New Technologies, Challenges and Trends in Additive Manufacturing for Production of Optimal Topologies

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Abstract

In this paper an overview about the conventional and generative manufacturing methods is presented. The advantages and disadvantages of each method regarding their application, efficiency and the implemented material are discussed and new trends in the field of rapid prototyping are introduced. The article describes how by application of hybrid methods the advantages of both techniques are exploited. Furthermore, Laminate Object Manufacturing and Fused Deposition Modelling are in the focus and their application for production of optimal topological components and fabrication of parts with fiber filament is considered.

Keywords: Generative manufacturing, rapid prototyping, additive fabricating, laminate object manufacturing, fused deposition modelling

Introduction

Production and manufacturing techniques have always played a vital role in human life. Besides the quality of the produced parts, criteria like production time, strength, tolerance of components have continuously been improved. The development of computer science and numerical control additionally enhanced the production techniques. Machining with the help of computerized numerical control (CNC) fabricates precisely most of metal components with any arbitrary contour. By increasing demands for a cheap and rapid production of prototypes, however, a new field was opened in the 50 and 60s to produce new components in shorter intervals in one single step. Unlike conventional subtractive or formative methods, the materials are added in this technique to form the final shape. The technique was therefore named "additive manufacturing" method (AM), or, because of its direct connection with virtual modeling, it is also called "Direct Digital Manufacturing" (DDM). The technique got more momentum in recent years because of the advances in relevant fields of laser, computer science and control [1]. Nowadays, this method can be traced in different fields of science, from fashion, jewelry, medical, biotechnical, dental and food industry to architecture, automotive, aerospace and military. In this contribution, the authors summarize AM methods and discuss the applications and trends in this field. The methods are compared with conventional production methods, and new research in hybrid methods is illustrated.

The conventional manufacturing methods are generally divided into subtractive and formative types. In subtracting techniques as, for example, machining, milling, drilling and sawing, parts of initial specimen are cut at different stages to get the final geometry. Today, these processes are performed automatically, either with the help of preprogrammed CNC machines or robots. The requirement on machine language, setup and process plans for the user, the high cost of these machines and the required infrastructure motivates the manufacturer to use the formative technology. In formative methods like pressing, forging and casting, the final component is produced via a cold or hot work on the material. Hence, at the last production stage, not only the component is produced but the mechanical properties of the parts are also improved via work hardening. The application of these methods is, however, limited to specific geometries and, therefore, it is normally combined with pre-subtractive operations. The formative methods are energy-intensive methods and cause lots of waste material, which exploit the environment. In addition, the conventional methods are very sensitive to human failure. Wrong programming of the machine causes severe damages to workers and facilities.

AM on the other hand reduces the development time and prototype costs extremely. Via this method, the components are produced by putting material layers on each other to form the final geometries, which normally could not be produced via subtractive methods. In cases, where the parts consist of many cavities, the generative methods could be employed. Figure 1 depicts some models, which were produced by the 3D printer developed at ISW by putting melted elastomeric filament in different layers.

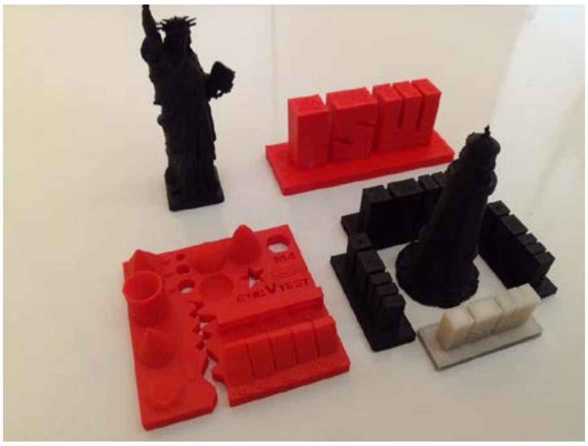

Figure 1: Examples of plastic components produced by the 3D printer designed and manufactured at ISW

Additive Manufacturing Technologies

In comparison to conventional methods, additive manufacturing methods are cleaner, user-friendlier and cheaper. The biggest advantage of these methods is the possibility for production of individual prototypes for self-manufacturing. With the help of 3D printers, for example, any household product can be copied, produced or replaced. The application of AM is not limited to real prototypes but has been developed from fabrication of tiny products in micro- and nanoscale [2] to printing of large-scale products as, for example, houses (Lockheed Martin Machine).

