Chapter

Utilization of Additive Manufacturing to Produce Tools

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Abstract

In the last decade, customized design and small series production gained importance in various industries. The production of these special tools becomes one of the most important costs for the production process. With the advances in additive manufacturing (AM) technologies, tools can be produced efficiently in short lead times and costs with additive manufacturing. In this chapter, first, an overview on the additive technologies to produces tools, also called rapid tooling, will be given. The advantages as well as disadvantages will be discussed. Following that, on an example of metal forming tools, different materials coupled with different additive production techniques will be compared. Also, most important points will be highlighted to select the most appropriate tool material and manufacturing method. Finally, a methodology to identify the tool life will be suggested, and its validation and verification on a simplified deep drawing geometry will be depicted. The comparison of numerical prediction and experimental results are shown to be in good agreement.

Keywords: rapid tooling, tool design, additive manufacturing, sheet metal forming tools, tool life prediction

1. Introduction

In this section, first of all the history and the literature data of the rapid tooling will be mentioned. Then, the AM using methods of rapid tooling will be explained in detail. Finally, examples to be taken into consideration when making the tool will be given basic flow chart of the processes can be seen in **Figure 1**.

AM techniques for tool production (known in literature rapid tooling [RT]) provide efficiency in terms of time and cost, while RT is often the best known manufacturing method for complicated structures in low numbers [2]. AM techniques for manufacturing, prototyping, and tool production methods can also allow producers to manufacture high-quality elements in a short period [3, 4]. In today's world, with the technology advancing rapidly, companies are looking for ways to manufacture varied and complicated items with high quality while reducing the cost and time needed [5].

AM techniques for tool production defines a method resulting from mixing AM techniques for prototyping with standard tooling disciplines to produce a die rapidly or components of a functional model from CAD information at a reduced cost and in less time than conventional machining methods.

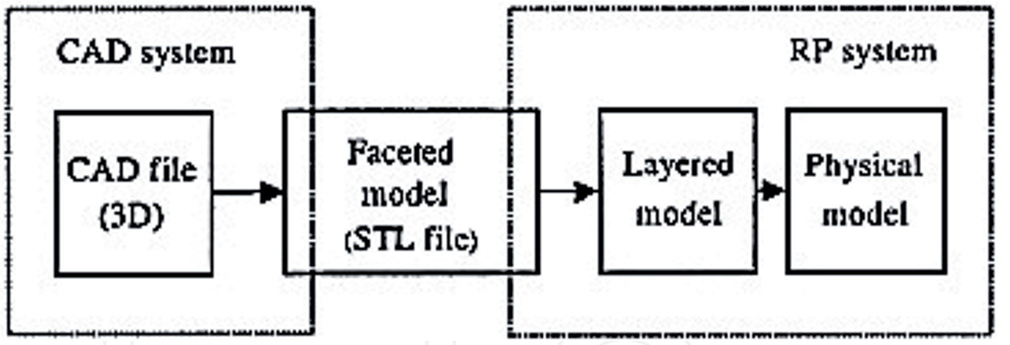

Figure 1.
Data transfer between the computer-aided design (CAD) and the RP system [1].

2. Additive methods to produce tools (rapid tooling)

There are two main categories. One category includes indirect methods using AM techniques for prototyping master designs to manufacture a mold, while the other category is a direct strategy, where the rapid prototyping machine constructs the real inserts of the core and cavity mold.

Due to its market potential, many businesses prefer AM techniques for tool produce and growth. Each method comes with a number of strengths that are contracted by limitations. Yet these advances cause a flurry of requests from businesses in the Americas, Europe, Asia, and other advanced markets due to their potential effect. Meanwhile, in both of these methods, numerous facilities are working hard to determine whether the time is correct to phase further information can be seen in **Table 1**.

2.1 Indirect methods of rapid tooling

To achieve various lead times, expenses, and process capabilities, there occurred several pattern-based methods in manufacturing a mold. To compose a pattern, the precision of RP processes gets considered with each part structure and the precision of the RP process preferred:

- Vacuum casting.
- Kirksite tooling.
- Electroforming.
- RTV silicone rubber molds.
- Wax injection molding.
- RIM.
- Spin casting.
- Plaster molds.
- Rapid solidification process.
- Sprayed steel.
- Cast resin tooling.

