Design and Validation of 3D-Printed Tools for Stamping of DP600

Nader Asnafi¹, Jukka Rajalampi², and David Aspenberg³

1 Örebro University, School of Science & Technology, SE-701 82, Örebro, Sweden
2 RISE IVF, Villaregatan 30, SE-293 38 Olofström, Sweden
3 DYNAmore Nordic, Brigadgatan 5, SE-587 58 Linköping, Sweden

nader.asnafi@oru.se

Abstract. This paper is focused on automotive stamping tools & dies and the impact of 3D metal printing on design and production of such tools & dies. Forming (U-bend) and trimming/cutting/blanking tools & dies designed both conventionally and by topology optimization were 3D-printed, using Laser-based Powder Bed Fusion (LPBF), in the maraging steel DIN 1.2709. These 3D-printed tools were then used to form (U-bend) and trim/cut/blank 2-mm thick hot-dip galvanized DP600. An approval of the forming tool required that 50,000 U-bends were formed in 2-mm thick DP600 without any surface scratches on the sheet metal part. An approval of the trimming/cutting/blanking tool required 100,000 trimming strokes with this tool, where the maximum (sheet metal) burr height was lower than 0.2 mm (lower than 10% of the sheet thickness (2 mm in this study)). The 3D-printed forming and trimming/cutting/blanking tools & dies - both the conventionally designed and the topology optimized versions – managed the criteria mentioned above and were therefore approved. The approval means that these concepts can now be used to make production stamping tools and dies. This paper describes the topology optimization, the forming & trimming/cutting/blanking testing, the results yielding an approval of the 3D-printed tool concepts, and the 3D-printed production tools for stamping of DP600.

1. Introduction

The tool and die design and manufacturing is an important phase in the development of new components/products that are to be mass-produced. This phase determines both the lead time (Time-To-Production / -Market) and the amount of investments required to start the production. These factors are of great significance to the competitiveness of almost all industrial sectors.

Figure 1 displays the lead time for development of a new car model (Time-To-Market) at Volvo Cars. The figure shows the actual values in 1991, 1998, & 2012 and the target for 2020. Tools & dies for production of the autobody parts of a new car model cost 100-140 million Euro and take ca 10-12 months to design and manufacture. The lead time for tools & dies must therefore be reduced significantly to enable the reduction of the lead time for development and launch of a new car model. One of the purposes of this study was to investigate how metal additive manufacturing (henceforth also called 3D printing or AM) based on Laser-based Powder Bed Fusion (LPBF) influences the lead time for and the costs of stamping tool & die design and manufacturing.

A car body consists of parts that are stamped in different sheet materials, Figure 2. The selected sheet material, the forming/trimming severity and the production volume size determine the selected tool & die concept (tool & die material, hardening method, surface requirements, and coating). The identified...
tool & die concept for the selected sheet material must be approved in a certain certification or validation procedure before it is used for production tools & dies (intended for the same sheet material) at Volvo Cars. The number of (metallic) powder materials that can be used to 3D-print stamping tools & dies is still limited, [1]. This investigation aimed at approval (or disapproval) of the performance of DIN 1.2709 (as tool/die material) in both solid and topology optimized 3D-printed (LPBF) tools & dies for stamping of 2-mm thick hot-dip galvanized DP600. This approval/disapproval (certification/validation) follows the above-mentioned procedure at Volvo Cars and will be described below.

The maximum size that can be 3D-printed by LPBF today is 500 mm x 500 mm x 500 mm, [1]. This study aimed also at investigating the potential of AM for stamping tools and dies with regard to lead time reduction, tool & die design, and the costs, despite this size limitation in AM by LPBF.

2. Materials

Table 1 displays the chemical composition and Table 2 shows the mechanical properties of maraging steel DIN 1.2709.

