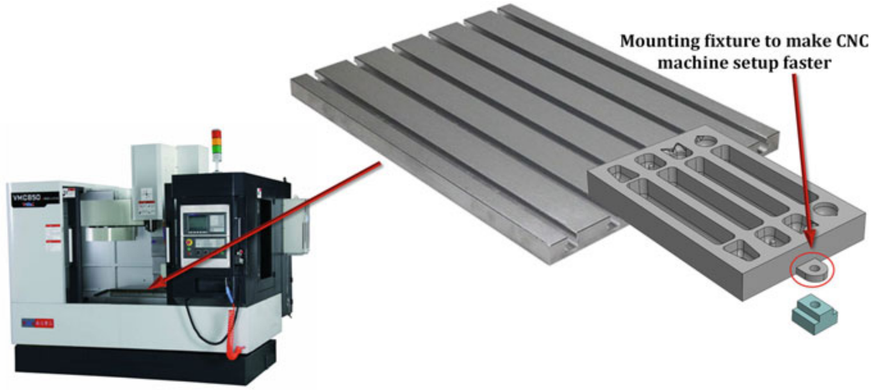


Fig. 6.23 Additional fixtures on AM mould inserts (Courtesy of Olaf Diegel)

inserts for easier mount of AM mould insert on CNC machine bed (Fig. 6.23) for the finishing operation.

A range of AM tool steel powders are available for the production of AM hard moulds/tools:

- Maraging 300
- Tool Steel H13
- Stainless Steel CX
- Stainless Steel 316L
- Stainless Steel 15-5PH
- Stainless Steel 17-4PH.

Maraging 300 alloy steel is a very high strength iron base, molybdenum, cobalt and nickel alloy with excellent properties, workability and heat treatment characteristics. This kind of steel is characterized by having excellent strength combined with high toughness. The parts are easily machinable after the building process and can be easily post-hardened to more than 50 HRC. They also have excellent polishability. Maraging alloy provides a high value for critical parts in aerospace, structural, component and tooling applications.

Tool Steel H13 works excellent at high temperature and can withstand drastic cooling rates. These properties, together with abrasion resistance and machinability, makes it ideal for high-temperature tooling and wearing resistant parts, like mould inserts.

StainlessSteel CX is a tooling grade steel with a good corrosion resistance combined with high strength and hardness. This material is intended for injection moulding tools and tool parts and other industrial applications where high strength and hardness are required. Parts built of StainlessSteel CX can be machined, shot-peened and polished in as-built or heat-treated status.

Austenitic stainless steel 316L, with high strength and corrosion resistance, can be reduced to low temperature in a wide range of temperatures. It is applied in various engineering applications such as aerospace and petrochemical, as well as toolmaking, food processing and medical treatment.

Martensitic stainless steel 15-5PH, also known as Martensitic aging (precipitated hardening) stainless steel, has high strength, good toughness and corrosion resistance, is a further hardening of the ferrite-free steel. At present, it is widely used in aerospace, petrochemical, chemical, food processing, paper and metal processing industries.

Martensitic stainless steel 17–4 PH still has high strength and high toughness under 315 °C, and strong corrosion resistance and can bring excellent ductility as the laser machining state.

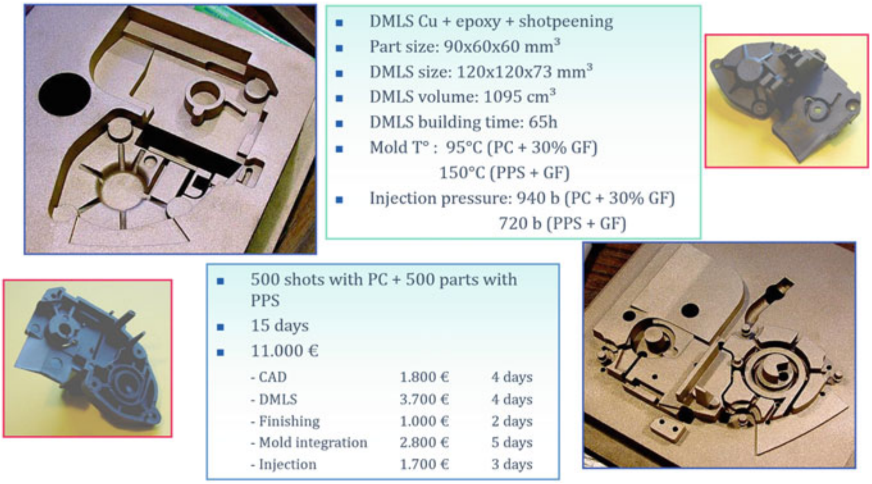
Main advantages of AM application for tooling can be summarized as:

- production of mould inserts with complex geometry in shorter time
- production of mould inserts with improved efficiency (conformal cooling/multi-material).

Generally, AM allows production of very complex geometries with very low cost or without increase of the costs for production. In case of conventional mould/tool production, complex mould insert geometry is very often split into a few simpler mould inserts, which means longer production times as well as more potential problems with multiple tolerances. In case of AM, very complex mould insert geometry can be produced from one piece and thus in shorter time. Figure 6.24 presents a project of production of complex mould with DMLS technology. The whole project of mould design, production and injection moulding was realised within 15 days which cannot be accomplished by conventional tooling.

6.2.2 Efficient AM Moulds—Conformal Cooling

Improperly designed mould cooling systems (cooling channels) often result in two undesirable outcomes. Firstly, moulded part cooling and injection moulding cycle times are much longer than what could have been achieved. Secondly, significant temperature gradients arise across the mould, causing differential shrinkage and



- DMLS Cu + epoxy + shotpeening
- Part size: 90x60x60 mm^3
- DMLS size: 120x120x73 mm^3
- DMLS volume: 1095 cm^3
- DMLS building time: 65h
- Mold T° : 95°C (PC + 30% GF)
  150°C (PPS + GF)
- Injection pressure: 940 b (PC + 30% GF)
  720 b (PPS + GF)

- 500 shots with PC + 500 parts with PPS
- 15 days
- 11.000 €

- CAD	1.800 €	4 days
- DMLS	3.700 €	4 days
- Finishing	1.000 €	2 days
- Mold integration	2.800 €	5 days
- Injection	1.700 €	3 days

Fig. 6.24 Project of DMLS mould production for injection moulding (Courtesy of SIRRIS)

warpage of the moulded parts. To operate effectively, cooling systems must be carefully designed to manage the heat flow throughout the mould without incurring undue cost or complexity.

When we are speaking about moulds for mass production, saving in injection moulding cycle time of just a few seconds means huge savings in total production. Injection moulding cycle consists of few phases: mould closing, polymer melt injection, packing pressure phase, moulded part cooling, mould opening and moulded part ejection (Fig. 6.25). Moulded part cooling is the most important part of the injection moulding process for two facts: it consumes from 50 to 80% of the injection moulding cycle time and it has the strongest influence on achieving required quality of injection moulded parts (Fig. 6.26).

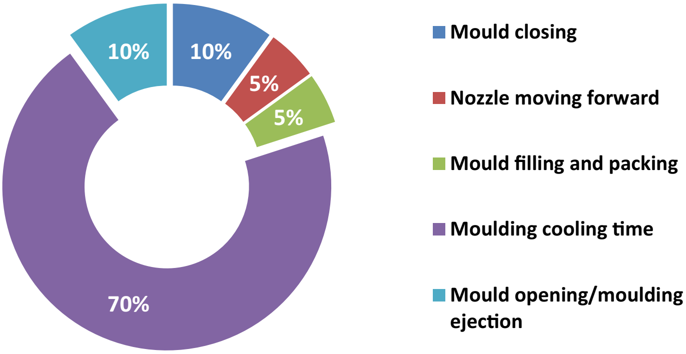


Fig. 6.25 Injection moulding cycle time analysis (*Source* Damir Godec)

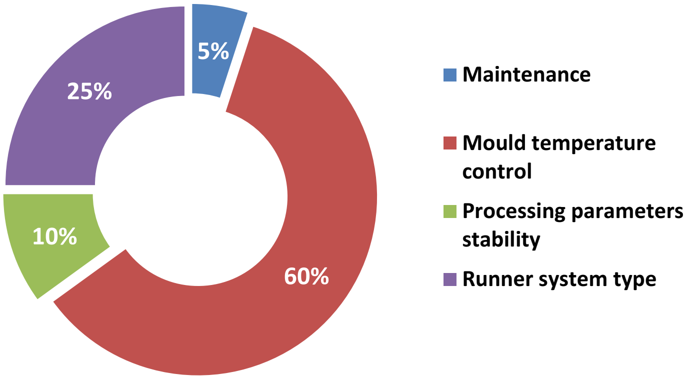


Fig. 6.26 Influencing factors on quality of injection moulded parts (*Source* Damir Godec)

In order to remove a moulded part from the mould, the material must be sufficiently cooled to provide ejection without distortion. Adequate mould cooling can be considered to have occurred if the part surface is hard enough to prevent ejector pins from penetrating. Cooling channel placement determines cooling efficiency and uniformity. Positioning the channels too close to the cavity surface can cause cold spots and uneven cooling. If they are too far away, cooling becomes more uniform but less efficient. As shown in Fig. 6.27, uneven distances to the cavity surface lead to an uneven heat exchange.

Cooling efficiency is particularly dependent on cooling channel characteristics such as proximity to the mould cavity, cross-sectional area, length, route and surface roughness. However, the design of conventional drilled cooling channels in injection moulds is limited by traditional manufacturing constraints such as the linear nature of the drilling process, which restricts the ability to conform the channel to the contour of the mould cavity (Fig. 6.28a). Variation in the proximity of cooling channels to the mould cavity results in uneven heat dissipation, leading to: increased cycle time, part warping and sink marks, internal part stresses, and reduced tool life due to thermal stresses.

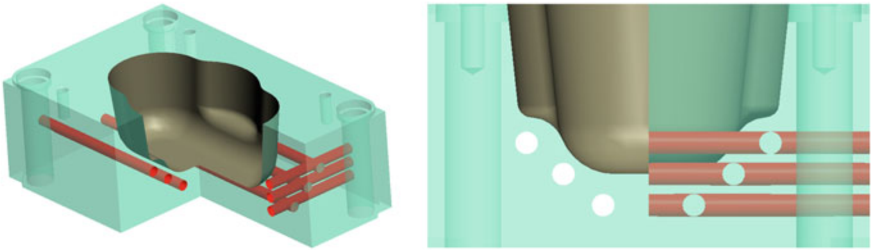


Fig. 6.27 Conventional tooling mould temperature control (uneven distances to the cavity surface or impossibility to reach some cavity areas) (*Source* Damir Godec)

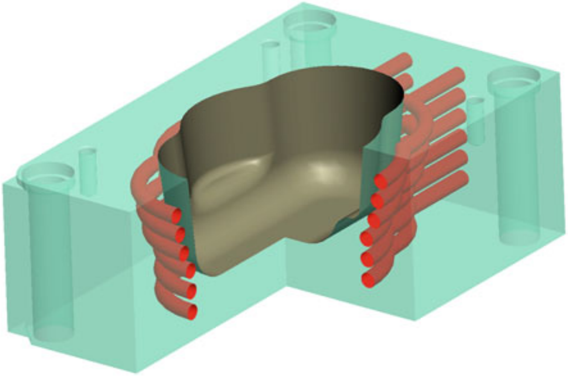


Fig. 6.28 Conformal mould cooling channels (*Source* Damir Godec)

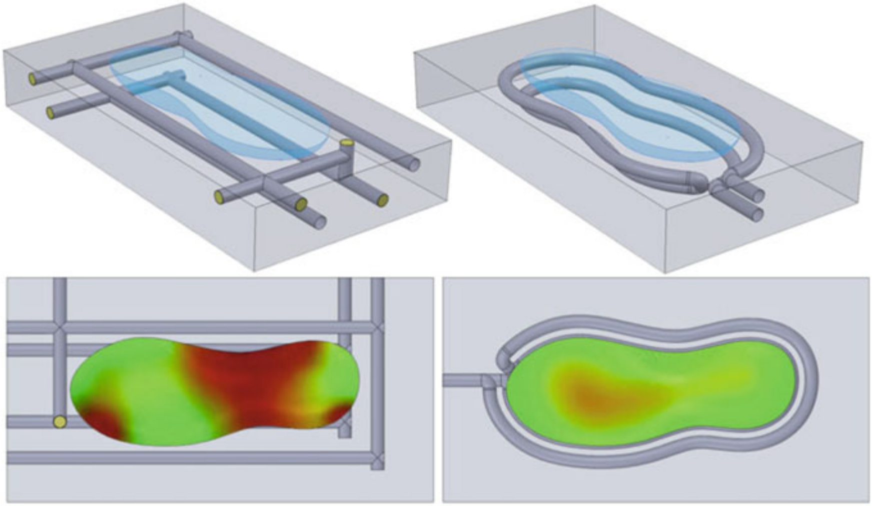


Fig. 6.29 Heat distribution comparison between conventional and conformal cooling channels (Courtesy of Olaf Diegel)

In case of moulds for mass production, the injection moulding cycle time is much more important than the time and the costs necessary for mould production. Therefore, a lot of toolmakers apply new strategies in mould design and production. Most of them are focused on optimisation of heat exchange in the moulds in order to reduce injection moulding cycle time as well as to improve moulded part quality and to extend the mould lifetime. AM tooling with conformal cooling is the possible answer to those requirements.

AM mould inserts can be built with internal cooling channels that follow the contour of the cavity beneath the surface (Fig. 6.28b). Because the form of the channels follows the contour of the mould, the method is called conformal cooling. Due to the more intensive heat exchange, the productivity of a polymer injection mould can be increased significantly. Conformal cooling channels, applied with no engineering simulation or analysis will, generally, result in about a 10% cycle time improvement. On the other hand, conformal cooling channels, applied with engineering simulation and analysis will, generally, result in cycle time improvements from 20 to 40%.

The use of conformal cooling channels also optimizes the moulding process by providing a constant temperature gradient and thus more even heat distribution throughout the mould (), while increasing the total surface area of the cooling circuit. This also results in savings in manufacturing the inserts. When plastic cools evenly, internal stress is minimized. This results in a higher quality parts with less warping or sink marks. The more controlled cooling offered by conformal cooling channels allows you to precisely control how the plastic solidifies in the mould and, therefore, to minimize part distortion and shrinkage (Fig. 6.29).

The ultimate objective in optimisation of the injection moulding cycle time and moulded part quality is the creation of a mould temperature control system, which enables a constant and adapted temperature level for the polymer material, during the running injection moulding process on each point of the moulding surface. In order to achieve this result, when applying conformal cooling, appropriate coolant flow strategy and cooling channel shape have to be determined. The general opinion is that, when designing conformal cooling channels, it's always recommended to use an injection moulding simulation software package (CAE) in order to identify different temperature zones within a mould so that the conformal cooling channels can be separated and optimized within each region. CAE software can successfully assist in evaluating the effectiveness of cooling layout designs and verify potential design problems at early stage.

When designing conformal cooling channels, the first decision that needs to be made is which coolant flow strategy to use. There are three different strategies: zigzag pattern, parallel channel design and spiral channel design (Fig. 6.30). A zigzag pattern, also known as a series cooling path (Fig. 6.30a), has part regions cooled one

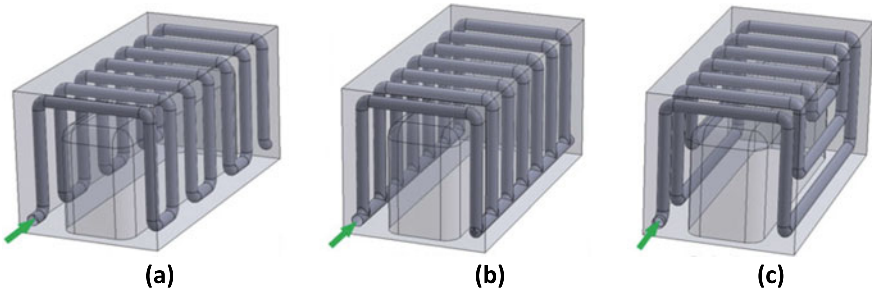


Fig. 6.30 Types of cooling strategies that can be employed with conformal cooling: **a** zigzag, **b** parallel, **c** spiral (Courtesy of Olaf Diegel)

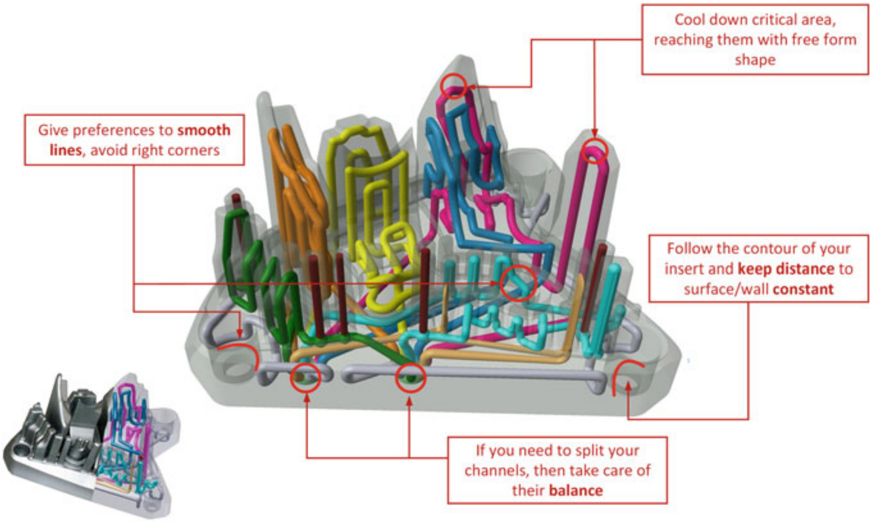


Fig. 6.31 Conformal cooling of complex mould insert (© Copyright Renishaw plc. All rights reserved. Image is reproduced with the permission of Renishaw)

after the other rather than at the same time. Cooling in series is generally not preferred unless parts are small enough that the delay is negligible. A parallel channel design (Fig. 6.30b) allows for different areas of the mould to be cooled at the same time. The main drawback of the parallel cooling method is that it requires a lot of coolant. A spiral conformal cooling channel design (Fig. 6.30c) is often used with parts that have curved or spherical elements.