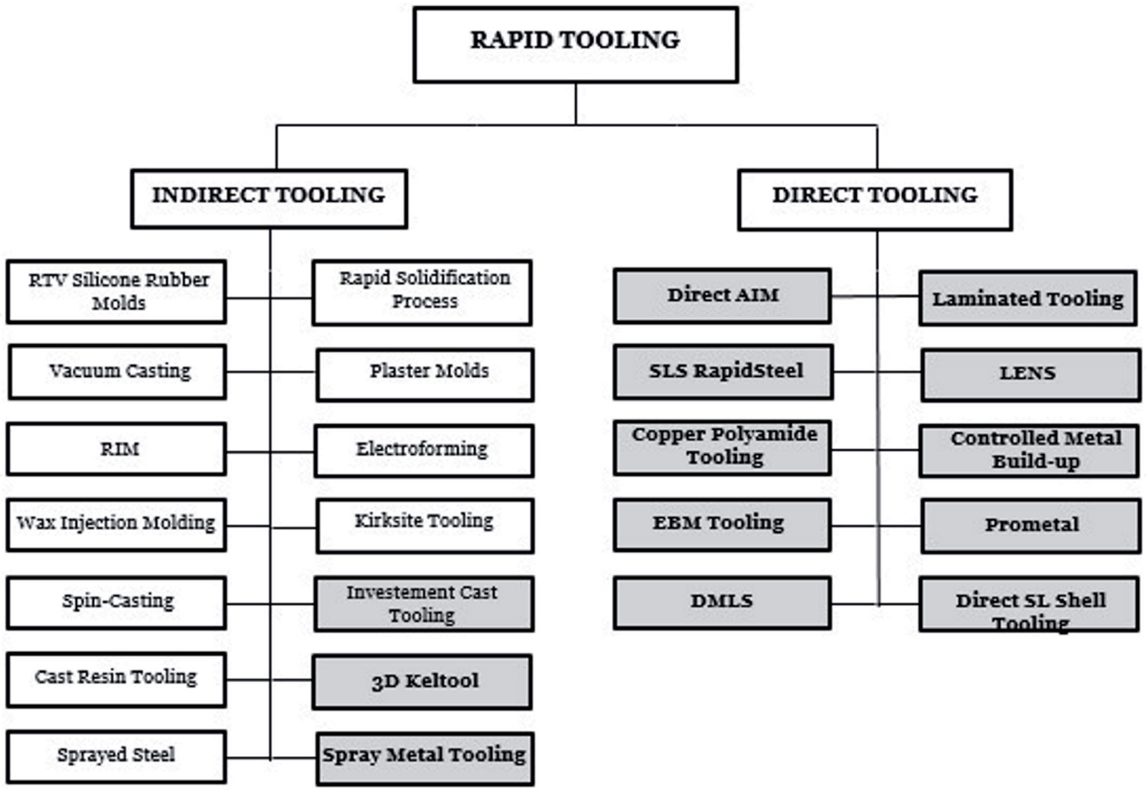

Table 1.
Methods of rapid tooling.

2.1.1 Investment cast tooling

Investment casting has been used for thousands of years as a manufacturing method and is particularly suited to finely detailed metal parts being formed and high melting point metals being used.

Founded in 1947, Vaupell uses SLA patterns for casting to quickly deliver 3D-printed patterns for casting to customers in aerospace industry. Here, AM (SLA) is used to manufacture a sacrificial model. Using this sacrificial model, investment casting is carried out as it would traditionally be the model with a ceramic coating, scorching the model, filling the remaining ceramic shell with molten metal, and removing the ceramic case after the metal has been solidified and cooled [6].

2.1.2 3D Keltool

As a first step in the 3D Keltool process, cavity mold inserts and a core get designed in CAD to get followed by manufacture of the core and cavity patterns with stereolithography or some other processes. Once these core and cavity patterns meet the requirements of the surface, silicone rubber cast gets applied on them to form molds in which a mixture of a metal powder and binder get poured and packed.

The instruments used in this process illustrate very qualified surface finish and definition. In general, lead time results in shorter time period than the conventional tooling. The main limitation is the size restriction. The size of a mold insert could be 100 × 150 × 215 mm (4 × 5.9 × 8.5 inches) at most. If the x and/or y dimension gets smaller, the z-direction has the possibility to extend to 145 mm (5.75 inches). To manufacture larger items, some tool makers have two or more cheek-to-cheek inserts in a die base [6].

2.1.3 Spray metal tooling

Metal spray molds had been used effectively in low-pressure procedures including RIM, vacuum forming, and rotational molding. Currently, the improvements in spray metals and spraying methods give rise to its use in injection molding.

The order of steps is like the one applied to manufacture epoxy molds, with the exception that the pattern is sprayed first with metal and then supported by epoxy resin filled with metal. The process of spraying with, for example, an electrical compressed air gun gets applied until the required shell thickness is met (0.5 mm + – mm is reported). In this technique, the material consisting of pattern must have increased strength and durability to withstand the thermal impact inherent: in this regard, the use of ABS FDM masters, polycarbonate SLS masters, and machinable wax gave positive results some of the indirect methods which uses AM, and their advantages and disadvantages are shown in **Table 2**. In addition to them,

METHOD	ADVANTAGES	DISADVANTAGES
Investment Cast Tooling	Suited to forming finely detailed metal components and working with high-melting point metals.	Size limitations and usually only smaller castings can be made.
3D Keltool	Very good definition and surface finish.	Size limitations.
Spray Metal Tooling	Excellent abrasion resistance (nickel-spray tooling).	Required skilled or semi-skilled labor so the labor cost may be relatively higher than other rapid tooling techniques.

Table 2.
Advantages and disadvantages of indirect methods, which use AM.

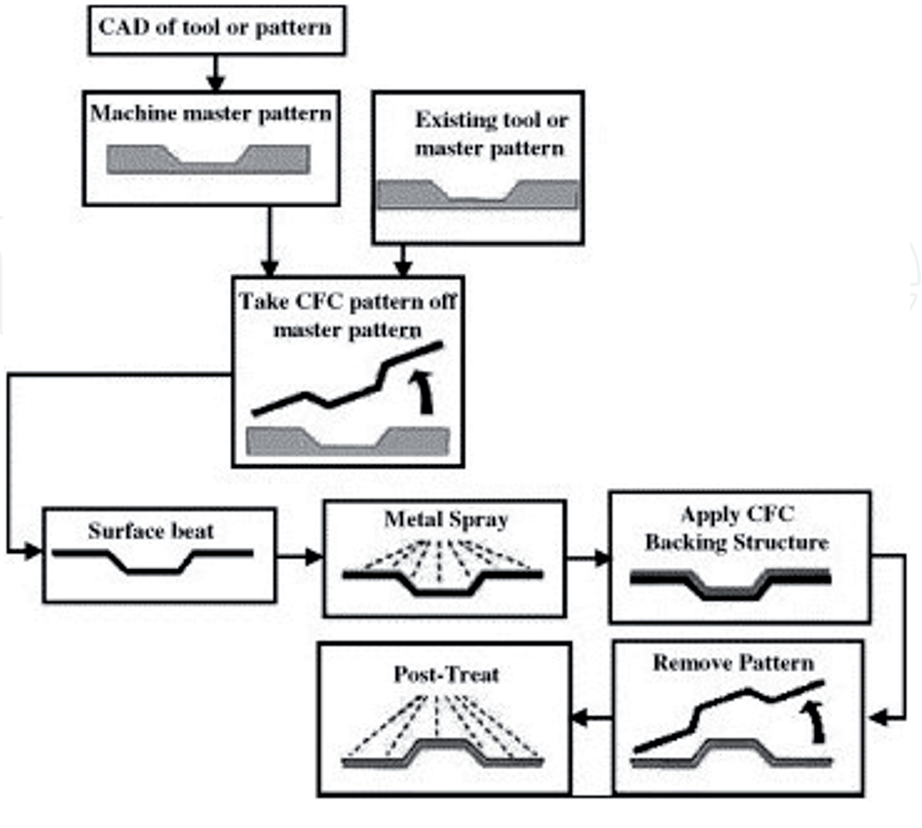

Figure 2.
Spray metal tooling [7].

a reflective coating could be protective. Also, SLA models were tried process of the spray metal tooling depicted in **Figure 2** [6].