### Table 1. Chemical composition of maraging steel DIN 1.2709, [2].

| Element | Fe  | Ni  | Co  | Mo  | Ti  | Si  | Mn  | C   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| weight % | Balance | 17.0-19.0 | 9.0-11.0 | 4.0-6.0 | 0.9-1.0 | ≤ 1.0 | ≤ 1.0 | ≤ 0.03 |

### Table 2. Mechanical properties of maraging steel DIN 1.2709, [2].

| Property                        | After 3D printing | After heat treatment |
|---------------------------------|-------------------|---------------------|
| Yield strength, $R_{p0.2}$ (MPa)| 860               | 1930                |
| Tensile strength, $R_m$ (MPa)   | 1110              | 2000                |
| Fracture elongation, $A_{500}$ (%) | 11               | 1                    |
| Hardness (HRC)                  | 37                | 55                   |

### Table 3. Chemical composition of the workpiece (sheet) material, i.e. DP600, [3].

| Element | Fe  | P   | S   | Al  | Cr  | Si  | Mn  | C   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| weight % | Balance | ≤ 0.02 | ≤ 0.004 | ≥ 0.020 | ≤ 0.50 | ≤ 0.30 | 1≤.66 | ≤ 0.120 |

### Table 4. Properties of the workpiece (sheet) material, i.e. 2-mm thick sheet of DP600, [3].

| Property                                | Value                   |
|-----------------------------------------|-------------------------|
| Sheet thickness (mm)                    | 2.0                     |
| Yield strength, $R_{p0.2}$ (MPa)        | 350-480                 |
| Tensile strength, $R_m$ (MPa)           | 600-700                 |
| Fracture elongation, $A_{500}$ (%)      | ≥ 18                    |
| Hot-dip galvanized: Layer thickness (µm)/weight (g/m²) | 10 (per side)/140 |
2-mm thick sheet of hot-dip galvanized DP600 was used as the sheet material in the certification/approval of 3D metal printed stamping tools and dies. The chemical composition of this sheet material is shown in Table 3. The properties of the same material are displayed in Table 4. In the industrial tests, 1-mm thick sheet of the same material (a more gentle case compared to the certified case) was used.

3. Experimental procedure

3.1. Certification/Validation procedure

The procedure used within Volvo Cars to approve (or disapprove) the combination of a selected tool concept for stamping (including deep drawing) of a targeted sheet material grade was applied in this investigation. According to this procedure, the selected forming tool concept (i.e. tool material, hardening method, surface roughness and coating) is used to make a so-called U-bend forming tool. The sheet material grade of interest is formed in a U-bend shape in this tool. The binder force is selected in such a fashion that the strain level in the U-bend wall is 60% of FLC0, the minimum level of the Forming Limit Curve of the selected sheet material. The approval criterion is the surface of the stamped U-bend. Scratches on this surface cannot be accepted. On a four-level scale (starting with 0 and ending with 3), only levels 0 and 1 can be accepted. The tool concept that manages 50,000 U-bends (strokes) in the selected sheet material without class 2 surface is approved as a tool concept for production tools (to be used for forming of the selected sheet material). This is illustrated in Figure 3. In this investigation, the selected tool concept comprises maraging steel (DIN 1.2709) 3D-printed both solidly and after topology optimization, hardened to 55 HRC and with a surface roughness of Ra = 0.2 µm (see also Table 2). The selected sheet material is 2-mm thick hot-dip galvanized DP600 (see Table 4).

Figure 3. The experimental set-up for certification/approval of the forming (U-bending) tool, [1].

Figure 4. The experimental set-up for certification/approval of the trimming/plaining/cutting tool.
According to the above-mentioned Volvo Cars procedure, the selected trimming/blanking/cutting tool concept (i.e. tool material, hardening method, surface roughness and coating) is used to make such a tool to trim/blank/cut the sheet material grade of interest. The approval criterion is the burr height on the trimmed/blanked/cut sheet. For approval, this burr height must be lower than 10% of the sheet thickness. A tool concept that manages 100,000 strokes with a burr height (on the trimmed/blanked/cut sheet) that is lower than 10% of the sheet thickness is then approved as a concept for production tools intended for the selected sheet material. This is illustrated in Figure 4. In this investigation, the tool concept comprises maraging steel (DIN 1.2709) 3D-printed both solidly and after topology optimization, and hardened to 55 HRC (see Table 2). The selected sheet material is 2-mm thick hot-dip galvanized DP600 (see Table 4).