In the 1980s, the companies Helisys and Cubital first proposed 3D printers [3]. These companies do not exist anymore, but many other companies proposed different concepts and machines of AM during that time. The most common AM technologies for these machines are:

- Stereo-Lithography (SL)
- Selective Laser Sintering (SLS)
- Fused Deposition Modelling (FDM)
- 3D Printing (3DP)
- Laminate Object Manufacturing (LOM)

Almost each of the AM techniques starts with computer-supported model conceptualization. The design is realized via a CAD model and is converted into a STL (Standard Triangle Language) or AMF (Additive Manufacturing File) format. These model formats are read by most AM machines. Depending on the machine setup, these models could be manipulated or corrected. After the machine setup and conversion of the formats into G code, the component is built [4]. Depending on the method and surface quality, the rough surface is polished in a separate finishing process. This is named the cleanup or post processing step. In the following, the most common AM methods are explained:

Stereo Lithography is the most accurate AM technique, which can produce components with a preciseness up to 1 micromere [5]. In this technique, the laser or ultraviolet beams are employed to accelerate the polymerization of specific areas in a fluid media. This fluid media is normally acrylic or epoxide, which will be curing by emitting lasers. The laser starts from the first layer in the media and hardens one layer after another. The final solid geometry is then removed from the fluid media.

Instead of liquid media in Stereo Lithography, a solid media from powder could be employed. The thermoplastic powders are then melted in a sintering process via CO_2 laser, infrared or electron beam to adhere the inserted granulate in the power and create the three-dimensional geometry. This method has been commercially developed since 1992 via DTM and was called “Selective Laser Sintering” (SLS). The word ‘selective’ describes the nature of the method to select and harden special parts of the powder media. Hence, at the end of the production, some parts of the powder remain in the cavities, which must be removed in the finishing process. Almost all thermoplastic materials like metals and ceramics could be applied with this method, but mostly components out of plastic are produced as the melting temperature is low. Without a finishing process, the end product here normally has a rough surface, which is the biggest disadvantage of this method.

Fused Deposition Modelling (FDM) or Fused Layer Modelling (FLM) is a technique, in which the molded filament like ABS or PLA is put in layers to create the geometry. Stratasys Inc. commercialized the method first in 1991. Via this technique, the thermoplastic wires are melted into a pasty form and injected through a nozzle in purposeful locations for building the parts. By the Fused Filament Fabrication (FFF) both full and hollow bodies could be fabricated. At the ISW also a FDM machine has been designed and fabricated, which is explained in the next chapters.

The 3D printing method normally refers to the entire AM process. However, it is also relevant for machines, in which the colorful ink with mixture of binding agent is injected from a nozzle and merges the powder grains to form the geometry. Each layer is created by injecting the mixture on the previous powder layer on the needed coordinates. This method, which has been developed since 1998 in Z402 machines, is especially suitable for colorful concept models or end products from ABS or ceramics.

“Laminated Object Manufacturing” is the product-specific name of the company Helisys and its follower Cubic Technology. The process functions by dividing the raw material in different layers and cutting the layers in specific desired forms, and finally combining them [6]. The materials with this method are mostly papers, plastic, ceramics and metal. The foils are cut by CO_2 laser, cutter, or machining. The paper, plastic and wooden sheets are laminated with Polyethylene adhesive. Metallic layers will be laminated via welding, diffusion or epoxy adhesive, and ceramics layers will be sintered. With this method, massive components can be constructed. Technically, the method is not complicated and different materials can be employed for construction of the structure. The anisotropic characteristic of the components is the disadvantage of the technique. In the next chapter, a new method will be introduced, which applies an LOM method for constructing the topologically optimal geometry of the components.

