Investigation of the suitability of a tool element manufactured by fused filament fabrication for incremental sheet metal forming

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Abstract. Incremental sheet forming (ISF) constitutes a flexible production process for sheet materials for small to medium batch sizes, in which the geometry of the part is created via the movement of a stylus. ISF can be carried out with or without support from the opposite side. With the use of dies, the geometry deviation can be reduced. In order to be able to guarantee an overall flexible process, the ability to produce dies quickly and individually from the lot size one is necessary. In addition to milling, which has been the primary method used up to date, additive manufacturing (AM) also meets the requirements for flexible die production. To investigate the suitability of additive manufacturing to produce dies for ISF, a pyramid-shaped die was fabricated from polylactic acid (PLA) using the fused filament fabrication (FFF) process. This die was used for three incremental sheet metal forming operations using pure aluminum sheets and was compared with an identical milled tool. Based on the measurement results, the suitability of 3D printed dies for ISF is examined, and opportunities as well as application limits for such dies are discussed.

Introduction

Incremental sheet forming (ISF) is one of the sheet metal forming processes, which are not dependent on a part-specific die. This category includes mechanical processes such as hammer forming and forming by means of shot peening or water jets, as well as thermal processes such as thermal straightening and forming by means of laser beams. All these processes are characterized by high flexibility due to the easily controllable local forming zone. Furthermore, adjustments to the sequence are possible, and the investment costs for dies are significantly lower or completely omitted. However, while using these processes, only low productivities can be achieved, therefore they are preferably used for small to medium lot sizes.

ISF has evolved from the process of spinning and was originally used for prototyping [1]. In the meantime, a wide range of applications has emerged, and an almost unlimited variety of sheet geometries can be produced [2]. In contrast to conventional sheet metal forming processes, the forming is carried out via the continuous movement of a stylus. The simplest variant without a counter die is the so-called single-point ISF. In addition, other variants with an underlying die or support have been continuously developed to further improve the geometrical accuracy of the ISF [3]. The die supports the already formed geometry and reduces the subsequent deformation of these areas. ISF with a die can achieve the highest geometrical accuracy [4]. Due to the recorded lower global tool load also, easy-to-machine and low-cost materials (e.g. plastic, wood, foam or plywood) are suitable for the technology [2]. Nowadays, the dies are most commonly manufactured by milling from a full block or bonded material.

However, to conduct an overall flexible ISF process, a fast and adaptable strategy for manufacturing of the dies is required. Due to the small lot sizes, the production of the die for the ISF is an important factor in the time and cost incurred. This challenge could have been overcome by the development in the field of rapid tooling (RT); here, the tool is generated by adding material layer-by-layer [5]. Different RT approaches, including the generation of plastic tools, have been intensively studied for conventional sheet metal forming processes [6]. At first, RT with plastics focused on patterns for casting and indirect tooling, which do not have to bear the high loads that occurred in direct tooling applications [7]. Already 20 years ago [5] stereolithography was used to produce plastic AM dies, which have been used as masters for casting tools from aluminum reinforced epoxy resin. Direct RT among others was the domain of metal tools additively manufactured by selective laser sintering (SLS). This process produces stiff tools with a rough surface, which increases wear and friction [6]. One of the first applications of the SLS tool for sheet metal forming was realized by Cheah et al. [8].

Costs and time for generating FFF tools. FFF has been used to produce tools for conventional sheet metal forming, especially because the low cost of materials and printers offers high potential cost savings compared to metal tools [9]. The tools for conventional sheet forming “are generally expensive and the lead time is relatively long, drawbacks in cost and time are not problematic in comparison with direct manufacturing of parts” [10,]. Using FFF with the same material can reduce the cost for manufacturing a deep drawing tool consisting of a die, a counter die, and a blankholder by 78 % by milling polyamide 6 (PA6)/PLA tools and by 93 %. Bergweiler [11] showed that if the die fabrication is not possible to perform in-house, costs and fabrication time can be saved by using online loan additive manufacturing compared to external loan milling.

FFF for generating dies for incremental sheet metal forming. While in the last years' much work has been done in researching the usability of FFF tools for conventional deep drawing, the use for ISF received only limited attention. Rieger [4] used robots for FFF printing acrylonitrile butadiene styrene (ABS) dies and for the subsequent ISF. At first, the die was printed horizontally on a wall using one robot and afterwards a second robot formed a metal sheet onto this die using ISF without repositioning the die in between. The experiments were performed with 0.8 mm thick DC04 steel sheets.