2.2 Direct methods of rapid tooling

All the past AM techniques mentioned include indirect production of a master model producing the tool. The time required to manufacture and complete its pattern is one of the major issues with the manufacturing tool. Moreover, such replication methods can still cause increase in inaccuracies. As a result, although the most of direct tooling techniques have constraints, corporations ask directly produced tooling.

Applying additive "layer manufacturing" methods, further properties may get included in the item, which cannot be acquired with conventional tooling techniques. Conformal heating (or cooling) channels provide the system with the ability to heat or cool the exact points needed, and it is the most critical property of it. It is shown that conformal channels could result with the reduction in cycle times of injection molding by up to 40% [6].

2.2.1 Direct AIM

Rather than making a master stereolithography pattern around which a material is cast, it also is possible to build the cavity directly on the stereolithography machine. This method has been described as Direct AIM by 3D Systems (Valencia, CA). (AIM stands for ACES Injection Molding. ACES stands for "accurate clear epoxy solid," which is a stereolithography construction style.) Even though they are not as strong or difficult as standard tools, various thermoplastics can get injected into those cavities so that elements to get used could get manufactured. Even though only less abrasive and lower melting polymers can get molded, studies are going on in order to increase its applicability [6].

2.2.2 SLS RapidSteel

Just as a cavity can be produced directly by stereolithography, the laser sintering method can also be used to construct tool cavities directly. Digital core and cavity geometry models are developed and sent to a Sinterstation manufacturing device in RapidSteel powder with DTM's RapidSteel (also known as RapidTool, earlier similar methods are known as Indirect Metal Selective Laser Sintering). This material comprises of mild stainless-steel particles that are covered with a thin layer of a material for a polymer binder. The Sinterstation generates green components that fire in a furnace afterwards. The furnace removes the polymer binder and by capillary action infiltrates bronze into the inserts of the mold. This method generates a completely thick tool consisting of approximately 60% steel and 40% bronze. Then the inserts are completed, drilled for ejector pins, and fitted to the base of the mold.

The technique generates a durable mold that can be used as well as die-casting apps for injection mold tooling. Hundreds of aluminum, zinc, and magnesium components were casted using RapidSteel molds. The technique enables complicated geometries, and molds from RapidSteel can resist injection molding circumstances. RapidSteel, however, needs finishing and polishing that can take time scheme of the SLS process can be seen in **Figure 3** [6].

2.2.3 Copper polyamide tooling

The DTM (Austin, Texas) copper polyamide tooling method is consisted of selective laser sintering of a matrix of copper and polyamide powder to manufacture

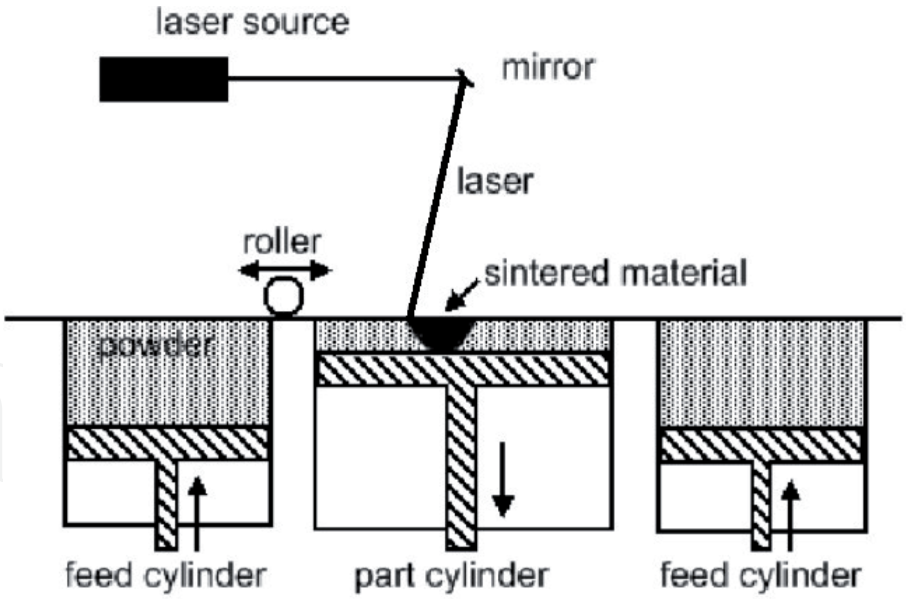

Figure 3.
DTM SLS Sinterstation 2500 plus [8].

a tool. All sintering process happens among the polyamide powder particles. This technique provides improvements in toughness of items unlike some of the other smooth tooling techniques and heat transfer. The copper is not only appropriate for these properties but also can offer some advantages to users like operating a device with pressure and temperature settings which are closer to the environment of the process. The main inconvenience of it is the material's low resistance [7].

2.2.4 EBM tooling

Arcam provides technology to manufacture completely solid metal elements with electron beam melting (EBM). Parts layer by layer are made by the EBM technology using strong electron beam (4 kW power), which melts metal powder. The use of EBM method performed in a vacuum provides users with stress relaxed components with better mechanical, chemical, and material properties the casting and forming.

The method depends on the use of high-level energy thanks to its ability to provide high fusion ability and high productivity. The EBM method is mainly developed in order to process refractory as well as resistant materials (tantalum, niobium, molybdenum, tungsten, vanadium, hafnium, zirconium, titanium) and alloys thereof. It is defined primarily by not only high-speed manufacturing but also complicated geometries of elements with comparable mechanical characteristics to heat-treated products [7].