On complex tools, one can sometimes combine cooling strategies where, for example, part of the tool uses a zigzag type of strategy, while the rest of the tool employs a parallel strategy. For very complex mould inserts specific rules have to be employed for optimal cooling (Fig. 6.31).

When considering coolant channel shapes produced with AM, one must be aware of the effect of the ability of the AM system to effectively produce them, as well as their effect on cooling efficiency. The design guidelines used for conventional cooling circuits can also be applied to conformal cooling channels. Some of the recommended dimensions are given in the schematic in Fig. 6.32 and the recommended channel diameters based on the average wall thickness of the moulded plastic part are shown in Table 6.2.

Generally, the optimal cooling channel diameter is usually between 4 and 12 mm (depending on the design and the material of the moulded part). The diameter should, however, be carefully chosen depending on the AM system being used. It must also be taken into account that round horizontal channels, for example, will require internal support material if their diameter is above 8 mm.

The freedom offered by AM opens a lot more possibilities when it comes to optimising the coolant flow in the cooling circuits. One of those possible optimisations is

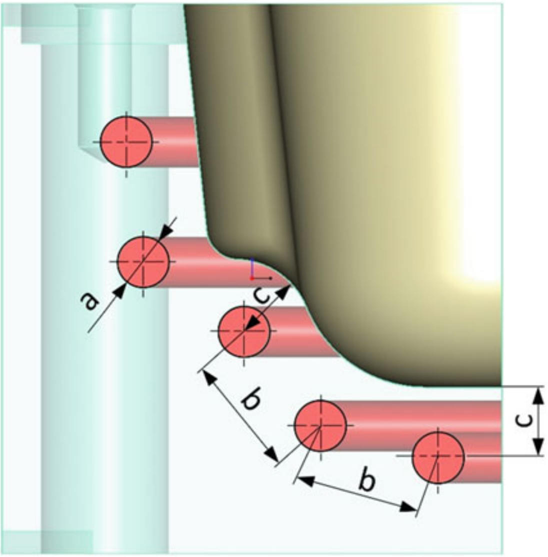


Fig. 6.32 Conformal cooling channels—recommandations for design (*Source* Damir Godec)

Table 6.2 Conformal cooling channel diameter and spacing based on moulded part wall thickness

Moulded part wall thickness (mm)	Channel diameter (mm) *b*	Centreline distance between channels *a*	Distance between channel centre and cavity *c*
0–2	4–8	(2 ÷ 3) · b	(1.5 ÷ 2) · b
2–4	8–12	(2 ÷ 3) · b	(1.5 ÷ 2) · b
4–6	12–14	(2 ÷ 3) · b	(1.5 ÷ 2) · b

to change the cross section of the channels in order to improve the coolant flow. The most common channel shape is, generally, round but, on occasion, vertical elliptical holes, or house-shaped or teardrop-shaped channels are also used (Fig. 6.33).

The cooling performance can, sometimes, also be increased by ribbing the shape of the channel which causes an increase of channel perimeter as well as increase in the expected turbulence in the channel (higher Reynolds number), which thus increases cooling (Fig. 6.34).

Figure 6.35 shows conformal cooling channels with different cross sections and their characteristics.

As alternative to application of single channels, mould designers for a mould cooling employ a whole hollow surface structures beneath the cavity wall. Two main types of hollow surfaces are mostly applied. One structure consists of large number of consecutive knots which run through larger inlets or outlets (Fig. 6.36). Consecutive knots configuration guarantees volume flow large enough for efficient mould insert cooling. Small channel diameter enables cooling of very small details in mould insert

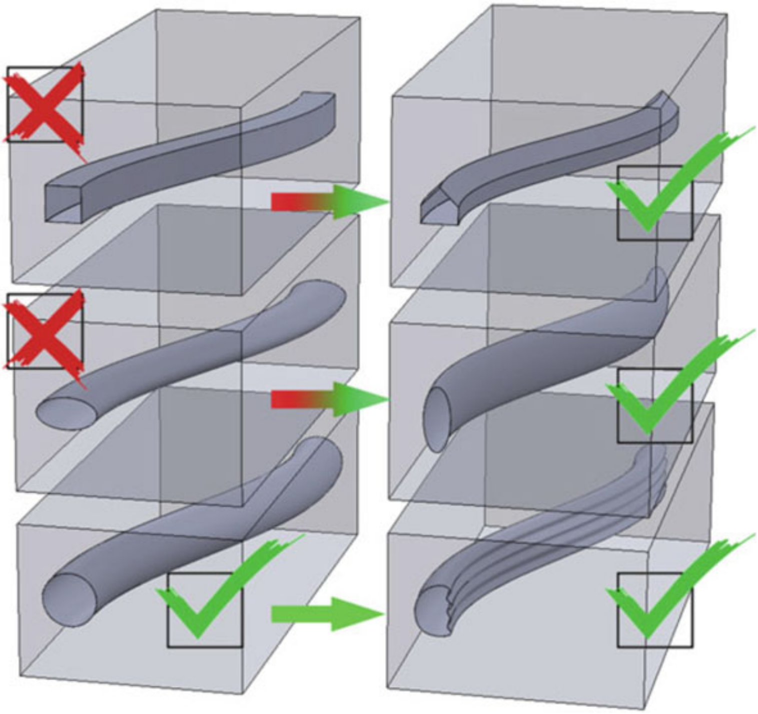


Fig. 6.33 Recommended shapes of conformal channels cross section (Courtesy of Olaf Diegel)

(width of only 4.5 mm). In this case, a dome-shaped structures with dimensions from 4.5 · 5 mm and larger, are also available.

Second structure type consists of mesh surfaces for mould insert cooling placed only 2 mm beneath the mould insert cavity wall and must achieve a large coolant volume flow. Small distance from mould insert cavity wall enables very efficient cooling, and very short cycle times. Mould insert temperature can be controlled locally over the insert and thus decrease (or even remove) unwanted moulded part thermal deformation and achieve target moulded part shrinkage. Mesh surface can be combined with insulation layer, which enables rapid temperature changes in moulded part cooling time phase in the mould cavity (Fig. 6.37).

6.2.3 *Efficient AM Moulds—Optimised Build Time in Tooling*

Tooling is a typical application in which the bulk of the tool is a large mass of metal which serves little purpose. It is there because by CNC machining we try to minimize the amount of cutting that needs to happen. AM provides the opportunity of creating

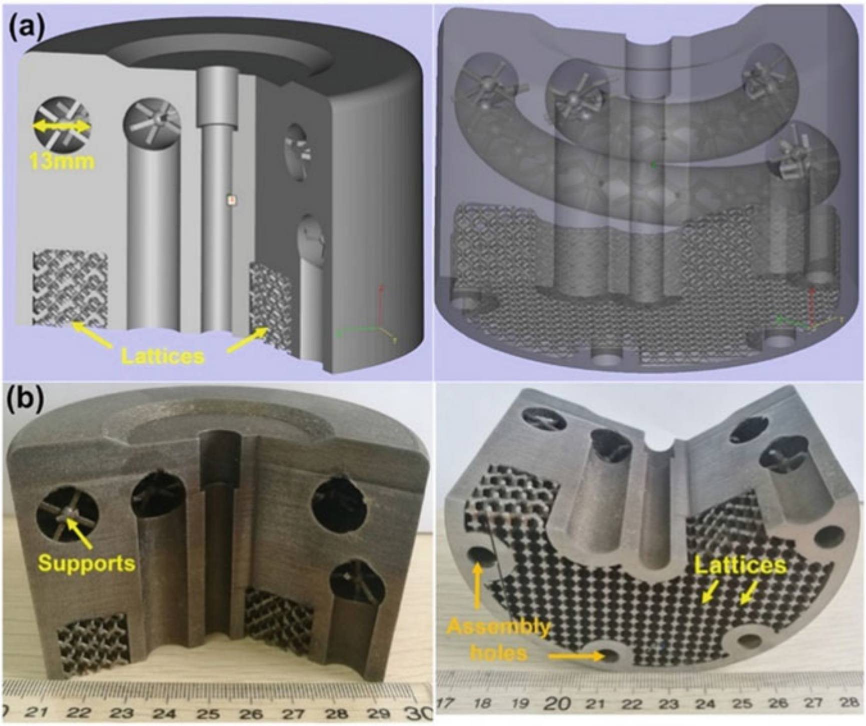


Fig. 6.34 Novel Conformall cooled mould insert: **a** CAD models of novel conformal coolled mould insert, **b** the corresponding mould insert processed by PBF-LB/M (Reprinted from Materials and Design, Vol. 196/109147, Chaolin et al. [10], Copyright 2021, with permission from Elsevier)

much lighter tools that have an even metal wall thickness and take less time and cost to manufacture.

Using the tool for a shoe insert (Fig. 6.38), we can see that the vast bulk of the tool is a solid mass of steel. AM application in tooling offers a possibility to reduce the amount of the material used. Whether this can be done will of course depend on many factors such as the pressure the tool will be subjected to, etc. But, in many applications, a wall thickness of 10–20 mm is more than adequate, and still leaves enough material for conformal cooling channels.

Other option to achieve a similar goal would include filling the inside of the tool with a honeycomb structure (Fig. 6.39), or a lattice (Fig. 6.40). Lattice structure also has the influence on the mould/tool insert elasticity. Lattice structures should have sufficient strength to withstand the injection pressure, but at the same time enough flexibility for the surface to expand and retract during the cycle. The elasticity of lattice structures can be made highly anisotropic in laser powder bed fusion process. Generally, a lattice structure containing large cells will give a higher elasticity than a structure with smaller cells. Figure 6.40 illustrates a mould insert where a large portion of the mould insert consists of lattice structures. This means that much less

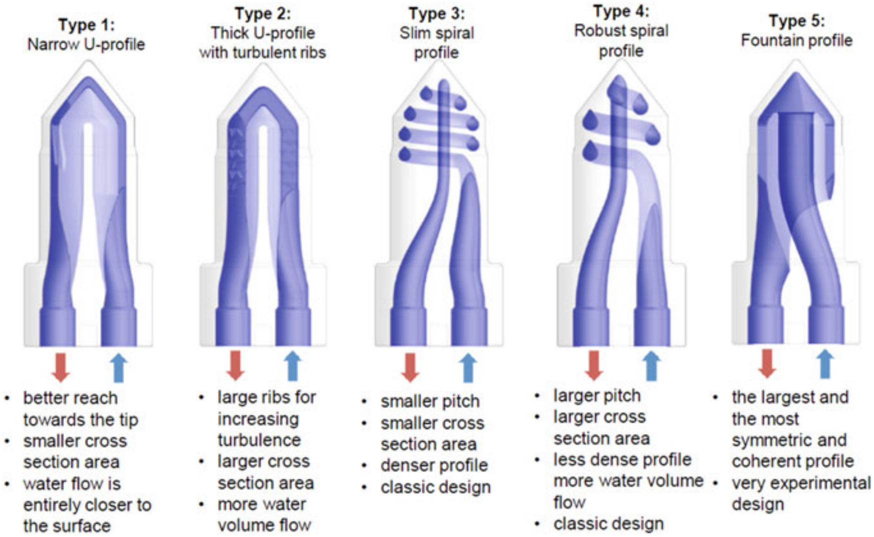


Fig. 6.35 Different types of conformal cooling channels cross sections (Courtesy of ABB Oy)

material and shorter machine time is needed to produce the mould insert. In addition, the structural flexibility is higher which could reduce thermal fatigue. The cooling channels are placed at some distance from the wall of the insert. With this design, cracks in the insert wall will not propagate into the cooling channel, causing leakage of coolant into the mould cavity. Another point is that the thermal fluctuations in the cooling channels will be low, as there is slower heat transfer to the channels.

The problem is that there will not be much thermal conductivity between the lattice structure and the cooling channels. One solution to such a problem is to make the elements of the lattice structure thicker towards the edges, or to make the structure smaller with larger connections. Both proposals increase the melted mass between the surface and the cooling channels. For faster/cheaper production it is also possible to entrap powder in the section between the cooling channel and the surface, since entrapped powder has much more thermal conductivity than air.

6.3 AM Application in Medicine

The medical industry is one of the fastest-growing sectors within AM, and is used for a range of applications, from patient-specific implants to realistic functional prototypes and advanced medical tools. AM provides extensive customisation as per the individual patient data and requirements for medical applications. Individual patient models are in three-dimensional (3D) sections developed through customised software. These include implants, soft tissue, foreign bodies, vascular structures,

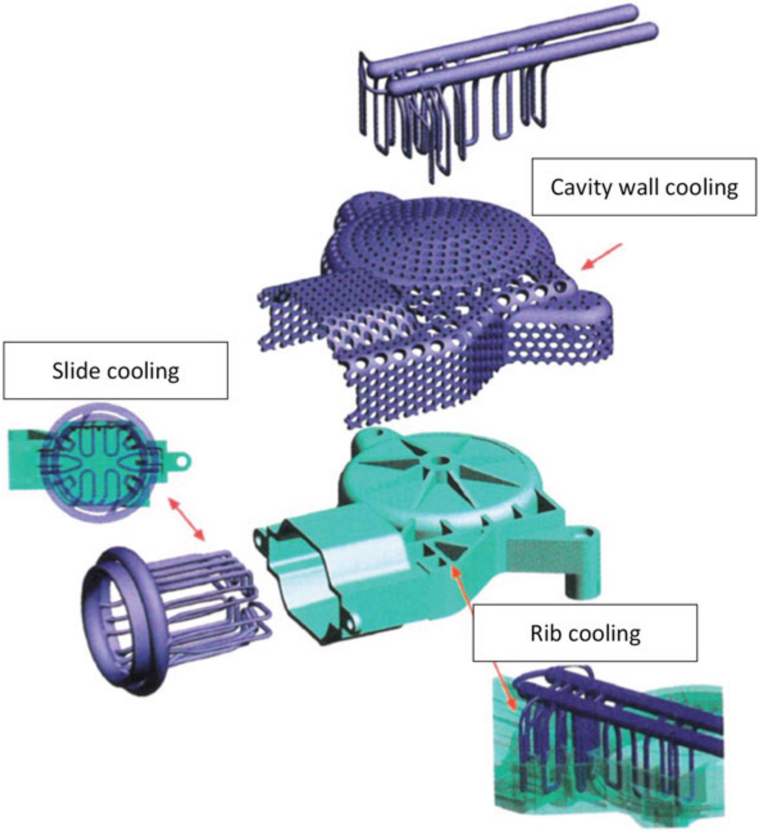


Fig. 6.36 Surface hollow structures for efficient mould cooling (Courtesy of GE Additive/Concept Laser)

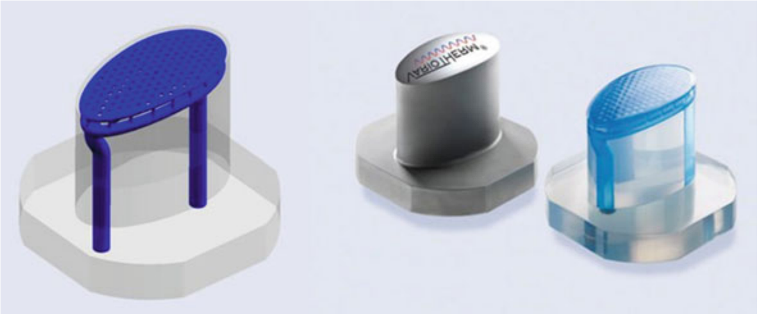


Fig. 6.37 Mesh surface for efficient mould insert cooling (Courtesy of GE Additive/Concept Laser)

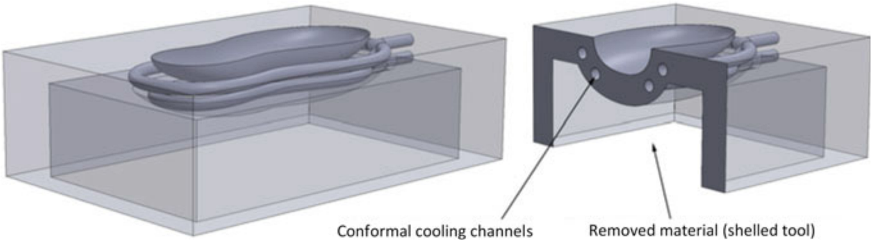


Fig. 6.38 Example of improving the print time and cost of a tool by shelling its interior (Courtesy by Olaf Diegel)