LOM for Production of Optimal Topologies

In order to achieve better mechanical characteristics for structures and components, optimization algorithms are employed in a finite element simulation. Optimization can be generally divided into two groups: parameter and parameter-free optimization. In parameter optimization, the specific dimensions of the component are parameterized and the effect of different design points on predefined objective function is studied. Models are created usually in CAD format and the parameters are varied with gradient-based local or Monte Carlo global algorithms. In parameter-free optimization, both topology and topography of the components can be optimized. While optimizing the topology of the components, mass and stiffness are concentrated in regions, where more force and energy is transmitted. An automatic method for performing a topology optimization is based on the finite element simulation. From mathematical point of view, a topology optimization is a problem of compliance minimization (equation 1), based on the variation of element densities. The compliance is defined based on equation 2. The density of each element can be varied between zero and material density. The summation of element densities and volumes results in predefined structure mass as it has been clarified in equation 3.

$$\min \underline{S}(\rho_i) \tag{1}$$

$$\underline{S} = f^T u \tag{2}$$

$$\sum_{i=1}^{n} \rho_i V_i = M, \qquad 0 < \rho_i < \rho_{Max} \tag{3}$$

The variation of densities for each element is performed based on sensitivity analysis algorithms. Depending on the low or high amount of element density penalization, different results and topologies can be introduced. In figure 2, the results of topology optimization of a structure has been depicted. With penalization factors higher than three, the elements have either full density or no material. Such geometries can be fabricated with introduced conventional methods. If the penalization factor is equal to one (the best results), the densities of the elements are distributed between zero and full material; therefore, conventional methods are not useful in producing fuzzy densities.

Figure 2: Results of topology optimization of a structure with penalization factor 3 on the right and the result of stiffer structure with penalization factor 1 on the left

The components with distributed densities, however, can be divided into different layers and connected via laminated object manufacturing. The result of topology optimization is interpreted and then different microstructure layers are generated. These layers consist of mini-cavities of different shapes and sizes. In the sections where the material is not required, the cavities are larger and in other sections, no cavity is generated. An automatic algorithm discretizes each layer and calculate the average density of each net. Based on this average density the size of the cavity is determined and it is position in the center of net. The metal layers are then lasered, glued and pressed together in order to form the final component. Figure 3 depicts schematically how these layers could be constructed to shape an optimum topology of a chair. This method can be employed for structures, where the weight plays an important role and when keeping the production costs at a minimum is also of interest. The vision is the application of this method in aerospace, automobile or in machine tool industry.

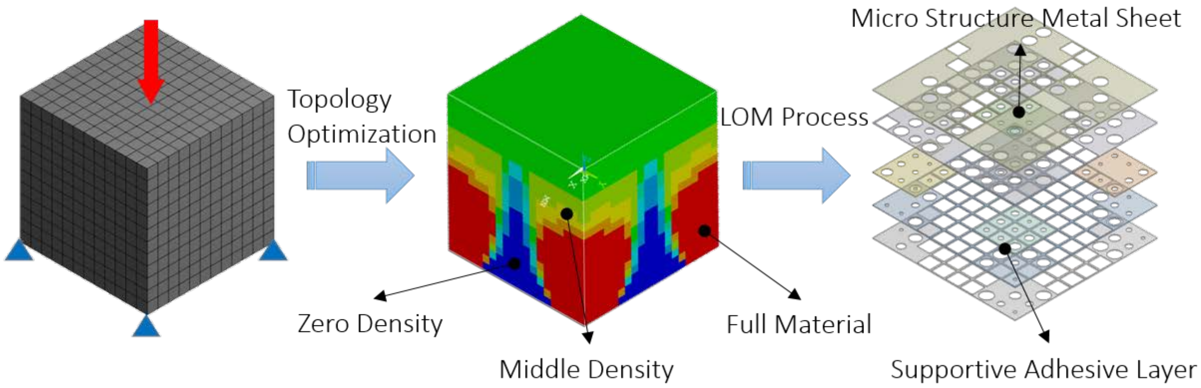

Figure 3: Topology optimization of a chair and the LOM for manufacturing of the Structure via macro-cavities in square forms

