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Published in:
Procedia CIRP

Link to article, DOI:
10.1016/j.procir.2021.10.014

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
3D printing to facilitate flexible sheet metal forming production

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Abstract

This study presents and discusses the possibility of using 3D printed polymer tools to achieve a flexible metal forming production line. An example is given of the design of a sheet metal part from tool printing to the actual forming and evaluation of the achieved precision of the formed part. The time spent by the engineer/operator during the full process cycle is documented and compared to the time it would take to make the corresponding tool by conventional metal machining. The time savings revealed in the paper are relevant for a low number of parts to be formed in a flexible manufacturing environment, while it is less relevant in mass production where metal forming is conventionally an attractive process. Besides the time invested by the engineer/operator, it is also important to keep the costs of the tools at a minimum in flexible manufacturing. Therefore, the paper also presents a comparison of the costs for printed tools as compared to conventional tools made from metal machining.

This analysis considers the cost of raw materials, machine time and electricity consumption. The environmental aspects of metal forming are also considered, with the lubricating oils and greases typically used to improve frictional conditions being replaced by the polymers, which themselves have anti-friction properties. Finally, the recyclability of the tools is significant when they are only used to form a few parts. Different types of polymers and printing strategies are discussed in relation to recyclability and compared to the alternative metal tools.

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Peer-review under responsibility of the scientific committee of the 9th CIRP Global Web Conference – Sustainable, resilient, and agile manufacturing and service operations : Lessons from COVID-19 (CIRPc 2021)

Keywords: Additive manufacturing, sheet metal forming, flexible production, environmental impact, economical impact

1. Introduction

Sheet metal forming is one of the most common production methods in industry. It can be used to efficiently shape desired geometries from widely available flat sheets. There are various benefits to the method, such as the minimal scrap that is generated and the production capacity that can be achieved. The main drawback is the massive amount of time and money that goes into setting up a new production line due to which this method is typically reserved for mass manufacture [1].

In the modern market, the key to being competitive in certain branches lies in short lead-times, economic production, and easy customization of parts [2]. These factors cannot be used to describe sheet metal forming in the conventional sense but through rapid tooling (RT), i.e., rapidly fabricating production tools, this becomes possible [3]. Methods, such as Fused Filament Fabrication (FFF) and Selective Laser Sintering (SLS), have been utilized to reduce the cost and time necessary to fabricate tools for new sheet metal forming production lines. Zelený et al. [4] saved more than 50% of the time necessary when producing tools by FFF compared to wire Electrical Discharge Machining (EDM), which is one of the conventional toolmaking methods. They also showed that not all RT methods are suitable, as Selective Laser Melting (SLM) increased the tool production time and cost compared. Cheah et al. [5] showed that using SLS to fabricate embossing tools cut costs by 60% and time by 40% compared to conventional toolmaking. They also note the ease
of which complicated shapes can be included in the tool surface for stamping into the formed part.

The reduced time and cost necessary to produce a set of sheet metal forming tools makes the method more suitable for small series production. This allows the benefits of conventional sheet metal forming to be realized without requiring as substantial of an initial investment as before. Due to the nature of 3D printing, the possibility of fabricating complicated and multi-component tools also becomes larger and requires less effort on the part of the tool makers. The range of geometries that can be realized through sheet metal forming is therefore expanded. Beyond small series production, additive manufacturing can also be used to prototype tools as proofs-of-concept before the tool design is finalized.

Beyond the benefits discussed previously, 3D printed polymer tools offer secondary benefits due to the nature of the tool material. Aksenov and Kononov [6] formed heat exchanger plates using plastic tools and found that lubrication was not necessary as the plastic had anti-friction properties. Leacock et al. [7] confirmed this but found that the friction increased as the plastic tools experienced wear. They also noted that by not using a lubricant, degreasing after forming was not necessary, reducing lead-time and production costs further while improving the sustainability of the process. Nakamura et al. [8] performed bending experiments and noted that using plastic tools reduces the chance of scratches being made on the formed part compared to using metal tools. This is due to the tools being much softer than the metal they are in contact with, preventing them from being able to scratch it. Zaragosa et al. [9] developed a modular hybrid system, where a set of plastic tools are assembled in a metal frame. The plastic tools would be made from recyclable or reusable material, lowering the environmental impact of this method of small series production. Many of the references cited in this paper have outright stated that 3D printing of tools is a viable method of realizing small series production by sheet metal forming. It allows for a customizable, low-cost, and relatively quick application of a method that otherwise demands huge start-up costs and time. However, there are some factors that are a detriment to this approach. The tools are made from plastic, meaning that they are relatively soft compared to the workpiece. This makes elastic tool deflection inevitable. Various ways of reducing this effect have been investigated, such as by extensive optimization of the printing strategy [7], by having one of the tools be plastic and the other metal [8], or by reinforcing the tools [10]. Tool wear is accelerated due to the tool material being relatively weak. This may not be a problem in small series production but is one of the main obstacles for applying this approach to fabricate tools for larger series and mass manufacture. This goes to show that this approach should only be used for prototyping or small series production purposes.