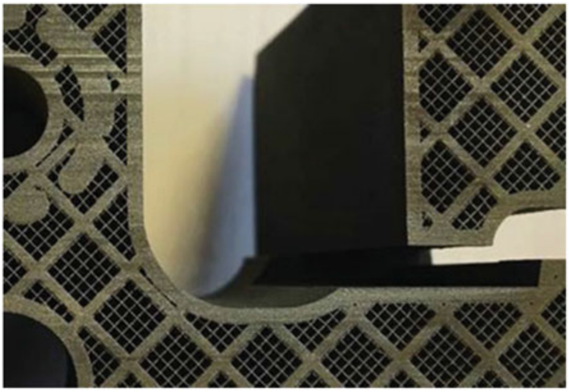


Fig. 6.39 Honeycomb structure used on inside of sheet metal tool to reduce its print time and cost (Courtesy by Olaf Diegel)

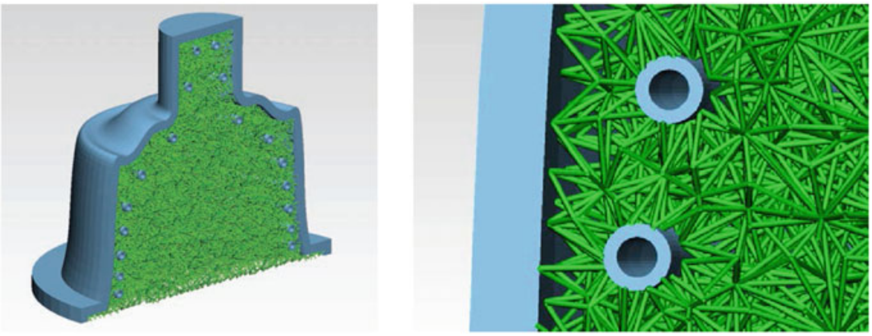


Fig. 6.40 A split mould tool with internal lattice structures (Reprinted from Procedia CIRP, Vol 54, Brøtan et al. [9], Copyright 2021, with permission from Elsevier)

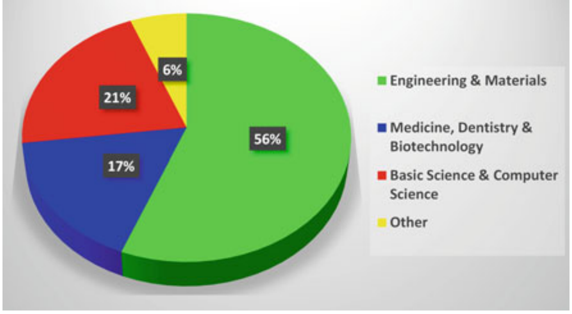


Fig. 6.41 Medical application of AM (Javaid and Haleem [34], Courtesy of Mohd Javaid)

etc. Magnetic Resonances Imaging (MRI) technology or Computerised Tomography (CT) are usually used for capturing model data.

Application of AM in medical sectors can be divide into a few areas:

- medical research and development
- preclinical testing and planning
- production of medical devices
- pharmaceutical application
- bioprinting/tissue fabrication.

6.3.1 Medical Research and Development

AM models can greatly contribute to medical research by providing realistic anatomical models and prototypes. And as AM speeds up the product design cycle, biomedical engineers can now create very complex models and prototypes that much faster.

Share of AM in medical applications is shown in Fig. 6.41. Engineering and materials have significant contribution in this area which is 56%. Medicine, dentistry and biotechnology have 17%, basic science and computer science have 21%, and other fields have 6% contribution in this particular area. It indicates that engineering and materials areas have demonstrated a great potential in this field, because this is tool-less production which produces complex shapes quickly, in lesser time.

6.3.2 Preclinical Testing and Planning

AM models allow physicians to visualise patient's anatomy and assess complex pathologies directly, overcoming the challenges of digital images which lack 3-dimensional realism. And thanks to advances in multi-material AM (e.g. PolyJet technology), additively manufactured models made up of different materials can be create to replicate characteristics of human tissues and bones. This method can help surgeons plan an operation in advance and improve surgical precision and postoperative outcomes.

Generally, development and production of models for medical testing and planning can be divided into a three main groups:

- general application
- anatomical modelling (patient-matched)
- surgical planning.

General application medical models

In case of general application, non-personalized models, instruments or prototypes are produced (Fig. 6.42). Mostly it is about plastic or metal specializes instruments for hospital/surgical use, for testing parts built with new materials or for prototypes used for iterative design processes.

Anatomical medical models

When the aim of AM models is anatomical modelling, they are used for patient-matched anatomical models from medical imaging studies (CT/MRI). This type of models have numerous application such as: models for surgical preparation (Fig. 6.43), simulation (Fig. 6.44), models for teaching or training (Fig. 6.45), models for communication with patients and colleagues (Fig. 6.46), demo models to test fit and fixation of an instrument, etc.

Medical models for surgical planning

AM is also used for different types of templates, guides, and models, after preparing a patient-specific, surgical plan in a software environment (AM items are brought into operating room). Guides can be divided into a group that does not need cutting

Fig. 6.42 Example of AM medical device (general medical model) for prototyping and testing (Courtesy of Formlabs)

Fig. 6.43 AM model for surgical preparation (surgery time reduction up to 75%) (Dr. Mickey Gidon and Department of Neurosurgery at Soroka)

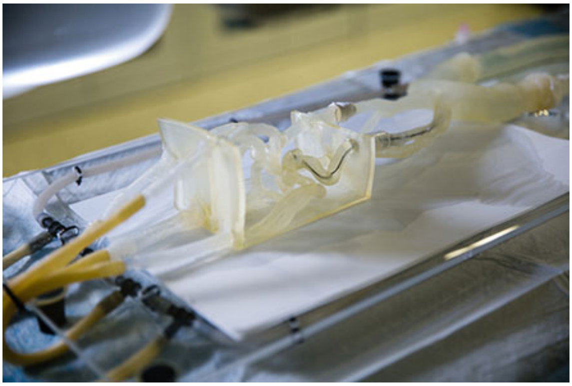


Fig. 6.44 AM model for simulation (aneurysm simulation) (Courtesy of Stratasys)

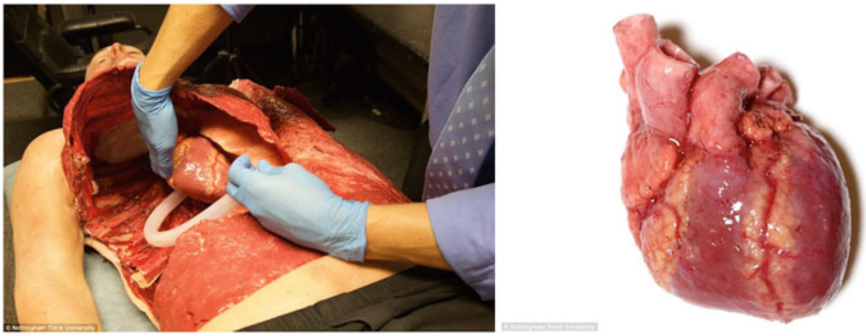


Fig. 6.45 AM model for teaching/training (Courtesy of Richard Arm)

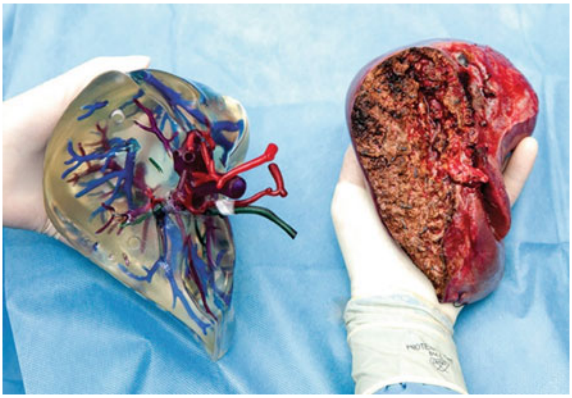


Fig. 6.46 AM model for communication (Courtesy of Stratasys)

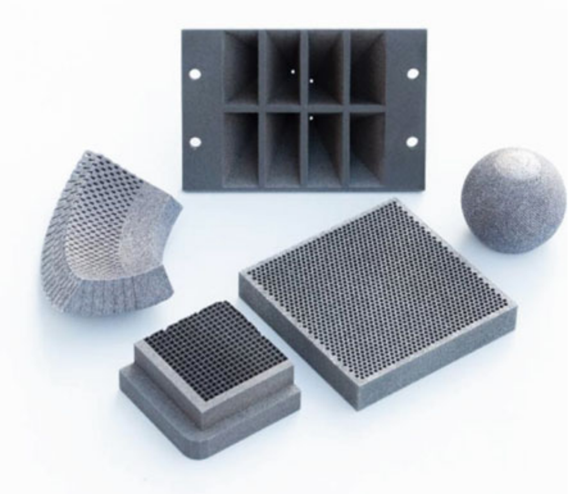


Fig. 6.47 Examples of complex AM tungsten models (e.g. collimators) for advanced medical imaging (Courtesy of M&I Materials Ltd.—Wolfmet 3D)

or injection for marking (surgical marking guides, implant placement guides, radiation shields (Fig. 6.47), imaging frames) and a group of cutting/drilling guides for surgical injection/instrumentation (surgical saw guides, surgical drill guides (Fig. 6.48), guiding osteotomies in the bone).

6.3.3 Production of Medical Devices

With the global market for AM produces medical devices expected to reach more than 1.0 billion EUR by 2026. (Future Market Insights), AM offers significant value to produce customised medical products. From complex-shaped implants, personalised prosthetics and hearing aids to fit-for-purpose tools, additive manufacturing enables

Fig. 6.48 Examples of AM surgical drill guide (dental application) (Courtesy of Formlabs)

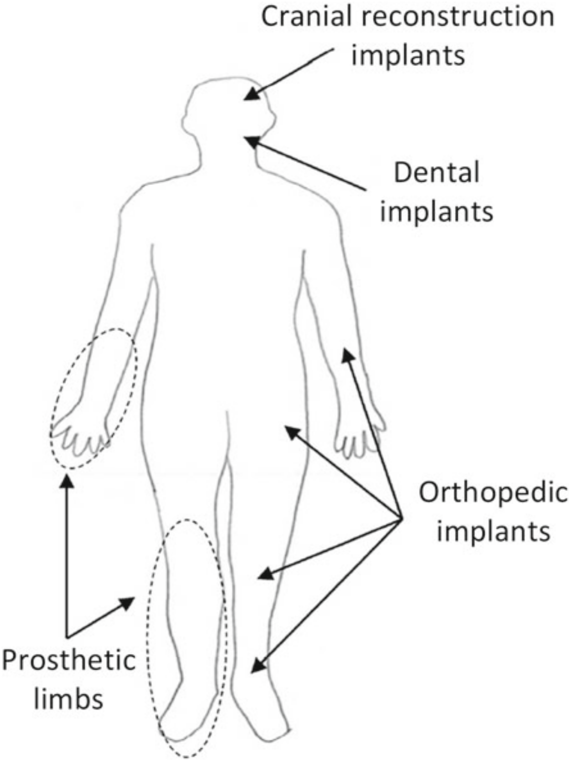


Fig. 6.49 Examples of AM in current medical models with AM major influence (Courtesy of ASME)

the production of one-off devices that would be impractical to manufacture using traditional manufacturing.

In case of AM of medical devices, there are three main groups of products (Fig. 6.49):

- personalised (precision) prosthetics
- temporary/permanent implants
- wearable (active) devices/covers.

AM is making a huge impact in the production of affordable yet highly accurate prosthetics. Using traditional manufacturing methods, it can take weeks to create a device matching a patient's requirements. Today, this is no longer the case, as AM prosthetics is significantly less time-consuming and, in many cases, can be produced at a fraction of the cost of traditionally fabricated prosthetics. In this case AM has been used for a patient-matched prosthetics/orthotics that can be in direct contact with mucosal surface (e.g. complex facial (Fig. 6.50) and cranial prosthetics, dental (Fig. 6.51) and orthodontic (Fig. 6.52) applications), as well as without direct contact with mucosal surface (e.g. glasses, body braces (Fig. 6.53), hearing aids (Fig. 6.54), prosthetic limbs and attachments (Fig. 6.55), etc.) and different type of assistive devices.

According to a recent report by SmartTech Publishing, the dental market will reach 9.5 billion EUR by 2027. Today, dental labs can additively manufacture bridges, aligners, crowns, orthodontic appliances and stone models, which can be customised to fit the patent.

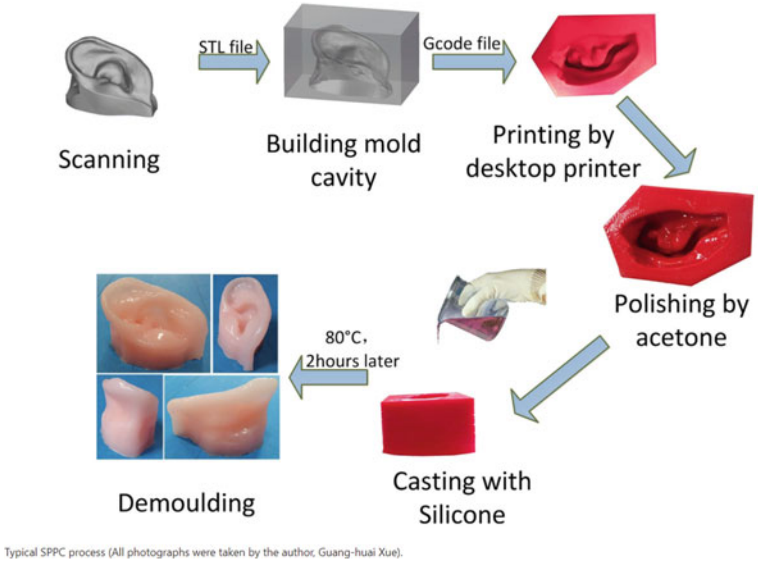


Fig. 6.50 Examples of AM fabrication of silicone ear (He et al. [27] 2014—licenseds under CC BY-NC-ND 4.0)

Fig. 6.51 Example of AM CoCr dental crowns (Schweiger et al. [71], 2010.—licensed under CC BY 4.0)

Fig. 6.52 Example of AM orthodontic application (aligner) (Courtesy of Stratasys)

Over 10,000,000 people are now wearing 3D printed hearing aids with more than 90% of all hearing aids globally now being created using AM. Not only has AM technology significantly reduced the cost of custom hearing aids when compared to traditional manufacturing but the ability to produce the complex and organic surfaces required for a hearing aid has reduced returns because of bad fit from 40 to 10%.

It is important to note that in any application of AM in medical production it is advisable to adhere to the Technical Considerations for Additive Manufactured Medical Devices/Guidance for Industry and Food and Drug Administration Staff (5th December 2017) as well as The European Union Medical Device Regulation—EU MDR, Regulation (EU) 2017/745 (5th April 2017). As the requirements for medical production are very high, it is necessary to take into account quality control and it is necessary to adopt ISO 13485: 2016 procedures and certainly regulate the research or production activities of AM for medicine.

One of the fastest growing segments within medical AM is implants production. Advances in AM have enabled the production of implants made to match the patient's anatomy. Furthermore, with biocompatible materials such as titanium and

Fig. 6.53 Examples of AM orthotics: **a** Forearm static fixation, **b** hand prosthesis, **c** Spinal brace, **d** Ankle–foot orthosis (Barrios-Muriel et al. [6] 295.—licensed under CC BY 4.0)

Fig. 6.54 Examples of AM hearing aid (Courtesy of Formlabs)

cobalt chrome alloys, AM orthopaedic and cranial implants can be manufactured with the right surface roughness, resulting in reduced rejection rates. The possibility of creating topologically optimised designs also means that an implant can be designed with complex organic geometry and reduced weight. This AM area is used for production of "off-the-shelf" (ability to create fine details easily, such as porous structures/surfaces) and patient-matched implants.

Fig. 6.55 Examples of AM prosthetic covering (Courtesy of Anatomic Studios, photographer Stefan von Stengel)

There are two main groups of implants: serialised implants which can be temporary or permanent (metallic implants—titanium (Figs. 6.56, 6.57), titanium alloys, cobalt chrome alloy and polymeric implants—PEEK/PEKK implants (Fig. 6.58)) and patient-matched reconstructive implants (small quantity implants—limb salvage, oncology cases, spinal implants, temporary/removable implants—nasal stents, permanent implants: non-dissolvable—knee/bone implant (Fig. 6.59) or dissolvable—tracheal splint).

Beside direct AM of implants, there is also possibility of indirect AM application for implants production. In first step it is necessary to produce appropriate AM mould (Fig. 6.60), which is in second step used for implant production.

Wearable (active) devices are devices that include electronics or other active element. This group of products involves wearable sensors, lab on a chip, microfluidics (Fig. 6.61) and electronics for active devices.

Design for AM of medical models

When developing and production medical models either for preclinical testing and planning, or for applications such are implants, prosthetics, orthoses, etc. medical process chain can be divided into eight major steps (Fig. 6.62). Data varies from patient to the patient. We need imaging and scanning, which is produced through various scanning procedure such as CT convert data in the 3D digital form.

