3D printed prototyping tools for flexible sheet metal drawing

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ABSTRACT Due to the change from mass production to mass personalized production and the resulting intrinsic product flexibility, the automotive industry, among others, is looking for cost-efficient and resource-saving production methods to combining global just-in-time production. In addition to geometric manufacturing flexibility, additive manufacturing offers a resource-saving application for rapid prototyping and small series in pre-development. In this study, the FDM process was utilized to manufacture the tooling to draw a small series of sheet metal parts in combination with the rubber pad forming process. Therefore, a variety of common AM polymer materials (PETG, PLA and ABS) is compared in compression tests, from which PLA is selected to be applied as sheet metal forming die. For the rubber pad forming process, relevant processing parameters, i.e. press force and rubber cushion hardness, are studied with respect to forming depth. The product batch was examined by an optical evaluation using a metrological system. The scans of the tool and sheet metal parts confirm the mechanical integrity of the additively manufactured die from polymer and thus the suitability of this approach for small series in sheet metal drawing processes, e.g. for automotive applications.

Keywords: additive manufacturing, forming flexibility, production on demand, rapid prototyping, rubber pad forming, sheet metal forming

I. INTRODUCTION

Over the past decades, the consumer demand enabled the transformation from mass production to mass personalized production, where on-demand high output and flexibility as well as customization led to an increase in product variety (see Figure 1).

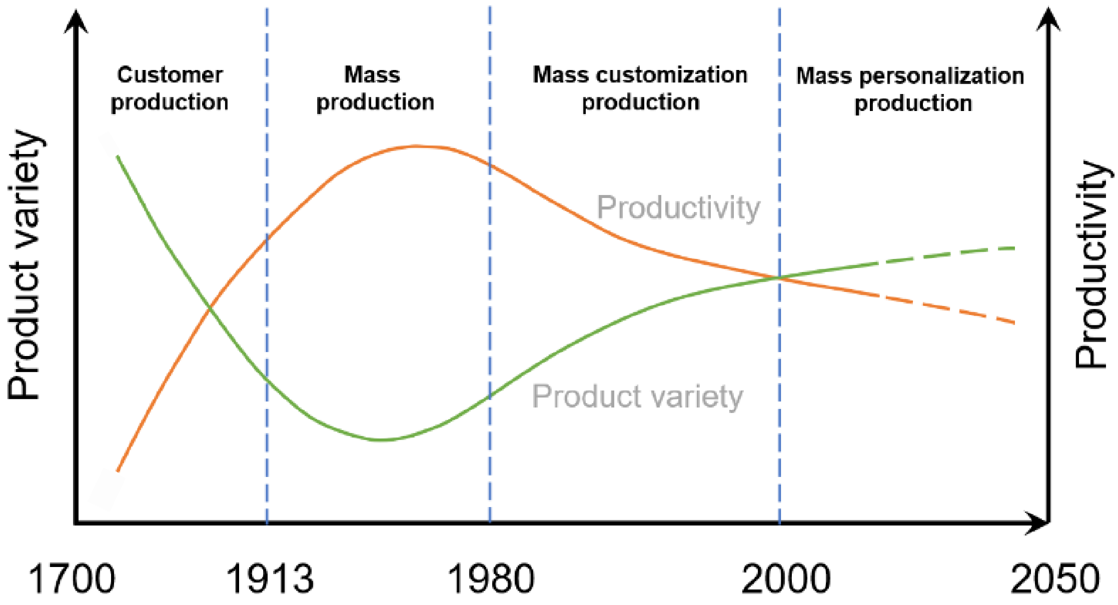

Figure 1: Evolution of production paradigms as associated with the four industrial revolutions, according to *(Wang et al. 2017)*.

In this context, various types of flexibility such as machine (various operations performed without set-up change) or product (ease of introducing products into an existing product mix) flexibility are differentiated. The capacity to quickly adapt to new, partly unknown requirements may be achieved by designing reconfigurable manufacturing systems with fast exchange reconfiguration modules (ElMaraghy 2005). However, the achievable agility is directly dependent on how fast and easy reconfiguration modules become usable in the manufacturing system. The availability of inexpensive additive manufacturing systems may provide a relevant contribution to tackling the high complexity of layout design in reconfigurable manufacturing systems (Maganha, Silva, and Ferreira 2019) by providing an easily available, close to process source of reconfigurable tool components.
Customer integration and personalization remain as major issues with regard to low-cost mass production. In order to reconcile large-scale manufacturing and personalized diversification, quality, variety and reduction of cost and time are restrictive factors given by conventional manufacturing methods (Wang et al. 2017). Customization with

respect to manufacturing flexibility is inherent in for processes like welding and machining, but still challenging or insufficient concerning forming. During the production of large lot sizes, conventional forming techniques are fast and accurate but insufficient when producing variants, which is due to expensive tooling. To ensure mass customization and personalization in metal forming, flexibility plays a vital role (Ersoy and Çelik 2019; Yang et al. 2018).

