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ADDITIVE MANUFACTURING IN PRACTICAL USE

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ABSTRACT

Today's product designer is being asked to develop high quality, innovative products at an ever increasing pace. To meet this need, Additive Manufacturing has shown the possibilities of enabling complex geometry and economic small batch production. As a result, AM opens a new opportunity for designers to create innovative products that were unfeasible to be manufactured economically before. Examples of AM applications include aerospace and automotive components, packaging, medical implants, hearing aid shells and surgical guides, and consumer products as diverse as light shades, furniture and jewellery. Many of these products have creative design elements such as aesthetical features, light weight structures, reduced number of parts, complex geometric forms etc. This paper gives an overview over the possibilities of Additive Manufacturing and shows methods of its popular use.

Keywords: Additive Manufacturing, bespoke production, medical instruments, resection guides

1. INTRODUCTION

When graphically capable computer available at favourable price, ensuring 3D designing and modelling of products and ideas, had appeared, also the idea of the transfer of the 3D CAD model from computer into the "touchable" form was born. Similarly as the user of the programme for text editing prints in the end his product by means of the printer, the users of software for CAD designing want to touch their models i.e. to "print" them in a way or to bring them otherwise out of the computer. In 1986 that wish caused a new idea to be created and realized by A. Herbert, C. Hull and M. Kodama who independently of each other developed the systems for layered manufacture of parts by the process of selective solidification of photo-polymers. Already one year later the company 3Dsystems, newly founded by Hull, launched the device SLA-1 onto the market. It worked according to the process, patented by Hull, called stereolithography which is still today the most popular process of rapid manufacture of prototypes. The company 3Dsystems was soon followed by new companies with new patented technologies, which enriched the market of such devices and, above all, caused an unavoidable development of rapid manufacture of prototypes. The latest, in the first place, brings more and more precise and fast processes including the processes by which it is already possible to make final products and not only the prototypes. Since then we more and more frequently speak about rapid production and less about rapid manufacture of prototypes. Therefore, a new nomenclature has appeared in 2009 that combines all the layered technologies under the common naming Additive Manufacturing.

Table 1. Chronology of the beginnings of the development of Additive Manufacturing

End of 70ies-1982:	The Americans, A. Herbert and c. Hull and the Japanese, M. Kodama, independently of each other developed the system for selective solidification of photo-polymers for layerd manufacture of 3D objects.
1986:	C. Hull patented the technology called stereolithopraphy .
	C. Hull and R. Fried founded 3Dsystems, a company for the development, production and marketing of machines for stereolithography.
1986-1987:	Several alternative systems for rapid prototyping were developed.
1988:	3Dsystem started to market the first machine for rapid prototyping: SLA-1.
1989:	3Dsystem started to market the SLA-250.
1991-1993:	Cubital, DTM, EOS, Helysys and Stratasys started to commercialize their technologies.

Although the theory speaks about four basic principles of Additive Manufacturing, the majority of commercial devices function according to the so-called adding process where the manufacture of parts is executed in layers. Let us imagine that the 3D computer model is "cut" into thin layers of the thickness, let us suppose, of one sheet of office paper. Thus a great number of layers are obtained, each representing one cross-section of the whole model. Such cross-section is a 2D picture, which could be printed by the ordinary printer. If all cross-sections were printed on paper they could be cut out by scissors, spread with glue and put one onto the other in correct order and a touchable model would be formed. Such a model could be painted and submitted to the client for evaluation, before the start of series production of parts that nobody would like. Of critical importance in this description are the scissors and the fact that they not cut by themselves. Therefore, a considerable number of different Additive Manufacturing technologies have been developed some of them using paper for building but all of them having the following process in common:

- The 3D CAD model of the desired object is entered into the programme by which the model is prepared for manufacture. The preparation includes examination of the model and placing it into the working space of the device. Because of the layered manufacture the placing of the model influences the surface quality and the manufacturing time, which depends particularly on the model height (Z) during manufacture.
- Manufacture of the supporting system, if needed by the process, and "cutting" of the model into layers follow.
- Then the data on the individual layers travel up to the control unit of the rapid manufacture device, which assures their manufacture. After making each layer the feeding system lowers down for the thickness of one layer, followed by the manufacture of the next layers.