Fig. 6.56 Example of AM titanium cranial implant (Sun and Shang [82]—licensed under CC BY 4.0)

The process chain starts from diagnosis. For the application of AM in medical models development, images and scanned data of patients are required as input data (Fig. 6.63).

Computer data of the patient can be obtained in three ways:

- by scanning with laser or optical scanners in case that only patient outer body surface is necessary (e.g. for production of different types of orthoses and prosthesis);
- by application of medical diagnostic procedure (Computed Tomography—CT or Magnetic Resonance Imaging—MRI) which results with so called DICOM data format (Digital Imaging and Communications in Medicine) used for obtaining a CAD model of patient bones (e.g. for production of medical customised implants, for production of customised surgical guides etc.) (Fig. 6.64);
- by application of medical diagnostic procedure CT or MRI (DICOM data format) for obtaining CAD models of patient soft tissue (e.g. internal organs and tissue for complex surgical planning, for organs production by AM of living cells—bioprinting, etc.).

Procedure of 3D scanning with laser or optical scanner is relatively simple and similar to obtaining models in technical area. However, procedure of getting patient CAD data from DICOM data is very complex and requires specific knowledge on human anatomy as well as for understanding and interpreting results obtained through medical diagnostic procedure and application of specialised software (Fig. 6.65).

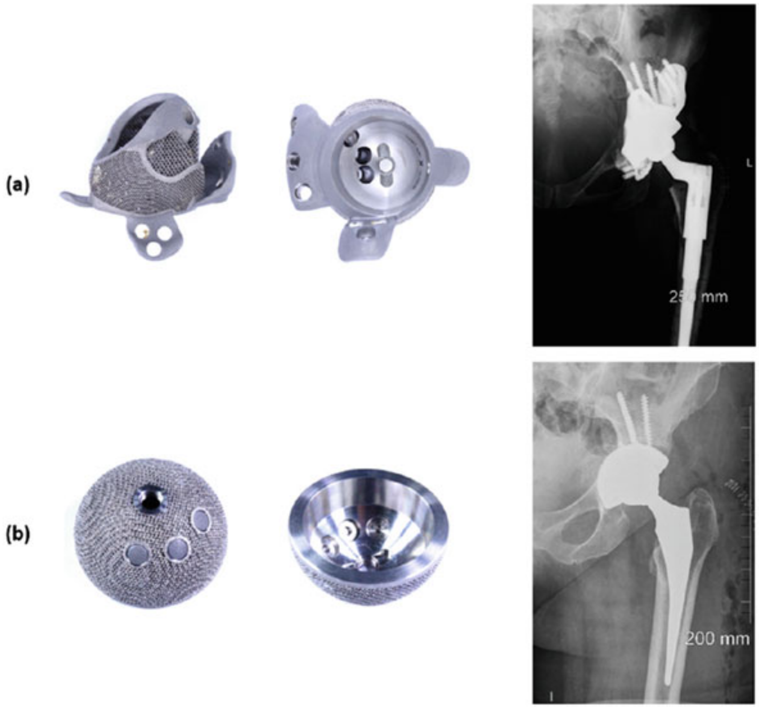


Fig. 6.57 Example of AM titanium hip implant: **a** custom, **b** of-the-shelf (Dall'Ava et al. [12] 729.—licensed under CC BY 4.0)

For success realisation of medical model development, a cooperation among medical and technical experts is necessary. The result of medical diagnostic procedure is file with point cloud which represents a geometry of the patient in three-dimensional space. With specialised software it is possible to segment total point cloud into a several point clouds and separates the cloud that represents specific part of the patient body for which it is necessary to develop CAD model (Fig. 6.66).

After segmentation of point cloud of specific patient body part/organ, it is necessary to generate surfaces that connects points from the cloud, which results with initial CAD model of patient body part/organ in STL file format necessary for AM. In next step, it is necessary to customise initial CAD model to adjust it for the application and patient (e.g. modelling of implant fixation system).

In following step AM helps to transform the original design of the customised implant to the physical model. There is the importance of biomechanical simulation to determine the strength of the medical model. In case of implant production, after all simulation has done, regulatory approval is must before manufacturing. After building the model, post processing is compulsory for increasing strength and surface finish quality. Final steps, in case of implants, are sterilisation and surgery (Fig. 6.67).

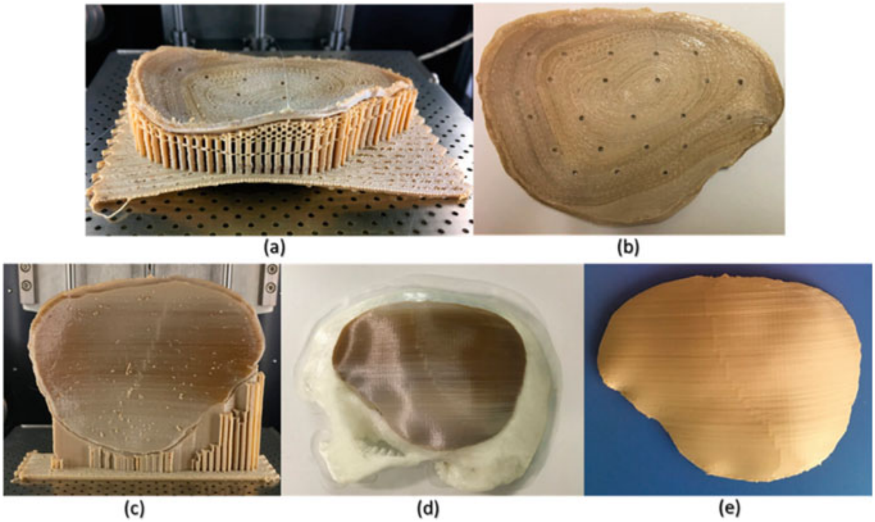
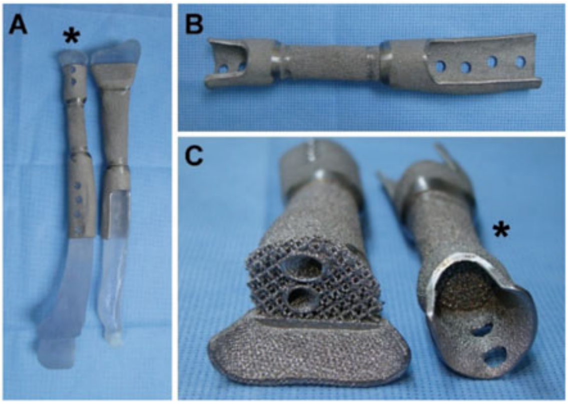


Fig. 6.58 FFF PEEK 3D printed cranial implant in different orientations. **a** horizontally printed cranial implant showing raft; **b** horizontally printed cranial implant—internal surface; **c** vertical printed cranial implant; **d** 3D printed skull biomodel; **e** annealed vertically printed cranial implant displaying (Sharma et al. [73] 2818.—licensed under CC BY 4.0)

Fig. 6.59 AM metallic bone implant: **a** 3D-printed implants of both forearm bones with the host bone models, **b** a volar view of the ulnar implant, **c** the mesh-structured junctional area of the implants (Park et al. [58], 553.—licensed under CC BY 4.0)



In the future AM will have a better capability of enhancing product customisation and usage with reasonable cost. AM has disrupted all the traditional fabrication of medical models. This technology fabricates implant with its specific geometrical dimensions, and it replaces conventional scaffold fabrication methods. This technology is beneficial in surgical planning; the models provide surgical and physician team with a visual aid to make surgery planning better. It has potential to fabricate customised fixtures and implants; complex geometry is also fabricated in short time. This is needed for designing and manufacturing of surgical aid tools,

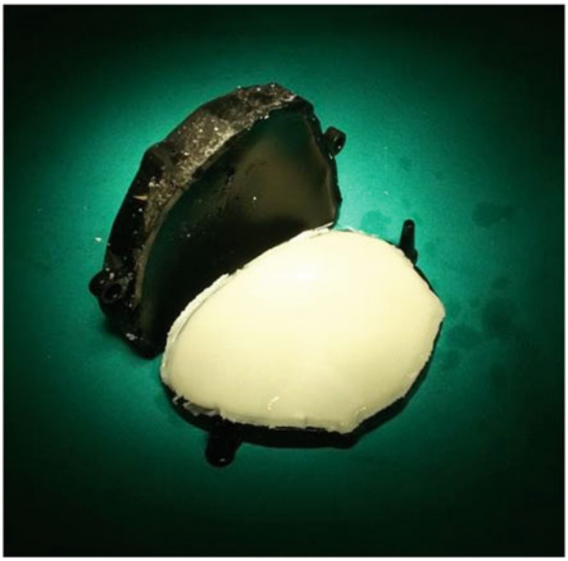


Fig. 6.60 Example of AM (PolyJet) mould for production of bone cement cranial implant (*Source* AdTec SME project—UNIZAG FSB)

bio-models, implants, various scaffolds for tissue engineering and development of multiple medical devices and surgical training models. In future medical will have to work in close collaboration with AM researchers and commercial product developers.

6.3.4 AM Pharmaceutical Application

There are several different AM approaches that have potential for pharmaceutical production (Fig. 6.68). However, only a few methods have been successfully explored with the purpose of producing pharmaceuticals. The primary AM techniques that have been applied toward pharmaceutical manufacturing thus far include Binder Jetting, Material Extrusion, and Material Jetting.

Widespread commercialization of AM of pharmaceuticals has the potential to disrupt the supply chain used by the healthcare industry worldwide with the cost-saving potential of minimizing waste related to unused, expired medications. But despite the potential of this technology, many clinical and regulatory challenges will need to be addressed prior to large-scale implementation of AM fabricated therapeutics for precision medicine applications.

One main advantage of using AM for pharmaceutical manufacturing is that pharmaceuticals can be easily tailored for each patient. This is achieved through changing the release profile of the pharmaceutical, which essentially means adjusting when and for how long the active agent is released into the body. This can be adjusted by changing the relative quantities of the active and inactive form of the constituents or

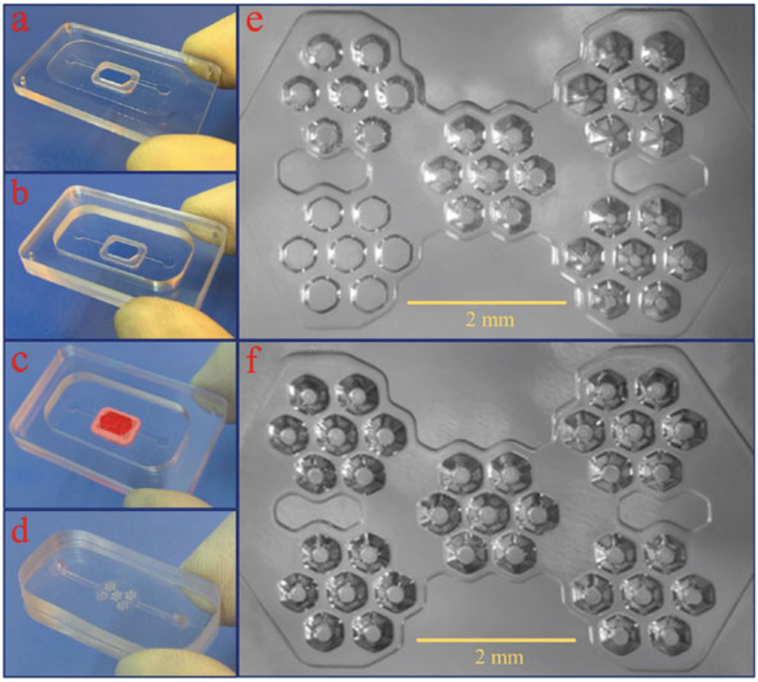


Fig. 6.61 Microfluidic device—Steps to produce the master mold and casting with PDMS. **a**, **b** Two CNC milled parts are bonded to each other permanently using a solvent bonding method. **c** The 3D printed mold is assembled on the CNC mold and fixed with reusable putty adhesive. **d** The cover and microwell PDMS layers bonded together using the plasma bonding method to produce the microwell chip. **e**, **f** The optical micrographs of PDMS layers with the variable and constant depth (300 µm) microwells (Behroodi et al. [7]—licensed under CC BY 4.0)

by compartmentalizing or layering the tablet to change how drugs are released in the patient's body.

Another main advantage is the potential for on-demand drugs. In an emergency situation, it will be much easier to produce medicine for a patient as it can be printed in a hospital environment, rather than relying on the stocks containing a drug with the correct dose and release profile.

Long term stability of a drug would be less important (expire date), as they can be printed as soon as they are needed, so it would be possible to design more effective drugs with faster action, as they don't need a long shelf life.

All of these changes would normally be impossible or very difficult to achieve through conventional methods, as it would involve changing the entire manufacturing process.

While there are many benefits to the incorporation of AM to the facilitation of precision medicine in healthcare practice, there are significant obstacles, which must be overcome in order for this to occur. Of those obstacles, a few have been explored in the literature and are stated here. The first obstacle is the question of legal license over

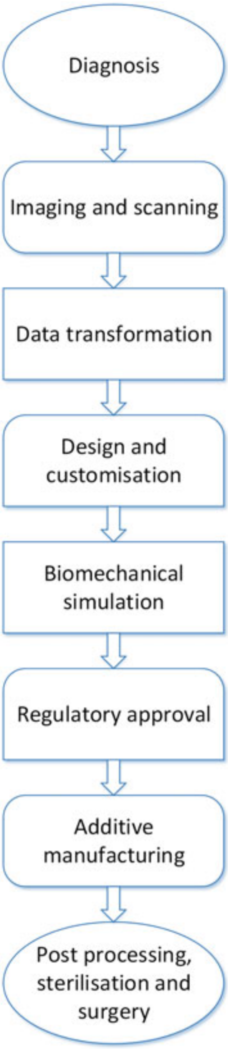


Fig. 6.62 Process chain development in medical application of AM (Javaid and Haleem [34], Courtesy of Mohd Javaid)

the active ingredients in many current medications. The second obstacle is the cost of printing a polypill compared to the cost of currently available mass manufactured medications for use in chronic disease states. The third obstacle is the establishment of new clinical guidelines, which facilitate provider prescriptions for chronic disease states.

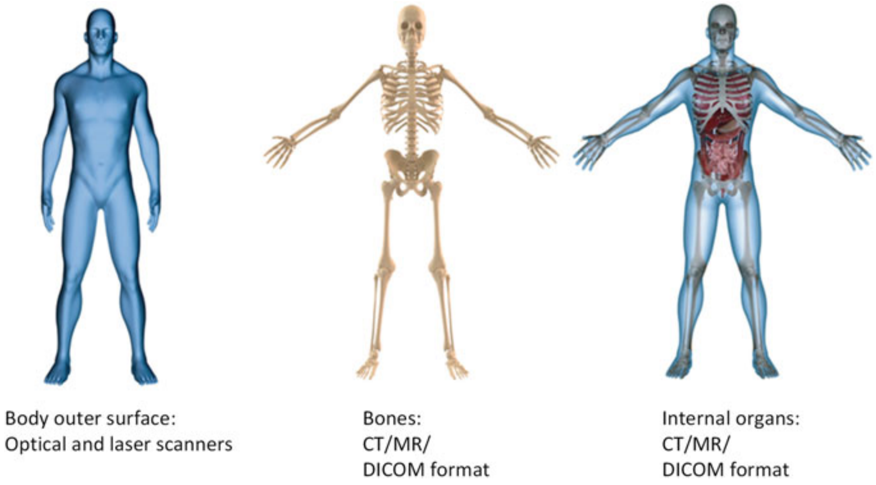
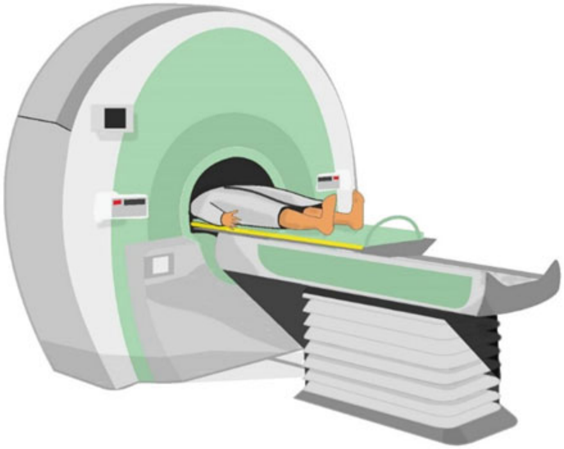


Fig. 6.63 Input data types for AM development of medical models (*Source* AdTec SME project—UNIZAG FSB)

Fig. 6.64 Application of medical 3D diagnostic procedure (CT or MRI) for obtaining DICOM data (Courtesy of Miodrag Katalenić)



6.3.5 AM for Bioprinting/Tissue Fabrication

Bioprinting is an additive manufacturing process where biomaterials such as cells and growth factors are combined to create tissue-like structures that imitate natural tissues.

The technology uses a material known as bioink to create these structures in a layer-by-layer manner. The technique is widely applicable to the fields of medicine and bioengineering. Recently, the technology has even made advancements in the production of cartilage tissue for use in reconstruction and regeneration.