2.2.5 Direct metal laser sintering

Direct metal laser sintering (DMLS) from EOS consists of metal powders processed directly in a laser sintering machine. The machine manufactures not only tool inserts but also metal parts. Two materials are available for DMSL method and this method depicted in **Figure 4**:

1. Bronze-based materials are preferable for injection molding of up to 1000 elements in various products.

2. Steel-based material which is advantageous for injection molded components of up to 100,000 plastics [7].

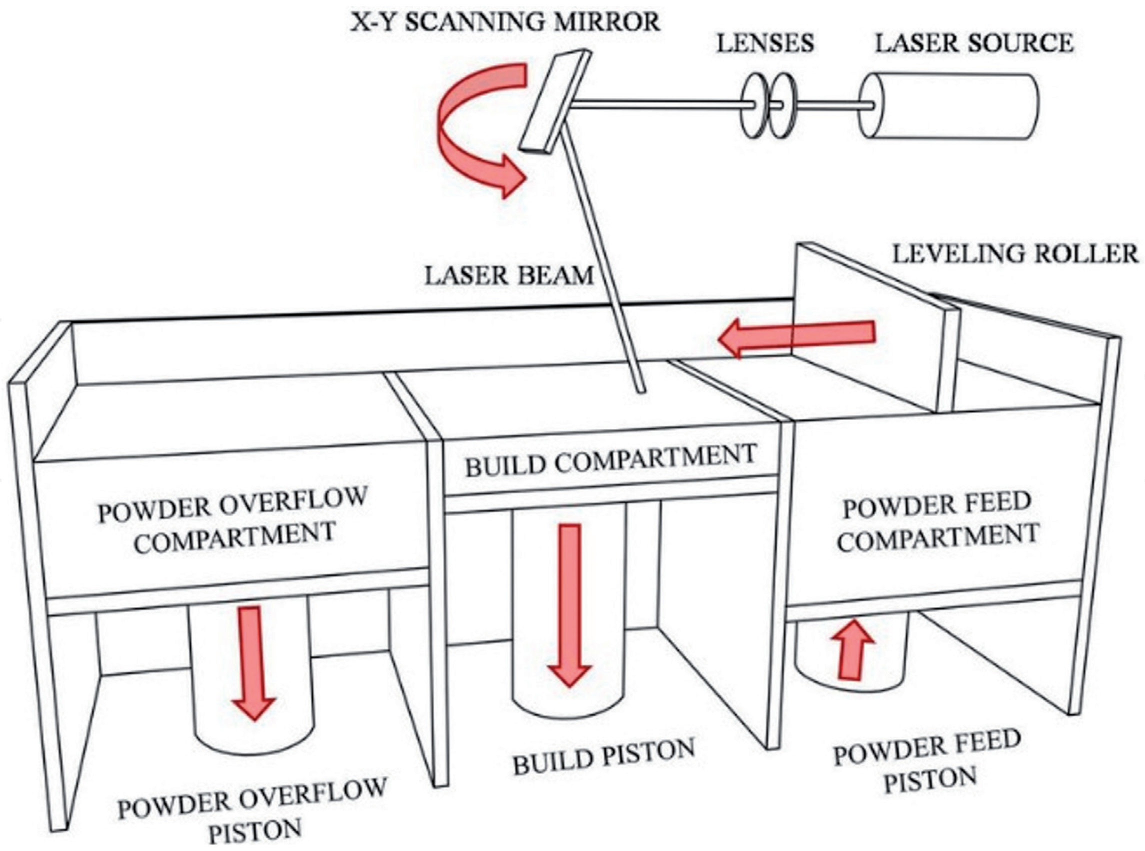

Figure 4.
DMLS 3D printing process [9].

2.2.6 Laminated tooling

Laminated tooling is another applicable option to construct cavities on an AM used prototyping machine. By using a CAD model, sheet layers of metal are sliced, which uses comparable principles to the laminated object manufacturing (LOM) method to multiply slices. Either water-jet or laser cutting techniques are usually applied to obtain the profiles. Manufacturing the molding tool requires CAD model to take the form of the necessary cavity. A mass of laminates can be accomplished to replicate by cutting all the cavity slices into sheet metal. To eliminate complicated post-process cutter path planning, a pseudo-solid cavity in hardened tool steel is manufactured by using either clamping or diffusion bonding related picture can be seen in **Figure 5** [6].

2.2.7 Lens

The Optomec (Albuquerque, New Mexico) laser-engineered net shaping (LENS) system—initially created at the Sandia National Laboratories—is used to build elements into a laser, primarily laser cladding using a metal powder feed. Through a highly intense laser beam into a molten metal pool, a metal powder is injected in this method. The manufacturing method takes place for oxygen-free operation in a low-pressure argon chamber. A movement scheme drives a platform through x and y planes (two-dimensional) as the laser beam traces the cross section of the fabricated portion which can be seen in **Figure 6** [7].

2.2.8 Controlled metal buildup (CMB)

Albrecht Röders GmbH & Co. KG (Soltau, Germany) has marketed a method called controlled metal buildup (CMB). At the Fraunhofer Institute for Production