3.2. The selected industrial case
Due to the size limitations (in 3D metal printing by LPBF) mentioned above, the puller and the punch, which constitute a working station of the progressive die for the car body part C-Bow Lower, were selected. See Figure 5. The part, C-Bow Lower, is made in 1-mm thick hot-dip galvanized D600. This progressive die has been used (produced parts) in a couple of years. The puller and the punch shown in Figure 5 were selected for 3D-printing to evaluate the lead time, costs and performance compared to those of the existing conventionally made versions.

Figure 6 displays the requirements set and the materials and manufacturing processes used for the conventional and 3D-printed versions of the puller and punch for the C-Bow Lower progressive die in Figure 5. As shown in Figure 6, the requirements are the same, regardless of how the puller and punch are manufactured. The manufacturing process for the conventionally made puller and punch is the process that was used to make these portions of the die, as the progressive die for the C-Bow Lower was made. The 3D printed versions of the puller and punch were made in this study to compare 3D printing with conventional toolmaking.
Figure 6. The requirements set and the materials and manufacturing processes for the conventional and 3D-printed versions of the puller and punch for the C-Bow Lower progressive die in Figure 5. EDM = Electrical Discharge Machining. SS = Swedish Standard.

| CONVENTIONAL PROCESS | 3D METAL PRINTING |
|-----------------------|-------------------|
| **Punch**             | **Punch**         |
| Requirements:         | Requirements:     |
| - Hardness (after hardening) = 55 HRC | - Hardness (after hardening) = 55 HRC |
| - Surface roughness in the working area = $R_s = 0.8 \mu m$ | - Surface roughness in the working area = $R_s = 0.8 \mu m$ |
| Material = SS263 (tempered) | Material = Maraging steel (1.2709) |
| **Process:** 1: Milling | **Process:** 1: 3D printing of punch and puller |
| 2: Hardening | 2: Post-processing |
| 3: Wire EDM | 3: Hardening of the punch |
| **Puller**            | **Puller**        |
| Requirements:         | Requirements:     |
| - Hardness (after hardening) = No requirement | - Hardness (after hardening) = No requirement |
| - Surface roughness in the working area = $R_s = 2-3 \mu m$ | - Surface roughness in the working area = $R_s = 2-3 \mu m$ |
| Material = SS2172 | Material = Maraging steel (1.2709) |
| **Process:** 1: Milling | **Process:** 1: 3D printing of punch and puller |
| 2: Wire EDM | 2: Post-processing |

Figure 7. Topology optimization of the U-bend tool with different volume fractions (fully red and dark blue colors = solid material), [4].

Figure 8. The Z-displacement at the tool/die draw radius for different volume fractions, [4].

4. Simulations and topology optimization
The U-bend forming tool and the trimming/blanking/cutting die shown in Figures 3 and 4 were topology-optimized. Figure 7 shows the results of the topology optimization for the U-bend tool (the
fully red and dark blue colors in Figure 7 = solid material). LS-TaSC was used to topology optimize the left U-bend tool. LS-TaSC is the tool for the topology optimization of non-linear problems involving dynamic loads and contact conditions analyzed by LS-DYNA.

In topology optimization of the U-bend tool using LS-TaSC, a 3D model was created assuming that extrusion constraint prevailed. The extrusion constraint means that the part (the left U-bend tool in this case) can be made by extrusion, i.e. the cross section is the same throughout the part in the extrusion direction. The width direction of the U-bend tool was considered as the extrusion direction.