An approach to develop a flexible production system based on 3D printed tools is put forward in this work. First, the printing strategy that is used to fabricate the tools is optimized in terms of dimensional accuracy and stiffness based on a literature study. In previous work, the authors presented the accuracy obtainable in V-bending and groove pressing and evaluated the performance of 3D-printed tools used in these conditions [11]. Secondly, the economical and environmental aspects of applying this approach to small series production sheet metal forming is considered. A demonstration of the flexibility attainable by RT sheet metal forming is presented. The cost, working time and environmental footprint as compared to conventional tool making are discussed. Lastly, an outlook for a flexible forming unit for industrial use is given.

2. 3D printing of tools

The 3D printing process selected in this paper is Fused Filament Fabrication, widely known by its trademark Filament Deposition Modeling (FDM). This process is commonly used in the field of rapid prototyping for several reasons, some of which are:

- FDM is more affordable than SLM.
- FDM does not require the use of powder, which is more expensive and difficult to handle in comparison to polymeric filaments.
- FDM does not necessitate thermal post-processing as Vat Photopolymerization-based Additive Manufacturing (VPAM) does.

In FDM, the part is printed layer by layer by extruding a molten polymer filament through a nozzle onto a building platform. The tools produced in this work were printed with an Ultimaker 2+ printer using a polylactic acid (PLA) filament.

The printing parameters serve an essential role in assuring the final strength and quality of the printed tools [1, 12]. In this work, in accordance with an investigation carried out by Kuznetsov et al. [12], a vertical printing orientation was selected. This orientation maximizes the resistance of the tool to compressive forces since the forces are perpendicular to the layers, reducing the likelihood of delamination. A layer thickness of 0.1 mm was selected; the lower the layer thickness the stronger the bonding between layers. Another parameter that influences the layer bonding is the infill density, which was fixed at 50% to ensure adequate bonding without drastically affecting the printing time. The shell thickness was chosen to be 2.1 mm or double the standard 1.05 mm that the printer offers as default. The thicker shell thickness improves the stiffness of the tool without increasing material use or printing time overly.

The printing accuracy was investigated and deviations for the x and y printing directions were found to be comparable, of 20 μm and 62 μm respectively. A deviation of 40 μm was detected in the z direction. The surface roughness of the printed tools was also investigated. The Ra value was determined to be $2.96 \pm 0.27 \mu m$ across the layers, and $0.78 \pm 0.45 \mu m$ parallel to the layers.

3. Demonstration of flexibility by sheet metal bending

The part shown in Fig. 1 is used as an example in this work to demonstrate the forming of a part that requires simultaneous movement of multiple tools. The initial workpiece is a 90 mm long, 30 mm wide strip of 1.0 mm thick 1050 aluminum. The dimensions that are measured to analyze geometrical accuracy are also shown in Fig. 1; namely the width of the internal shape
and three radii representing different challenges. $R_c$ and $R_b$ are related to the internal geometry created by a secondary tool, while $R_l$ is related to the radius formed around the primary tool when the strip is formed in a single step.

Fig. 1. Selected geometry for the study. The cross-section identifies dimensions that are measured to evaluate the precision of formed components. Nominal dimensions: $R_c = 2$ mm, $R_b = 1$ mm, $R_l = 1.7$ mm, and $w = 4.15$ mm.

The forming process is performed using an electric press that has a capacity of 150 kN. The tools were assembled in a steel frame, to improve the overall stiffness of the tool assembly. The steel frame was installed in a sub-press to ensure proper guidance of the tools during forming. In the present example, four tool parts were printed and installed with four springs of a stiffness of 2.33 N/mm, as shown in Fig. 2a.

