Forming and trimming of 2-mm thick DP600 sheet steel in tools and dies 3D-printed in maraging steel by laser-based powder bed fusion

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Abstract. In a previous investigation, 3D-printed solid and topology optimized semi-industrial tools for forming and trimming of 2-mm thick hot-dip galvanized DP600 were certified. This certification required 50,000 strokes in U-bend forming and 100,000 strokes in trimming/cutting/blanking. The present paper focuses on the tool wear, the U-bend sheet surfaces, the shear and fracture zone lengths in trimming, and the punch forces in this certification. The 3D-printed tools behave as conventional tools do. Although small, there seems to be a difference in wear at the profile radius between the solid and topology optimized U-bending tool halves 3D-printed in maraging steel DIN1.2709.

1. Introduction
The state-of-the-art for additive manufacturing (henceforth also referred to as AM or 3D-printing) of metals is described in [1]. Additive manufacturing is subject to a technology assessment in [2]. Based on these and other relevant reviews, the research needs and challenges for the Swedish industrial use of metal additive manufacturing were identified [3]. Metal powders for tool applications, new tool design options and the shift in toolmaking are of great significance in the industrialization of additive manufacturing and for the global industrial competitiveness [1, 2, and 3].

In [4], inserts in a body panel stamping tool were 3D-printed in maraging steel DIN 1.2709. The 3D-printed inserts exhibited the same performance as the conventionally made, however, with reduced lead time and minimized internal process logistics [4]. In [5], solid and topology optimized semi-industrial tools for forming and trimming of 2-mm thick hot-dip galvanized DP600 were certified. This certification required 50,000 (50k) strokes in U-bend forming and 100,000 (100k) strokes in trimming/cutting/blanking. The present paper focuses on the tool wear, the U-bend sheet surfaces, the shear and fracture zone lengths in trimming, and the punch forces in this certification.

2. Materials
Table 1 displays the chemical composition and Table 2 shows the mechanical properties of maraging steel DIN 1.2709. To determine these properties (Table 2), 5 tensile specimens (circular cross section, $\phi 5\text{mm}$) per direction were 3D-printed, heat-treated, machined and tested. Table 2 displays the average values. 3D Systems ProX DMP and the AM process parameters in Table 3 were used to make these specimens (and the semi-industrial tools). The heat treatment was conducted at 490°C in 6 hours, after
Table 1. Chemical composition of maraging steel DIN 1.2709 [6].

| 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 after AM and heat treatment.

| Property                  | Built vertically | Built horizontally |
|---------------------------|------------------|--------------------|
| Yield strength, $R_{p0.2}$ (MPa) | 1999             | 1977               |
| Tensile strength, $R_m$ (MPa)     | 2120             | 2167               |
| Hardness (HRC)             | 56               | 56                 |

Table 3. The used 3D printer and AM process parameters.

| Material (tool material) | Used 3D printer | Layer thickness ($\mu$m) | Laser power (W) | Scan speed (mm/s) | Hatch distance ($\mu$m) |
|--------------------------|-----------------|--------------------------|-----------------|------------------|------------------------|
| DIN 1.2709               | 3D Systems ProX DMP 300 | 40                       | 185             | 1200             | 70                     |

Table 4. Chemical composition of the workpiece (sheet) material, i.e. DP600 [7].

| Element | Fe | P | S | Al | Cr | Si | Mn | C |
|---------|----|---|---|----|----|----|----|---|
| weight % | Balance | ≤ 0.02 | ≤ 0.004 | ≥ 0.020 | ≤ 0.50 | ≤ 0.30 | ≤ 1.66 | ≤ 0.12 |

Table 5. Properties of the workpiece (sheet) material, i.e. 2-mm thick sheet of DP600 [7].

| Property                          | Value                |
|-----------------------------------|----------------------|
| Sheet thickness (mm)              | 2.0                  |
| Yield strength, $R_{p0.2}$ (MPa)  | 350-480              |
| Tensile strength, $R_m$ (MPa)     | 600-700              |
| Fracture elongation, $A_80$ (%)   | ≥ 18                 |
| Hot-dip galvanized: Layer thickness ($\mu$m)/weight (g/m²) | 10 (per side)/140 |

which the specimens (or the tools) were allowed to cool down in the furnace (in air).

As sheet material, 2-mm thick hot-dip galvanized DP600 was used in this certification. For the chemical composition and properties of this material, see Tables 4 & 5 respectively.

3. Experimental procedure

3.1. Tools and dies

The experimental procedure used at Volvo Cars to certify a tool concept was applied in this investigation. According to this procedure, the selected tool concept (i.e. tool material, hardening method, surface roughness and coating) is used to make [5]

- a so-called U-bend forming tool. The sheet material grade of interest is formed in a U-bend shape with a draw depth of 50 mm in this tool. The approval criterion is the surface of the stamped U-bend. Scratches on this surface cannot be accepted. On a four-level scale, 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. This is illustrated in Figure 1.

- a tool to trim/blank/cut the sheet material grade of interest. This sheet material is trimmed along a 150 mm long straight line. 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 lower than 10% of the sheet thickness is approved. This is illustrated in Figure 2.
Figure 1. The experimental set-up for certification of the forming (U-bending) tool. See also [5].

Figure 2. The experimental set-up for certification of the trimming/blanking/cutting tool. The trimming is conducted by 2 upper dies mounted along a straight line. See also [5].

For the certification in this study, the stamping tool concept comprised DIN 1.2709 (Table 2), 3D-printed both solidly and after topology optimization in 3D Systems ProX DMP 300 with the process parameters shown in Table 3, hardened to 55 HRC, and machined to a surface roughness of 0.2 µm. The hardening was conducted by heat-treatment at 490°C in 6 hours, after which the tool is allowed to cool down in the furnace (in air). None of the tools is coated. The selected sheet material is 2-mm thick hot-dip galvanized DP600 (Table 5).