The manufacture of layers differs from process to process and depends particularly on the material. Today a great number of materials are available but various polymers, from the well-known thermoplastics to carefully hidden photo-polymers, are preferred. There is a lot of powder processes including metallic powders and some processes using paper and PVC sheets for manufacture.

2. ADDITIVE MANUFACTURING PROCESSES

In Additive Manufacturing the material is successively added to the desired place in order to make the desired model. There are a variety of adding processes and they include the processes of selective solidification, selective sintering and aimed deposition. The first commercial process was from the group of selective consolidation, named stereolithography, and presented in 1987. The basis of all adding processes is the described manufacture in layers; therefore, these processes are also known as layered technologies or Solid Free Form Fabrication, Direct digital manufacturing or even e-manufacturing, the names that suggests the possibilities or the way in which the model is brought to a real life. Nowadays all these technologies are popularly named 3D printing, although the name can rightfuly be used only for one of the four groups of the Additive Manufacturing processes.

Depending on the type of adding of material the adding processes are divided into:

- selective solidification,
- selective sintering,
- aimed deposition,
- pattern lamination.

In selective solidification, by means of the energy beam (light, electrons etc.) formed in advance, the plastic resin is solidified at certain places to form the desired model. At present, the processes are limited to photo-solidification, where for solidification the directed light beam, usually coming from the laser source, is used. The source can also be the UV light masked by specially prepared masks having the shape of the individual layers or, more often, the DLP projector, known from the lecture rooms, through which the shape of layers is projected to the surface of the photopolymeric resin.

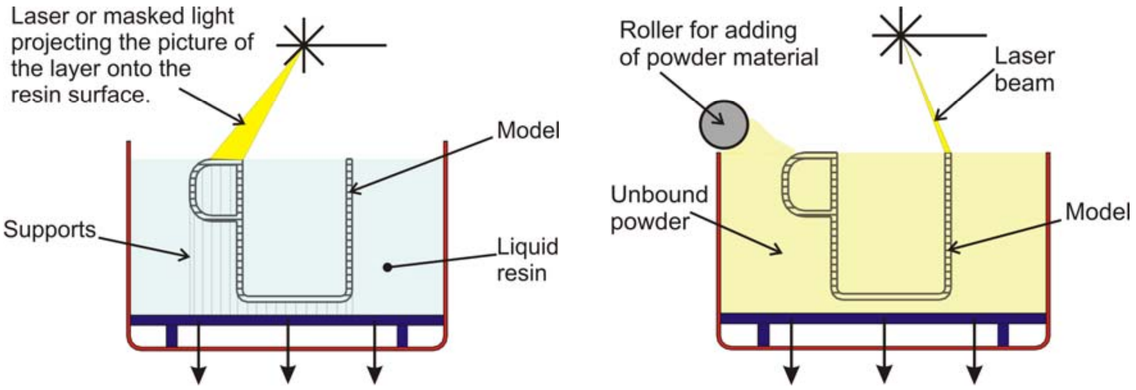

Figure 1. Principles of selective solidification (left) and selective laser sintering (right)

The processes of selective sintering or melting belong to so called powder bed technologies where the powder of building material is spread over the building tray and consecutively melted (sintered) into a solid layer of final parts. The process repeats with consecutive layers, until the whole part is finished. Today the devices exist that supply the required heat by means of the electron beam or even infrared heaters.

The aimed deposition is a group of processes, where the stream of material is directed to certain places of the growing model through the printing heads. Therefore the devices functioning according to these process, have been called 3D printers. Depending on the shape of the material stream and the manner of formation of the product three deposition processes are distinguished:

- drops,
- continuous,
- drops-on-powder.

In the drop deposition the material is deposited by the stream of small drop from the “printing” head. The process is similar to the technology of ink-jet printers, except that it is not the ink that comes from the printing head but the material from which the model is formed.

Continuous deposition implies that the material is deposited in the continuous stream through the extrusion nozzle. The material, usually used is the thermoplastic, which is heated by the device and deposited, in the form of a thin thread into the hose.