The vertical maximum displacement of a node slightly above the die profile radius was used as a measure of stiffness, Figure 8. Based on these results, the U-bend tool topology optimized at the fraction volume 0.45 was selected (since fraction volume 0.45 gives, as displayed in Figure 8, the greatest material efficiency at a stiffness value that is very close to that of the fully solid fraction volume 1). The right U-bend tool (Figure 3) was 3D-printed as a solid piece, whilst the left U-bend tool was first topology optimized at the fraction volume of 0.45 (Figures 7 and 8) and then 3D-printed. Both U-bend tool halves were 3D-printed in DIN 1.2709.

5. Results and discussion

Figure 9 displays the U-bending tool. The right tool half is 3D-printed as a solid piece. The left tool half is topology optimized at the volume fraction of 0.45 and 3D-printed. Both tool halves are 3D-printed in DIN 1.2709. The initial hardness was 56 HRC and the initial surface roughness was R_a = 0.2 µm in both cases. Both tool halves managed 50,000 strokes in 2-mm thick DP600 with approved surface.

Compared to the 3D-printed solid tool half, the topology optimized and 3D-printed tool half exhibits a weight reduction (or improved material usage) by 19.4% and a lead time reduction by 11.1%. Initially, the profile radius of the left tool half (topology optimized) was 5.05 mm and that of the right tool half (solid) was 5.04 mm. After 50,000 strokes, the maximum wear measured as a change in the profile radius was only 0.0186 mm. See Figure 9.

Figure 9. The U-bending tool: the right tool half is 3D-printed as a solid piece and the left tool half is topology optimized at the volume fraction of 0.45 and 3D-printed. Both tool halves are 3D-printed in maraging steel (DIN 1.2709). Both tool halves managed 50,000 U-bends with approved surface, [1].

Figure 10 displays the 3D-printed solid and topology optimized trimming/blanking/cutting tools. The hardness varies between 54 and 56 HRC. Both tool versions managed 100,000 strokes with approved results.

Figure 10. 3D-printed solid and topology optimized trimming/blanking/cutting tools. The hardness varies between 54 and 56 HRC. The surface roughness R_a = 0.2 µm. The topology optimized
tool weighs 47% less than the solid tool. Both the solid and topology optimized tools managed 100,000 strokes in 2-mm thick DP600 with a burr height lower than 0.2 mm and were thereby approved. After 100,000 strokes, the maximum wear measured as a change in the profile radius was 0.100 mm on the solid tool and 0.196 mm on the topology optimized tool. Compared to the 3D-printed solid tool, the topology optimized and 3D-printed tool exhibits a lead time reduction by 29.6%. See Figure 10.

Figure 11 displays the 3D-printed puller and punch in the progressive die shown in Figure 5. The puller and the punch were 3D-printed simultaneously (the same print) in maraging steel DIN 1.2709 (see Tables 1 & 2). It was selected to print a so-called honeycomb inner structure with a facade/outer shell thickness of 1.5 mm. Machining tests were conducted on the puller by milling at three different cusp heights – 6 μm, 3 μm and 0.6 μm. No problems were encountered and the milling yielded the expected results. 2D and 3D surface roughness measurements were conducted directly after 3D printing and after milling at the above-mentioned three cusp heights. The surface roughness was $R_a = 4.92 \mu m$ ($S_a = 5.23 \mu m$) directly after 3D printing and $R_a = 0.71 \mu m$ ($S_a = 0.85 \mu m$) after 3D printing and milling at a cusp height of 0.6 μm. The average hardness was 56 HRC.