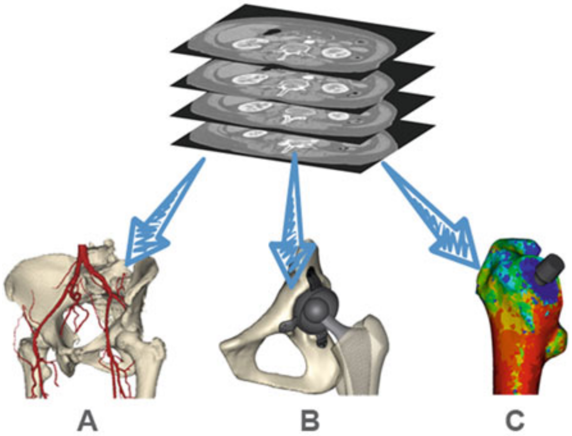


Fig. 6.65 Application of specialised software for DICOM data transfer (*Source* AdTec SME project—UNIZAG FSB)

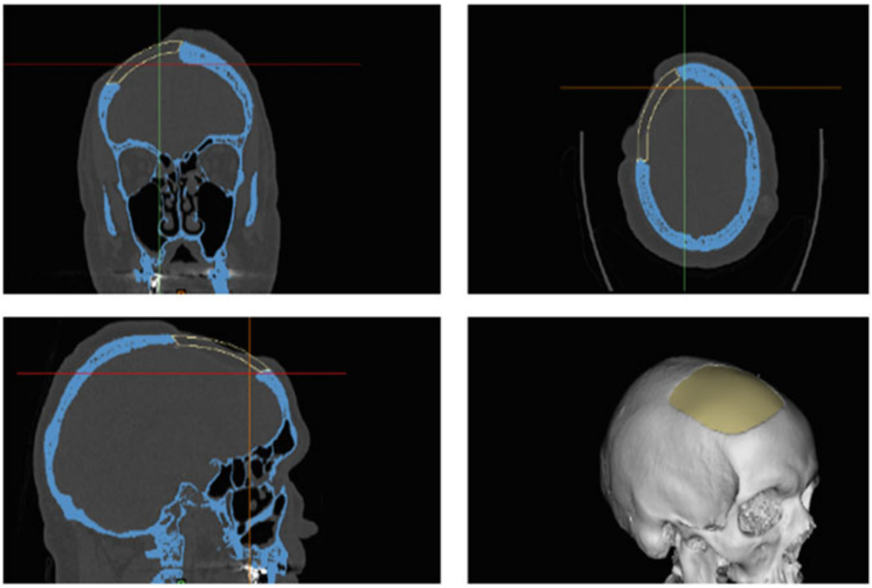


Fig. 6.66 Procedure of DICOM data segmentation (Courtesy of Miodrag Katalenić)

In essence, bioprinting works in a similar way to conventional AM. A digital model becomes a physical 3D object layer-by-layer. In this instance, however, a living cell suspension is utilized instead of a thermoplastic or a resin.

For this reason, in order to optimize cell viability and achieve a printing resolution adequate for a correct cell–matrix structure, it's necessary to maintain sterile printing

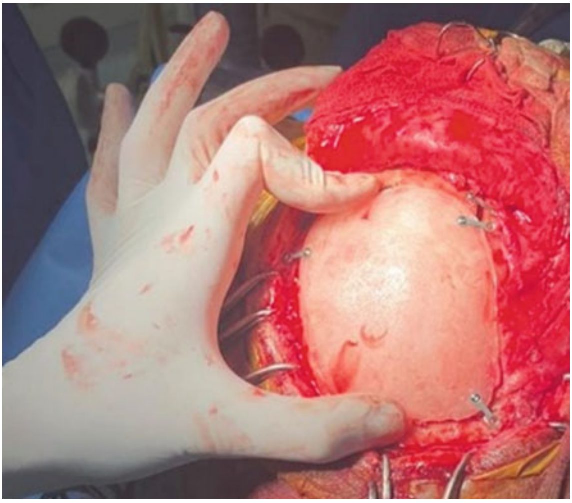


Fig. 6.67 Medical model customisation—surgery and implant fixation (Photo by Miodrag Katalenić)

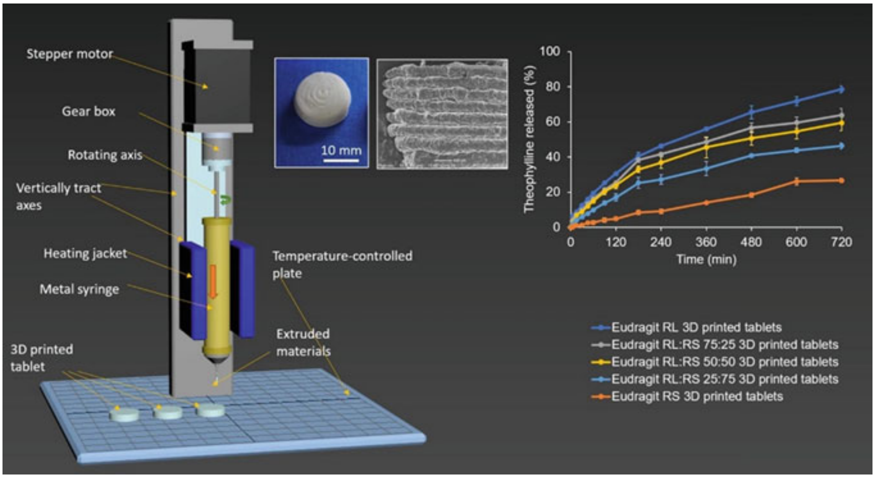


Fig. 6.68 AM of tablets: **a** Set-up for direct extrusion 3D printing. The printer is equipped with a metal syringe surrounded by a temperature-controlled heating jacket. The syringe is fitted with a luer-lock stainless steel needle, and the pharmaceutical ink (compressed powder) is added. The ink is then extruded by a piston pushed by a computer-controlled stepper motor equipped with gear to produce 3D-printed tablet. **b** Top and **c** side photographs of 3D-printed tablets based on Eudragit RL: RS: 100:0, 75:25, 50:50, 25:75, and 0:100. (Abdella et al. [1], 1524,—licensed under CC BY 4.0)

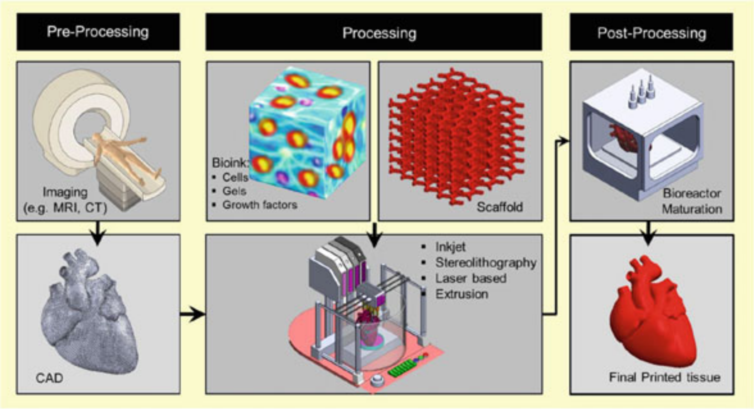


Fig. 6.69 Overview schematic of the bioprinting processes Copyright © 2021 Ramadan and Zourob [63], 648.—licensed under CC BY)

conditions. This ensures accuracy in complex tissues, requisite cell-to-cell distances, and correct output.

The process principally involves preparation, printing, maturation, and application. This can be summarized in the three key steps (Fig. 6.69):

- *Pre-bioprinting* involves creating the digital model that the printer will produce. In first step 3D imaging is necessary to get the exact dimensions of the tissue (CT or MRI scans). 3D imaging should provide a perfect fit of the tissue with little or no adjustment required on the part of the surgeon. In second step a 3D modelling is necessary for generating a CAD model of part to be printed.
- *Bioprinting* is the actual AM process, where bioink is prepared, placed in a printer cartridge and deposition takes place based on the digital model. Bioink is a combination of living cells and a compatible base, like collagen, gelatin, hyaluronan, silk, alginate or nanocellulose. The latter provides cells with scaffolding to grow on and nutriment to survive on. The complete substance is based on the patient and is function-specific. After preparation AM process of depositing the bioink layer-by-layer can start. The delivery of smaller or larger deposits highly depends on the number of nozzles and the kind of tissue being printed. The mixture comes out of the nozzle as a highly viscous fluid.
- *Post-bioprinting* is the mechanical and chemical stimulation of printed parts so as to create stable structures for the biological material. As deposition takes place, the layer starts as a viscous liquid and solidifies to hold its shape. The process of blending and solidification is known as crosslinking and may be aided by UV light, specific chemicals, or heat. Once the printing is complete, the printed structure is then placed in growth media to grow and mature. During this maturation period, the biomaterial loaded into the Bio-ink disintegrates allowing the cells to interact more with each other. This increased cell–cell interaction creates stronger bonds between the cells, which consequently allows for stronger shape formation.

3D bioprinters can be commonly classified into four groups based on their working principles. In this section, we introduced seven types of bioprinters: (1) inkjet-based, (2) extrusion-based, (3) laser-assisted, (4) stereolithography, (5) acoustic, (6) microvalve, and (7) needle array bioprinters.

The greatest importance of bioprinting lies in the resulting tissue-like structures that mimic the actual micro- and macro-environment of human tissues and organs. This is critical in drug testing and clinical trials, with the potential to drastically reduce the need for animal trials.

Here are a few of the main application areas of bioprinting (Fig. 6.70):

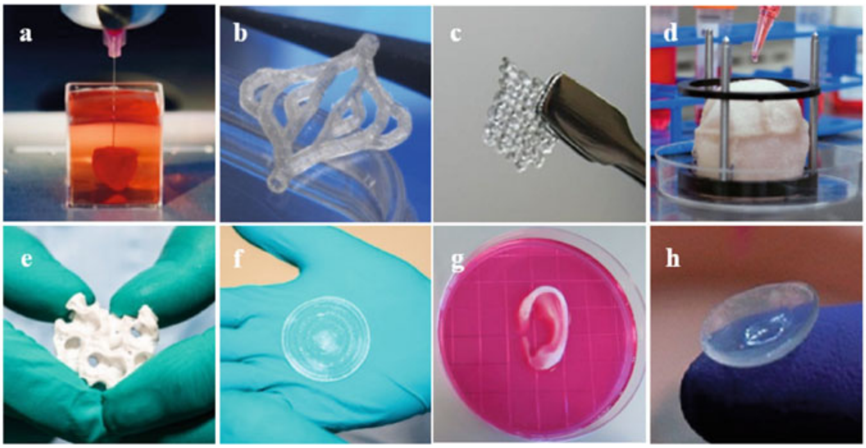


Fig. 6.70 Examples of 3D bioprinted tissues: **a** heart, **b** blood vessels, **c** ovarian cells, **d** bladder, **e** bone, **f** skin, **g** ear, and **h** cornea (Saini et al. [69], 4966.—licensed under CC BY 4.0)

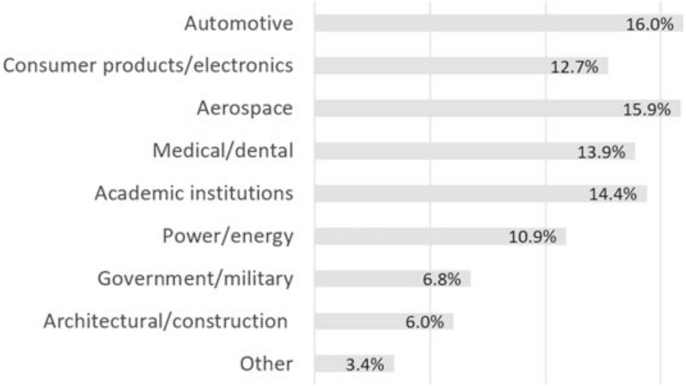


Fig. 6.71 AM Industry sector use percentages (Courtesy Wohlers Associates, generated by Olaf Diegel)

- *Artificial organs* are one of the greatest drivers of the technology due to the high rise of vital organ failure. Availability of AM produced organs helps to solve organ-related issues faster and quicker.
- Development of tissues for *pharmaceutical testing*, when AM, is a more cost-effective and ethical option. It also helps in identifying side effects of drugs and allows recommended drugs to be administered to humans with validated safe dosages.
- *Cosmetic surgery*, particularly plastic surgery and skin grafting, also benefits from the technology. In this particular application, bioprinted skin tissue could be commercialized. Some AM produces tissues are already being bioprinted for research on therapeutic purposes.
- *Bone tissue regeneration* as well as prosthetics and dental applications.

There are various other uses and applications of bioprinting, including producing foodstuffs such as meat and vegetables.

6.4 AM Applications in the Transport Industry

6.4.1 Aerospace Industry

The advantage of additive manufacturing (AM) has made the aerospace industry a substantial user of AM. In 2019 the aerospace sector represented approximately 15% of the overall AM market (Wohlers Report 2020) (Fig. 6.71).

A good example of aerospace industry adoption is the GE GE9X engine, manufactured by GE Aviation, used on the Boeing 777X that was recently certified by the FAA, and is the most fuel-efficient engine in its class (Fig. 6.72). The engine has over 300 AM manufactured parts, including 3D-printed titanium aluminide turbine blades and fuel nozzle tips.

The aerospace sector was an early adopter of AM, with companies such as Boeing and Bell Helicopters using AM to produce non-structural polymer parts since the mid-1990s. Since then, Boeing has installed over 60,000 production parts on 16 different commercial and military aircraft. Other heavy users of AM include Airbus, the European Space Agency, Honeywell Aerospace, Lockheed Martin, NASA, Northrup Grumman, and SpaceX (Fig. 6.73).

While prototypes for aerospace components can be made from a range of plastic materials, the main interest from the industry is in end-use functional parts for aerospace applications, and these must meet stringent requirements. Top-quality flight-certified materials are, therefore, necessary to 3D print functional parts. The selection of flight-worthy materials is still relatively poor but is growing rapidly. There is currently a choice of engineering-grade thermoplastics (Polyethylenes such as ULTEM 9085 and ULTEM 1010, and polyamide compounds such as: Nylon 12

Fig. 6.72 GE9X engine used on the Boeing 777X (Courtesy of Boeing and GE)

Fig. 6.73 Spark igniter manufactured using AM in Inconel 718 (Courtesy of NASA Marshall Space Flight Center, Photo by Olaf Diegel)

FR) and metal powders (high-performance alloys, titanium, aluminium, stainless steel, and nickel-based alloys, for example).

Reduced production times and speed to market

AM can substantially reduce production times and therefore increase speed to market, which can represent competitive advantage to companies. An example of this is the MGTD-20 Gas-turbine engine which is used on a Russian UAV. By using AM the engine was reduced to half the cost and was 20 times faster to produce.

Light-weighting

In the Aerospace industry, the amount of scrap material generated in production is referred to using the buy-to-fly ratio, which is defined as the ratio of the weight of raw material used to manufacture the part to the weight of the final part. With conventional manufacturing titanium aircraft components, for example, may have a buy-to-fly ratio between 12:1 and 25:1. This means that 12–25 kg of raw material is required to produce 1 kg of parts. This means that up to 90% of the material is machined away. In contrast, metal additive manufacturing can reduce this ratio to between 3:1 and 12:1. This is because metal AM typically use only the necessary amount of material needed to create a part, with only a small amount of wastage for support material. It is this comparatively low buy-to-fly ratio that makes AM so critical to the aerospace industry and has seen this industry become its most vital proponent.

Any reduction in overall aircraft weight results in considerable fuel saving, so the lighter parts enabled by AM produce considerable savings for the aerospace companies. In addition, any consumer products that have to be shipped around the world by air benefit by being lighter and both costing less to ship as well as also aiding in reducing the aircraft fuel consumption.

Weight savings are highly relevant to space applications too. Every kilogram that needs to go up to space will cost around US$20,000 to get there so, again, any reduction in weight can result in substantial cost savings. An example of this is the Atos titanium satellite mounting bracket with weight reduced by over 950 g (the original component weighed 1454 g, the new component AM made weighed only 500 g) or a 70% weight reduction over the conventionally manufactured part.

A similar example of such weight reduction is Swiss company RUAG, where they were successful in redesigning a Sentinel satellite bracket for AM in which the minimum stiffness requirements were exceeded by more than 30%, while its weight was reduced by 40% and met all space industry requirements tests.

Part consolidation

Part consolidation is another advantage made possible by AM. Part consolidation is about taking a product that was conventionally manufactured by assembling many simple parts into a product made of much fewer parts. Fewer parts means fewer production steps and labor, fewer chances of assembly faults, fewer joints to lea and, in most case, also represent substantial weight reductions.

Fig. 6.74 Leap fuel nozzle (Courtesy of GE Additive)

An example of this that has seen a lot of press is the GE LEAP engine fuel nozzle, in which the company was able to bring the number of components needed down from 20 to just 1 (Fig. 6.74).

Repairs and maintenance

Although AM largest area of growth is in final-part production, its use in non-direct part production should not be ignored. The last decade has also seen AM being used a great deal for the production of jigs and fixtures, as well as in many production and maintenance tools.

Maintenance and repair are extremely important functions in the aerospace industry. The average lifespan of an aircraft ranges between 20 and 30 years, making maintenance, repair and overhaul, if it can be aided or ameliorated through the use of AM a critical advantage.