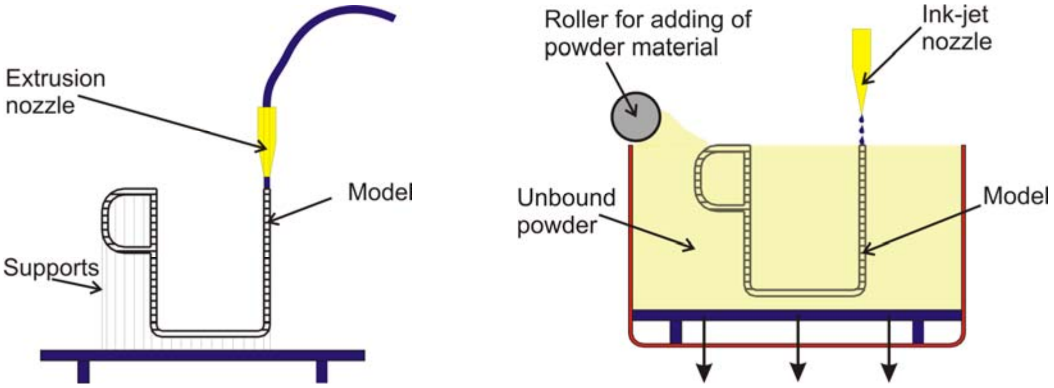

Figure 2. Principles of continuous aimed deposition (left) and drop-on-powder (right)

The drop-on-powder deposition differs from the drops deposition in that it is not the material which comes from the printing head but only the binder falling onto the layer of powder material. The model is formed by binding of the material under the influence of the binder.

Pattern lamination is very similar to the principle of layered manufacture described at the beginning except that the cutting sub assembly of the device assumes the role of the scissors. The materials, usually paper or PVC, in the form of thin layers (sheets and plates) is shaped/cut out by the device and glued into the model. The process takes place always in two steps. In the first step the cutting sub assembly of the device cuts out the pattern of the layer deposited; in the second step the gluing sub-assembly assures mutual jointing of layers. The cutting sub-assembly can be designed as a laser cutting device or as a blade led by the control system on the layer similarly to the pen of the plotter.

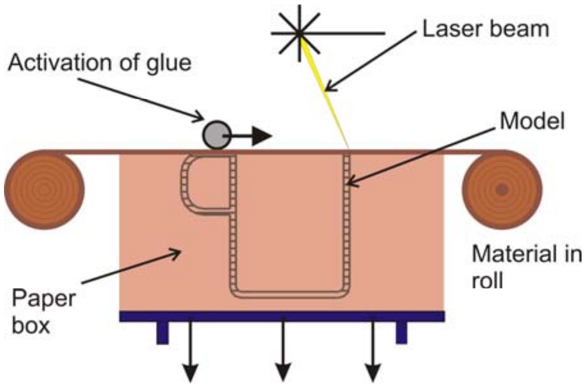

Figure 3. Principle of pattern lamination

3. USING THE ADDITIVE MANUFACTURING

A prerequisite for its use is the availability of the CAD and, consequently, of the technical documentation in the numerical – computer form. All designing must be based on 3D techniques i.e. modelling and not only on drawing of 2D drawings by means of computer. In addition the fact must be taken into account that the additive manufacturing processes are not intended for large series of identical and simple products but for a small number of products as complicated as possible. For such products the alternative methods are too complicated and too expensive, therefore they do not allow the repetition of the process in terms of searching for more favourable design solutions. On the basis of what was said above the factors determining selection of rapid manufacture technologies can be summed into the following four categories:

- small number of products,
- data on the products shape must be available in computer form,
- desired shape of product is complicated,
- possibility of subsequent changing of shape is important

The first two criteria must be satisfied. The third and fourth criteria indicate the specialities of the use of additive manufacture processes, which come to full value in case of complicated products and everywhere, where fast changing of the shape versions is important. The third criterion is connected particularly with the price of manufacture, since simple products can be made cheaper by conventional processes. The fourth condition relates particularly to prototype production and shape studies, which can represent an important market advantage. The prices of additive manufacture depend particularly on the quantity of the material used and, of course, on the time of manufacture. Since layered manufacture is in question, the time depends exclusively on the product size, whereas the shape complexity does not influence it at all. This is in complete opposition to the conventional manufacturing processes where the manufacturing time depends particularly on the number of the operations executed, which is conditioned by the complexity of shape.

Due to the properties and specialities stated above the additive manufacturing has extended to the most different areas and has not remained within the industrial environments. Today the use of processes of rapid manufacture can be divided into five fields:

- direct, single or small – series production,
- industrial models, prototypes and design concept models,
- tools such as dies and moulds,
- scientific, mathematical, statistical, medical and other presentations of 3D data,
- computer design and sculpturing.

