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3D Metal Printing from an Industrial Perspective—Product Design, Production, and Business Models

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Abstract: This paper is focused on automotive stamping tools and dies as well as the impact of 3D metal printing and metals related 3D-printing on design and production of such tools and dies. The purpose has been to find out the current industrial potential of 3D-printing as far as lead time, costs, shapes, material usage, metal piece size, surface roughness, hardness, strength, and machinability are concerned. The business transformational impact of 3D-printing is also addressed in this paper. The obtained results show that the lead time can be halved, the costs are somewhat higher, and the strength, hardness, surface roughness, and machinability of the 3D-printed metallic tools and dies are as good as those of the conventionally made. The maximum size of a metal piece that can be 3D-printed today by Powder Bed Fusion (PBF) is, in the best case, 500 mm × 500 mm × 500 mm. 3D-printing can also be used for the pattern to make the mold box in iron and steel casting. It is also possible to eliminate the casting pattern, since the mold box can be 3D-printed directly. All this has started to have a large business impact, and it is therefore of great significance to outline and execute an action plan almost immediately.

Keywords: 3D-printing, Additive manufacturing, Metal, PBF, SLA, Automotive, Stamping, Tools, Dies, Design, Topology optimization, Production, Maraging steel, Business transformation

3D-Metalldruck aus industrieller Sicht—Produktdesign, Produktion und Geschäftsmodelle

Zusammenfassung: Dieser Beitrag konzentriert sich auf Stanzwerkzeuge für die Automobilindustrie sowie auf den Einfluss des 3D-Metalldrucks beim Entwurf und der Herstellung solcher Werkzeuge und Formen. Ziel war es, das derzeitige industrielle Potenzial des 3D-Drucks in Bezug auf Vorlaufzeit, Kosten, Formen, Materialverbrauch, Metallstückgröße, Oberflächenrauheit, Härte, Festigkeit und Bearbeitbarkeit zu ermitteln.

In diesem Artikel wird auch auf die Auswirkungen des 3D-Drucks auf die Wirtschaftlichkeit eingegangen. Die erzielten Ergebnisse zeigen, dass die Durchlaufzeit halbiert werden kann, die Kosten etwas höher sind und die Festigkeit, Härte, Oberflächenrauheit und Bearbeitbarkeit der 3D-gedruckten metallischen Werkzeuge und Formen genauso gut sind wie die herkömmlich hergestellten. Die maximale Größe eines Metallstücks, das heute mit Powder Bed Fusion (PBF) 3D-gedruckt werden kann, beträgt im besten Fall 500 mm × 500 mm × 500 mm.

Das 3D-Druckverfahren kann auch zur Herstellung des Musters verwendet werden, mit dem der Formkasten aus Eisen- und Stahlguss hergestellt wird. Es ist auch möglich, das Gussmuster zu entfernen, da der Formkasten direkt 3D-gedruckt werden kann. All dies hat zu großen wirtschaftlichen Auswirkungen geführt, und es ist daher von großer Bedeutung, fast sofort Maßnahmen zu planen und umzusetzen.

Schlüsselwörter: 3D-Druck, Additive Fertigung, Metall, PBF, SLA, Automobilindustrie, Stanzen, Werkzeuge, Formen, Design, Topologieoptimierung, Produktion, Maraging-Stahl, Unternehmenstransformation

1. Introduction

Tool and die design and manufacturing are 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 for the competitiveness of almost all industrial sectors.

Fig. 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

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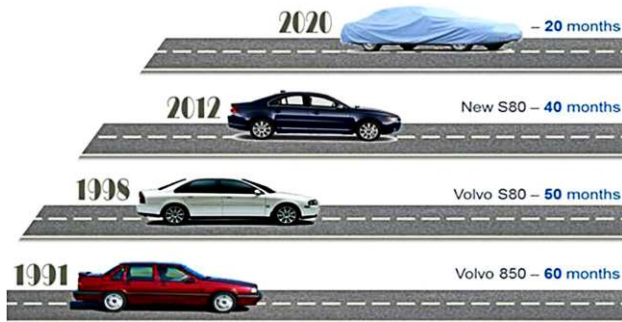SE-701 82 Örebro, Sweden
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Fig. 1: Lead time for development of a new car model: 1991, 1998, & 2012, & the target for 2020 (courtesy of Volvo Cars)

2020. This lead time is highly dependent upon the lead time for tools and dies required to make the new car body components. The lead time for tools and dies must therefore be reduced significantly to enable the reduction of the lead time for development of a new car model.

A car body consists of parts that are stamped in different sheet materials (Fig. 2). The selected sheet material, the forming/trimming severity, and the production volume size determine the selected tool and die solution. In many cases, the used tool and die comprise a portion that is cast (the green and yellow sections in Fig. 3) and the forming/trimming sections that are made in wrought steel (Fig. 3).

The targets for the present investigation were to study and evaluate how 3D-printing can be used in tool and die design and manufacture and how it affects the costs and lead time. To conduct this study, the following questions needed to be responded to:

- Up to which size can large metal pieces currently be 3D-printed?
- Which are the metallic materials that can be printed to industrial tools/dies today?
- Which are the lead time and costs for 3D-printed tools/dies? How do these tools/dies compare with those conventionally made?
- The tool/die weight/design? What can be accomplished?
- The strength, surface roughness, and hardness of the printed metal piece?
- Can the printed metal piece be machined, polished, hardened, and surface-coated?
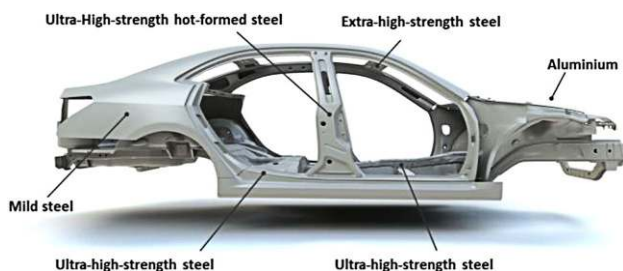- Is it possible to 3D-print the casting pattern (today made in polystyrene)?