It was shown that with the use of a 3D-printed die for the ISF, a significant improvement in geometry accuracy could be achieved compared to the ISF without a die. The used test geometry resulted in a maximum deviation of the sheet of 17 mm when the ISF was conducted without a die, as well as with the use of a second stylus from the opposite side. This deviation occurred due to the subsequent deformation of the sheet. In the experiments with the use of a 3D printed die either in the form of a full support (tested with 77 % and 38 % infill degree) or as a partial support (38 % infill degree) the subsequent deformation could be completely eliminated. The full dies with 77 % and 38 % infill degree respectively, generated sheets with very similar geometric accuracy. With the use of the partial dies the subsequent deformation only occurred in parts of the sheet, where there was no support in place. The authors concluded, that for the dies used, the base surfaces of the test geometry must be supported, but it is not necessary to support the geometry itself. In addition, the use of FFF printed dies with an infill degree as low as 38 % proved suitable for the ISF. Following the work of Rieger [4], this research is going in a similar direction, by manufacturing a die in a FFF process and using it subsequently for the ISF-process. Due to the good availability and the potential cost savings by using a commercial desktop FFF printer, the suitability of such a printer for ISF shall be further investigated in this work. The motivation of this work is based on this. The novelty of pyramid-shaped, FFF-printed dies being suitable for incremental sheet metal forming and the deviations of tool and part at small batch sizes are to be investigated.

Methodology

Manufacturing and measurements of the ISF dies. For the geometry of the die a truncated square pyramid with an edge length of 125 mm, a height of 50 mm and an angle of the side walls of 45° was selected as a case study. Due to the geometry, a constant high effective strain in the sheet can be realized at the pyramid side faces, and in addition, the influence of corners on the resulting geometry can be investigated. The printing was performed using an Ultimaker S5 printer with the inexpensive, comparatively strong and good processible filament Ultrafuse PLA white from the company BASF as the printed material.

In comparison to dies for deep drawing, where the major load on the die is in the direction of the press movement, the dies for the ISF are subjected to the load from the stylus, which is mainly dependent on the formed geometry. Since the truncated pyramid has a wall angle of 45°, an infill pattern was looked for, which feature a high compressive strength in this direction. The octet pattern was chosen for this purpose based on the perpendicular and parallel orientation of the lines to the object edges, which are expected to increase the strength perpendicular to the pyramid side faces. A unit cell of the octet pattern is shown in Fig. 1 a. The degree of filling was deliberately selected to be very low to save printing time and to test the application limits of the filling structures. Since Rieger [4] used an infill degree of 38 %, which worked fine with a 0.8 mm thick DC04 sheet, an even lower infill degree of 20 % was investigated in this work. The printed die wall thickness is 1 mm. To minimize the stair stepping effect a 0.4 mm nozzle in combination with a layer height of 0.1 mm was used. To enable the printing a polyvinylacetat (PVA) support structure was applied, which was subsequently dissolved in a water bath. The complete printing time of the die was 41 h.

The finished print of the die made from white PLA is displayed in Fig. 1 b. For comparison, another die with the same geometry was milled from a polyurethane block (Fig. 1 c).

Figure 1: a) unit cell of the octet infill pattern b) 3D printed die c) milled die

The printed and the milled dies were 3D measured after the fabrication using the fringe projection method with a COMET 6 measurement system from the company Steinbichler. The geometry deviations are displayed in Fig. 2. The largest deviation of the printed dies occurred in the area of the lower pyramid corners, which bulged upwards by up to one millimeter. This bulging is caused due to the warpage of the PLA during the cooling down. Furthermore, the stair-stepping effect of the FFF process is visible on the surface. In addition, artifacts of the filling pattern are visible in Fig. 2 b in the form of z-parallel rings on the pyramid side faces. The milled die (Fig. 2 c) showed higher geometric accuracy, and the maximum deviation amounts less than 0.1 mm.