The wider and wider area of direct manufacture of finished products by additive manufacturing processes, will soon join the fields mentioned above. Researches in this area are particularly intensive in the military area, in manufacture of spare parts and in logistical support. At present, the applications of this kind are most frequent in medicine, particularly in surgery, tooth prosthetics and orthopaedics where the results are very exciting.

In the last three years a new type of user, a so called domestic user is joining the group that grows rapidly beyond the expectations. With the emerge of relatively inexpensive 3D printers (price range at 1.000 €) these technologies are starting to reach our homes. At first only to the homes of dedicated makers and tech-geeks but also to the homes of children with technologically aware parents.

4. APLICATIONS OF ADDITIVE MANUFACTURING IN MEDICINE

Additive Manufacturing technologies has been extensively used in medicine since the beginning of 21st century. Their applications mostly range from serial implants to custom models for surgical planning, custom implants and prosthetics and patient specific instruments for surgical procedures. Selective laser sintering and melting and electron beam melting are at the moment mostly used technologies used to produce medical implants and instruments. Laser sintering of PA12 based materials is a common choice of engineers and medical doctors looking for a reliable solution to provide them with instruments such as surgical guides and models that can be used inside the OP theatre and in contact with the OP field.

Orthopedic surgeons usually deal with a problem of defining the anatomical kinematics of their patients that needs to be retained after putting the joint prostheses into place. The problem can be effectively solved using modern CAD techniques based on CT scans and Additive Manufacturing technologies to produce patient specific instruments. Modern CAD techniques enable for reliable definition of mechanical axis in virtual 3D space, which is much preciser than clasical X-ray based planning methods. The main problem of virtual surgical planing is how to retain the calculated and simulated geometry when moving from virtual models to the patients in OP theatre. Nowadays it can be solved using special jigs, fixtures and guides that are designed inside the virtual CAD environment and produced using the Additive Manufacturing technologies. This way the orientation of anatomical features in the global coordinate system of the body can be transferred to the so called Patient Specific Instrument using special features of the patient’s hard tissues (osteofits, etc.). These features assure that the jig fixture or guide will fit to the body part in only one position thus preserving the anatomic angles defined in the virtual coordinate system.

At University of Maribor, Faculty of Mechanical Engineering several medical projects have been performed in the last 7 years, ranging from cranial implants production to maxillofacial and orthopaedic guides and implants. Cranial implants produced by means of additive manufacturing meanwhile evolved into a standard procedure at the Neurosurgical department of University Clinical Centre what proves the usability and effectiveness of the method.

5. TOTAL HIP REPLACEMENT GUIDES

This individual resection and bone stock preserving technique should enable the optimal prosthesis fit and positioning, with less postoperative complications due to quicker and less demanding procedure. The development of resection guides starts by the determination of exact preoperative CT-joint anatomy with clear segmentation of CT-scans to get an individual joint model. The second step is the detection of individual anatomical parameters with center of the joint rotation and determination of inclination and version angles. Using the determined individual anatomy and disposable bone stock, the optimal endoprosthesis size and position were determined.

The ability to measure different relevant lengths and angles of the lower limb in 3D space is essential in the analysis of lower limb anatomy and biomechanics.

A CT scan was performed on each joint with 1 mm slice thickness. The images were stored in DICOM format and transferred to a workstation running EBS ver. 2.2.1 software (Ekliptik, Slovenia) to generate a 3D reconstruction model for the targeted joint. Upon this preoperative 3D-CT scan of degenerated joint, a virtual and individual plastic 3D-joint-model with the determination of optimal and exact joint resection levels for Endoprosthesis placement has been created. The resection guides (joint jigs) were designed and produced at the Faculty of Mechanical Engineering Maribor in the EOS Formiga laser sintering machine. The material used was CE-certificated PA2200 polyamide material. Together with the guides the joint models were made to enable better communication and preoperative planing (Fig. 4).

