Additive manufacturing of a stretch forming die using 3D printing technology

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Abstract. 3D printing is a maturing technology, that can be used from fast prototyping to industrial scale. A key aspect of 3D printing is the ability to control the material density, thus it’s hardness. This factor assures that 3D printing is not only economical competitive, but it also provides parts with improved mechanical properties. Furthermore, it is a good alternative for manufacturing stretch-forming dies. Implementing 3D printed dies offers an economical advantage, as cost for producing are a fraction of the cost of standard metal die, and the technology behind the process is simpler. Therefore, in this paper we have chosen to study stretch forming on a die that has components 3D printed from polylactic acid (PLA). The length and width of the punch is maintained constant while the radius varied from R180 ÷ R1080 [mm], with an increment of 180 [mm]. A total number of 6 punches were used in these experiments to stretch sheet metal stripes made of aluminium 2024-T0, a material specific for aircraft skin. In addition to the shape of the resulted part, in the present study other process parameters have been investigated (punch force, part radius and deviation from circularity).

1. Introduction
Dieter Zetsche, CEO of Mercedes, declares that 3D printing technology gained a huge interest due to the fact that the price of a printer came down from $18,000 to $400 within 10 years, while the speed increased by 100 times. The process is so versatile that he predicts that anyone with a smart phone that has 3D scanning capabilities will be able in the near future to make, for example, his own shoes. This estimation is based on the fact that on the international space station a 3D printed was installed, in order to eliminate the need for a large amount of spare parts. As a part of additive manufacturing process, 3D printers use various materials as plastic, metal, ceramic, wood, magnetic materials, and grapheme [1–4]. As Mercedes is already printing 3D part for their trucks, its CEO estimates that by 2027 almost 10% of the manufacturing world-wide will be 3D printed based [3]. Plastic tools made on 3D printers are used in processes for sheet metal forming [5]. Higher mechanical properties are obtained for 3D printed parts when using lower randomness to lattice materials [6] given by the infill rate, and depending on infill shapes (rectangular, triangular, concentric, cubic or honeycomb), stiffness layers, printing orientation angle, print speed and print temperature [1].

2. 3D printed punch. Process parameters
The stretch forming process represents an important part of aircraft skin manufacturing. As aluminium sheets are relatively easy to be drawn into shape, the process does not involve numerous steps. One down side of this technology is the manufacturing of the stretch-forming die, which is very time and cost consuming. Numerous approaches were implemented, from variable shape dies to combined
processes (stretch forming + SPIF) with promising results, but the metal die still have to be manufactured, partially if not totally.

Our approach to this issue is to replace the metal punch with a 3D printed one. Numerous tests were conducted in the field of 3D printing materials for both tensile and compression [1, 5, 6]. Results lead to the conclusion that PLA plastic material serves the purpose of this study. Taken into consideration in making the 3D printed punch were parameters like: layer height, wall thickness, infill density, infill pattern, build plate temperature, printing temperature and speed, as shown in table 1.

Table 1. 3D printed punch parameters

| Punch | Layer height [mm] | Wall thickness [mm] | Infill Density [%] | Infill pattern | Printing temperature [°C] | Build plate temperature [°C] | Print speed [mm/s] | Print time [h:m] | Approximative PLA quantity [g] |
|-------|-------------------|---------------------|-------------------|----------------|---------------------------|----------------------------|-------------------|----------------|-----------------------------|
| R180  | 0.4               | 1.6                 | 75                | LINES         | 210                       | 60                         | 60                | 11h17min       | 407                         |
| R360  |                   |                     |                   |                |                           |                            |                   | 9h18min        | 341                         |
| R540  |                   |                     |                   |                |                           |                            |                   | 9h6min         | 321                         |
| R720  | 0.4               | 1.6                 | 75                | LINES         | 210                       | 60                         | 60                | 8h52min        | 312                         |
| R900  |                   |                     |                   |                |                           |                            |                   | 8h43min        | 306                         |
| R1080 |                   |                     |                   |                |                           |                            |                   | 8h34min        | 302                         |

The printer used in this study is a Ultimaker Original Plus, along with an INNOFILL 3D PLA 2.85 [mm] wire. As the punches were compressed under the stretch-forming process, the best infill patterns in this case was “LINES”, which prints a layer at 45° and the next one perpendicular on the direction of the previous. The 3D printer’s software, Ultimaker CURA, highlights trajectories layer by layer as shown in figure 1, along with information regarding the printing time [h:m] and approximative PLA quantity [g] (table 1).

