DESIGN FOR ADDITIVE MANUFACTURING TECHNOLOGIES: NEW APPLICATIONS OF 3D-PRINTING FOR RAPID PROTOTYPING AND RAPID TOOLING

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ABSTRACT
The application of additive manufacturing technologies is becoming established in an increasing number of product development sectors. This allows a number of additive manufacturing technologies to be used quickly and inexpensively for prototypes and also small series. 3D-Printing (3DP) is among these one of the highly cost efficient technologies. Due to the low strength of the printed models today the use of 3DP is restricted to presentation models. These models are commonly fixed and rigid, e.g. no functions or motions are demonstrated.
This paper presents two new developments that offer new applications for 3DP. First a new design method to create moveable functional models is introduced. In addition the results of a new application of 3D printing with plaster powder for the rapid manufacture of thermoforming tools are illustrated.
For all these applications it is particularly important to take into account also the special requirements for the design of the 3D printed prototypes and components. Furthermore, the operating principle of these new technologies, with which the material is usually built up in layers, also offers numerous new design options which reach far beyond conventional design. The innovations of the design process, in particular, are worked out for the 3D printing technology and their benefits are illustrated in this paper. Two case studies demonstrate the advantages of the developed applications. Besides the technical boundary conditions, the economic advantages and disadvantages in comparison to conventional technologies are also described.

Keywords: Additive Manufacturing, design process, CAD, functional model, thermoforming, rapid prototyping, rapid tooling

1 INTRODUCTION
Numerous additive manufacturing technologies have been developed since the mid-eighties, including stereolithography (STL) as oldest technology as well as laminated object manufacturing (LOM). In addition, technologies such as direct and indirect laser sintering (LS) have become established. There are a number of names for these technologies, which depend on the machine manufacturers. All technologies have in common that the material is built up in layers. However, there are great differences in the materials used, which range from plastic powder and wires and metal powder up to plaster powder [1-2].
The application areas of the models, components and tools created with these technologies are diverse and not limited to technical applications. These technologies are also used, for example, in the fields of medicine, architecture and archaeology. The largest area of application is Rapid Prototyping (RP) for the manufacture of models for the three-dimensional representation of products and artefacts which are usually only available as virtual data models. Examples are CAD-based product models as well as anatomic models based on data from computer tomographies.
With Rapid Manufacturing, additive manufacturing technologies are used for the construction of commercial products. A typical example is the manufacture of hearing aid housings. A housing is created in layers on the basis of a wax impression of the ear canal of a patient and customised to the ear canal of the patient. Furthermore, rapid manufacturing is also of increasing significance in the manufacture of highly customised products [3].

The current trend towards mass customisation [4] with the prices for the hardware for the manufacture of individual products simultaneously falling is a great opportunity for additive manufacturing technologies to rapidly spread at small companies. At the end of this vision is the application of “personal fabricators” at private households for the manufacture of household articles or toys of customised design [5-7]. Ultimately, the additive manufacturing technologies for Rapid Tooling (RT) are used to manufacture a tool, not the actual component. This tool, for example, may be a mould for the thermoforming of plastic sheets, a simple injection-moulding tool or a dead mould for casting. These technologies as well allow products to be customised inexpensively.

3D printing (3DP) was developed in the early nineties at the Massachusetts Institute of Technology MIT and was introduced to the market in 1996. On the basis of a platform, powder is applied in layers and then sprayed with a binding agent and also paint. The layer thickness is about 0.1 mm. The platform is then lowered and the process starts again. In this way, the component is created layer by layer. The non-bonded powder is extracted at the end of the construction process. It may be reused directly without any regeneration required. Since the model printed in this way still exhibits a low level of strength, it is subjected to after-treatment after the removal of the powder. The printed component is infiltrated with resin which usually penetrates the component a few millimetres deep. This increases, on the hand, the strength of the printed component and, on the other hand, the brightness of the printed colours.

This new additive manufacturing technology varies from conventional technologies in particular in that coloured models are possible. The model costs are also relatively low, since the systems used do not require any expensive laser equipment [8]. However, a disadvantage of this technology is the strength of the models which is currently still very low and makes it difficult to use them as tools [9]. Furthermore, printed models are usually inflexible, since it is not possible to separate individual parts of an assembly due to the layer thickness of about 0.1 mm. It is therefore not possible to represent functions, such as the rotation of a shaft in a housing [10].