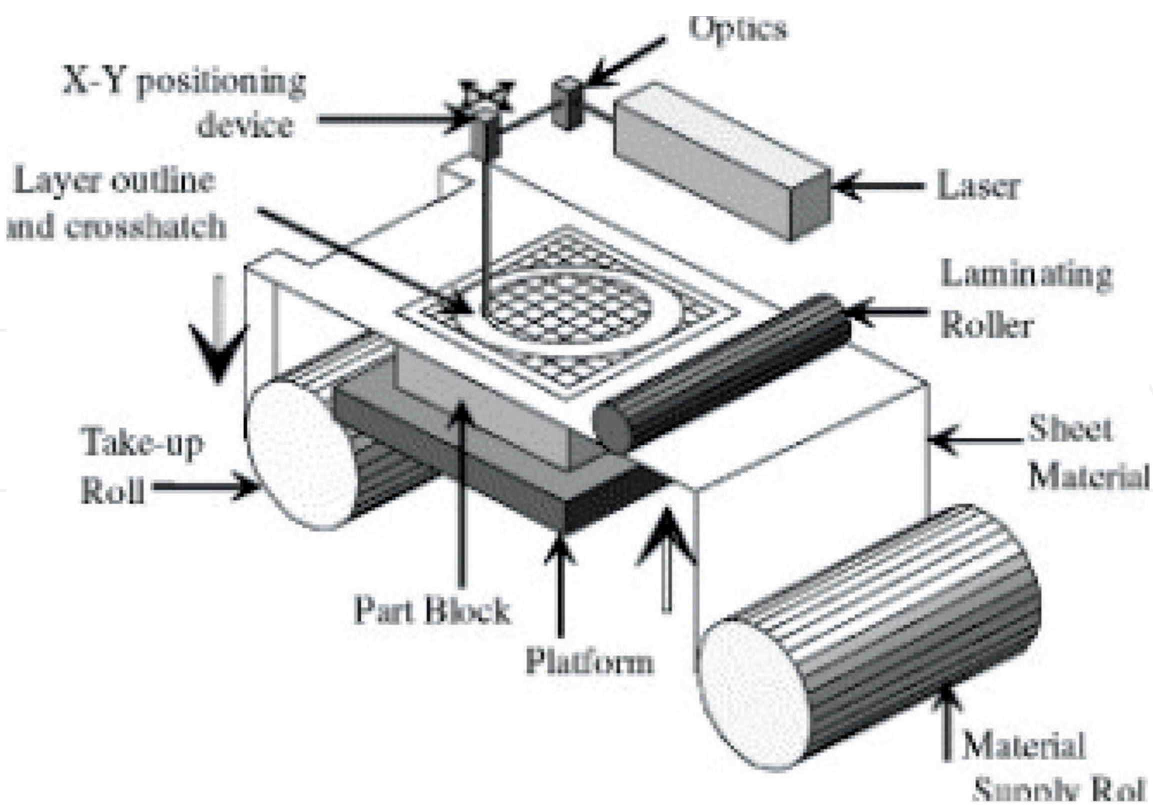

Figure 5.
Laminated tooling process [10].

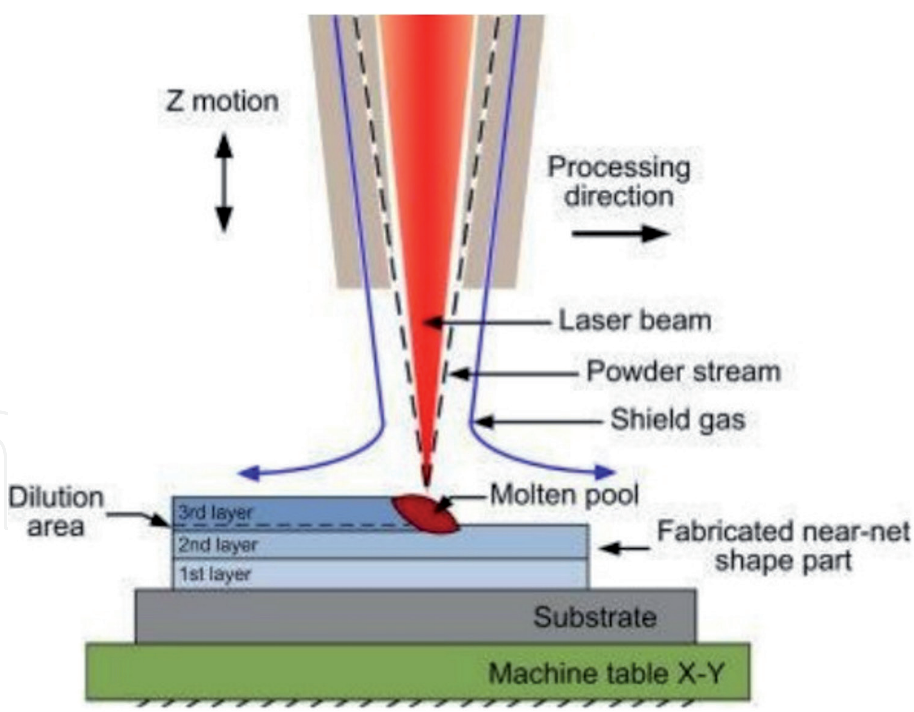

Figure 6.
Laser-engineered net shaping (LENS) process [11].

Technology (IPT) (Aachen, Germany), the fundamental technology was initially created. Three systems were purchased by the business last year.

Components having 100% density are resulted by using this method covering lased cladding and friction. The material is deposited by CMB from a steel wire, and a 1–2 kW HDL laser welds the steel to the workpiece surface. Before every fresh layer is deposited, a cutter with a high speed is used to flat each layer [6].

METHOD	ADVANTAGES	DISADVANTAGES
Direct AIM	Quick process and it produces parts using production thermoplastics.	Low tool strength.
SLS RapidSteel	Quick process, good tool strength and its use for injection molding and die casting	Equipment cost and size limitations.
Copper Polyamide Tooling	Boasts an increase in tool toughness and heat transfer.	Low material strength
EBM Tooling	Improves productivity, reduce cycle time and reduces production cost.	Equipment and powder costs.
DMLS	Suitable production of tool inserts also it has good surface finish.	Low speed requirements.
Laminated Tooling	It has the ability to change the design of parts quickly by the replacement of laminates.	The need for finish machining to remove the stair steps.
LENS	100 percent dense parts	Poor surface finish and small feature definition.
Controlled Metal Build-up	Involves laser cladding and milling that results in 100 percent dense parts	General welding disadvantages.
Prometal	Acceptable results.	Reliability problems.
Direct SL Shell Tooling	Molding cools faster, thus shortening cycle time.	General stereolithography disadvantages.