Figure 1. Simulation of the 3D printing trajectories, displayed layer by layer

For better understating the behaviour of a 3D printed stretch forming die, 6 parts were created, that were designed in such a way that they are fastened to a dynamometer via an intermediary steel support (fastening system).

Figure 2. Design parameters and isometric view of the 3D printed punch and fastening system

The punches have the same shape while the radius is variable (180, 360, 540, 720, 900 and 1080). The design of the punches (figure 2) is consistent with the interior shape of the retaining plate, from the
hydraulic press, used in this experimental study, as highlighted in figure 3. The 180 [mm] length was restricted to the 3D printer’s printing space. After the printing process, the punches were measured for radius dimension and circularity deviation using a 3 axes Tesa 3D Micro Hite CMM equipment. The measurements were taken in 7 points (figure 2), across the radius of each 3D printed die. The average measured values for the radius and deviation from circularity are highlighted in table 2. As the ideal size varies with each printed model, the CMM measurements were used as reference base, for both the ANOVA analysis and springback measurements.

Table 2. 3D printed punch measurements

| Radius [mm] | 180   | 360   | 540   | 720   | 900   | 1080  |
|-------------|-------|-------|-------|-------|-------|-------|
| Measured radius [mm] | 182.383 | 365.146 | 553.904 | 738.847 | 942.176 | 1149.964 |
| Deviation from circularity [um] | 0.005 | 0.123 | 0.006 | 0.06 | 0.061 | 0.083 |

3. Experimental setup

The experimental studies were conducted on a Hydramold HPHL-075.300 hydraulic press, which is made out of two main parts: control unit and hydraulic press, as shown in figure 3. The press has a vertical center hydraulic piston on which a metal base plate support is mounted. The movement, on the Z axes, is controlled on both distance of travel and speed. On the metal base plate six hydraulic clamping devices were mounted. The metal sheet is placed in between the main and the clamping plate. The hydraulic clamping system assures a firm lock. In the upper part of the hydraulic press the Kistler 9272 dynamometer is clamped fixed into position. The metal fastening system is then mounted on it, while the 3D printed punches can be easily mounted/dismounted in place using screws. While the hydraulic clamping system is turned on, at a constant pressure of 20 [bar], the retaining system moves upwards 20 [mm], deforming the sheet metal.

The material used in this experimental study was aluminum alloy 2024-T0, commonly used in the aviation sector for the aircraft’s fuselage manufacturing, also known as the aircraft skin. Usually thicknesses of 1.0÷1.2 [mm] are used for enveloping assemblies like: flaps, spoilers, ailerons, belly, nose and cabin sections. In this study the sheet metal blanks were cut at 315 x 46 [mm]. The part size was chosen so it can be easily mounted on the hydraulic press’s main plate.

The experimental plan is based on the variation of the measured punch radii $R_P$ (table 2), deformation speeds ($v = 0.2, 0.7, 1.2$ [mm/s]) and material thickness ($t = 1.0, 1.2$ [mm]). The total number of tests resulted from a full factorial design of experiments, that contained 36 trials. Thus, the responses analyzed were: the pressing force, parts radius and parts deviation from circularity.

The elastic springback was analyzed using GOM ATOS 3D imaging metrology system. In this case both the punches and parts were scanned, using the 3/7 [mm] white on black markers. The overlap
between each part and the corresponding die was assured by the best-fit alignment algorithm, included in the equipment software, and it was limited to a length of 150 [mm].