2 DESIGN FOR RAPID PROTOTYPING OF FUNCTIONAL MODELS

To overcome the disadvantage of inflexible models for 3D printing, the authors adapted the design process of the model by inserting an additional preprocessing of the CAD-Data (see Figure 1).

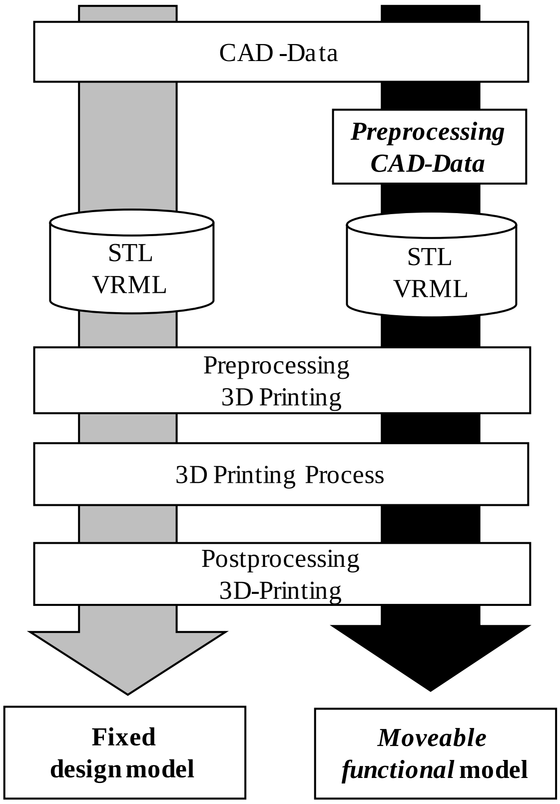


Figure 1. Design process for fixed models (left) and functional models (right)

The inflexibility of the models is based on the layered structure which results in all individual parts of the model sticking together and, in this way, losing their functions. When adapting the design, it must therefore be clarified first which functions are to be represented in the model. These are usually rotations and translations. The components which are to exercise these functions then have to be separated. They are separated in the CAD system, since the current software packages for the operation of 3D printers usually do not exhibit any features for the separation of assemblies.
A parting line is therefore worked out and implemented in the CAD system by inserting a gap between the assemblies to be separated. Loose powder is deposited in this gap during the printing process. This loose powder has to be removed together with the remaining excess powder after the printing process. This is mainly done by blowing out the powder with compressed air. To do so, the gap needs to be accessed by the compressed air. In the event of complex shapes, it may be necessary to print individual components separately to achieve the required accessibility.

3 CASE STUDY: FUNCTIONAL MODEL OF A VALVE

The required design changes are to be shown by the example of a throttle valve (see Figure 2). The function of the lever and that of the shaft consist of closing or opening the valve by means of a rotational movement in order to control the flow rate of a medium. In a standard 3D printing process, all components would stick together, making it impossible to move (rotate) the shaft and allowing only a certain valve setting to be represented.