6.4.2 Railway Industry

The railway industry is an exciting field to watch when it comes to the adoption of additive manufacturing. Various companies have begun deploying the technology for use in the production of on-demand spare parts. Below follows an account of a small number of operators, but it is reasonable to assume that similar needs and procedures to fulfill these needs are valid also to a greater number of operators. One of the leaders in adopting AM technology is Siemens Mobility Services, which work with the printer manufacturer Stratasys to print maintenance parts for the for the German and UK rail industries.

Dutch Railway is using 3D printing to produce spare parts. Not only is the railway industry growing, but so is 3D printing spare parts for trains, which will also segue into producing end parts. GE Transportation merged with industrial train part manufacturer Wabtec in 2018, which then bought GE's H2 metal binder jetting system with the plan to use it in the production of up to 250 components by 2025. Additive manufacturing enables Siemens Mobility Services to keep original parts available for rail traffic over decades and improve their designs—all based on 3D data and without a need for tools. What Siemens is offering is called Easy Sparovation Part. It opens new possibilities for replacing and modernizing system parts and upgrading vehicles with new components. For example, it provides spare parts equipped with newly integrated functions and significantly fewer individual components. With Easy Sparovation Part from Siemens Mobility Services, spare parts are manufactured as required—based on prepared CAD component data. One of the many advantages is the rapid availability of spare parts produced by AM technology—ideal for sporadic demand that cannot be scheduled, such as parts needed due to accidents or vandalism. Additive manufacturing enables Siemens's customers to incorporate new insights gained from practical applications and materials technology, implement ergonomic improvements, and integrate additional functions—turning spare parts into "improved parts". An example on how Siemens have expanded their business with AM technology is that they have bought two Stratasys Fortus 450mc systems to produce spare parts for its Russian business, just as Siemens Mobility have been awarded a contract to build 13 high-speed Velaro trains for RZD, a Russian train company (2019). Siemens will not only construct the vehicles but maintain and service them over the next 30 years. Siemens has already installed two new Fortus systems in its Siemens Mobility locations in St. Petersburg and Moscow. There, the 3D printers will be used to execute the German multinational's Easy Sparovation Part network, in which 3D print parts from a digital inventory allow for in-house production of spare parts. This contract allows Siemens to service 16 existing trains and an additional 13 over the next 30 years using AM technology. The Fortus 450mc systems may print using industrial-grade materials that can operate in the extreme temperatures that Russia is known for. Stratasys also offers materials that meet the regulatory certifications necessary for 3D printing interior cabin parts.

Raise3D is an innovative manufacturer of AM technology. They visit depots and locomotive repair plants; these visits have produced a list of scarce pieces and other products with delivery problems. This could be discontinued component parts or products with lost documentation. If necessary Raise3D scan parts or create 3D models in software for reengineering. They have recently made a sleeper transfer, which is intended for transfer rail tracks, using their 3D printers.

Also, Bombardier is no stranger to 3D printing. Bombardier Transportation is a global mobility solutions provider. Its lead engineering site for the region Central and Eastern Europe and Israel is in Hennigsdorf, Germany. This location is responsible for pre- and small-series production of mainline and metro projects, as well as design validation to enable the large-scale manufacture of passenger vehicles at other Bombardier Transportation sites around the world. In May of 2019, they adopted the Stratasys F900 3D printer to be used for 3D printing end-use rail parts. They have also stated in the past they would like to install a 3D printer in every engineering department for prototyping parts.

For Bombardier Transportation, the printer F900 marks a shift in service. Bombardier Transportation is now building a digital inventory, ensuring spare part needs are fulfilled on-demand regardless of the train model or its age. By simply storing 3D scans of parts, Bombardier Transportation bypasses the physical storage of parts. When a part is needed, Bombardier Transportation uses the F900 to build it from the digital CAD file. A significant benefit of the F900 is the way it enables the team to quickly recreate digital parts into certified train-ready parts, leading to fast and direct service for its customers. According to Marco Michel, Vice President Operations at Bombardier Transportation, the integration of Stratasys additive manufacturing at the Hennigsdorf-based facility has enabled the company to manufacture certain customized spare parts on-demand via digital inventory at significantly lower cost.

CAF, a Spanish manufacturer of railway vehicles, equipment, and buses, has also succeeded in using 3D printing for production of spare parts and functional components. Since September 2016, CAF is said to have produced around 2 400 3D-printed parts for use in its rolling stock, including cup holders, radio brackets, window frames, wiper covers, and door supports. The company also uses large-scale 3D printing to produce external parts measuring up to several meters. Among such parts are front-end components, 3D-printed for an Urbos tram. CAF names the ability to produce parts, with different dimensions and complex geometries, as a key benefit of 3D printing technologies. The company says it helps them to break the dependency on molds and original patterns when producing components, reducing the time to market for a new part.

AM technology provides SJ (Swedish Railways) with a simpler production, cheaper spare parts, and higher quality. The AM effort at SJ is an important part in their new program for digitalization. The program is intended to strengthen long term competitiveness by providing better punctuality of the trains and more satisfied customers. The first 3D-Printed spare parts at SJ are the further development of a toilet paper holder in plastics for the 3000-trains, air vents, electrical sockets, and a toilet door lock in metal. SJ focus on spare parts that are no longer available on the market that are expensive to replace. Anders Gustavsson, one of the heads of project managers at SJ claims that more and more spare parts will be printed for the

SJ trains. Anders Gustavsson argue that AM has an enormous potential from a range of different perspectives. He asserts that lead times, store holding, design, logistics and administration will all be positively affected. The most importantly for SJ is however to keep all the trains rolling. AM technology will contribute to this end by offering more effective maintenance and more "robust" trains. So far, only less critical parts have been printed. But SJ has recently started to consider printing also more challenging parts. The first part is a box lid for a bearing that must pass a thorough safety test. SJ collaborates with, for example, Postnord Stålfors who delivers AM services. SJ is also a part of an international network of leading digital enterprises where knowledge exchange drives the development of AM technology even further. Andreas Stjernudde, IT project leader at SJ, states that this is necessary as the 3D industry must work harder to lower the cost of 3D printing to make the technology competitive enough for a greater number of companies.

6.4.3 Maritime Transport Industry

The maritime transport industry has not adopted additive manufacturing at the same rate as aerospace or the automotive industries, but is gaining momentum on their own terms. The aerospace industry and automotive industry have had strong incentives to adopt early AM technologies, among others, the need for lightweight parts. The maritime transport industry is still discovering the different usages and benefits it can get from the technology. As of November 2020, the world fleet value is estimated to be worth USD 950 billion with an average annual capital allocation to new vessels estimated at USD 88.7 billion. The maritime transport industry, as virtually untouched markets, are very promising segments for additive manufacturing.

The structure of this industries is quite specific, especially the ship industry. It relies heavily upon a system of classification and certification by third parties, the classification societies, for ships to be sold, registered and insured. This is indispensable to assure that ships can sail months at sea under harsh conditions, and to assure the safety of persons and goods. Introduction of new technologies, materials and components in the ship industry depends on this classification and certification system. The classification societies have been central to the ship industry under a long time. The first classification society, Lloyd's register (LR) has been established in 1760, Bureau Veritas (BV) in 1828, American Bureau of Shipping (ABS) in 1861, Registro Italiano Navale (RINA) in 1861, Det Norske Veritas (DNV) in 1864, Germanischer Lloyd (GL) in 1867. All these classification societies still exist today (GL has merged with DNV in 2013 to form DNV GL; the society changed its name to DNV in March 2021). There are exceptions to this general scheme, for example components not critical to safety do not generally need to get certified, but the pace in which the industry is introducing AM is largely dependent upon the possibility to certify materials, components and products.

The boat industry has a more diverse organization, depending on the size of the boat and on the flag state. Very small boats or racing boats do not typically need such types of certifications. But in Europe, for example, pleasure boats from 2.5 to 24 m must comply to the Recreational Craft Directive, which imposes boats to be CE marked by a notified body, some of them being classification societies (RINA, DNV, BV). Safety concerns, cost and a conservative mindset in some boat segments are also delaying the introduction of AM.

The classification societies have started working on the challenges and benefits of AM very recently. LR and DNV, for example, started their investigations in 2014. However, the classification societies and the industry in general have worked systematically and at high speed. Relatively quickly, the first certification guidelines for the additive manufacturing technology have been published: LR published its *Guidance notes for Additive Manufacturing certification* in January 2016, DNV guidelines are from November 2017, and ABS guidelines are from September 2018. Since then, 3D printed products have started to be certified, along with manufacturing facilities. The latter is important because it accelerates the certifications of products manufactured in these sites. Examples of certified manufacturing facilities are AML Technologies (Australia) that became the first wire-arc additive manufacturing (WAAM) facility to get an LR certificate in 2018, and Thyssenkrupp, which became the first company certified for additive manufacturing and post-processing of austenitic stainless steel parts by DNV in summer 2019. The whole industry in general is multiplying research and joint industrial programmes to ease the development and diffusion and of the AM technology. Especially Singapore is aspiring to become an AM technology hub and has invested heavily in this segment. Most classifications societies and major industrial actors have AM facilities in the city-state. All in all, the ship industry strategic and disciplined work might well become a textbook case of a progressive, but systematic and fast, deployment of the AM technology, and is worth following up.

Industrially commercialized products are thus starting to appear, but most of the current products, even if fully functional and installed on ships, are part of feasibility study projects. The main focus of the industry is currently on spare and replacement parts. Spare and replacement parts represent USD 13 billion a year and older vessels suffers from part availability. In a market feasibility study performed by major actors of the industry and partly funded by Singapore, 100 parts were shortlisted and their potential for 3D printing analyzed, among the 600,000 parts ordered by the industrial partners in the last three years. This gives a direction for further application of the AM technology. Such inventories happen worldwide. U.S. Navy's Naval Sea Systems Command (NAVSEA), for example, has approved a total of 182 3-D printable parts (October 2020) and more than 600 more are undergoing engineering review.

The first certified 3D-printed propeller (verified by BV) was manufactured in 2017. A replacement part, it was developed by Promarin, manufactured by The Rotterdam Additive Manufacturing LAB (RAMLAB), in collaboration with Autodesk, Damen Shipyard Group and BV. It was fabricated with the WAAM technique, which is in essence a welding technique where the welding material are melt on top of each others layer by layer (Fig. 6.75). The printing took ten days; the 1.2 mm filament used was a nickel-aluminium-bronze alloy. Weighing 180 kg after post-processing

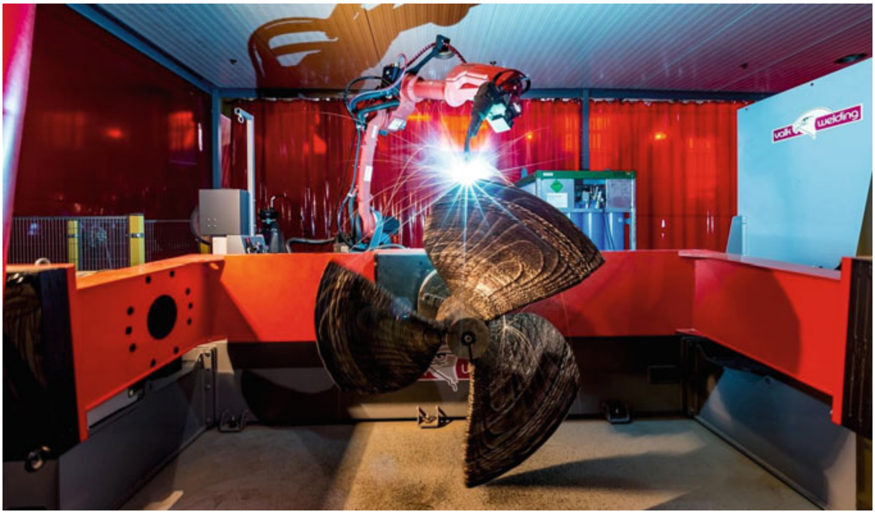


Fig. 6.75 Manufacturing of the WAAMpeller (Courtesy of RAMLAB)

(Fig. 6.76), it is installed on a Damen Stan Tug 1606, a 15.5 m long, 5.5 m broad tug with a 16-ton bollard pull (Fig. 6.77).

Wilhelmsen group, a products and services company for the merchant fleet, has partnered with Ivaldi group, a 3D printing company focusing on the marine industry, to redesign spare parts for its customers in an early adopter program to assess the possibilities and gains of AM for different components. Thus, a handwheel made of cast iron has been re-designed in polyamide/nylon. Polymer handwheels present the advantage of preventing damage to valve stems compared with traditional handwheels. Another product is the scupper plug, used to close drainage holes to prevent oil or contaminant spills. They do not exist in standard forms. 3D printed scupper plugs as spare and replacement parts have been developed for Berge Bulk, a major

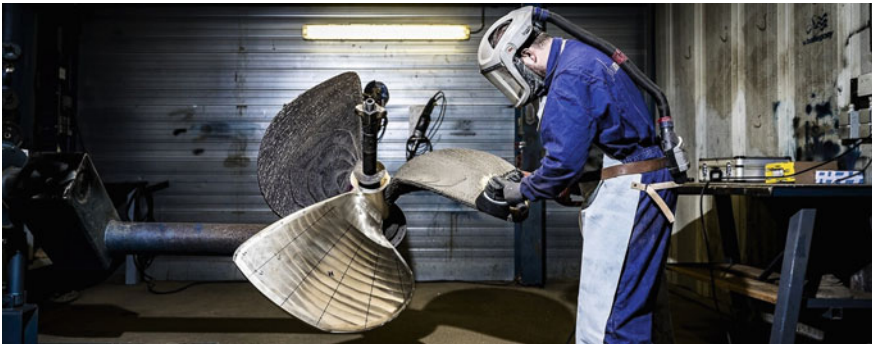


Fig. 6.76 Post-processing: grinding the WAAMpeller (Courtesy of RAMLAB)

Fig. 6.77 The WAAMpellers on the Damen Tug (Courtesy of RAMLAB)

dry bulk cargo owner. All the elements of the part had to be redesigned, the biggest challenge was making the insert expand without collapsing. The first scupper plugs have been delivered on the *Berge Mafadi* in 2020, see Fig. 6.78. A 3D pattern for sand casting of a guide bar has also been developed by Wilhelmsen group and Ivaldi group (Fig. 6.79). According to, the original manufacturing cost of the guide was USD 2000 with a lead time of twelve weeks; the current manufacturing cost is USD 1225 for a lead time of four weeks. The 3D printed pattern cost is of USD 22.74 (wooden pattern cost: USD575.00). All these components have showed shorter lead-time and cost benefits.

Sembcorp Marine, a large engineering marine company, and 3D Metalforge, a well-known metal printer manufacturer, together with the classification society ABS, have developed and installed working 3D-printed mechanical parts aboard the oil tanker *Polar Endeavor* (shipowner ConocoPhillips Polar Tankers). According to ABS, the replacement parts (see Fig. 6.80) are of higher quality than conventionally manufactured products.

The number of 3D printed spare parts in use is quite small and the number of new parts developed with 3D printing is even smaller. But not less impressive. One

Fig. 6.78 Left: Damaged scupper plug. Right: 3D printed scupper plug (Courtesy of Wilhelmsen group and Ivaldi group)

Fig. 6.79 Left: 3D pattern (bottom)/wood pattern (top). Right: Guide bar (Courtesy of Wilhelmsen group and Ivaldi group)

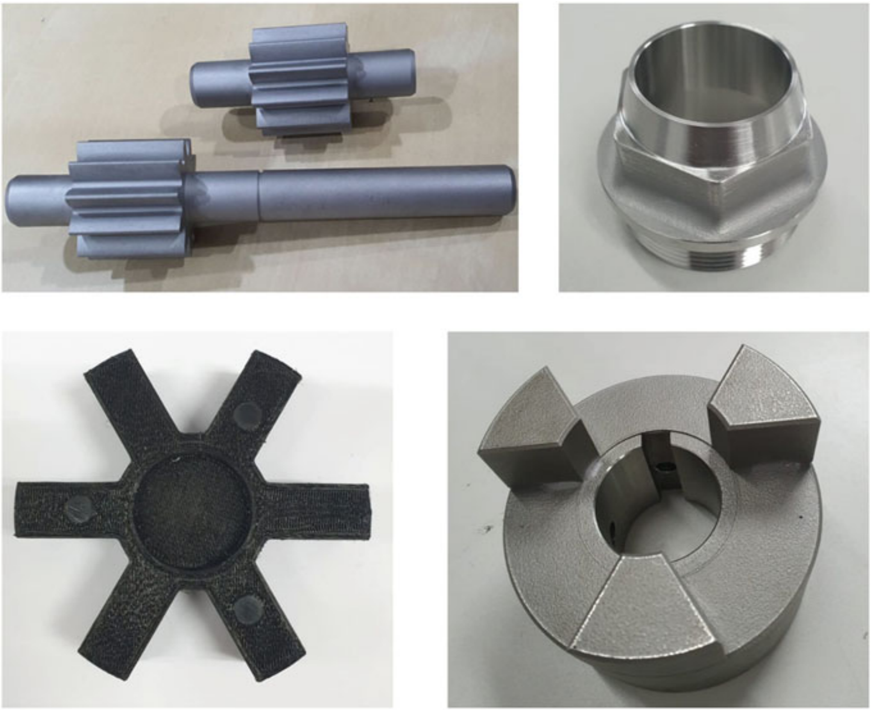


Fig. 6.80 Top left: Gear set with shaft for a centrifugal pump. Top right: nozzle for a combined brine/air injector. Bottom: full flexible coupling for an effluent pump (Courtesy of Sembcorp Marine and ConocoPhillips Polar Tankers Inc.)

example is the hull of the TAHOE T16, from White River Marine Group, a five-meter-long speedboat. 3D printing was used to create a pattern onto which the hull mold was cast. The hull mold was then used to manufacture several hulls. This is the same manufacturing principle as that of the fabrication of silicone molds, see Sect. 6.1.1. The pattern of the T16 hull has been manufactured with the help of a large-scale additive manufacturing technique (SLAM), by Thermwood. The development of the pattern has been done in collaboration with Techmer PM and Marine Concepts. The pattern, about 4 cm thick of 20% carbon fiber filled ABS was manufactured in six sections (Fig. 6.81). The printing took about 30 h. After printing, these sections were bonded together (Fig. 6.82) and machined. The trimmed pattern, with a weight of about 1500 kg, was sanded and polished. The fiberglass mold was then cast on the pattern (Fig. 6.83). The whole manufacturing process took about ten days. According to Thermwood, the process could be accelerated with the use of a vertical layer printer. A vertical layer printer, as the name indicates, prints the layers vertically instead of horizontally. This allows for a printing in one part instead of sections.