Fig. 2b-e shows the forming operation at selected tool positions. While the primary punch, mounted on the upper side of the sub-press, gives rise to the overall geometry, the lower tools facilitate the inner geometry by horizontal movement realized by the 74.5° inclined interface between two of the printed parts. Fig. 2f shows parts that have been formed.

The nominal component has a challenging geometry in the transition from the upper vertical part to the curvature characterized by $R_c$ and $R_b$. There is a horizontal section of only 1 mm that was not achieved during the actual forming tests. This was mainly due the lack of closure between the primary punch and the secondary punch. Furthermore, spring-back acts in the direction of smearing out the horizontal plateau.

Fig. 3 shows the measured dimensions of the selected key features shown in Fig. 1 after they are normalized with respect to the nominal dimensions. The first five parts formed using the tools are included. The figure also includes the corresponding measurements of the primary punch. $R_l$ is not measured on the primary punch as it is not defined by it, but rather by the secondary punch.

The dimensional accuracy of the primary punch is considered satisfactory as the nominal dimensions lie within a single standard deviation from the measured value. The largest deviations found in the formed workpieces are the radii, $R_c$ and $R_b$, which are both related to the inner shape as discussed above. Dimensions of features formed by the primary punch, the width $w$ and nose radius $R_c$, are closer to being nominal.
The radius $R_b$ is furthest from the nominal value, being up to 30% larger than nominal, with a standard deviation of 12%. The deviation in the radius $R_c$ is smaller, although still significant, being up to 20% larger than nominal and having a standard deviation of up to 10%. The measured radius $R_b$ and width $w$ were deemed satisfactory. The measured maximum for $R_c$ was only 2% larger than nominal, with a standard deviation of 4%, whereas the measured maximum for $w$ was 6% larger than nominal with a standard deviation of 2%.

The deviation in the radius $R_b$ to 30% larger than nominal, with a standard deviation of 12%.

4. Economical and environmental considerations

This section presents an investigation of the economical and environmental aspects of using FDM as a method of producing sheet forming tools. The focus is on tool cost, working time and the environmental footprint of the printing material.

4.1. Tool costs

The following cost analysis considers different factors, such as the cost of raw materials, machine time and electricity consumption. The cost of the printed tools is influenced by the raw material and electricity consumption. Additionally, printing settings such as infill density and layer thickness will affect it, but variations of those are not investigated in this paper. The printing settings, identified as optimal in Section 2, are used for the tools shown in Section 3. Material cost and electricity consumption, based on being in Denmark, are:

- Primacreator PLA filament cost: 23.3 EUR/kg [13].
- Electricity consumption: 0.3 EUR /kWh [14], which lead to 0.07 EUR /1h printing.

Table 1 presents the printing time, weight, and corresponding manufacturing costs of each tool component in the assembly shown in Section 3. Tools made from a common, low-cost carbon steel are used to establish a reference. The production costs of these tools are outlined in Table 2 for production by wire EDM and milling. The following factors are considered in the tool cost analysis:

- Raw material cost (carbon steel) is 1.34 EUR/kg (Danish supplier).
- Cost of wire EDM and milling processes, quoted by workshop leader: 120 EUR/hour.
- Wire EDM with two trim cuts, estimated to reach a surface roughness (Ra) of 0.6 μm.
- Milling time includes finishing and is estimated to achieve a final surface roughness (Ra) of 1.2 μm.
- The initial volume of raw material for milling is smaller than for wire EDM as the components are produced separately.
- The tool assembly was re-designed to make it easier to produce by wire EDM and milling. This includes changes such as the guiding pins (see Fig. 2a) being mounted by screws after production of the tools instead of being printed directly.