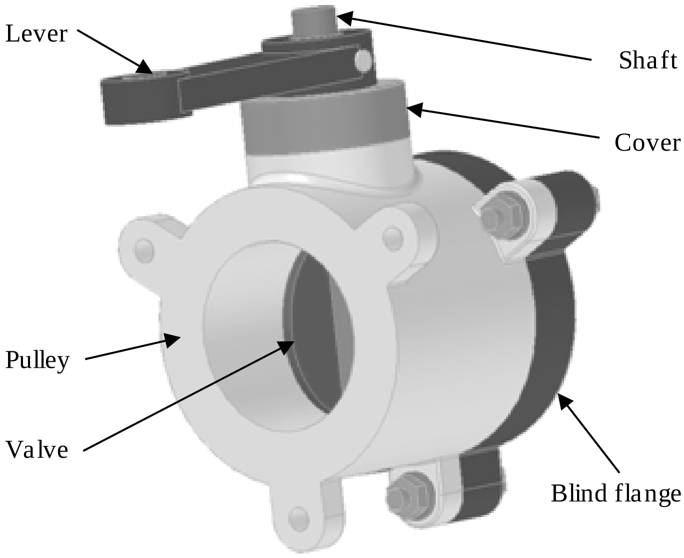


Figure 2. Case study: valve with rotating shaft and lever

As shown in Figure 3 the components which exercise a function are separated by a gap in the CAD system during pre-processing. For complex components, such as the shaft, it may also be necessary to simplify the shape. Other components, such as the lever, can be printed separately in order to be subsequently joined to the shaft.
The components are separated by these measures and the loose powder applied to the gaps during the manufacturing process can be removed during the after-treatment. It should also be observed that the components are separated for the infiltration. At the end of the after-treatment a 3D model is available which is able to represent all valve settings and therefore also the operation of the valve.
An additional work step is necessary for the creation of a functional 3D printing process, notably the pre-processing of the CAD data. From a technical perspective, this should be done in the same CAD system in which the model to be printed was created. This reduces the amount of work required for changes and the data remain consistent.
From an economic perspective, the creation of a functional 3D printing process is more complex in comparison to a conventional 3D printing process, since the function has to be determined first and the gap design also has to be implemented in the CAD system. In contrast, the savings due to the lower consumption of powder are marginal. However, overall the flexible functional model is a great deal more useful than the rigid presentation model.

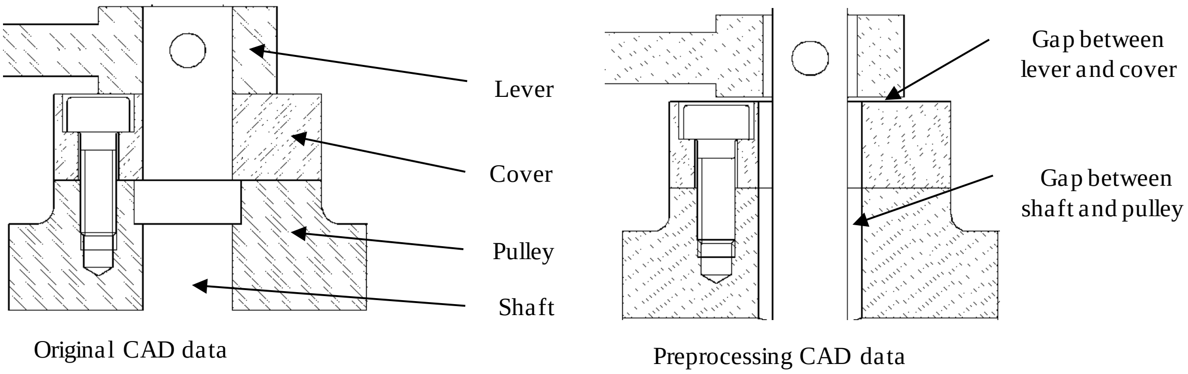


Figure 3. Changes in the CAD data (preprocessing)

4 DESIGN FOR RAPID TOOLING

Up to now the relatively low strength and the insufficient experience in heating the printed tools have spoken against its application for thermoforming of plastic sheets. This new application of 3D printing with plaster powder for the rapid manufacture of thermoforming tools is developed and tested by the authors.

Obviously 3D printing processes have several essential economic advantages over conventional manufacturing technologies for thermoforming tools. On the one hand, additive technologies are considerably faster than conventional, metal-cutting technologies (see Figure 4). This advantage is based on the omission of the programming of the tool paths in the CAM system which is essential for conventional machining.

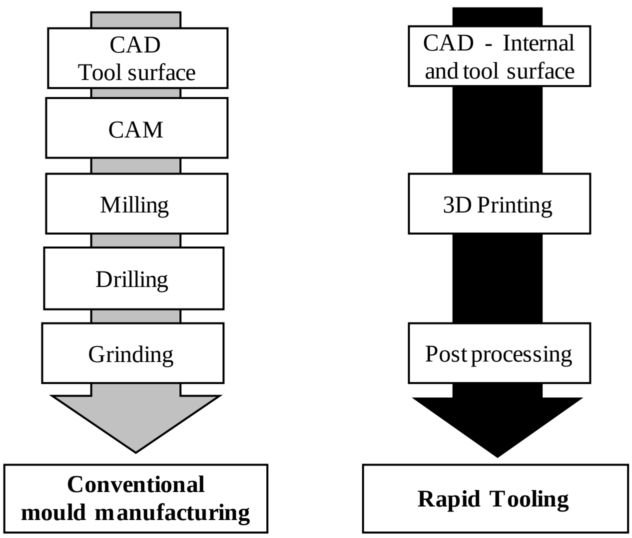


Figure 4. Conventional mould manufacturing and rapid tooling

Furthermore, 3D printing is also less expensive than a great deal of other additive technologies (e.g. laser sintering), since the 3D printers are based on simple components which are a great deal cheaper than, for example, a laser (see Figure 5).