Table 3.
Advantages and disadvantages of direct methods which use AM.

2.2.9 ProMetal

The ProMetal AM used tool production system of Extrude Hone—named RTS-300—is 3DP method for the manufacture of metal components and tooling. Steel parts up to size of 12 ‘12 ‘10 inches (300 ‘300 ‘250 mm) can be achieved by the machine. ProMetal applications covers vacuum forming, lost foam patterns, injection molding, blow molding, and powder metal part manufacturing [6].

2.2.10 Direct SL shell tooling

Thin SL shells in shell tooling are applied to manufacture inserts reinforced by materials with high thermal conductivity like aluminum-filled epoxy. Therefore, higher mold strengths are attainable in contrast to those achieved by the direct AIM tooling technique, which builds a strong resin mold. Due to aluminum's increased conductivity, which offers faster cooling of mold, the cycle time gets shorter. To improve wear resistance, metal plate can be used to cover the outer surface brief advantages/disadvantages chart of direct methods is depicted in **Table 3** [12].

3. Design of deep drawing tools produced by rapid tooling technologies

In all industries, customized and tailored design is gaining importance, and therefore small series production has increased in the last decade. The increasing number of variant types and also the decreasing number of the same parts affect the manufacturing processes deeply. For instance, metal forming is known to be economical for large series production. One of the main factors affecting the cost of the metal forming process is tool costs. Conventional methods and materials to produce forming tools result in certain disadvantages: Not only the production process takes too much time, but also the whole process is expensive.

Therefore, rapid tooling methodologies are gaining importance also for metal forming technologies in recent years. Rapid tooling methods offer indispensable advantages in time, though the cost of the tool must be optimized according to the number of parts to be produced, material couple to be chosen, and the production methodology.

To optimize the part quality, the method, and the cost prediction, a methodology to predict the most appropriate rapid tooling method as well as the prediction of the tool life becomes indispensable.

As the abrasive wear on the metal forming tools increases, it is getting more and more important to predict the tool wear and the life of the tool, when the tool is in design stage. By this way the most appropriate tool materials, design, and maintenance periods can be planned.

First a methodology to ensure that the chosen rapid tooling technique and material are appropriate to produce the part must be introduced. This includes the dimensional accuracy, mechanical properties, the surface quality of the rapid tooling process, the related production process parameters like deformation of the tool, temperature distribution, and a determination of tribologically matching material couple and surface properties important factors can also be seen in **Figure 7**.

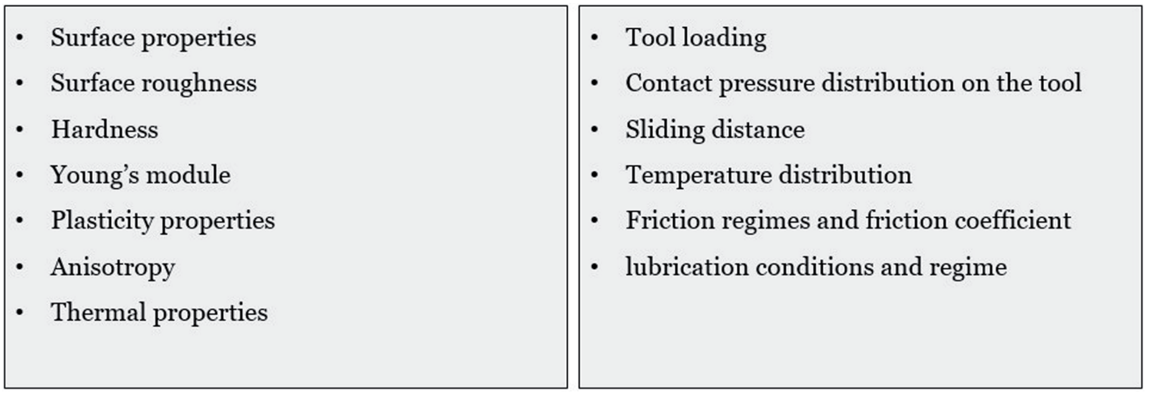

Figure 7.
The main factors affecting the choice of the rapid tooling material and production method.

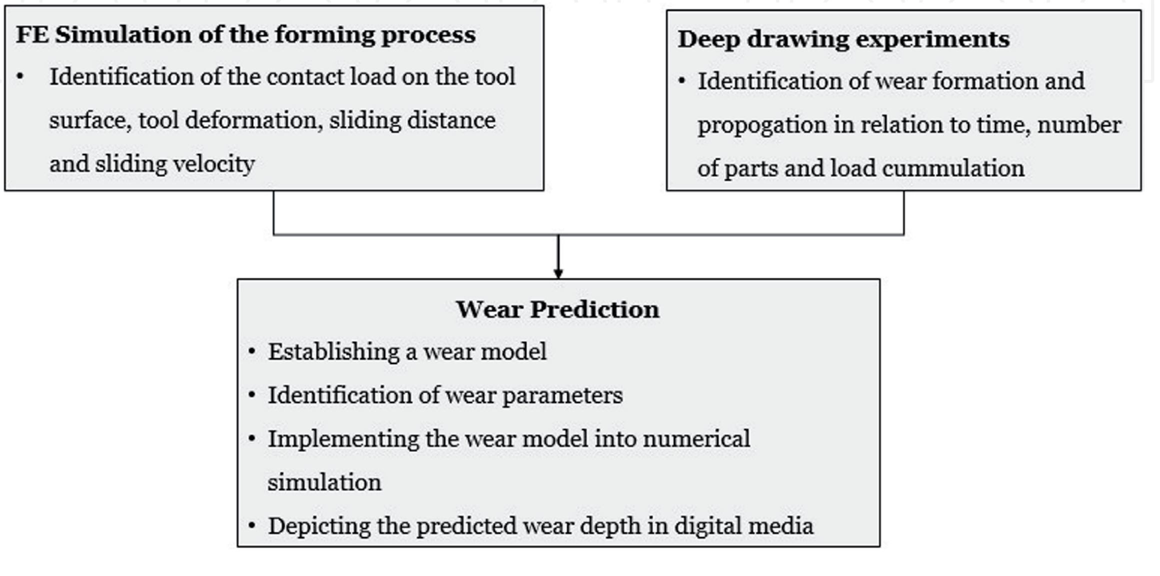

Figure 8.
Approach to predict the wear on forming tools.