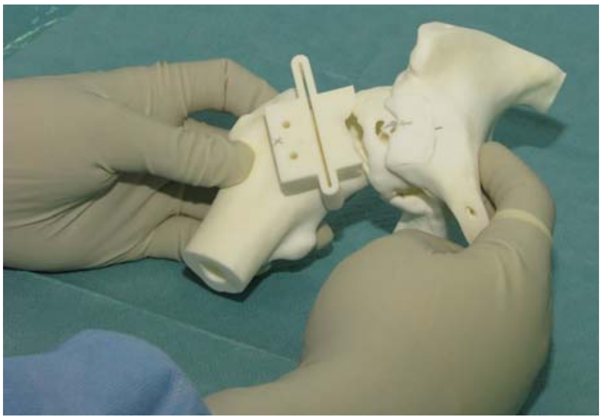

Figure 4. Guides and joint model in the OP theatre at the beginning of the operation

The presented resection guide technology is unique at the moment of writing and is aimed at:

- determination of exact preoperative CT-joint anatomy with individual joint model
- manufacturing of personalized resection guides and facilitation of surgical technique
- optimal planning of bone cuts and positioning of the Endoprosthesis components
- estimation and prediction of operation pretentiousness
- less invasive approach and shortening of operative time
- diminishing of Endoprosthesis position outliers
- reduction of intraoperative and postoperative complications
- less instrumentation with consecutive diminishing of sterilization costs
- optimization of joint kinematics with better long term results.

Using the pelvis position in a CT scanner space a global coordinate system has been defined that has been used for determination of original anatomical angles and lengths. For each patient the femur length, i.e. the length between the center of the femoral head and the center of the femoral notch, the tibia length i.e. the length between the center of the tibia plateau and the center of the tibia plafond and the total length i.e. the length between the center of the femoral head and the center of the tibia plafond have been determined. Additionaly the femoral head diameter, representing the optimal circle diameter fitting the femoral head has been determined. Important are also

- the femoral neck length between the center of the femoral neck and the point joining the neck- and the diaphysis axis,
- the neck-shaft angle between the femoral neck axis and the axis of the diaphysis and
- the femoral offset representing the distance between the center of the femoral head and the axis of the diaphysis.

Definition of the exact acetabular inclination and anteversion angles was important for the acetabular cup placement. Using the 3D-CT model the inclination and the anteversion of original acetabulum have been defined. The optimal spherical surface covering the real acetabulum has been determined to predict the optimal size of acetabular cup. The optimal depth of selected cup has been determined according to the geometry of available bone stock. The femoral part of the hip has been used to determine an anteversion of the original femoral head. Considering the acetabular anteversion we tried to determine the optimal combined anteversion of acetabular and femoral endoprosthesis parts.

Detecting the optimal cylinder volume fitting the femoral canal a femoral steam axis, its size and position have been determined. All these parameters enabled for optimal resection line detection and definition of femoral steam placement and its anteversion. Regarding to the hip biomechanics the center of rotation for femoral head has been determined and the optimal offset for the femoral component set.

Considering the 3D-CT model of the patient hip the position and the size of the resection guides for acetabular and femoral cuts have been defined. Due to the limited operative field the jigs have to be shaped in a way that they do not disturb the surgeon's view, or forcing him to modify his operative approach.

For the acetabular component a central jig has been developed that fits optimally to the acetabular fossa, without brushing the acetabular ream, or fully remove the capsule (Fig. 5). In case of complete asymmetrical cartilage mantle its removal for original bone fitting jig was required. After the jig is clicking into the bone stock, it has been fixed with the central pin, determining the center, depth, inclination and anteversion of the original acetabulum. It has been reamed off with the cannulated reamer, with optimal preoperatively determined reamer-size. The last step is the positioning of the acetabular component into the prepared bone stock with optimal size, anteversion and inclination of the cup (Fig. 6).

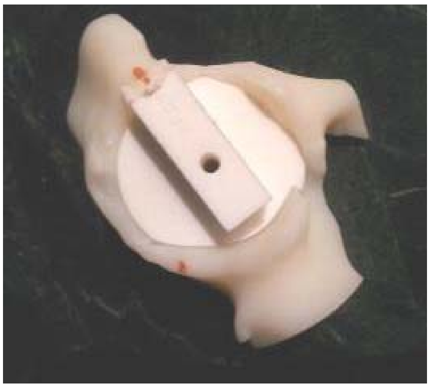

Figure 5. Acetabular jig with central pin hole for the exact reamer placement determining the direction and the depth of the acetabular EP-component

Figure 6. Positioning of the cannulated acetabular reamer into the central acetabular pin hole

Important for Hip Endoprosthesis stability is especially the determination of the optimal acetabular angle values. Due to our first data, the ideal acetabular inclination was around 40 °, dependent to the available bone stock between 30° and 50°. The ideal anteversion of acetabular part was around 15°. Due to available bone stock the anteversion should be between 10° and 20°. The optimal combined anteversion of acetabular and femoral component has been determined with respect to femoral anteversion (optimal 15°). The value of combined anteversion should be between 25° to 45°, with our optimal value of 35°.