However, additive manufacturing technologies have considerable technical advantages over conventional technologies for this application too. These advantages are based on the layered structure of the printed tools. Preparations are required in the design area in this respect, which are usually implemented by means of a CAD system. When thermoforming, a plate or sheet is heated and then pulled in heated condition over the cold tool. In order for the plate to be created as close as possible to the contour of the tool, the thermoforming process is supported by a vacuum. Channels are required within the tool for this purpose to enable the vacuum in particular in the cavities of the tool.

The decisive advantage of additive technologies is the flexible design of these channels. Any (e.g. bent or spiral) profiles can be created without difficulty here, whereas these channels can only be straight in the conventional manufacture since they are drilled. The cross-section of the channels also no longer depends on the round shape of the drill, and may now be of oval or even rectangular design.

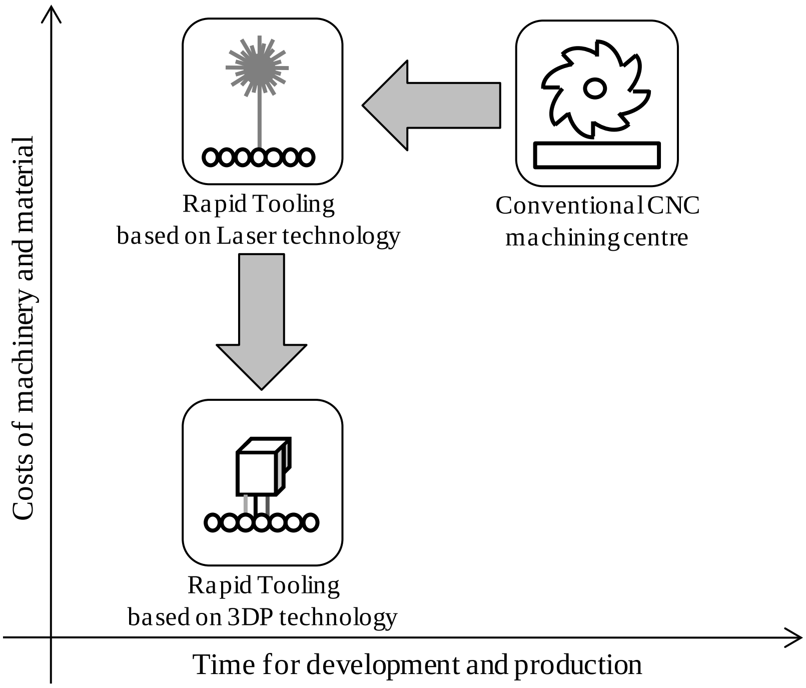


Figure 5. Comparison of different tool building methods

Another advantage of the engineering design of the tools is that additional components, such as spacers on the underside, can be integrated directly in the tool. Drill holes for mounting the tool are also already integrated in the CAD system. This allows these shapes to be made at the same time as the tool due to the layered structure. Subsequent installation or an additional cycle for drilling the holes is no longer necessary. This additionally reduces the manufacture time compared to conventional manufacturing processes.

5 CASE STUDY: THERMOFORMING OF PLASTIC SHEETS

A thermoforming tool was constructed for an automobile model as an example. In doing so, the external shape was taken from CAD before the additional design steps were performed (see Figure 6).