![Fig. 3. Measured dimensions of the primary punch and five formed parts, normalized with respect to evaluation dimensions identified in Fig. 1. Error bars represent standard deviations based on five measurements.](image)

<table>
<thead>
<tr>
<th>Tool</th>
<th>Primary punch</th>
<th>Secondary punch</th>
<th>Guiding tool</th>
<th>Frame</th>
<th>All tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print time</td>
<td>8.41</td>
<td>2.32</td>
<td>6.18</td>
<td>18.35</td>
<td>36.96</td>
</tr>
<tr>
<td>Weight [g]</td>
<td>49</td>
<td>15</td>
<td>36</td>
<td>108</td>
<td>208</td>
</tr>
<tr>
<td>Volume [cm³]</td>
<td>62.3</td>
<td>15.5</td>
<td>43.5</td>
<td>130</td>
<td>251</td>
</tr>
<tr>
<td>Electricity cost [EUR]</td>
<td>0.60</td>
<td>0.17</td>
<td>0.40</td>
<td>1.23</td>
<td>2.40</td>
</tr>
<tr>
<td>Material cost [EUR]</td>
<td>1.10</td>
<td>0.35</td>
<td>0.84</td>
<td>2.52</td>
<td>4.81</td>
</tr>
<tr>
<td>Total cost</td>
<td>1.70</td>
<td>0.52</td>
<td>1.24</td>
<td>3.75</td>
<td>7.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tools</th>
<th>Wire EDM</th>
<th>Milling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial raw material volume [cm³]</td>
<td>845</td>
<td>637</td>
</tr>
<tr>
<td>Final tools volume [cm³]</td>
<td>252</td>
<td>252</td>
</tr>
<tr>
<td>Production time [hh:mm]</td>
<td>6:45</td>
<td>23:00</td>
</tr>
<tr>
<td>Operating cost [EUR]</td>
<td>810</td>
<td>2,760</td>
</tr>
<tr>
<td>Raw steel cost [EUR]</td>
<td>9.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Total cost [EUR]</td>
<td>820</td>
<td>2,767</td>
</tr>
</tbody>
</table>

3D printed tools are significantly cheaper than tools produced by the other methods chosen here. On the other hand, additive manufacturing takes more than 5 times as long as wire EDM and 1.5 times as long as milling. However, the printing can take place over night and without an operator (in the present work, four identical printers produced the four tools in parallel overnight). The price of the four tool parts, in terms of electricity and material used, is calculated to be 7.21 euros in case of printing. This represents considerable savings when compared to wire EDM and milling, which result in total costs of 820 euros and 2,767 euros respectively. The prices quoted here for wire EDM and milling are based on the Danish market and may vary between workshops due to most of the cost being in the production. A different solution for comparison was found using Xometry, where the tool parts cost 900 euros, and would arrive from China after 13 days.
The FDM printing technology distinguishes itself from the others for being an almost zero material waste process due to the precise control of the extruded material. This is not the case for the conventional subtractive manufacturing methods. Table 2 shows that the volume of wasted material is up to 594 cm³ in the case of wire EDM. In terms of direct impact on the cost, this material waste accounts for 2 euros.

The 3D printer used in the present work (Ultimaker 2+) cost 1700 euros, which means that starting out it will be more expensive than producing a single set of tools by wire EDM. However, it pays off as soon as a second set of tools is made. It should be noted that these numbers are based on Danish prices.

For a future flexible manufacturing unit, it should be mentioned that the newer version of the 3D printer (Ultimaker 2+ Connect) can be operated through a Wi-Fi or Ethernet connection. This allows printing to be commenced from anywhere within a company’s network but comes at a higher price; namely 2182 euros [15].

4.2. Operator working time

The employment of RT technologies, such as FDM, for toolmaking leads to a drastic reduction of the operator working time as compared to the traditional manufacturing processes. The operator cost has not been included in the previous analysis in Section 4.1 but would only make 3D printing more favorable as the process is largely hands-free. According to a study conducted by Srinivasan and Bassan [16], the use of FDM can reduce the manufacturing cost and production time considerably.

4.3. Recyclability and polymer choice

In this study, the behavior of a PLA thermoplastic polymer under sheet metal forming conditions was investigated and compared to tool steel. On one hand, PLA is one of the most common FDM printing materials and is used for a wide variety of applications. It is favored for its biodegradability properties; in fact, it is produced from renewable resources, such as corn starch and sugarcane, and is stable in general atmospheric conditions. It biodegrades within 50 days in industrial composters and 48 months in water [12]. There is also an absence of unpleasant odors and toxic fumes when the material is heated, which makes it easy to use without needing a specific work environment.

On the other hand, steel is one of the most sustainable permanent materials on the market. It is characterized by a recycling rate of 90% in packaging industries, which can occur without loss of quality or degradation of properties compared to the virgin material [17, 18]. Thanks to these properties, and for environmental and economic benefits, such as raw material conservation and energy savings, steel recycling has become a priority among steel manufacturers over the years.