Fig. 2: A car body consists of components that are stamped in different sheet material grades
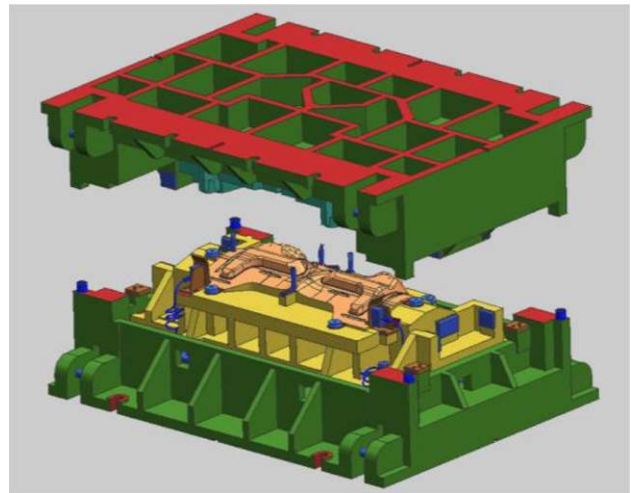

Fig. 3: In many cases, the used tool and die comprises a portion that is cast (the *green* and *yellow* sections) and the forming/trimming sections that are made in wrought steel

The present paper is an account of the responses found so far to the questions above.

2. Current Industrially Printable Sizes and Materials

Fig. 4 displays the current industrially printable metal piece sizes and the metallic materials that these pieces can be 3D-printed in. This figure is based on information from 3D Systems [1]. The other machine builders are within the same range.

As shown in Fig. 4, the maximum size that can be 3D-printed today is 500 mm × 500 mm × 500 mm. Several materials can be 3D-printed, some of them being classified as "full" and others as "partial". A material is classified as "full" if the powder is stocked, can be purchased and delivered rapidly, and the 3D-printing process parameters are fully optimized and set as default. A material is classified as "partial" if the powder is not stocked, cannot be delivered rapidly, and the 3D-printing process parameters for the material are not optimized fully yet. This classification is based on the available information from 3D Systems. The situation might however be different for different machine builders.

Among the so-called full materials in Fig. 4, the maraging steel (1.2709 according to the German designation system DIN) is the only suitable for stamping tools and dies. (More materials for 3D-printing of injection molds were launched during the past year, and more materials for 3D-printing of other types of tools and dies will be launched soon.) In Table 1, the mechanical properties of conventionally made AISI D2/DIN 1.2379, which is a very common/traditional material for stamping tools and dies, are compared to those of 3D-printed maraging steel DIN 1.2709. As displayed in this table, 3D-printed maraging steel DIN 1.2709 is fully comparable with AISI D2/DIN 1.2379.
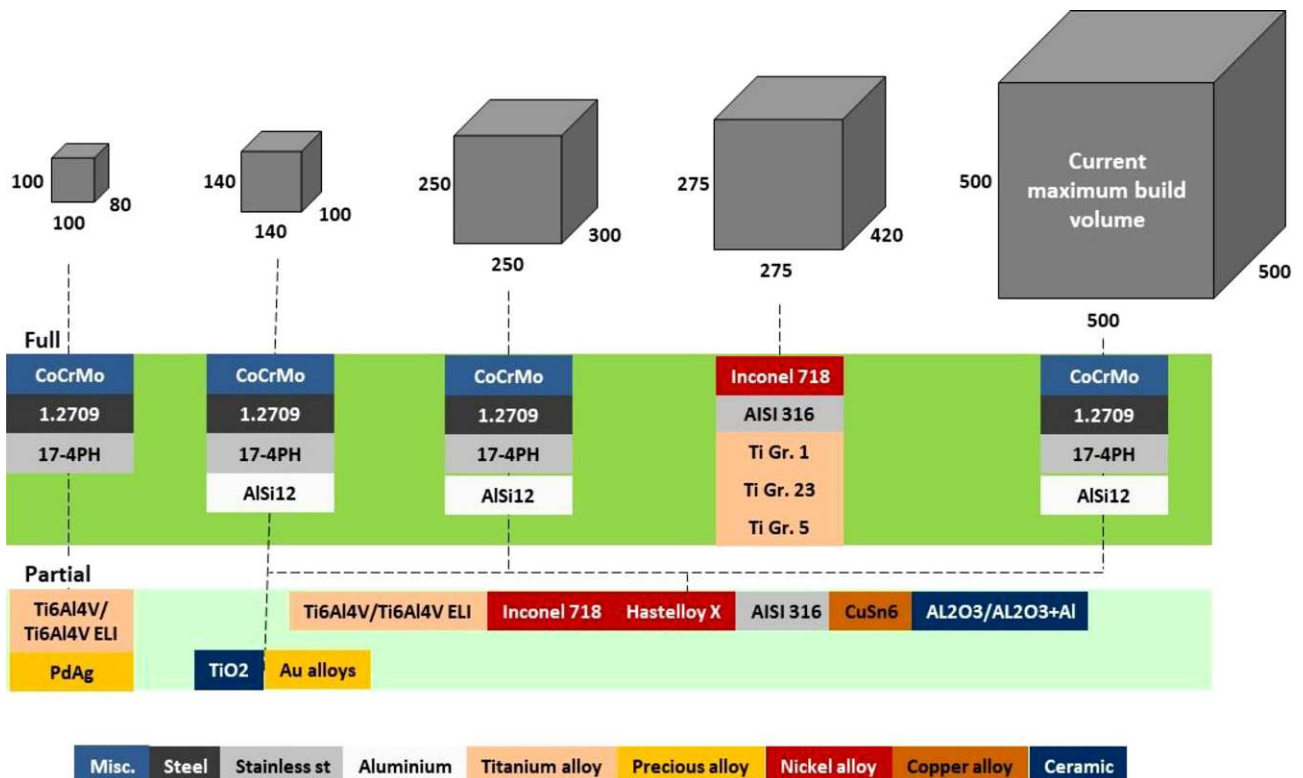
Fig. 4: The sizes of the metal pieces and the metallic materials these pieces can be 3D-printed in today. The figure is based on information from 3D Systems [1]. The other machine builders are within the same range