After placing the femoral jig the femur has been resected and the line above the lesser trochanter for the optimal leg length and off set determined. The resection lies in the right inclination and anteversion for the best femoral compound stability due to the combined anteversion (Fig. 7)

The procedure is completed by femoral component placing according to the resection lines and testing the stability of the hip Endoprosthesis.

The aim of the project was to develop a new technology of patient specific resection jigs, created for individual total hip replacement operations. A real 3D model of patient anatomy was created using a method of CT 3D reconstruction with computer segmentation that enabled accurate, patient specific bone cuts. The intraoperative applicability of the jigs and the postoperative outcome of Endoprosthesis positioning has been preliminary tested. These first tests promised optimal

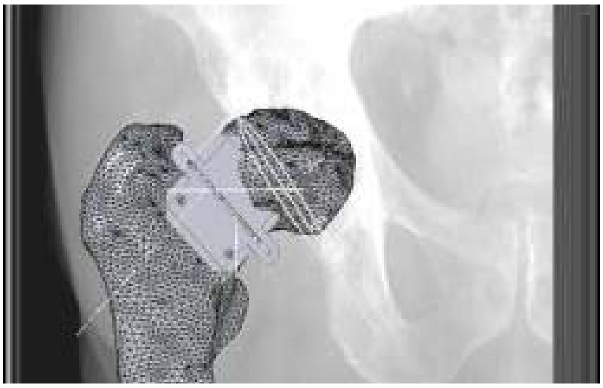

Figure 7. Femoral jig determining the right height, inclination and anteversion of the femoral resection

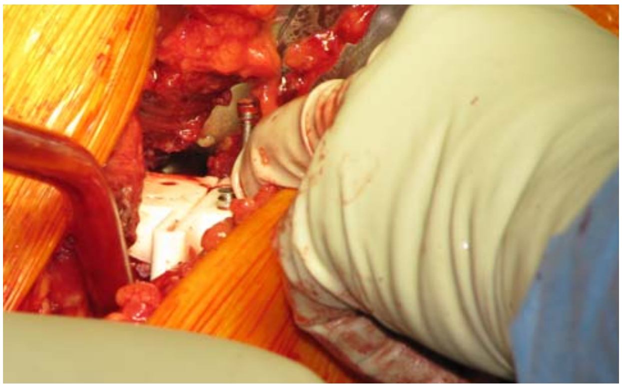

Figure 8. Femoral jig fixed with 2 pins for the intertrochanteric fixation and the resection slot for the femoral cut

endoprosthesis placement due to the available bone stock, with less surgical complication and better postoperative joint kinematic.

6. CONCLUSION

The development of additive manufacturing technologies and applications progresses in two areas. On one area the devices intended for as wide circle of users as possible are in the foreground and aim at small design offices. These devices gained have been de facto named 3D printers, with prices bellow 10.000€. Typicaly these devices are limited in their performance and throughput of products, but usually they do not require special working conditions, some of them do fit on top of a desk but none of them is really office friendly.

In the other end the devices are developed that ensure direct manufacture of end products. It is characteristic of this area that attempts are being made to use real materials, i.e., such materials as used in ordinary production. These devices are mainly used in selective sintering and/or selective melting of metals for production of individualised or even bespoke products.

Because of its characteristic properties (production of geometricaly complex parts in small series), additive manufacturing has been extensively used in medical applications for production of implants and surgical guides. Several companies (Lima, Zimmer,…) nowadays even use AM machines for serial production of orthopaedic implants with engineered trabecular structures. In dental applications selective laser melting has been adopted as a method for producing crowns, bridges and other dento-prosthetic elements, mostly because of its reliability, repetability, accuracy and chemical stability of used alloys.

In the future we can expect wide adoption of AM technologies in many areas. These methods will never replace classical machining and should not be understood in that way. Instead we have to consider these methods as another tool in the toolbox, which requires some new skills, knowledge, and most of all awareness of their existence. The latest mostly influences the steepness of the learning curve one have to absolve in order to become a new user of Additive Manufacturing.

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