Then the number of parts, which can be produced with this rapidly produced tool, must be predicted. In order to predict the operation time of a tool, the following approach is offered.

A metal forming process is economically advantageous, if and only if the tool costs can be controlled and predicted. Forecasts of the number of parts to be produced with the tools are of highest advantage. Therefore, in the PhD thesis, a method to predict tool wear is established and validated and verified an approach is depicted in **Figure 8** [13].

This approach is tested with a simple cup deep-drawing geometry. The die is made of rapid tooling, whereas the punch and blankholder are produced by conventional methods out of tool steel as given in **Figure 9**. For that reason, the punch and blankholder are modeled as rigid body, whereas the die is modeled with 3D deformable elements.

In order to enable testing, a follow-on tool is designed, and an optical and tactile measurement methodology is determined. The die made out of rapid tooling is measured at determined intervals, and the wear propagation over time is measured. Four different locations are measured, and the experiments are conducted up to five times. The details of the repeatability and reliability of the data and measurement methodology can be found in [13].

The contact pressure distribution is obtained by finite element methodology as depicted in **Figure 10**. As the die material is made out of rapid tooling, these materials are generally very susceptible to abrasive wear.

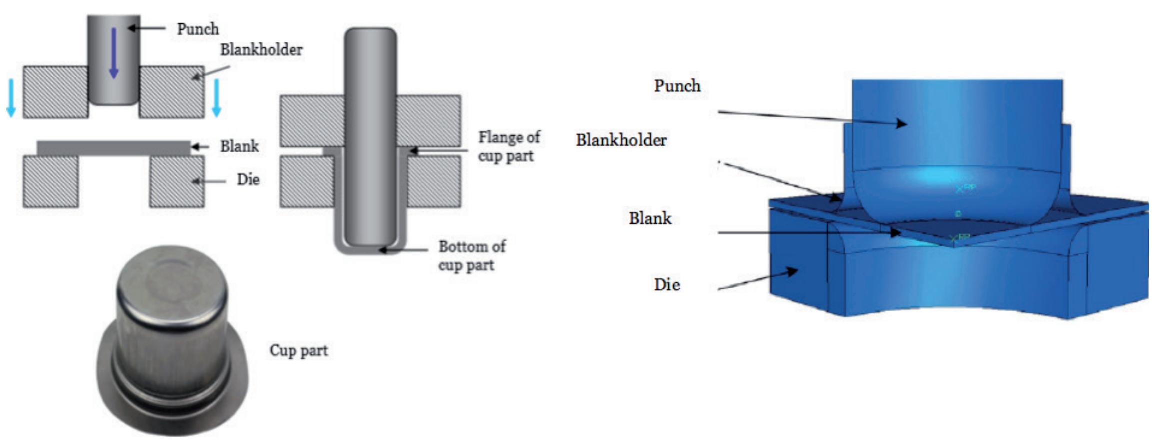

Figure 9.
(a) Schematic presentation of deep drawing of a cup geometry. (b) a quarter model of a simplified circular deep drawing geometry [14].

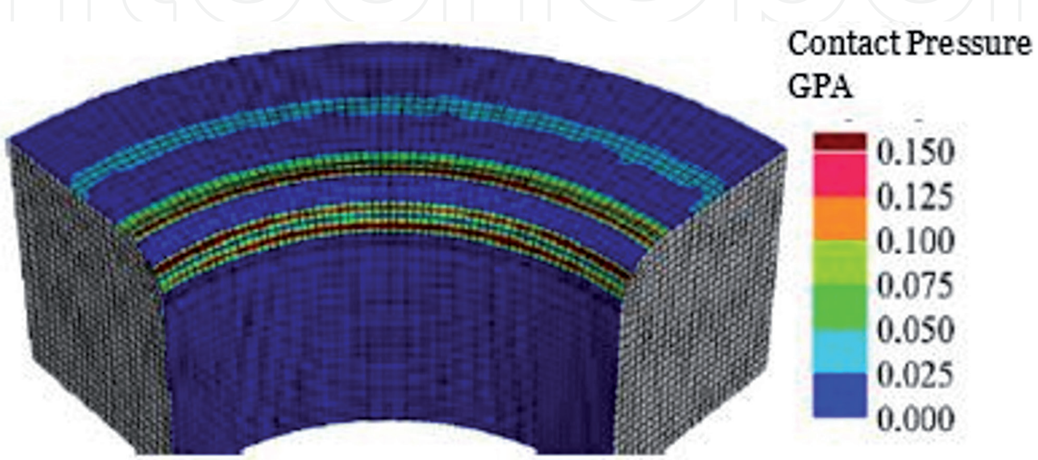

Figure 10.
Comparison of wear behavior of different rapidly produced tools (PA220 (PA-SLS), ZAMAK (SLA + casting), LaserFormA6 (SLS RapidSteel) vs. tool steel (conventional method) [14].

The key technology for predicting the development of wear in metal forming tools is numerical simulation. In forming applications, a wear is commonly described using models based on contact mechanics, the most important one being the Archard wear equation. Here the parameters affecting the wear are contact pressure, sliding distance, hardness, and a tribological constant.

With the offered methodology, the wear depth at each location at each punch stroke can be predicted. **Figure 11** depicts as an example a predicted vs. measured die radius wear rate after 10,000 punch strokes.