3. The Current Process of Stamping Tool and Die Design and Manufacture

Fig. 5 displays the chronological process description of the current stamping tool and die design and manufacture. In tool/die design, the properties and performance of the selected tool/die material, such as strength, machinability, heat-treatability, weldability, and resistance against abrasive and adhesive wear, chipping and cracking, are of great significance. Currently/conventionally however, the tool/die blocks/segments are solid pieces. (3D-printing enables manufacturing of hollow pieces, such as honeycomb and/or topology optimized structure. This type of structure will be addressed later on in this paper.) The tool/die can currently be made in *different* fashions:

a) The whole tool/die can be made of cast iron or steel. In this case, a casting pattern is made in polystyrene, a mold box is made, the whole tool/die is cast, and finally the cast piece is machined to the final shape. In this case, no wrought steel is used and there is no need for tool/die assembly. Fig. 6 shows some examples of casting pattern made in polystyrene.

b) The major portion of the tool/die (the green and yellow sections in Fig. 3) are cast, the working surfaces (the forming and trimming sections) are made in wrought steel, the cast and wrought steel portions are machined, and finally all tool/die pieces are assembled to a complete tool/die. Fig. 7 displays a forming die for a car body B-pillar, which comprises several segments assembled to a complete forming die.

TABLE 1
The mechanical properties as delivered/after 3D-printing and after heat treatment—conventionally made DIN 1.2379 compared to 3D-printed maraging steel DIN 1.2709. AISI = American Iron and Steel Institute. DIN = Deutsches Institut für Normung

	As delivered	After 3D printing	After heat treatment	After post heat treatment
	AISI D2/DIN 1.2379	Maraging Steel (DIN 1.2709)	AISI D2/DIN 1.2379	Maraging Steel (DIN 1.2709)
Yield strength (MPa)	350–550	860	1900	1930
Ultimate tensile strength (MPa)	706–870	1110	–	2000
Fracture elongation (%)	>11 & <20	11	–	1
Hardness (HRC)	18–26 (210–255 HB)	37	55	55

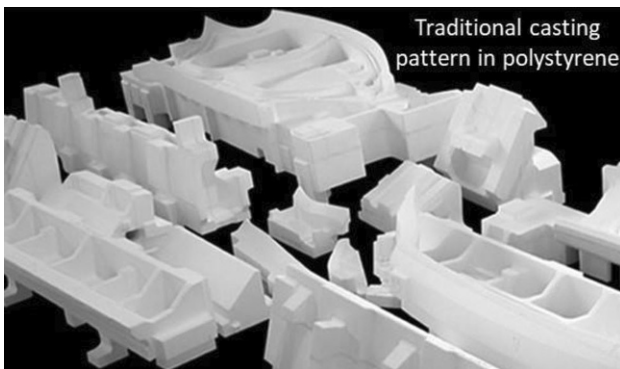**Fig. 5:** Chronological process description of the current tool & die design and manufacture
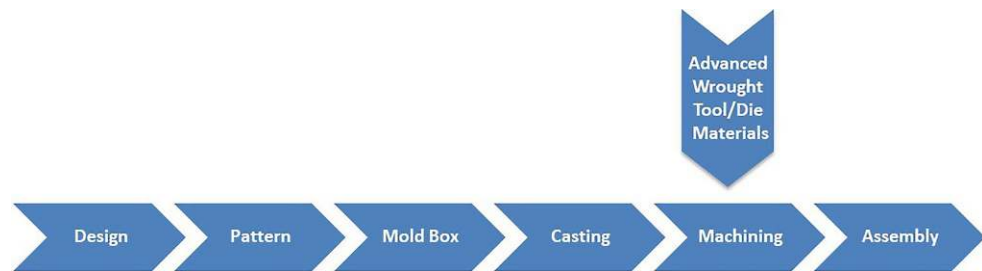
Advanced Wrought Tool/Die Materials

Design Pattern Mold Box Casting Machining Assembly

Traditional casting pattern in polystyrene

Fig. 6: Some examples of tradition casting pattern in polystyrene

CVD -coated insert

Inserts in Calmax

Calmax + plasma nitriding + CrN (PVD)
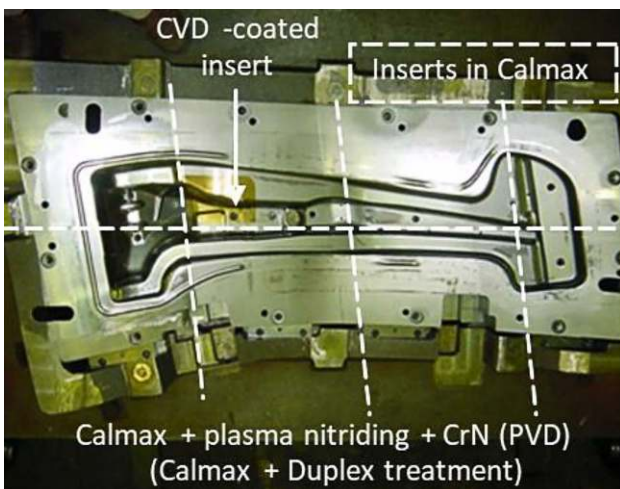(Calmax + Duplex treatment)

Fig. 7: Several segments assembled to a complete forming die for a B-pillar

The selected tool/die manufacturing process is dependent upon the strength of the sheet material that is to be formed and trimmed, the operational (forming and trimming) severity, the production volume size and more. In some cases, cast iron or cast steel is sufficient. In other cases, wrought steel with for instance a larger wear resistance is required in the working areas (forming/trimming tool/die sections). The selected approach affects the tool/die manufacturing lead time and costs. In Fig. 8, which concerns a forming die for an automotive side member, a process and cost comparison is made of a die made completely in cast steel and a die made of cast iron with wrought steel inserts.