4. Results and discussion
The samples were measured, taking into consideration the radius, deviation from circularity and springback effect. In figure 4 the deformed parts are highlighted by punch radius, material thickness and deformation speed.

![Image of deformed parts](image)

**Figure 4.** Al 2024-T0 deformed sheets

4.1. Analysis of the springback effect
One key aspect noted when analysing the springback effect is that the 180 [mm] radius die leads to heavy deviations. It can be observed, in figure 5, that the deviation reaches 5.76 [mm], whereas the increase in radius leads to a significant decrease in the springback effect.

![Image of springback effect](image)

**Figure 5.** Springback effect of 1.0 [mm] 2024-T0 aluminium blank

While the maximum value recorded, for the parts obtained by stretch-forming with punches R360÷1080, is just below 1.0 [mm], the lowest value for the 180 [mm] radius stretch parts is 2.41 [mm]. The same pattern can be observed when stretch-forming the 1.2 [mm] thick blanks. This tendency, highlighted in figure 6, presents a particularity when using the 360 [mm] radius die, where the overall values recorded are larger (0.869, 1.18, 1.43 [mm]), compared to those obtained for the thicker blanks (0.603, 0.619, 0.905 [mm]). Overall the springback effect, for both material thicknesses and deformation speed, has a downward trend as the punch radius increases.
4.2. **ANOVA statistical analysis**

The ANOVA analysis was performed using the DesignExpert software. The experimental plan, previously described, implied 4 responses. For each of these responses the model F-value, p-value, predicted and adjusted R² indicate that the analyses are significant. Furthermore, mathematical models were provided, based on the relationship between the input parameters and the responses.

4.2.1. **The effects of the input parameter on the punch force (P_f).** The analysis indicates that the model is significant, with a p-value smaller than 0.0001 and a R² of 0.7485. The force is directly influenced by the punch radius (p<0.0001) and deformation speed (p=0.1231). A linear model was suggested by the Anova analysis; therefore, the mathematical model is a linear equation (1). The correlation between the input factors and the response is shown in figure 7. It can be noted that when using high radius punches the force increases. As the deformation speed increases there was recorded a slight decrease in the punch force.

\[
P_f = 20263.47 + 6993.76P_R - 944.23\nu
\]

4.2.2. **The effects of the input parameter on the part radius (P_{part}).** According to the ANOVA results, it was found that the best fitted is a reduced quadratic model, with a p-value of under 0.0001 and a R² of 0.9868. The results indicate that the part radius is linear dependent on all the input parameters, as show in the resulted equation (2). The mathematical model along with figure 8 suggest that a slight larger part radius was obtained when a thicker material was processed, along with the increase in the deformation speed.

\[
P_{part} = \text{function of input parameters}
\]

**Figure 7.** The effects of deformation speed and punch radius on the punch force

**Figure 8.** The effects of deformation speed and punch radius on the part radius, for each thickness
\[ P_{\text{art}, R} = 724.62 + 493.99P_R + 25.07v + 18.78t \]  \hspace{1cm} (2)

4.2.3. The effects of the input parameter on the deviation from circularity \((D_C)\). The input data was subjected to a natural logarithm transformation, and it suggests that the punch radius is the most important factor in the increase of the deviation values, as highlighted in equation (3). It can be concluded from figure 9 that the higher deviation, the smaller the punch radius.

\[ \ln(D_C) = -2.23 - 0.5392P_r \]  \hspace{1cm} (3)

Figure 9. The effect of punch radius on the deviation from circularity

5. Conclusions
The analysis of this experimental data leads to concluding that an important aspect in stretch-forming of aluminum 2024-T0, using 3D printed dies, is represented by the radius value. It was noted that when using a small radius die the recorded punch forces were the smallest, while the deviation from circularity have high value, which is consistent with high values of the springback effect. A higher force on small radii is explained by the increase in surface contact.

Although the deformation forces were relatively high it was noted that the dies did not suffer any damage or dimensional deformations due to the stretch forming process.

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