New parts developed with additive manufacturing in the ship industry are following a classical learning process, starting with re-design of existing products to take advantage of the cost effectiveness of AM for small, and rapid tooling, such as the hull patterns. The other advantages of AM, such as form freedom, reduction of components, have been very scarcely explored. The racing boat segment,

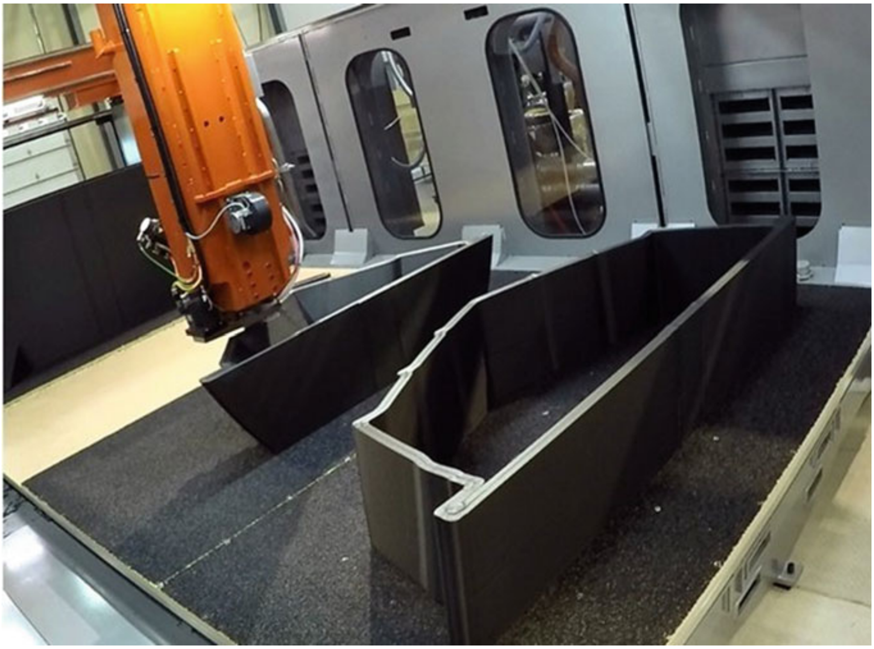


Fig. 6.81 Thermwood LSAM (3 m × 6 m) machine printing two of the six sections (Courtesy of Thermwood)

Fig. 6.82 Boat hull pattern after bonding together and before machining (Courtesy of Thermwood)

however, has some showcase of advanced 3D-printed components. Renishaw, a global engineering company, has developed manifolds for the Land Rover BAR, an America's Cup class yacht. The AM-based manifold is smoothing the hydraulic fluid flow decreasing power loss compared to a manifold manufactured with conventional methods (Fig. 6.84). Several other components of the Land Rover BAR have been designed with the AM process in mind (Fig. 6.85). The Land Rover BAR racing catamaran was one of the five participants to the 2017 Louis Vuitton America's Cup Challenger Playoffs, held to determine the challenger in the 2017 America's Cup (Fig. 6.86).

After the 2017 America's Cup Renishaw went on to work with INEOS TEAM UK in the 2021 America's Cup. Renishaw has developed, among several AM-based components, a mast ball for the T5 test boat (Figs. 6.87 and 6.88). The mast ball function is to transmit power from the rig into the foiling hull. Topological optimization was used in the design process, resulting in a stronger component than the original while weight was decreased by 20%.

As the ship and boat industries are rapidly adopting the AM technology, this review of current industrial applications is to become rapidly obsolete. Therefore, a glimpse of the very near future applications, for at least the most obvious application

Fig. 6.83 Removing fiberglass mold from boat hull pattern (Courtesy of Thermwood)

Fig. 6.84 Demonstration Land Rover BAR metal AM hydraulic manifold (Courtesy of Renishaw—© Copyright Renishaw plc. All rights reserved)

of 3D printing, is also presented. First, 3D printing is not only to be used for ships, but can also be used in ships. In the short run, printers on board could be used for printing simple spare parts. In the long run, they could be used as a mobile manufacturing centers, printing on the go or on sites where parts are difficult to obtain or are urgently needed (humanitarian crises or military operations). There are already 3D printers on ships: the *USS John P. Murtha*, a 200-m-long transport dock, has printers installed on board, with the possibility to print plastic parts. Maersk Tankers had also installed

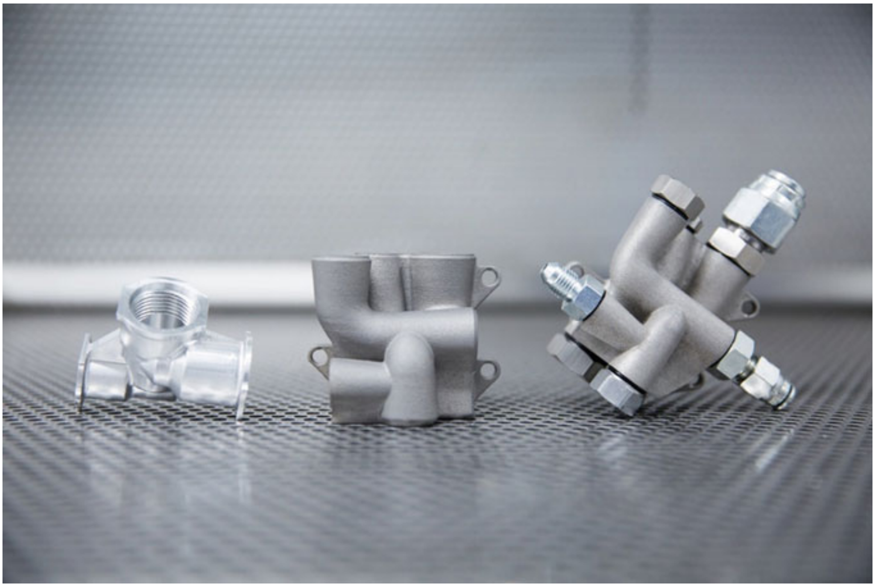


Fig. 6.85 Metal 3D-printed hydraulic system parts made by Renishaw for the Land Rover BAR yacht (Courtesy of Renishaw, credit: Harry KH)

Fig. 6.86 The Land Rover BAR racing catamaran (Courtesy of Renishaw, credit: Harry KH/Land Rover BAR)

nine tabletop printers on six ships and two rigs to test the possibility of printing spare parts, as part of a project from Green Ship of the Future, funded by the Danish Maritime Fund in 2017–2018. In this project, IP rights challenges were addressed, the printers being equipped with an encryption technology that ensured that the part models could not be re-used elsewhere. The constraints of a printer at sea (vibrations the rolling movements of the ship), the need for expertise and materials are currently limiting this technology to specific usages such as simple, non-critical parts with no

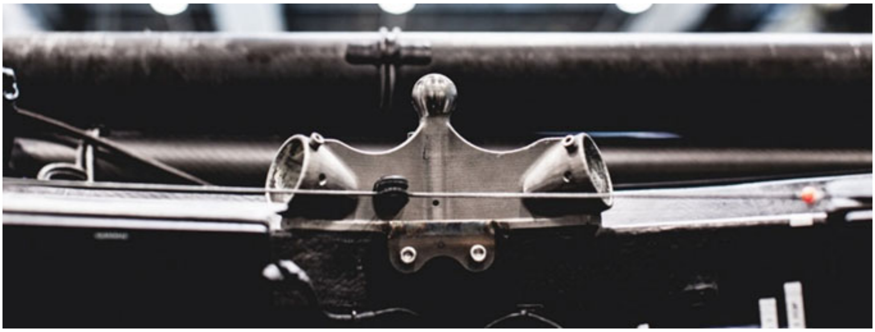


Fig. 6.87 T5 mast ball (Courtesy of Renishaw, credit: Harry KH/INEOS TEAM UK)

Fig. 6.88 The T5 test boat (Courtesy of Renishaw, credit: C Gregory/INEOS TEAM UK)

Fig. 6.89 DIN rail for relays and flexible couplings for IGG DO pump (orange is original), 3D printed on board (Courtesy of Maersk Tankers and Green Ship of the Future)

need of expertise. The following figures show examples of products printed on board during the project (Figs. 6.89 and 6.90).

The printing of molds for large ships (yachts) is also nearly feasible, such as illustrated with the figure below. Figure 6.91 shows two 1.5 m sections (screwed together) of a yacht hull mold, developed and manufactured by Thermwood. The material used is carbon fiber reinforced ABS thermoplastic.

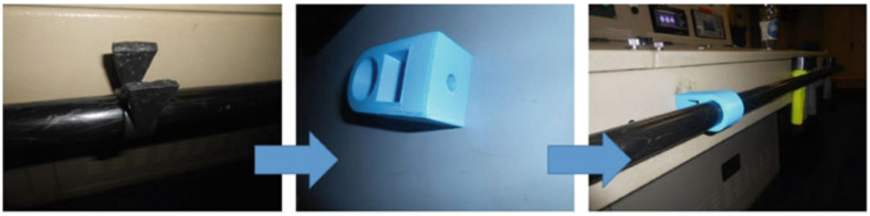


Fig. 6.90 Rail bracket replacement, 3D printed and installed on board (Courtesy of Maersk Tankers and Green Ship of the Future)

Fig. 6.91 Three-meter section from a 15-m-long yacht hull mold (Courtesy of Thermwood)

Last but not least, several boats have been directly printed. These are prototypes, still under test or development (one big concern is delamination of the printed layers), but quite near a fully functional product. The biggest one-piece printed boat is *3Dirigo* (Guinness World record), developed by Navatek, a ship design company, on the model of the Seablade 25, and manufactured in September 2019 by the UMaine Advanced

Fig. 6.92 3D printed boat from RISE and Cipax (Courtesy of RISE, Photographer Anna Hult AB)

Structures and Composites Center of the University of Maine. *3Dirigo* is 7.6 m long for 1350 kg. She was printed in plastics with 50% wood in 72 h with LSAM. She has been tested at the Alfond W^2 Ocean Engineering Laboratory, a facility equipped with a multidirectional wave basin and a wind machine. Another one-piece boat has been developed and manufactured by RISE Research Institute of Sweden, in collaboration with Cipax and other partners. Cipax is the company that owns the boat model, a Pioner 14 Active Dark Line. The boat is 4.2 m long. Seaworthy, she was launched in December 2020 in Gothenburg (Fig. 6.92). A significant advantage of a printed boat is the possibility to customize her for specific groups of users, such as law enforcement or fire service. There are still some challenges before 3D printed boats be able to fulfill the same specifications as conventionally manufactured boat. One is for example that the material for 3D printing is denser, which may require some specific requirements for maintaining floatability when the boat is full of water.

As an alternative to one-piece boats, Moi Composite, a company based in Italy, has developed a boat, the *MAMBO*, whose hull and deck consists of 50 printed parts (Fig. 6.93), made of continuous fiberglass and thermosetting vinyl ester resin, which have then been adhesively bonded and reinforced (laminated) fiberglass/polyester layer cored with PVC, before being sanded, primed and gel-coated. The continuous fiber manufacturing technology (CFM), patented, makes use of a robot depositing continuous fibers impregnated with thermosetting resin that is cured immediately (Figs. 6.94 and 6.95). Officially unveiled in October 2020, the *MAMBO,* 6.5 m long and of weighing 800 kg (1200 kg all equipped), is fully seaworthy, reaching a speed up to 26 knots (48 km/h). With curvatures that are impossible to manufacture conventionally, and no division between hull and deck, she is a telling example of the AM free-form possibilities for functionality and aesthetics (Fig. 6.96).

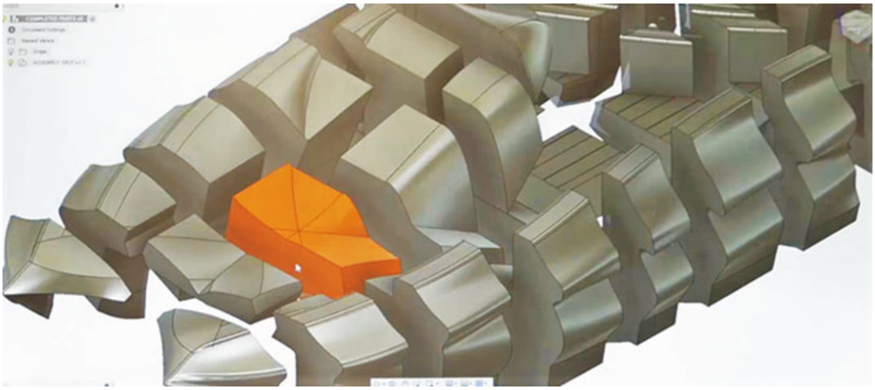


Fig. 6.93 CAD model of the boat section (Courtesy of Moi Composites)

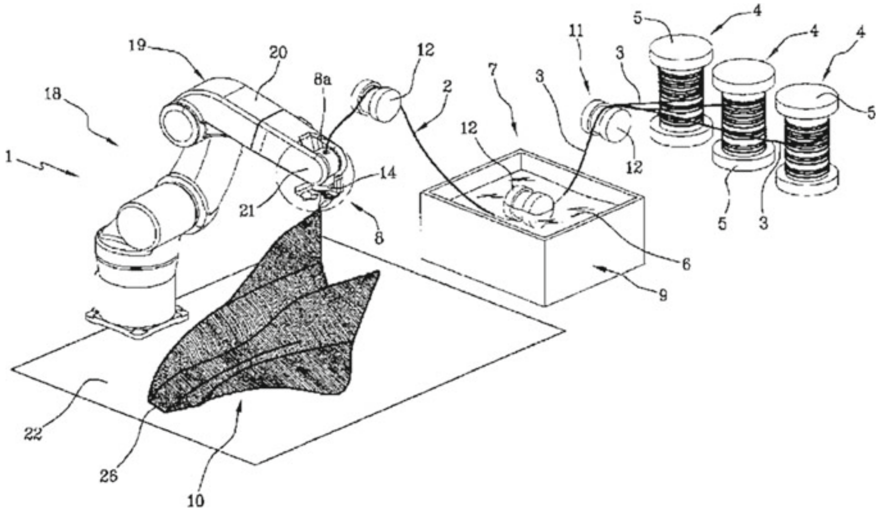


Fig. 6.94 The CFM technology

6.4.4 Automotive Industry

AM is rapidly growing technology that enable designers to create rapid prototypes as well as complex designs, which would not have been possible through traditional manufacturing processes. 3D printing in the automotive industry is expected to reach a market value of 2.5 billion dollars in the next 3 years. The novel technology provides innovative designs and design freedom. AM is used for testing, manufacturing, and assembling automotive parts and components with higher efficiency, optimization, and cost-efficiency.

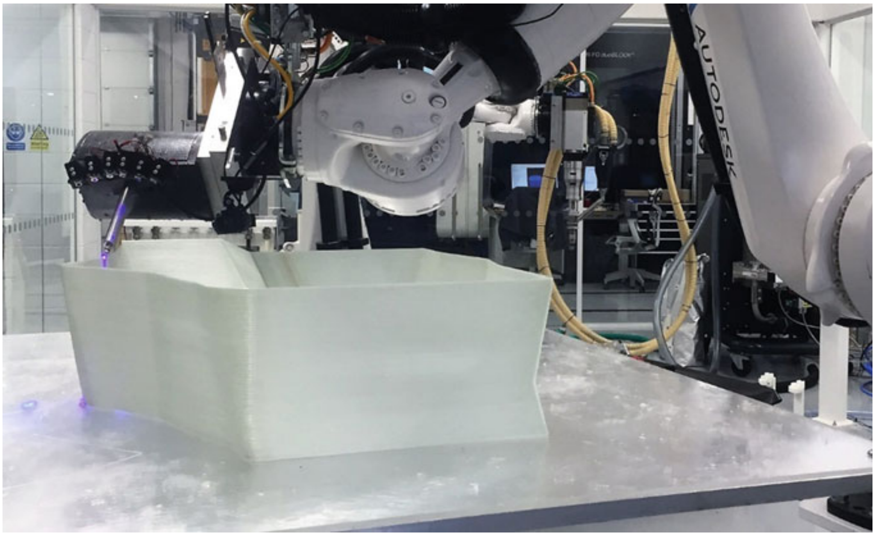


Fig. 6.95 Robot equipped with the CFM technology, printing of one boat section (Courtesy of Moi Composites)

Fig. 6.96 The MAMBO at sea (Courtesy of Moi Composites)

The role and importance of the additive manufacturing in automotive design and manufacturing stages can be split in 5 stages: Design, Validation, Pre-production, Production, and Customization (Table 6.3). The designs in the automotive industry usually start out as scale models that show the shape of a vehicle. The right models allow the design to progress smoothly and exhibit the general form of a concept. AM prototyping is common in the automotive industry. Moreover, AM enables the automotive industry to produce customized car parts quickly at low cost.