Due to the size limitations for 3D metal printing shown in Fig. 4, it is not yet possible to make the entire stamping tool/die for car body parts by 3D metal printing (tools/dies for very small sheet metal parts are neglected here). How can then 3D-printing be included in the tool and die design and manufacturing process, Fig. 5, which is the magnitude of the lead time reduction claimed to be possible to accomplish by 3D-printing, and what would complexity at no extra cost—one of the potential benefits with 3D-printing—mean for tools and dies?

4. The Selected Cases—The Tool and Die Manufacture Using and Design for 3D-Printing

To respond to the questions raised above, the

- puller and the punch, which constitute a working station/portion of the progressive die for the car body part C-Bow Lower, were selected for 3D metal printing (Fig. 9).
- puller and trim pad in the lower trim die for the car body component B-Pillar Inner Reinforcement were decided to be cast (in a metallic material) and the casting patterns for these portions were selected to be 3D-printed (Fig. 10).
- U-bend tool shown in Fig. 11 (top right photo in this figure) was chosen as the design object. This tool was selected to be topology optimized in order to study the impact of the new design possibilities (greater complexity enabled by 3D-printing) on tools and dies.

Fig. 12 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 Fig. 9. As shown in Fig. 12, 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. This progressive die has been used (produced parts) for a few years. The 3D-printed versions of the puller and punch were made in this study to compare 3D-printing with conventional manufacturing.

The U-bend tool in Fig. 11 was selected as the design object, since this U-bend test has been used as a qualifying test for tool/die concepts within the Swedish auto-

Fig. 8: A forming die for an automotive side member: process and cost comparison of a die made completely in cast steel (**a**, Total cost = 104,160€) and a die made of cast iron with wrought steel inserts (**b**, Total cost = 99,960 €)