Fabrication of biomimetic structures for use in the construction industry

The production of design elements and supporting structures by additive manufacturing using homogeneous materials is an established research topic in the fields of architecture and the building industry. This allows manufacturing geometrically complex structures at a model scale in order to perform design studies and to be able to produce complex structures economically in small lot sizes. A future goal is to generate such structures completely on site [7]. Therefore, research is carried out in the field of fabrication of biomimetic and biologically inspired (modular) structures.

As many biological systems and structures use the principle of fiber reinforcement, the ISW focuses its research on the integration of endless fibers in thermoplastic materials. A wide range of suitable fiber materials is available to influence the behavior of the composite constructions. When using natural fibers together with e.g. lignin, a fully recyclable and to 100 percent CO_2-neutral composite material can be produced. In architectonic applications, this will be of high importance.

Currently, the mechanical strength of conventional FDM parts is approximately 80-85% of corresponding injection-molded parts [8]. By integrating fibers into the workpieces in the direction of stresses, the strength of the workpieces can be increased. The thermoplastic filament that is used in conventional FDM systems can handle push and pull forces, which allows a trivial material supply that can be found in state of the art printers. The filament is pulled by a motor from the filament roll and pushed into the hot end and finally out of the extrusion die. In contrast, the fiber can handle only pulling forces and no pushing forces. This requires a non-trivial new material supply strategy. The associated research center Fraunhofer IPA has developed an extended FDM process by using a 6-axes industrial robot, including the possibility of extruding fiber-reinforced polymer materials. The first results of these investigations using a patented fiber printer nozzle are reported in [9] without presenting concrete numbers of strength improvement compared to conventional FDM workpieces. The new printing head combines 3K carbon fibers with a thermoplastic elastomer. Another possibility might be the use of natural fibers as reinforcement, which is shown in [10], where flax fibers made of the flax plant were investigated.

There are two major drawbacks of the presented solution, low infill of fibers (<20%) and the missing possibility of cutting the fiber during the extrusion process. Therefore, the ISW is developing a new printing head to overcome those drawbacks. Including a cutting mechanism into the printing head allows turning the fiber reinforcement on and off, depending on the workpiece requirements. Fibers are only placed where forces affect the workpiece properties. As forces are induced in different directions, the current limitation to one vertically build direction has to be overcome. All state of the art printers are limited to three-axes movements (building direction in z) so that the slicing software splits the workpiece description (STL format) into single slices. The height of theses slices is determined by the layer thickness. For each slice, a path is calculated in 2D resulting in G-code that can be interpreted by the machine control. The disadvantage of this approach is the limitation to one fixed direction and the limitation to STL files, which only approximates the outer geometry of the workpiece while the user selects one filling method for the complete workpiece, e.g. diagonal infill [11]. Chakraborty [12] provides an extension from conventional 3-axes systems to multi-axes movements. The focus is here on curved shell parts without fiber reinforcement. Structural optimizations with regard to load stresses or thermal effects are not carried out. Curvatures or corners within current trajectories apply strong shear forces to the fiber matrix increasing the risks of delamination or pull-off. Additionally, strong bending of the fiber at the nozzle tip might damage the fibers and increase wear of the nozzle. Therefore, new methods for trajectory planning, optimization and control are being developed.