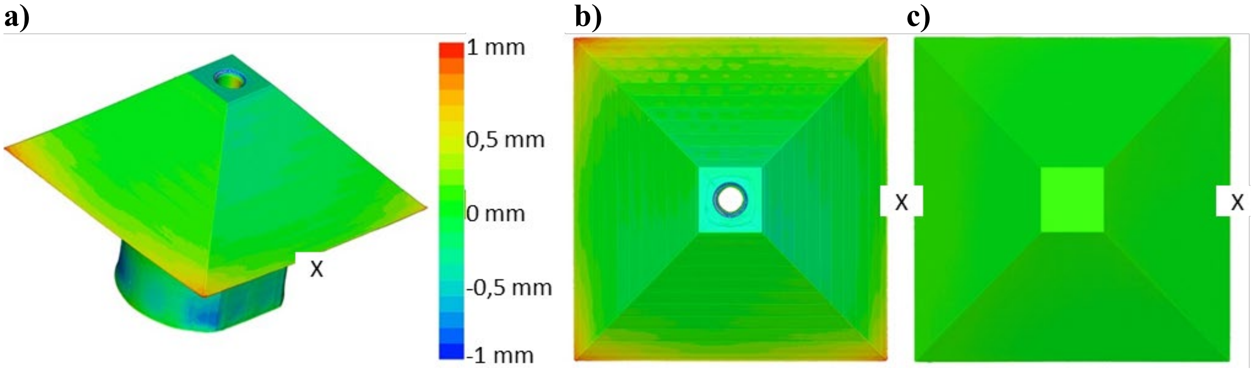

Figure 2: Geometry deviations of the a-b) printed die and c) milled die. The X points to the side with the flattened tool holder; the legend shows the deviation from the nominal geometry in mm.

Execution of the ISF. The ISF-process was executed on a fixture with a non-traversing clamping frame and a pure aluminum sheet (EN AW-1050A H11) with a thickness of 1.2 mm (Fig. 3 a). Due to the static clamping frame, the stylus always alternately moved on a path on the outside near the clamping frame and on a path on the inside at the die, so that from side-view a W-shaped part with wall angles of 45° is formed (Fig. 3 b). The desired geometry of the sheet contains only the inner pyramid.

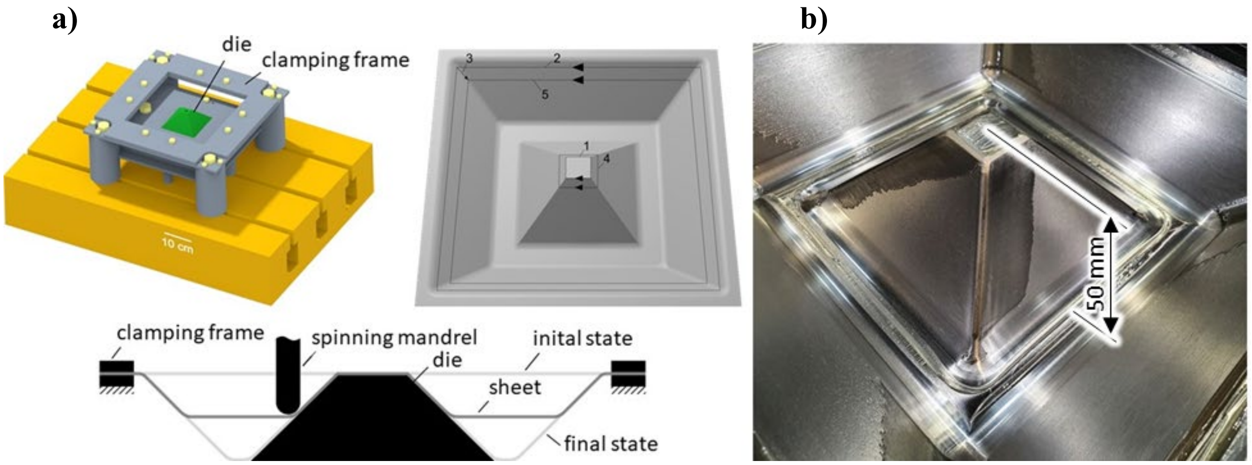

Figure 3: a) setup of the ISF trials b) Sheet metal after incremental forming with 50 mm infeed depth and light wrinkles at the bottom pyramid corners.

The tool used for the testing was a freely rotating, spherical hard metal stylus with a diameter of 30 mm. The sheet was lubricated on the upper side. The ISF was executed using a step increment of 0.5 mm and a movement speed of the stylus of 5 m/min, which resulted in a total forming time of 35 min. During the forming, the bottom of the sheet bulged upwards, which resulted in a small amount of wrinkling at the end of the base corners of the sheet. One sheet was formed using the milled die, and three sheets were formed using the printed die.

Results of the 3D measurements. The printed and the milled die as well as the formed sheets were 3D measured after each ISF. Only the inner pyramid of the sheets was measured because this part contains the desired geometry. The results are displayed in Fig. 4. The measurements of the sheets are fitted to the plane at the top of the truncated pyramid.