(Frohn-Sörensen et al. 2020) introduced a flexible manufacturing chain for an incremental bending process, where individualization can be achieved by the variation of different profile shapes for the same forming tool. Including the customer's individual anthropometry, (Michael Schiller, Chritopher Heftrich, and Bernd Engel 2020) processed a freeform bending method, where an individualized chair was manufactured automatically according to the body measurements of the customer. (Selmi and Belhadjsalah 2012) focussed on multipoint hydroforming with a flexible elastomeric die to reduce tool costs and to maximize product variability for a specific tool application.

Most often, the variation of the tools in forming processes and therefore the individualization of the products require either a large infrastructure or high tooling costs to achieve a degree of freedom (DoF) for flexibility (Ersoy and Çelik 2019). In order to enable economical product manufacturing, flexible tool production is required to efficiently achieve manufacturing high number of variants.

Rubber pad forming (RPF) is a well-established flexible-die forming process in the automotive, aerospace, energy and food industries. It allows manufacturing a variation of complex shapes (Liu et al. 2010). RPF, as developed at the Douglas Aircraft Company in the US during the Second World War. The tool comprises a rigid die (top) and an elastic rubber pad (bottom), which can either be attached in a negative (female) or positive (male, a.k.a GUÉRIN) process setup (Thiruvarudchelvan 1993) (cf. Figure 2).

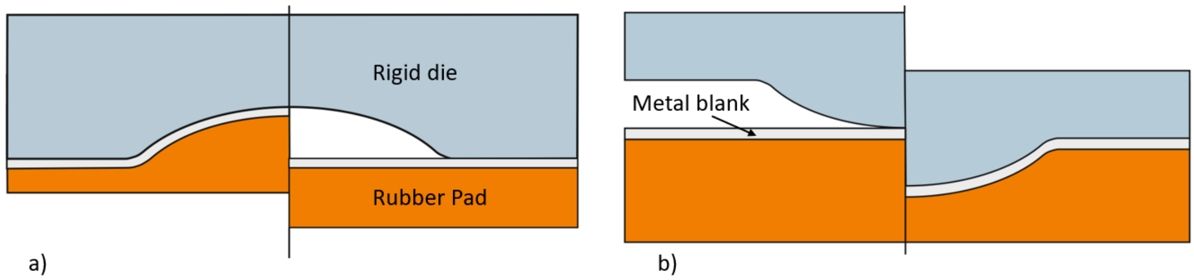

Figure 2:Tool setup for (a) negative (female) and (b) positive (male) rubber pad forming process

In addition, the male process variant has been improved subsequently by a blank holder, commonly denoted the MARFORM process (by the Glen L. Martin Company), to overcome the problem of wrinkles in the flange area, especially when forming parts with deeper cavities (E.L Deladi 2006). When applying force on the rigid die, the elastic rubber pad is deformed in the blank space of the rigid tool. The blank metal is squeezed in the blank section, which can be stated as a deep drawing and redrawing process. Moreover, the ductile behaviour of the rubber pad ensures a good friction coefficient.

Compared to conventional sheet metal forming processes, the advantages for RPF processes can be regarded as low cost (tooling), dimensional accuracy, high flexibility, short lead-time for tooling and part as well as good surface quality of the formed parts, especially for small and medium batch size production (Altan and Tekkaya 2012). Summing up those advantages, RPF could be an option for mass personalization, where a low volume production is required due to the high number of individual product variants (Cezarina et al. 2019), (Spoelstra, Djakow, and Homberg 2017), (Maziar Ramezani and Zaidi M. Ripin 2012). Since the RPF process consists of a flexible rubber pad and a form shaping die, the required product geometry is specified by the geometry of the die. For enhancing geometrical DoF and flexibility of the forming process, the die can either be adjusted flexibly or manufactured individually for each desired single shape, where the last option is usually correlated with high tooling costs and lead-time (Cezarina et al. 2019), (Elghawail et al. 2019), (Maziar Ramezani and Zaidi M. Ripin 2012).

To overcome those drawbacks, additive manufacturing (AM) techniques like fused deposition modelling (FDM) can be applied to the die manufacturing process, as their geometrical limitations are most likely to be restricted to the size of the building chamber. Additionally, AM enables a high level of geometrical freedom and flexibility due to its process (Stampfl and Hatzenbichler 2014). Over the past decade the impact of AM increased rapidly, next to their process and lead-times. Therefore, AM is highly desirable to manufacture tooling for forming processes. Especially the variance and integrity of AM base materials is a promising assortment for different applications in the design and manufacturing sector, as their mechanical properties have improved drastically over the past decade (Thompson et al. 2016). Hence, AM is a promising alternative to the traditional manufacturing techniques for producing sheet metal forming dies. As one of the most common AM techniques, Fused Deposition Modeling

(FDM) is applicable to a wide range of thermoplastics filaments such as polylactic acid (PLA), nylon or acrylonitrile butadiene styrene (ABS), which can be improved by fibers or metallic particles additionally. (Nakamura, Mori, and Abe 2020) improved V- bend tools by reinforcing metal steel bars to enhance the dimensional accuracy and mechanical performance of FDM printed PLA. (Durgun 2015) investigated AM printed polycarbonate dies in a sheet metal stamping process to reveal the dimensional wear behaviour and conformance for up to 101 parts. (Schuh et al. 2020) examined a two-sided AM punch model from PLA to inspect the formability of automotive sheet metal blanks. They concluded a simulative and experimental approach for the wear and deformation behaviour of the forming dies for up to 23 parts.