To explore the industrial potential of AM in stamping tool applications, the punches shown in Figures 1 & 2 were topology optimized and 3D-printed in this investigation. The topology optimization is described in [8]. Figures 3 and 4 display the solid and topology optimized U-bending and trimming tools/dies 3D-printed in DIN 1.2709. These tools were set up in the equipment shown in Figure 5, after which the U-bending and trimming were conducted respectively in accordance to the certification procedure described above. The U-bending tool managed 50,000 (50k) strokes in accordance to the requirement in Figure 1 and was therefore approved. The trimming tool managed 100,000 (100k) strokes in accordance to the requirements in Figure 2 and was therefore approved.
Figure 3. The 3D-printed U-bending tool: the right tool half = solid piece. The left tool half = topology optimized. Both tool halves are 3D-printed in maraging steel DIN 1.2709 [9].

Figure 4. The 3D-printed solid and topology optimized trimming/blanking/cutting tools. Both versions are 3D-printed in DIN 1.2709 [5].

3.2. Measurements
The wear, profile radius, and surface roughness were measured on the U-bend tool halves after 50k strokes, Figures 6-9.

The wear and edge (profile) radius on the trimming dies were measured after 100k strokes, Figures 10-11.

All of these measurements were conducted in Hommel-Etamic surfscan 120-400.

The load cell mounted in the eccentric press in Figure 5 was used to measure the U-bending (forming) and trimming forces.

Figure 5. The tools were set up in this eccentric press to form the U-bends and trim the sheet.

4. Results
Figures 12 and 13 display the U-bent sheet surface after 1k, 25k, and 50k strokes. The U-bending tool edge (profile) radius after 50k strokes is displayed in Figure 14. Figure 15 shows the U-bending maximum punch force as function of the stroke number. Figure 16 displays the roughness of the binder surfaces at different positions on the U-bending tool after 50k strokes. The wear after 50k strokes at the profile radius of the U-bending tool halves are shown in Figure 17. As displayed in this figure, there seems to be a difference in wear between the topology optimized and the solid tool halves. This difference is, however, small and difficult to measure.

Figure 18 depicts the shear and fracture zones on the trimmed sheet metal (2-mm thick hot-dip galvanized DP600) after 100k strokes. As displayed in this figure, the difference is very small between the results obtained with the topology optimized tool and those obtained with the solid tool. The sizes of the shear and fracture zones are displayed as function of the stroke number in Figure 19. Figure 20 depicts the wear after 100k strokes at the edge (profile) radius on the trim dies. The trim die edge radius was measured at different positions after 100k strokes. The obtained values are shown in Figure 21, which indicates that the topology optimized tool exhibits somewhat larger wear.

The trimming/cutting/blanking (punch) force versus the stroke number is displayed in Figure 22. The force exerted by the 3D-printed solid tool is initially approximately 10% higher and at around 65k strokes approximately 7% smaller than that exerted by the 3D-printed topology optimized tool. This difference is probably influenced by the spread in the mechanical properties of the sheet material.
Figure 6. The profile radius on the 3D-printed solid (left) and topology optimized (right) tool halves.

Figure 7. The top surface (the binder surface) on the 3D-printed solid (left) and topology optimized (right) tool halves.

Figure 8. Surface roughness measurement across the forming (drawing) direction.

Figure 9. Profile radius & surface roughness measurement along the forming direction.

Figure 10. Measurement directions on the trimming die. Measurement tip radius = 2µm. Cone angle = 60°. The photo displays the 3D-printed topology optimized trimming die.

Figure 11. The measurement positions on the trimming die. The photo displays the 3D-printed solid trimming die.
Figure 12. The U-bent sheet surface in contact with the 3D-printed topology optimized tool half from the stroke 50k, 25k and 1k respectively.

Figure 13. The U-bent sheet surface in contact with the 3D-printed solid tool half from the stroke 1k, 25k and 50k respectively.

Figure 14. The U-bending tool half edge (profile) radius at different positions after 50k strokes.

Figure 15. The U-bending maximum punch force as function of the stroke number.

Figure 16. The binder surface roughness at different positions on the U-bend tool after 50k strokes.

For up to 2-mm thick hot-dip galvanized DP600, the results of this investigation show that topology optimized and solid tools 3D-printed in maraging steel (DIN1.2709) exhibit a similar behaviour as conventionally designed forming tools made in “conventional” Calmax and Sleipner [10] and conventionally designed trimming tools manufactured in “conventional” Fermo and Sleipner [11].

The results of this investigation were used to design and manufacture industrial tools in DIN1.2709 by additive manufacturing [12].

5. Conclusions

3D-printed tools in maraging steel (DIN1.2709) behave as conventionally made tools do.

Although small, there is a difference in wear at the profile radius between the 3D-printed solid and topology optimized U-bending tool halves.

The trimming force exerted by the solid tool differs from that exerted by the topology optimized tool,
Figure 17. The wear at the U-bending tool profile radius after 50k strokes: Left = 3D-printed topology optimized tool half. Right = 3D-printed solid tool half. The sheet is drawn from the top to the bottom.

Figure 18. The shear and fracture zones on the trimmed sheet after 100k strokes. Left = trimmed with the 3D-printed topology optimized tool. Right = trimmed with the 3D-printed solid tool.

Figure 19. The size of the shear and fracture zones as function of the stroke number.

Figure 20. The wear after 100k strokes at the edge (profile) radius on the trim dies.
probably due to the spread in the mechanical properties of the sheet material.

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