The **Figure 12** shows the wear rate of different dies produced by AM technologies, measured at different time intervals. As expected all rapidly produced tools have higher wear, i.e., shorter operation times. LaserFormA6 a kind of stainless

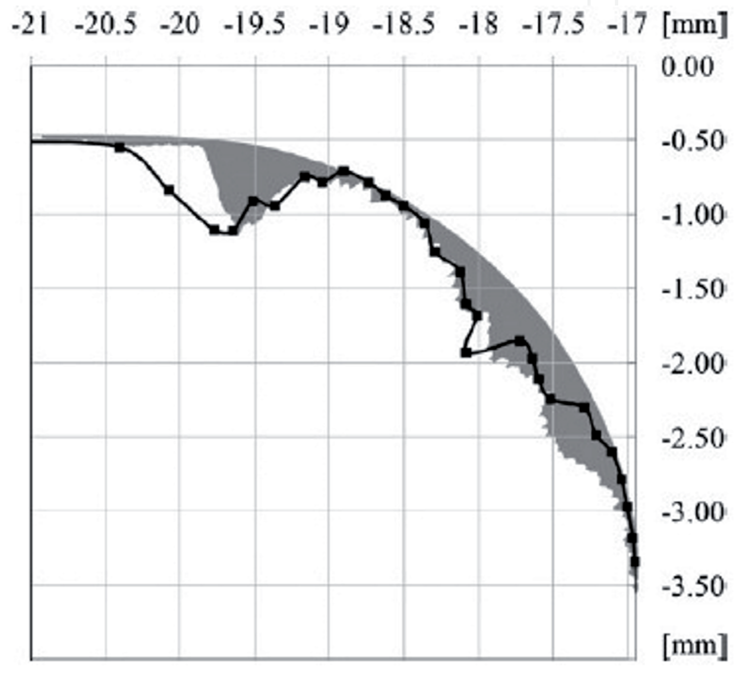

Figure 11.
Contact pressure obtained by finite element simulation [14].

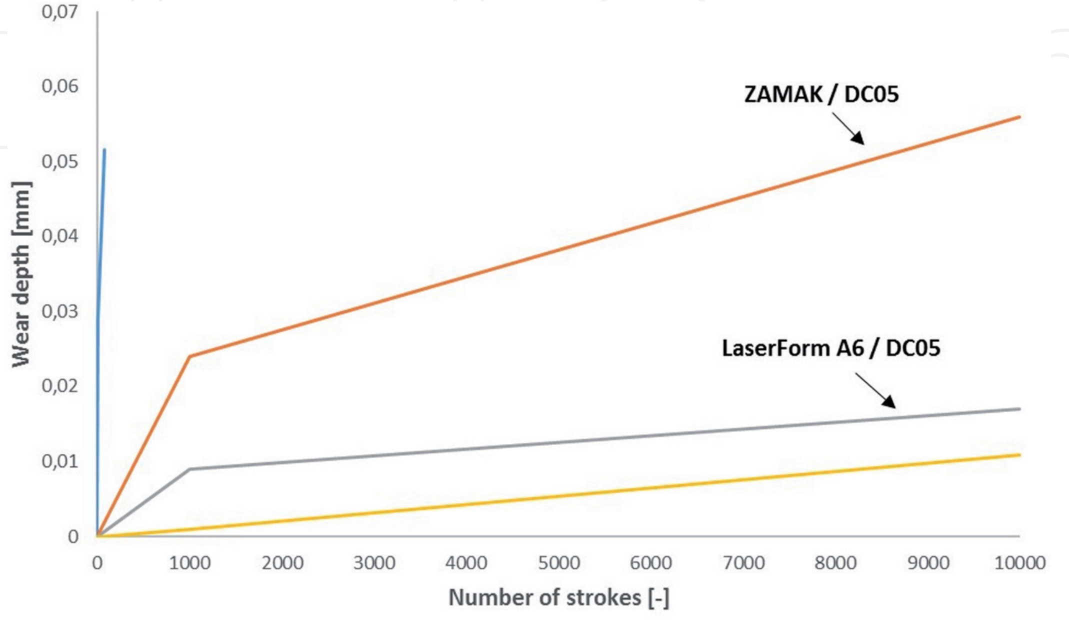

Figure 12.
Measured wear depth in the profile (gray) compared to the simulation results of the same location (black) [14].

steel powder produced by SLS RapidSteel has the best wear resistance as expected, among others. Polyamide die has remarkably high wear rate which indicates that these are not appropriate for any series more than 100 parts. ZAMAK (zinc, aluminum, copper alloy) produced by casting into a SLA mold turns out to have a moderate wear resistance. All these trends obtained in these experiments are in accordance with the Archard theory, where the wear of the tool is indirectly proportional to the hardness of the die materials. Still, when investigated in detail their wear behavior, their elastic deformation, and tribological behavior affect the wear distribution over time, i.e., number of parts, sliding distance, or wear work.

This implies that according to the geometry and the number of the parts needed, this method can also be considered an alternative for sheet metal forming tool.

4. Conclusion

Customized and tailored design is gaining significance in all areas in the recent decades. The growing amount of variants and the declining amount of the same components also have a profound impact on the production procedures. Additive manufacturing is gaining importance due to many advantages, and in tool design it is used mostly due to its lead time advantage. Even if AM in tool production offers indispensable advantages in time, the cost of the tool must be optimized according to the number of parts to be produced, the couple of materials to be selected, and the method of production.

A methodology for predicting the most suitable AM technique for tooling, as well as predicting the life of the tool, becomes indispensable in order to optimize the part quality, process, and price prediction. First, it must be guaranteed that the selected fast tooling method and material are suitable for producing the tool. This involves dimensional precision, mechanical characteristics, surface quality of the selected AM method, associated process parameters such as tool deformation and temperature distribution, and determination of corresponding material pair and surface characteristics tribologically.

In this chapter a metal forming tool in a simplified round die geometry is chosen as an example to predict the wear of a AM-produced tool, and the results show that the AM-produced tool has a shorter operation life, showing a wider range of lifetime depending on the AM technique and the tool material which are used.

From these results it can be concluded that in the chosen AM method, the material must be optimized according to the geometry of the part to be produced, number of parts to be produced, process parameters, tribological requirements, and the time and cost constraints.

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