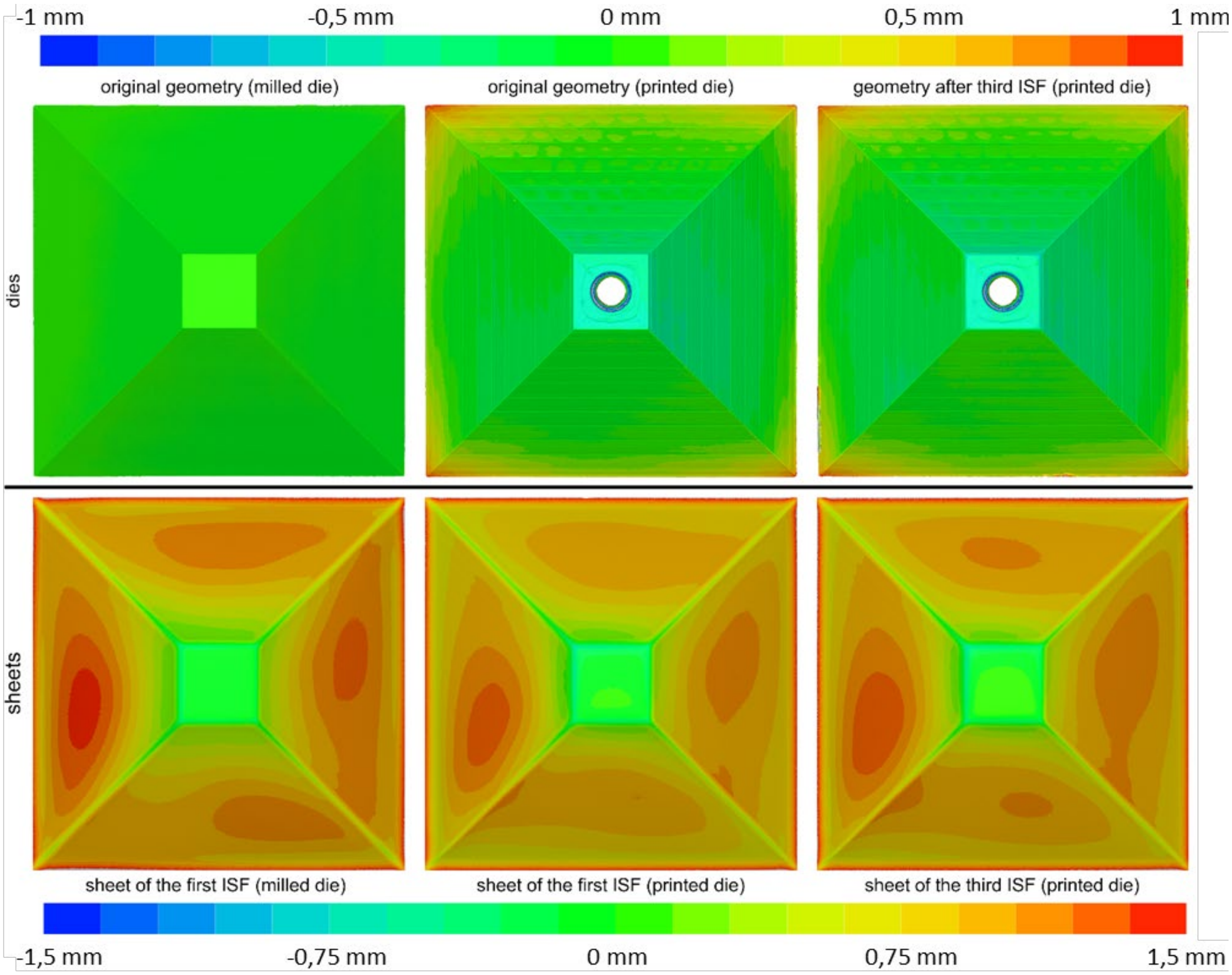

Figure 4: results of the 3D measurements of the dies and formed sheets in comparison to the nominal geometry. The deviations are in mm. The upper legend corresponds to the measured dies, and the lower legend to the measured sheets.

The results of the 3D measurements show that nearly no plastic deformation of the printed die occurred after three subsequent ISF. When comparing the printed die in the initial state and after the third ISF only the edges on the top plane of the truncated pyramid were minimally rounded and colored black based on the contact with the sheet. The top plane was slightly leveled after the third ISF, in comparison to the beginning, on the other hand, the edges of the pyramid side faces do not exhibit any deformation. Summing up, the die only faced insignificant plastic deformation. The fact that the die is deformed only elastically is an important requirement for the application of such dies in the ISF-process. The stability of the dies can also be seen in the resulting sheet geometries. The deviations between the three sheets, which were formed using the printed die, were negligible. This also shows the good reproducibility of the formed parts in this very small product series. Furthermore, it could be shown, that the resulting sheet geometries formed with the milled and the printed die are almost identical, which enables the printed die to be a viable substitute for the milled die.