Cast steel

Other (transport, documentation etc.)
17%

Planning
3%

Numerical Design/
Process Planning
9%

Casting &
Material
29%

Quality
Control
5%

Tryout
14%

Machining
23%

Total cost = 104160 €

Other (transport, documentation etc.)
18%

Planning
3%

Numerical Design/
Process Planning
9%

Casting & Materials
12%

Quality
Control
5%

Machining
29%

Tryout
14%

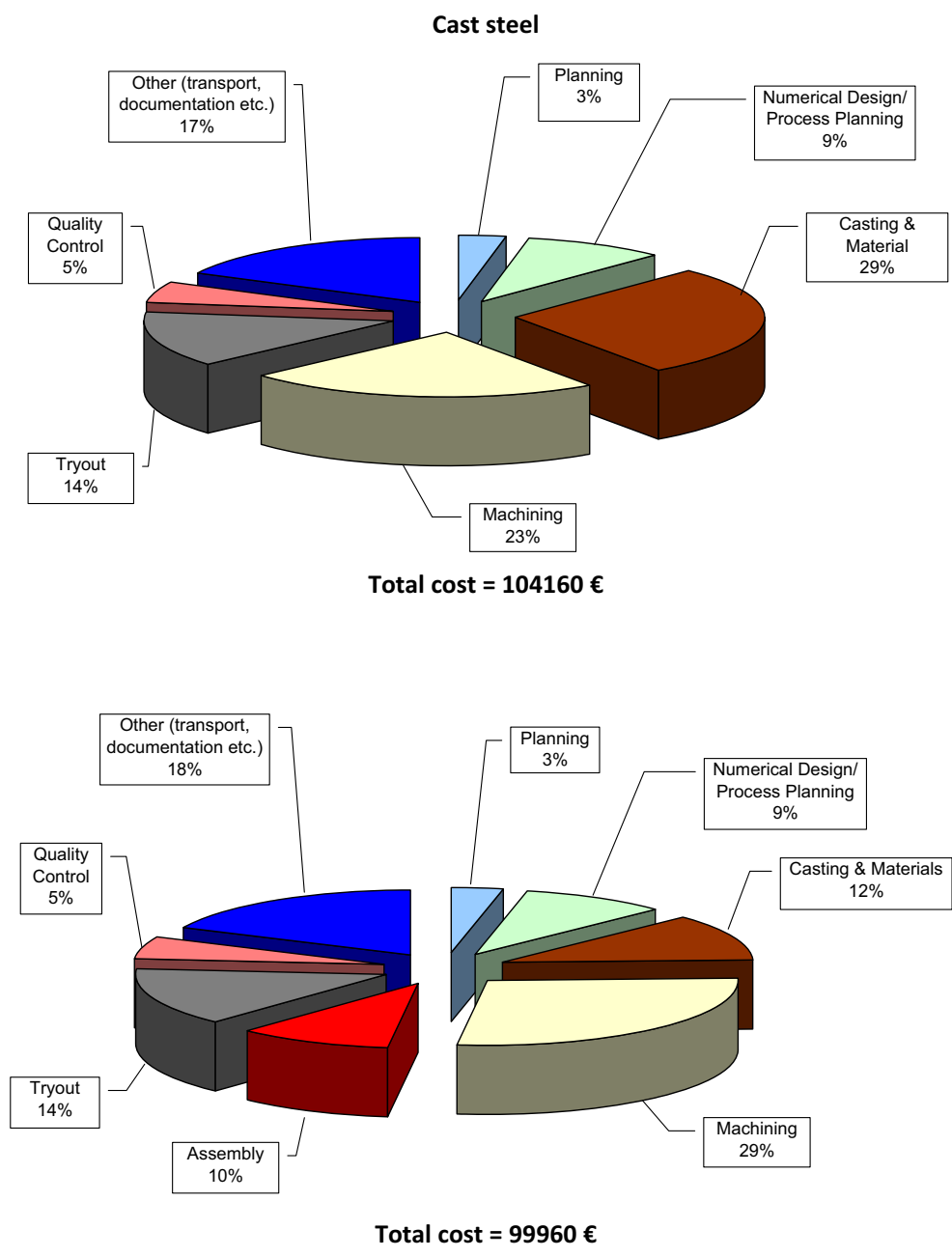Assembly
10%

Total cost = 99960 €

Fig. 9: The selected case for 3D metal printing: **a** the progressive die for the C-Bow Lower, **b** the station of this progressive die that was selected for 3D metal printing, and **c** the shape and dimensions of the selected punch & puller
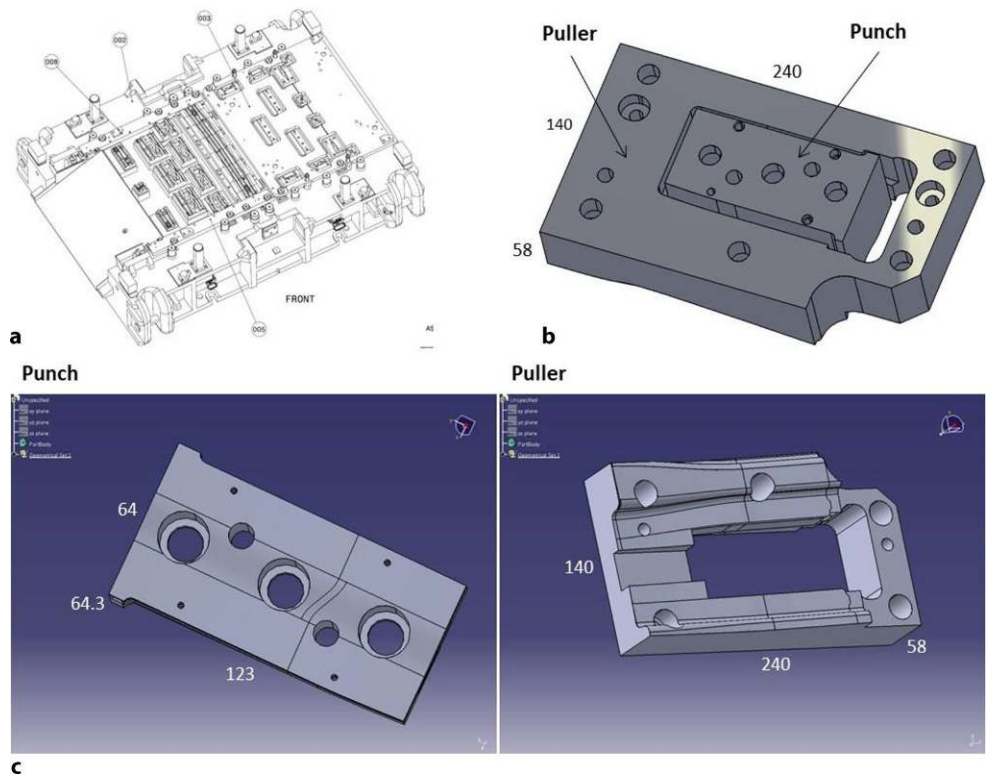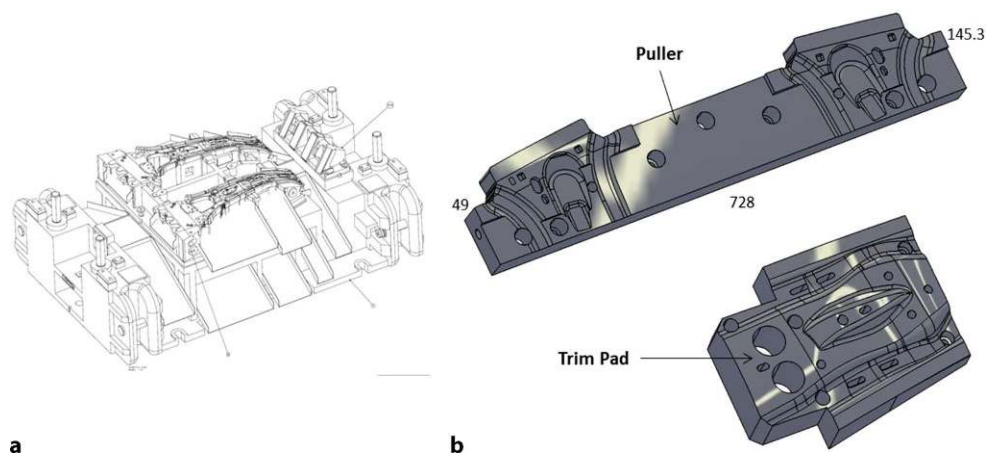