Hybrid manufacturing

In most processes, additive manufacturing creates workpieces with poor surface quality that have to be post-processed for removing staircase effects and for surface finishing. In conventional production systems, the part has to be moved to a milling machine and re-clamped for surface finishing. This requires two separate machines and manual process steps. Hybrid manufacturing is the combination of conventional subtractive (e.g. milling) and additive manufacturing processes on the same machine to overcome those drawbacks. The workpiece remains in the same clamping while the process can be switched by changing the processing tool. In the past years, research has focused mainly on hybrid manufacturing systems for metal parts, e.g. [13] or [14]. Most of the machines that are currently available on the market combine laser cladding and milling of metal workpieces in one machine tool. In some systems, the printing head can be even stored in the tool change of conventional machines. Currently, no commercial machine is available for combining FDM and milling of thermoplastic workpieces. An experimental test set-up of such a hybrid machine using low cost components instead of industrial components is described in [15]. However, this system is an experimental set-up with many manual steps in the programming, which is far away from being an industrial application. The machine developed by the ISW is based on industrial components (high dynamics and high accuracy) and implements two different concepts for quick switching between subtractive and additive processing.

The first solution implements the concept of a tool change, which is successfully applied for laser cladding machines. The FDM printing head is inserted into the spindle as shown in figure 4 a). As the filament roll is moved together with the tool center point, collisions of the extrusion die and the filament are avoided. Due to its size, the printing head is stored next to the milling tool changer on a separate frame. The tool change process is automatically performed by the numerical machine control while executing G-code.

The second solution implements a revolver concept shown in figure 4 b). In contrast to the previous concept, the printing head and the filament rolls are fixed on the same rotatory axis as the spindle. By rotating this axis by 90° the process can be switched from milling to FDM, without having to execute a tool change.

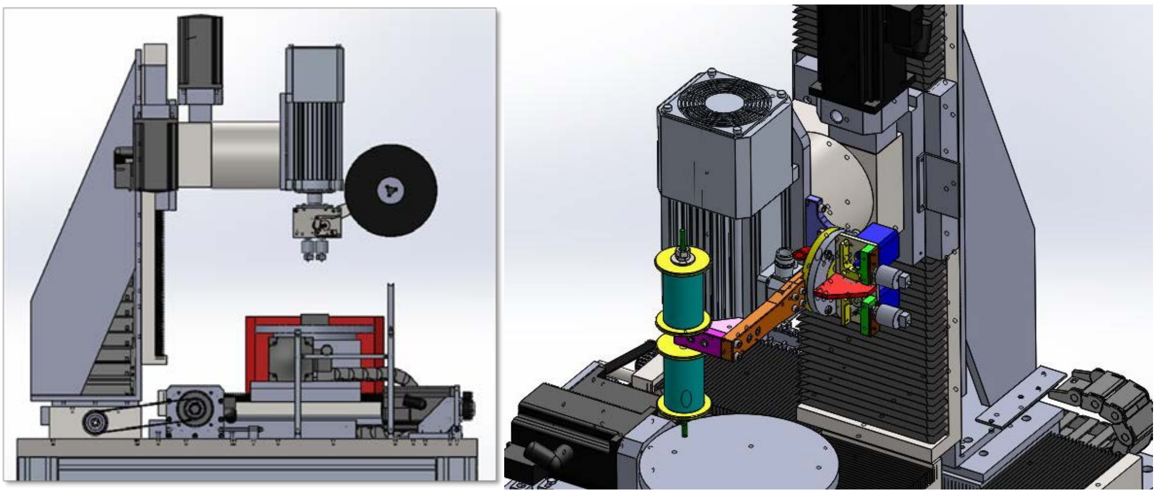

Figure 4. Hybrid manufacturing system with a) tool change (left) and b) revolver (right)

The two concepts described have been realized on the same industrial machine tool, so that experimental evaluation can be performed. Future investigations will analyze and compare the performance of both concepts.

Conclusion

In this paper, additive manufacturing methods were introduced and compared with conventional fabrication techniques. The advantages and drawbacks regarding their application were presented. In addition, it was explained how by employment of laminated object manufacturing, optimal structures can be constructed from the topology point of view. The current research on fiber reinforced filament in FDM was presented and research of the ISW on a machine for cutting and reorienting the fibers in the strain direction was introduced. At the end, the combination of subtractive and AM in hybrid machines was proposed, by which a more efficient manufacturing process and higher surface quality of the components is achieved.

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