Table 5. Lead time and total cost comparison for the puller & punch displayed in Figure 5 made conventionally and by the 3D-printing inclusive manufacturing process (Figure 6). See also Figure 11.

|                  | Lead time (working days) | Costs (Swedish Crowns/SEK) |
|------------------|--------------------------|-----------------------------|
|                  | Conventional | 3D-printed (honeycomb structure) | Conventional | 3D-printed (honeycomb structure) |
| Punch            | 8            | 10500                       |              |                                |
| Puller           | 6            | 15500                       |              |                                |
| Total            | 8            | 3.7                        | 26000        | 31000                         |

Table 5 depicts a comparison of the lead time and total costs for the puller and the punch in Figure 5 made conventionally and by the 3D-printing inclusive manufacturing process (Figure 6). As displayed in Table 5, the lead time is reduced from 8 days for the conventionally made puller and punch to 3.7 days for the 3D-printing inclusive manufacturing of the same tools. The total costs (comprising material, machine, salary, and logistics costs) increase, as displayed in Table 5, from 26,000 to 31,000 SEK, in case the 3D-printing inclusive process is selected. The total cost of the 3D-printing inclusive process is based on the assumption that the depreciation period for the 3D printing machine is 5 years. A 10 years long depreciation period for the 3D printing machine reduces the total costs to 29000 SEK.

The punch in the industrial case (Figures 5 and 11) was topology optimized using LS-TaSC in LSDYNA. This topology optimized punch was 3D-printed in maraging steel (DIN1.2709). Figure 12 displays the simulation results, the 3D-printed topology optimized punch, and the 3D-printed (with
honeycomb inner structure) conventionally designed version of the same punch. Both of these punches have so far run more than 120 thousand strokes without any problems.

Compared to a 3D-printed solid punch, topology optimization and a honeycomb inner structure improved the material usage (and thereby reduced the weight) and printing time by ca 45% & ca 34% respectively. This means that the same printing time reduction and improved material efficiency can be accomplished in at least two different fashions – topology optimization and a honeycomb inner structure.

**Figure 12.** The punch in the selected industrial case (Figure 5): (a) topology optimized using LS-TaSC in LS-DYNA and in compliance (stiffness) with the conventional punch, and (b) the 3D-printed topology optimized punch and the 3D-printed (with honeycomb inner structure) conventionally designed version of the same punch. Both versions are 3D-printed in maraging steel (DIN1.2709).

### 6. Conclusions

The following conclusions can be drawn:

- For 1-mm and 2-mm thick hot-dip galvanized DP600, 3D-printed maraging steel (DIN1.2709) yields stamping tools and dies which are as good as those made conventionally. Both conventional and topology optimized design yield good results.

- 3D printing improves the material usage and lead time significantly but leads to somewhat higher costs. In 3D printing, the same printing time reduction and improved material efficiency can be accomplished by either topology optimization or a hollow/honeycomb inner structure.

- 3D printing is expected to have a large business transformational impact on stamping tool and die design and manufacturing. It is therefore of great significance for companies to outline and execute an action plan to include the new design tools and 3D metal printing in the industrial infrastructure and business models. Inclusion of 3D metal printing might, for instance, require a new modularized tool design due to the current size limitations in AM by LPBF.

### Acknowledgments

The authors would like to thank Sweden’s Innovation Agency Vinnova for funding this investigation and 3D MetPrint, Dynamore Nordic, Hydroforming Design Light, IKEA, Ionbond Sweden, Melament, Nolato Lövepac, PLM Group, RISE IVF, Volvo Cars, Uddeholm and Örebro University for a fruitful and efficient collaboration.

### 7. References

[1] Asnafi N, Shams T, Aspenberg D and Öberg C 2018 3D Metal Printing from an Industrial Perspective – Product Design, Production and Business Models *Proceedings of Metal Additive Manufacturing Conference 2018* (Vienna, Austria, Nov 19-21) pp 304-313

[2] According to datasheet from 3D Systems, July 6th, 2018

[3] According to datasheet from Tibnor, July 6th, 2018

[4] Asnafi N and Alveflo A 2019 3D Metal printing of Stamping Tools & Dies and Injection Molds, to be presented at Tooling 2019 Conference and Exhibition (Aachen, Germany, May 12-16)