Fig. 10: The selected cases for 3D printing of casting pattern: **a** the lower trim die for the B-pillar Inner Reinforcement, **b** the portions of this lower trim die that were selected to be cast and for which the casting patterns were made by 3D printing
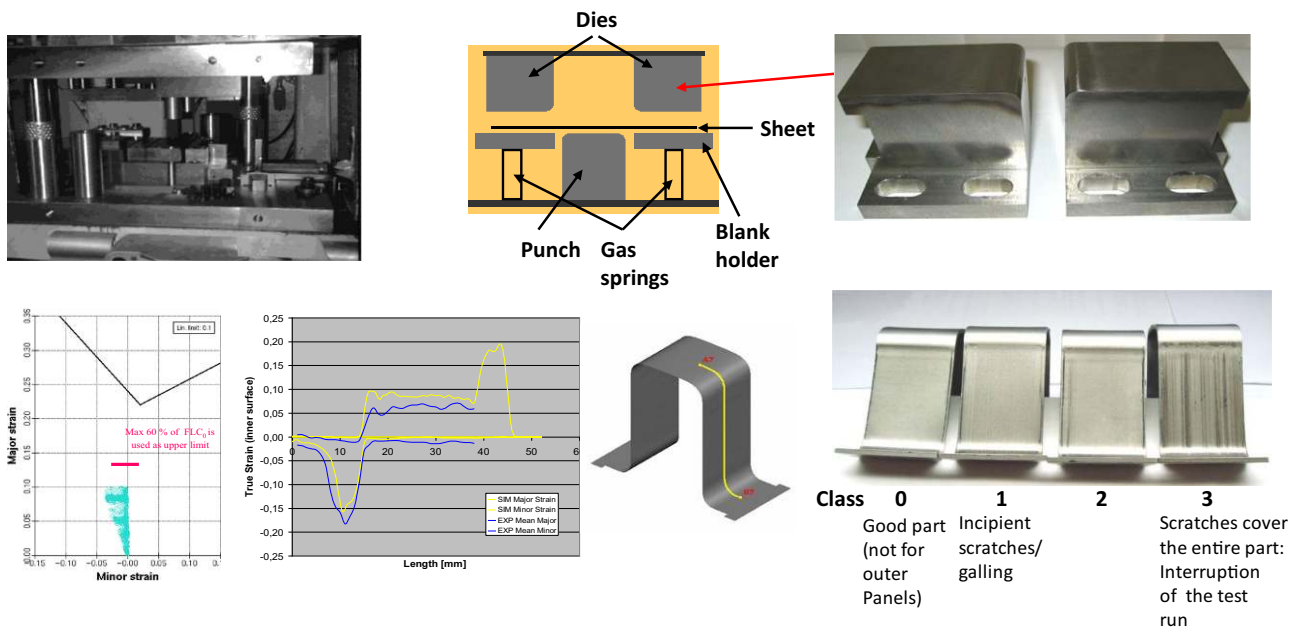
Fig. 11: The U-bend tool (top right photo) was selected as the design object in this study. The left U-bend tool half was selected to be topology optimized in order to study the impact of the new design possibilities (greater complexity enabled by 3D printing) on tools & dies

Fig. 12: 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 Fig. 9. EDM = Electrical Discharge Machining. SS = Swedish Standard

CONVENTIONAL PROCESS

Punch
Requirements:
- Hardness (after hardening) = 55 HRC
- Surface roughness in the working area = R_a = 0.8 μm

Material = SS2263 (tempered)
Process:
1: Milling
2: Hardening
3: Wire EDM

Puller
Requirements:
- Hardness (after hardening) = No requirement
- Surface roughness in the working area = R_a = 2-3 μm

Material = SS2172
Process:
1: Milling
2: Wire EDM

3D METAL PRINTING

Punch
Requirements:
- Hardness (after hardening) = 55 HRC
- Surface roughness in the working area = R_a = 0.8 μm

Material = Maraging steel (1.2709)

Puller
Requirements:
- Hardness (after hardening) = No requirement
- Surface roughness in the working area = R_a = 2-3 μm

Material = Maraging steel (1.2709)
Process:
1: 3D printing of punch and puller
2: Post-processing
3: Hardening of the punch
4: Machining of the working area

Fig. 13: The 3D-printed puller & punch in the progressive die displayed in Fig. 9. Material = DIN 1.2709. The honeycomb structure has a facade/outer shell thickness of 1.5 mm. Directly after 3D printing: S_a = 5.23 μm and R_a = 4.92 μm. After 3D Printing and milling at cusp height 0.6 μm: S_a = 0.85 μm and R_a = 0.71 μm
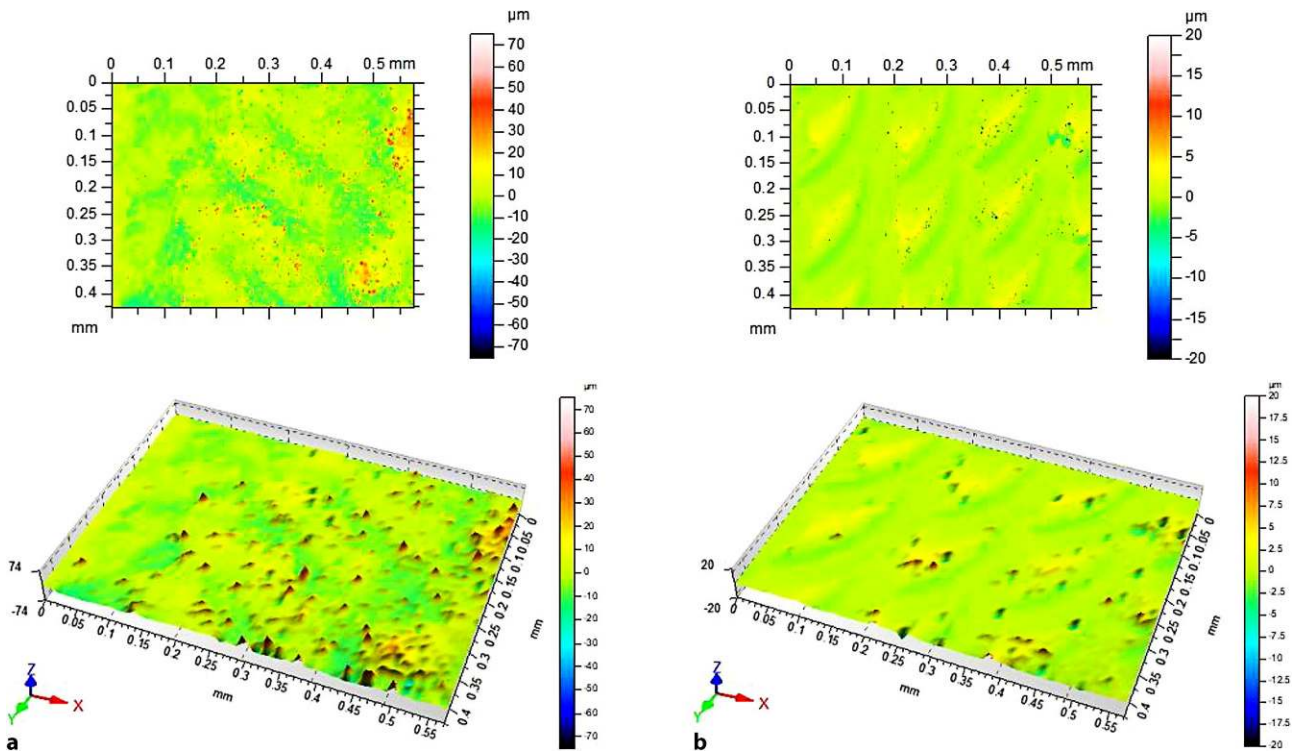
Fig. 14: The puller in Fig. 13: 3D surface roughness measurement directly after 3D printing (**a**, S_a = 5.23 µm and R_a = 4.92 µm) and after 3D printing followed by milling at a cusp height of 0.6 µm (**b**, S_a = 0.85 µm and R_a = 0.71 µm)