Steel production, which can generally be divided into 1) integrated (produced from iron ore) and 2) electric (produced from scrap), does have a significant impact on the environment in terms of energy use. The former produces large amounts of unwanted solid material, liquids and gas emissions during mining and production refining [19].

Finally, it should be noted that the volume of material waste is reduced considerably by using 3D printing as compared to conventional manufacturing, cf. the discussion at the end of Section 4.1.

The significant biodegradability properties, the possibility of using renewable resources, and almost zero raw material waste make the production of 3D printed PLA tools by FDM suitable for rapid prototyping, and small series production. However, steel tools are still better suited for sheet metal forming processes that are characterized by high production volume due to their resistance against wear and the tool cost being distributed over many formed parts.

5. Outlook: Flexible manufacturing unit for sheet metal forming

While sheet metal forming is traditionally reserved for mass production, the considerations presented in this work is aimed at showing the possibility of making sheet metal forming into a flexible process. It may be taken a step further and integrated into a flexible manufacturing unit for sheet metal forming, as illustrated in Fig. 4.

The 3D printing of tool parts and the forming of parts in an electric press are central processes in the flexible manufacturing unit, as shown in this work, where multiaxial tool movements were realized by inclined tool parts sliding against each other. Located at the center of the unit, a stationary robot with precision of around 0.1mm, will be able to move tool parts to an assembly inside the press, or a dedicated housing in a sub-press as in the present work. Additional features may be intentionally printed on the tools to make it easier for the robot to handle the tool parts. Tool parts could be cleaned before use by pressurized air, ensuring that fine particles are removed before use.

After installing the tools in the press, the robot takes virgin workpieces (e.g., by a vacuum gripper system) to the press and, after forming, it takes the formed parts out of the press and inserts the next workpiece to be formed. Cutting of initial
blanks could also be included in the flexible manufacturing unit. Several types of cutting may be considered. For example, a table sized water cutter would allow high flexibility both in terms of shapes, thicknesses, and sheet material.

In the future, the flexible manufacturing unit for sheet metal forming could be operated entirely remotely. Most of the work would be tool design, CAD modeling and interfacing with the different units. As mentioned in Section 4.1, the 3D printers are capable of being remotely controlled. The electric press utilized in the present work is also prepared for remote control (although that requires a software update). The CAD modeling should include the individual tool parts and an assembly, including assembly order, in the reference system of the press.

Concerns related to precision, cost, operator time and sustainability of printing tools were discussed in Sections 3 and 4. Individual cases must still be considered individually, but there seems to be potential in developing a flexible sheet forming unit such as the one outlined here.

It should also be considered that this work was based on using a relatively pliable workpiece material, whereas other applications may involve brass, spring steel or stainless steel. These are still to be evaluated, but at the same time these harder materials are also often used in smaller thicknesses.

6. Conclusions

This paper demonstrates the flexibility and potential of producing PLA tools for sheet metal forming by FDM. Results that may be of interest to the industrial community include:

- Features formed by the interaction of moving tools were characterized by larger deviations from nominal, while those formed along the primary punch were close to nominal.
- 3D printing of tools was shown to be cheap relative to conventional methods of tool production, although requiring initial investment. Tool sets of complexity and size similar to the one presented here cost less than 10 euros to produce by FDM. In comparison, wire EDM and milling were found to be relatively expensive. 3D printing of tools requires longer production time but can take place over night.
- PLA is a suitable material for rapid prototyping of tools for sheet metal forming when using FDM. It is also highly recyclable, biodegradable, and is made from renewable resources, making it an eco-friendly tool material.

An idea for the future of flexible manufacturing units for sheet metal forming was presented as an outlook. Here, additive manufacturing, sheet metal forming in a single step, and robotic handling are integrated to facilitate metal forming for smaller series production, bringing the benefits of the method over from it being only suitable for mass manufacture. This helps in preparing sheet metal forming for increasing demand for customization of products and individual parts, while also reducing cost and need for an operator on site.

Acknowledgements

Ulfar Arinbjarnar and Chris Valentin Nielsen would like to thank the Danish Council for Independent Research [grant no. DFF – 0136-00159A] for financial support.

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