AM technology is not new to the automotive industry, it was recognized as an opportunity three decades ago. The developed and manufactured components range

Table 6.3 AM in different phases of automotive life cycle

Design	Designs in the automotive industry often begin as scale models showcasing the form of a vehicle. These are often also regularly used for aerodynamic testing. Accurate models allow design intention to be clearly communicated and showcase the overall form of a concept
Validation	AM is used a lot for different prototyping in the automotive industry. From a full size parts printed with low cost fused deposition modelling (FDM) to a detail, full color components. Some AM engineering materials allow testing and validation
Pre-production	AM is used most for the production of low cost rapid tooling for injection molding, thermoforming and jig and fixtures. Tooling can be quickly manufactured at a low cost and then used to produce low to medium runs of parts. This validation mitigates the risk when investing in high-cost tooling at the production stage
Manufacturing	AM is a viable option for many medium-sized production runs, particularly for higher-end automobile manufacturers with limited production numbers
Customisation	Parts can be tailored to a specific vehicle (custom, lightweight suspension arms) or driver (helmet or seat). AM enables part consolidation and optimize topography of many custom automotive components

from prototypes to small plastic mountings and highly complex metal chassis parts. Car manufacturers are always looking for new ways to reduce their product's weight. A lighter car consumes less fuel, which makes it more environmentally friendly. Lighter structures can be achieved with design patterns such as lattices or reduce the number of parts with optimized design of the components.

By eliminating the need for new tooling and directly producing final parts, AM cuts down on overall lead time, thus improving market responsiveness. Furthermore, AM-manufactured lightweight components can lower handling costs, while on-demand and on-location production can lower inventory costs. Finally, AM can support decentralized production at low to medium volumes. All these AM capabilities combined allow companies to drive significant change within the supply chain—including cost reductions and the improved ability to manufacture products closer to customers, reduce supply chain complexity, and better serve consumer segments and markets without the need for extensive capital deployment.

The most common uses of additive manufacturing in the automotive industry are still prototyping, tooling, jigs and fixtures. However, the last two decades delivered a big progress, and additive manufacturing in automotive is expanding beyond these applications. Here are several examples from well-known automakers using additive manufacturing, their efforts, goals and boldest applications.

Examples of additive manufacturing

BMW has several implemented printed parts to their vehicles such as the convertible's roof bracket which has a unique complex shape that is very hard to produce using traditional methods. BMW demonstrated the first installation of brake calipers with bionic design. The calipers are 30 per cent lighter than conventional components and were manufactured using a metallic 3D printing process. This masterpiece

Fig. 6.97 Developed by Bugatti: This eight-piston monobloc brake caliper is the world's first brake caliper to be produced by 3-D printer and also the largest titanium functional component produced by additive manufacturing. (*Image credits* (© 2018 Bugatti Automobiles S.A.S.)

is carried along by 20" BMW Individual light alloy wheels in 730i V-spoke design. Another application of AM technology is the brakes of the new BMW M850i Coupe Night Sky Edition.

The brake calipers of the Chiron sport car are produced using bionic principles on the basis of a natural model (Fig. 6.97). The new architecture combines minimum weight with maximum stiffness. The inspiration for the design and mode of operation of the brakes was taken from motorsports. This particular titanium alloy, with the scientific designation of Ti6AI4V, is mainly used in the aerospace industry, for example for highly stressed undercarriage and wing components or in aircraft and rocket engines. The material offers considerably higher performance than aluminum, it has a tensile strength of 1,250 N/mm^2. The brake caliper (410 × 210 x 136 mm) weighs only 2.9 kg; the weight was reduced by about 40%. The high-performance 3-D printer opens up the possibility of design and manufacturing complex structures which are significantly stiffer and stronger than would be possible with any conventional production process.

Audi is dedicated to the manufacture of sports cars. The PolyJet technology allowed Audi to develop and evaluate different prototypes before producing the parts of a vehicle such as wheel covers, grilles, door handles or even rear light cabs, which are usually made of transparent plastic (Fig. 6.98). With 3D printing, they were able to speed up design, meeting the demands of their customers, and creation of final parts.

Additive manufacturing has a key role in motor sport, enabling the design of lighter, stronger and more efficient parts in a much shorter time frame. Ferrari use an EOS machine and titanium powder. AM increases the number of possible iterations

Fig. 6.98 The PolyJet technology allowed Audi to develop and evaluate different prototypes faster. The J750 3D enable printing of transparent plastic such as rear light cabs (*Image credits* Audi)

and accelerate its prototyping phase. The manufacturer has also designed 3D printed brake pedals with a hollow structure.

General Motors has designed a 3D-printed seat support in stainless steel for its future electric cars. The seat support would consist of only one part, as opposed to 8 different parts using conventional methods, would be 40% lighter and 20% stronger (Fig. 6.99). Manufacturing times are also reduced as there is no assembly phase at all.

Lamborghini argues that AM offers more than just saved costs and rapid production. AM represents endless opportunities of customization. Lamborghini's Sian Roadster customers are able to have their initials integrated in the design of this car element. An example, the AM technology is used to make a textured fuel cap with the Urus label and a clip component for an air duct (Fig. 6.100). No further post-processing is required after the print.

Volvo Trucks produces many jigs and tools using AM, slashing the tool turnaround times by more than 94%. Previously these tools were produced in metal using traditional manufacturing methods. The production plant's overall efficiency and flexibility was improved, helping meet delivery times while reducing waste and costs.

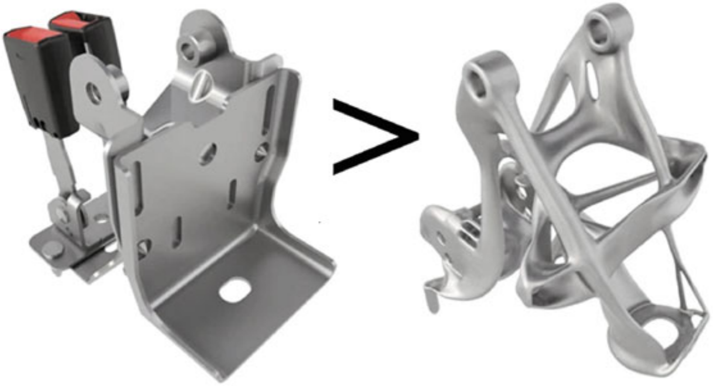


Fig. 6.99 3D-printed seat support in stainless steel for the General Motors future electric cars; designed in cooperation with Autodesk (*Image credits* General Motors and Autodesk)

Fig. 6.100 Lamborghini Urus Fuel Cover Cap digitally manufactured in EPX 82 epoxy resin (*Image credits* Lamborghini)

Different production tools include a range of different durable yet lightweight clamps, jigs, supports and even ergonomically designed tool holders that ensure a more organized working environment for operators.

Mercedes uses AM for truck parts made of metal. The components are more resistant, and cost-effectively production is enabled even for discontinued parts in small quantities. Mercedes is the first company to focus on 3D printing of spare parts for trucks.

Michelin, presented its AM prototype tire called UPTIS (Unique Puncture-proof Tire System), these tires have been designed to be airless in order to reduce the risk of flat tires and other air loss failures that result from puncture or road hazards. The wheel design was inspired by nature, with a honeycomb structure, and using only organic materials (Fig. 6.101). It gives strength to the wheel, as well as a very good resistance.

Porsche 3D printed engine pistons for the Porsche 911 GT2. The optimized pistons are 10% lighter than the traditionally manufactured ones. Porsche used a special aluminum alloy in order to obtain the best properties. Porsche dedicated to old and classic vehicles is using additive manufacturing for small series of spare parts. All parts meet the requirements in terms of fidelity, from a technical and visual point of view.

Renault Trucks Lyon Powertrain Engineering Department focused on using metal additive manufacturing for creating a prototype DTI 5 Euro-6 engine. Rocker arms and camshaft bearing caps were manufactured by metal 3D printing and successfully bench-tested for 600 h inside a Euro-6 engine (Fig. 6.102). The weight of a four-cylinder engine was reduced by 120 kg or 25%. The tests proved the durability of engine components made using AM. The number of components in the DTI 5 engine has been reduced by 25%, making a total of 200 fewer parts (Fig. 6.103).

Fig. 6.101 A prototype of Unique Puncture-proof Tire System (UPTIS) (*Image credits* MICHELIN—https://www.michelin.com/en/innovation/vision-concept/)

Fig. 6.102 A rocker arm manufactured by 3D printing on a bench test inside a Euro 6 engine (*Image credits* Renault)

Automotive parts often require internal channels for conformal cooling, hidden features, thin walls, fine meshes and complex curved surfaces. AM allows for the manufacture of highly complex structures which can still be extremely light and stable. One major benefit of additive manufacturing is that all printed parts can be post-processed in order to create a watertight and moisture resistant barrier. Part consolidation is a significant factor when considering how AM can benefit the reduction of material usage, thereby reducing weight and in the long run, cost.

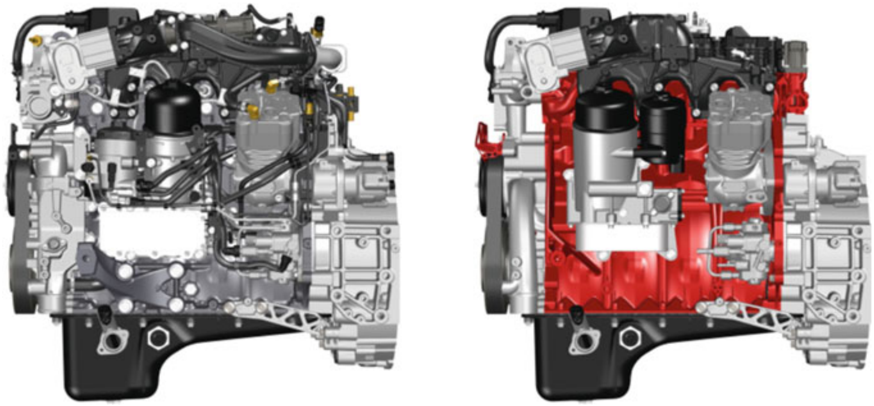
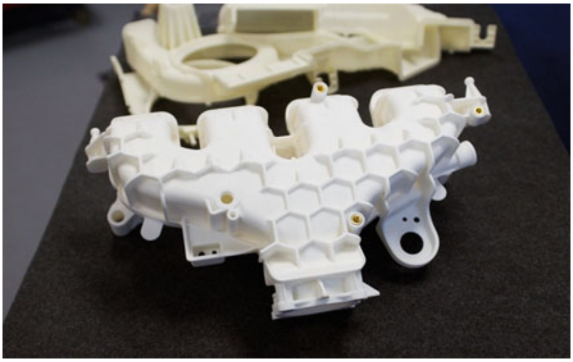


Fig. 6.103 Left: A conventional Renault Trucks DTI 5 Euro 6 engine, 841 parts. Right: the same engine exclusively designed using 3D metal printing to reduce weight and number of components (*Image credits* Renault)

By using PBF-LB/P to manufacture non-structural low volume parts for performance racing, highly optimized, and complex structures can be designed. SLS enables design in variable wall thicknesses and increase the strength to weight ratio through the application of structurally optimized surface webbing (Fig. 6.104).

Daimler AG has fully integrated 3D printing technology into the development process and series production for its commercial vehicles segment. Daimler Buses used 3D printing technology to quickly fulfill customers' individual wishes, replacement parts, and small series production. It takes a few days, from idea and design to production and delivery, to complete the entire process, which will be very economical for customers ordering small series and batch sizes from 1 to 50 units. Customers all over the world can quickly reorder any 3D printed part by looking up the specific part number, which can be found in the Daimler Buses order code lists and replacement parts catalogs. The component features multiple parts, including the lid and the handle, hinges and assembly clips, and interior compartments.

Fig. 6.104 A complex, functional ducting design printed in using PBF-LB/P nylon (*Image credits* Biehler 2014).



Formula Student Germany set out to design and build a reliable, lightweight axle-pivot (knuckle) with high rigidity (Fig. 6.105). The knuckle needed to withstand the dynamic loads that racing cars are subjected to while also reducing the overall weight of the car. The resulting design was a topographically complex single component, only capable of being manufactured using AM technologies. The final design was 35% lighter than the original design and improved rigidity by 20%.

3D Printing and the electric vehicles

As the industry moves away from the internal combustion engines toward electric vehicles, 3D printing rises as a solution that can speed up development and radically change the way we look at the design of car components. In electric vehicles, reduced weight reduces energy consumption and thus increasing driving range (Fig. 6.106).

The autonomous shuttle marks a substantial milestone in using 3D printing for EV production. The parts such as knuckle, upper control arm and a brake pedal, were

Fig. 6.105 The final optimized knuckle design (*Image credits* Uni Stuttgart, 2012)

Fig. 6.106 Arcimoto's FUV feature 3D-printed components. The use of 3D printing helped to reduce the weight of the vehicles (*Image credits* Arcimoto)

redesigned for 3D printing using generative design tool, achieving weight savings of between 34 and 49 per cent.

Applications of Additive Manufacturing in Automotive Electronics

Aside from mechanical components, additively manufactured electronic components are providing new ways to network vehicles, gather automotive data, and produce smart components. Additive manufacturing systems built for 3D printed electronics can reduce the costs and development time by embedding sensors directly into mechanical components and the structure of vehicles. Embedded sensors provide higher reliability and longer lifetime.

Power management, distribution, and charging systems for electric vehicles are a few examples of critical power electronics systems that can benefit from additive manufacturing. The adaptability of additive manufacturing processes allows designers to integrate complex components into simpler and lighter designs and print them as a single unit. This reduces material waste, decreases manufacturing time, and reduces the overall weight of the component. All of these are significant benefits for electric vehicles, helping reduce costs for consumers and improving fuel efficiency.

Additive manufacturing of Ti-45Al-4Nb-C by selective electron beam melting.

Selective electron beam melting (SEBM) is shown to be a viable production route for titanium aluminides components. Fully dense and crack free parts can be produced. The material properties were optimized by adjusting scanning strategy as well as heat treatment with particular consideration of the application to turbocharger wheels.

Basically, the measured deviation varies from +0.6 to –0.1 mm. Leading edge and trailing edge display deviations less than 0.3 mm. The transition zone between blade and hub shows a deviation in the range of +0.6 mm (Fig. 6.107). The observed errors of SEBM manufactured parts are larger than those of typical machined parts. First results of thermomechanical tests with additive manufactured turbocharger

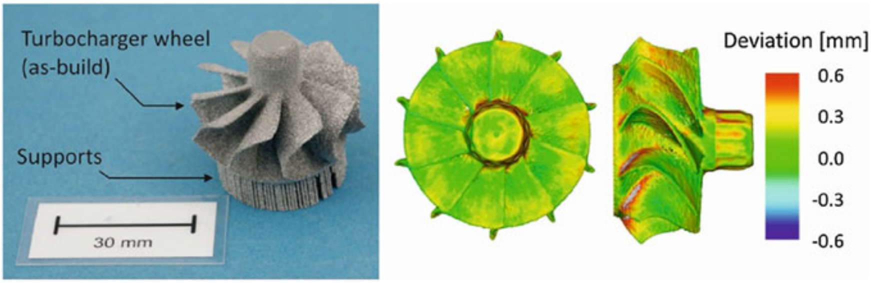


Fig. 6.107 As-built condition of turbocharger wheel (left) and resultant deviation from 3D-dataset (right). The back face is covered by supports and therefore not measured by fringe projection. The measured deviation of other sections varies from +0.6 to –0.1 mm [36]

wheels (surface roughness: as-built) display a reduced efficiency compared to standard turbocharger wheels. It is assumed, that the reduction in efficiency results from surface roughness and geometrical deviations.

Conclusions

Traditional manufacturing technologies like injection molding or casting, are very cost-effective for parts produced in high quantities of thousands and above. These methods include high initial investment and a very low cost of per-unit manufacturing. This financial model is not cost-effective for low volumes. On the other hand, AM in these cases is ideal, especially for highly complex parts. Just by eliminating the costs of initial investment or tooling, it can already save thousands of dollars, and lower the cost per part significantly.

AM promises to be a powerful complement to traditional manufacturing and the end-to-end supply chain. Mass customization will become less expensive, consumers will become micro-manufacturers, and customer demands will be met more quickly. In addition, the supply chain will become more local, globally connected, and more efficient. AM is going to change the way manufacturing will work in the future.

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