Hardness		
Point	HB	HRC
1	550	53
2	583	55
3	631	58
4	621	58
5	510	51
6	700	60
Average	599	56

Fig. 15: The hardness measured at the indicated sites on the puller

Fig. 16: Casting pattern for the trim pad shown in Fig. 10. This casting pattern was 3D-printed with SLA QuickCast technology using CastPro™ resin
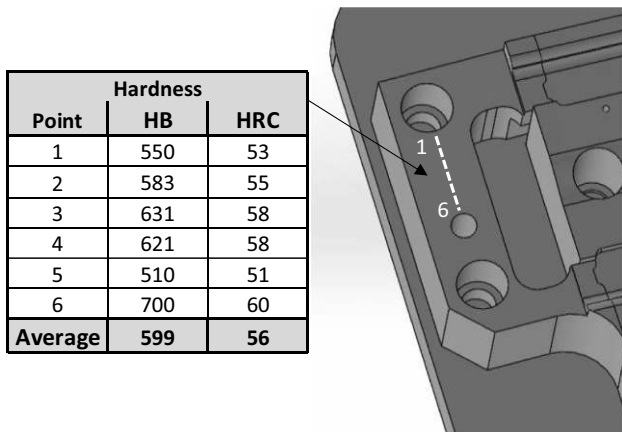
motive industry for many years. In this test, a tool/die concept (comprising the material, hardness, surface roughness, surface coating) is tested with the targeted sheet material. The U-bending operation is simulated. The purpose of the simulations is to find the binder force yielding a strain level in the U-bend wall that corresponds to 60% of FLC_{min} (the Forming Limit Curve minimum) of the sheet material (which normally is obtained at plane strain). This binder force is then used in the practical experiments shown in Fig. 11. Only the tool/die concepts that manage 50 thousand U-bends (50 thousand strokes) with a U-bend surface class ≤ 1 (incipient scratches/galling) are accepted as solutions for production tools/dies.

The U-bend tool on the right (Fig. 11) was 3D-printed as a solid piece, whilst the U-bend tool on the left was first topology optimized and then 3D-printed. Both U-bend tool halves were 3D-printed in DIN 1.2709 (Table 1). 2-mm thick hot-dip galvanized DP600 was selected as the sheet material. The topology optimization was preceded by a simulation of the U-bending of this sheet material to find the stresses exerted to the U-bend tool in the forming operation. LS-TaSC was then used to topology optimize the U-bend tool on the left. LS-TaSC is the tool for the topology optimization of non-linear problems involving dynamic

TABLE 2 **The lead times for the puller & punch shown in Fig. 9. See also Fig. 12**		
	Lead Time (Working days)	
	Conventional	3D Printed Honeycomb structure
Punch	8	–
Puller	6	–
Total	8	3.7

TABLE 3 **A cost comparison of the conventional process and the 3D-printing inclusive process. See also Fig. 12**		
	Cost (SEK)	
	Conventional	3D Printed Honeycomb structure
Punch	10,500	–
Puller	15,500	–
Total	26,000	31,000

loads and contact conditions [2]. It can be used to find a concept design for most structures analyzed by LS-DYNA.

In the topology optimization using LS-TaSC, a 3D model was created assuming that extrusion constraint prevailed. The extrusion constraint means that the part (the U-bend tool on the left 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 displacement of a node slightly above the die profile radius was used as a measure of stiffness.

5. Results

Fig. 13 displays the 3D-printed puller and punch in the progressive die shown in Fig. 9. The puller and the punch were 3D-printed simultaneously (the same print) in maraging steel DIN 1.2709 (see Table 1). The honeycomb structure has 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. In all three cases, 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 3D-printing followed by milling at the above-mentioned three cusp heights. Fig. 14 shows the results of the 3D surface roughness measurements directly after 3D-printing and after 3D-printing followed by milling at 0.6 μm in cusp height. The surface roughness was $R_a = 4.92$ μm ($S_a = 5.23$ μm) after 3D-printing and $R_a = 0.71$ μm ($S_a = 0.85$ μm) after 3D-printing and milling at a cusp height of 0.6 μm.