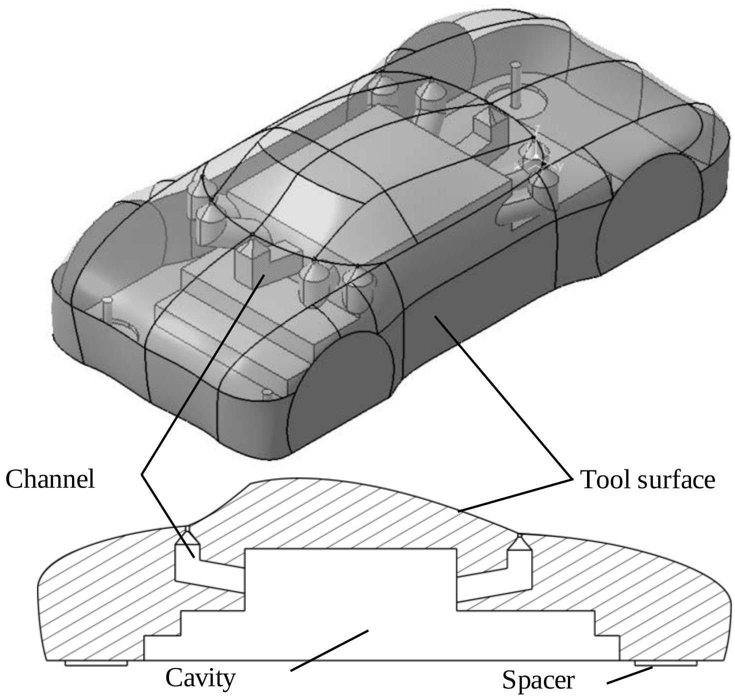
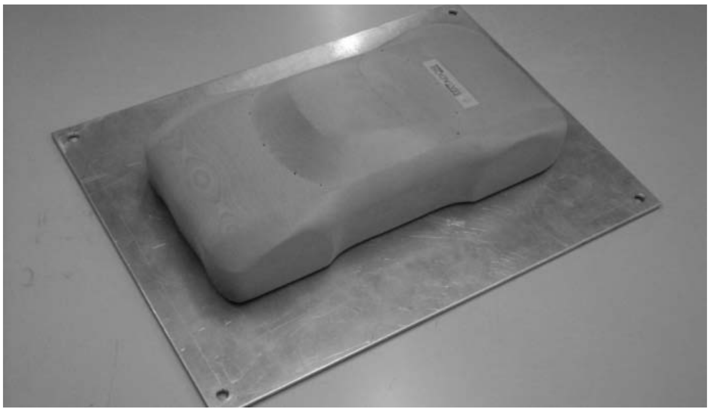
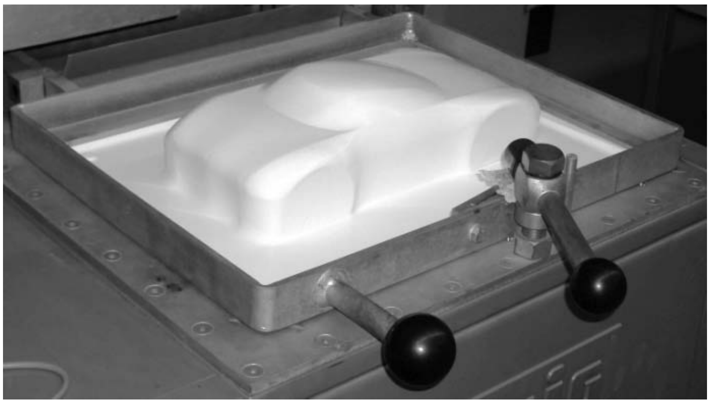


Figure 6. CAD model of a forming tool: 3D view and cross-section

First, a cavity was created in the interior of the tool in order to access the vacuum channels. The cavity also allowed the amount of powder required to be reduced considerably. A total of 10 channels were then designed for the vacuum in the tool. They initially had a diameter of about 12 mm which can be reduced to a diameter of 1.5 mm. It should be observed here that it is very difficult to remove the loose powder in the event of long channels with small diameters. The spacer under the tool (height of 1.5 mm) and the blind holes for the fastening screws were also designed.
The tool designed in this way and manufactured by means of 3D printing technology was used for thermoforming (see Figure 7). It was established that this tool is by all means able to withstand the thermal loads due to the heated plastic sheet (approx. 180° C). A small series of deep-drawn sheets was able to be manufactured.



a. Mounted mould



b. Thermoformed plastic sheet

Figure 7. Use of rapid tooling

Besides the new design options provided by the additive manufacturing technologies, their economic advantages can also be benefited from for the manufacture of tools. This includes, in particular, the quick implementation of the tools and hence short delivery times and development cycles. However, costs are also able to be reduced, since the low procurement and operating costs of 3D printers make the hourly machine rates considerably lower than with similar technologies based on laser technology or conventional technologies. These advantages compensate abundantly for the relatively high costs for powder and infiltration [11].

7 OUTLOOK

The application areas of Rapid Prototyping are extended considerably by the manufacture of functional prototypes. On the background of mass customisation, this is an important argument for 3D printing, since a number applications in the technical area, but also non-technical applications (e.g. in private households or for toys), are only made comprehensible and interesting by their operating principle, i.e. movements.
In the field of Rapid Tooling, 3D printing is an economic alternative to the slow conventional technologies and expensive additive manufacturing technologies based on laser technology. In this

respect, it is of particular interest to transfer this tool manufacture method also to other master forming and thermoforming technologies.
In the field of metal forming there are plans for tests in which the printed tools are to be used to form metal sheets. Since considerably higher loads are expected here than when thermoforming plastics, new post-processing methods are to be developed and used for these tests. These new types of methods are intended to increase the infiltration depth as well as the strength of the tool considerably.

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