However, the deviation from the nominal sheet geometry of up to 1.5 mm is clearly visible on the resulting sheet geometries using both dies. Thereby the deviations from the nominal geometry are independent of the type of die (printed or milled) but are an artifact of the ISF process, mainly caused by the sheet stringback, which was not considered in the used process control. The achieved geometric accuracy is comparable to the results of Rieger [4], who also used the completely 3D printed dies and likewise did not consider the sheet stringback in the ISF-process.

The layer height for 3D printing was deliberately chosen to be very low at 0.1 mm, as it was not possible to foresee how much the stair-stepping effect would affect the surface quality of the soft aluminum sheet. No imprints of the stair-stepping effect of the printed die could have been found on the downside surface of the formed sheets. By any further increase of the layer height, printing time can be significantly reduced. Thereby it must be ensured that the ISF does not leave any unwanted impressions on the sheet. Furthermore, when using sheets with higher hardness (e.g., steel sheets), it can be assumed that stair-stepping effects leave fewer impressions.

Comparison of milling and 3D printing for the dies production. The milling of the die took 73 min, in comparison, the production of the same die using 3D printing is significantly slower, it required 1 d and 17 h. Removing the support structures in a water bath lasted another 2 h.

Both programs for producing the dies were not optimized for the shortest possible process time. The milling was carried out on a CNC-milling center optimized for metal machining. By using a milling machine designed for plastics, the time required for milling can be significantly reduced. The same applies to 3D printing. Time can be saved by increasing the layer height. In addition, with a larger nozzle and a matching printer, the printing time can be reduced even further, but the print quality will be correspondingly lower. There is also potential for optimization of the support structure, which accounts for 15 h of the printing time. The support structure was generously designed, by adjusting the print, it will probably be possible to reduce this time by half. Nevertheless, the milling process can produce a functional die for the ISF considerably faster.

It should be noted that a 3D-printer can operate very well over a long time without supervision or tool changes like in the milling machine. For example, all printing times up to 16 h can be carried out very well overnight, and longer prints can be carried out over the weekend if necessary, so that the dies are ready in the morning of the next working day.

To calculate the material costs of dies it must be considered, that on the one hand the material mass needed for 3D printed dies is lower, because of the waste-free production and the lower material consumption through the use possible of filling patterns. On the other hand, the filament is more expensive than the block material. Calculated for to the used die geometry, 32 % of the material costs were saved compared to the milled die (Table 1). With a mass of only 181 g, the printed die is also 73 % lighter than the milled die with a mass of 675 g.

Table 1: Calculation of the material cost of the dies

Die type	Material	Mass [kg]	Price [€/kg]	Material costs [€]
3D printed	PLA	0,18	30	5,43
	PVA	0,08	80	6,48
				Σ 11,91
milled	Sika Block M945 (PUR)	2,39	7,4	**17,70**

Summary

It could be shown that FFF printed PLA dies with an infill density as low as 20 % are suitable for the ISF of fine pure aluminum sheets. With a use of a die fabricated by FFF the same sheet geometries could be reproducibly manufactured as with an identical milled die in a very small lot size. After three ISF operations, no plastic deformation of the dies could be detected. By using the 3D printer, it was possible to save almost one-third of the material costs for the dies used.

3D printed dies can thus be a viable alternative to milled dies. However, higher geometry deviations and printing times of up to several days must be accepted for the advantages of material cost savings and a high degree of design freedom.

The advantages of 3D printing regarding the production of dies for the ISF are the low investment cost for the 3D printer, the high freedom of design, the noncutting machining, the lower mass of the dies and the potential of saving material costs as well as the potential of printing new geometry on existing dies. On a contrary, there are the following disadvantagesdisadvantages of FFF 3D printing: the stair-stepping effect of varying magnitude depending on layer height, the slow production of the dies, the dies are less rigid and strong and the limitation that only thermoplastics can be processed. Furthermore, the 3D printing is only suitable for small dies and the warping increases with increasing die size also the larger geometry deviations occur (compared with milling) and support structures may be necessary and must be removed (depending on the model).By using FFF 3D printing concepts beyond a desktop printer, for example, by a robot with a mounted FFF print, the printing of the die and the forming of the sheet metal can be performed in the same machine in one setup. An example of such a system has already been successfully implemented by Rieger [4] with two robots. Furthermore, new possibilities evolve, like printing new geometries on existing dies without the need to fabricate a completely new die.

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