Fig. 15 shows the hardness measured at the indicated sites on the puller. The requirements displayed in Fig. 12 were therefore easily obtained by 3D-printing and post-processing. In other words, 3D-printing and post-processing yielded fully comparable and production-applicable puller and punch for the progressive die displayed in Fig. 9.

Table 2 depicts a comparison of the lead time for the conventionally made puller and punch, (Figs. 9 and 12), and that for the same tools made in a 3D-printing inclusive process (Figs. 9, 12 and 13). As shown in this table, the lead time is halved by 3D-printing.

Table 3 displays a cost comparison. The 3D-printing inclusive process costs more than the conventional process. It is, however, important to mention that the cost of the 3D-printing inclusive process is based on the assumption that the depreciation period for the 3D-printing machine is 5 years. In case a 10 years long depreciation period can be

TABLE 4 **The lead time values for the trim pad displayed in Fig. 10 (and Fig. 16)**			
	Lead Time (Working days)		
	Conventional	3D Printed Separately	Both Puller and Trim Pad
Casting Pattern/Trim Pad	14 days[a]	1 day	1 day
Casting Pattern/Puller	14 days[a]	1 day	
Total	14 days	1 day	1 day
[a]Delivery time			

TABLE 5 **A cost comparison of the conventional polystyrene pattern (Fig. 6) and the 3D printed version (Fig. 16)**			
	Cost (SEK)		
	Conventional	3D Printed Printed separately	Printed in one print
Casting Pattern/Trim Pad	2000	1498	5803
Casting Pattern/Puller	3000	4305	
Total	5000	5803	5803

Fig. 17: The U-bending tool: The right tool half is 3D-printed as a solid piece. The left tool half is topology optimized with a volume fraction of 0.45 and 3D-printed. Both tool halves are 3D-printed in maraging steel DIN 1.2709
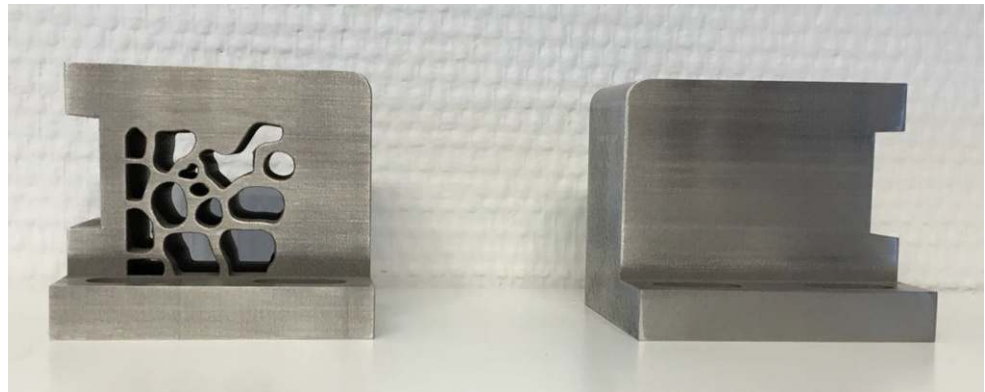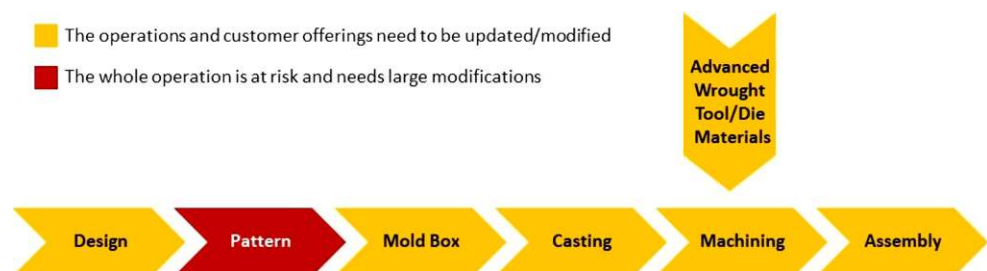

Fig. 18: The business transformational impact of 3D-printing. The required changes in the chronological process description of tool & die design and manufacture. Compare with Fig. 5

accepted, the cost of the 3D-printing inclusive process is reduced to 29,000 SEK.

The casting pattern for the trim pad in Fig. 10 is displayed in Fig. 16. This casting pattern was 3D-printed with SLA QuickCast technology using CastPro™ resins.

Table 4 shows the lead time values for the conventional (polystyrene) & 3D-printed casting patterns. As shown in this table, 3D-printing cuts the lead time drastically.

The cost of the conventionally made pattern is compared with that of the 3D-printed pattern in Table 5. 3D-printing increases the costs by 16%, Table 5.

The 3D-printed U-bend tool is depicted in Fig. 17 (see also Fig. 11). The right tool half is 3D-printed as a solid piece. The left tool half is topology optimized with a volume fraction of 0.45 and 3D-printed. LS-TaSC was, as described in Sect. 4, used to conduct the topology optimization. Both of the U-bend tool halves are 3D-printed in maraging steel DIN 1.2709.

6. Discussion and Conclusions

The obtained results show that the lead time is more than halved, the costs are somewhat higher, the strength, hardness, surface roughness, and machinability of the 3D-printed metallic tool and die are as good as those of the conventionally made, and the material usage can be improved significantly. The maximum size of a metal piece that can be 3D-printed today by Powder Bed Fusion is, in the best case, 500 mm × 500 mm × 500 mm. The number of available powder materials for 3D metal printing of stamping tools and dies is still very limited. 3D-printing can make the pattern used to make the mold box for iron and steel casting. It is also possible to eliminate the casting pattern

by 3D-printing the mold box directly (compare also Fig. 18 with Fig. 5). All this has a large business impact, and it is therefore of great significance to outline and execute an action plan almost immediately.

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