Despite, or perhaps because of the growing population and the increase in demand for resources and energy consumption, the attitude of humankind has changed significantly towards a more sustainable way of life. Natural and bio-based materials like PLA are promising to reduce the economic impact in the manufacturing industry (Anon 2019), (Pappu, Pickering, and Thakur 2019). In this context, in order to reduce tooling costs and, at the same time enhance the flexibility of the whole tooling, a RPF process was incorporated with an FDM printed drawing die in this study. A systematic evaluation of the forming die as well as the formed sheet metal parts can indicate the cyclic performance of polymer based materials. The motivation for this paper is to combine the advantages of the RPF and AM technology and to investigate a flexible and customizable process ("AM-RPF") for forming of sheet metal blanks, particularly for small batch sizes.

II. METHODOLOGY

The feasibility of additively manufacturing a die for sheet metal forming from polymer materials is the central objective of this investigation. Initially, a target geometry of dome shape model is created in CAD using an automotive standard drawing sheet metal. Moreover, a suitable AM polymer is required, which i) can be manufactured in an economically feasible environment, ii) withstands the occurring static compressive loads and iii) shows a ductile mechanical behavior. Based on this, preliminary material tests are conducted to choose the appropriate manufacturing technology. The experiments on rubber pad forming are conducted on a universal testing machine to assure precise evaluation of force over travel signals corresponding to the forming operation. Finally, an optical scanner is used to analyze the quality and formability of the dome shaped sheet metal surface of the herein objected exemplary product shape.

2.1 DESIGN

For the forming experiments, a tooling is designed to apply the rubber pad forming process to a universal testing machine. The facility provides a maximum press force application of 250 kN and intrinsic evaluation of force and displacement. According to (Niknejad, Rezaee, and Asl 2015), the “female” type rubber pad forming process (cf. Figure 2a) is applied to the forming of a dome from sheet metal. Next to the additively manufactured die from the favored polymer material, the shore hardness of the rubber pad needs to be considered as well, as its enclosing restrainer and the adaptation to the machine. The CAD of the assembly utilized in this work is shown in Figure 3.

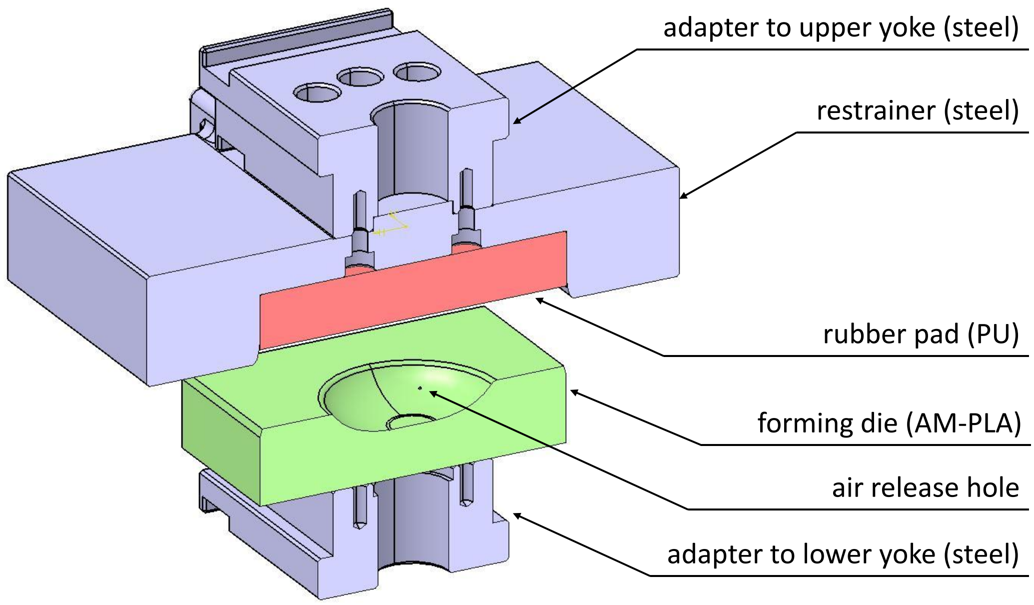

Figure 3: Cut view of the CAD model of the AM-RPF process: Rubber pad forming with an additively manufactured die, assembled on a universal testing machine.

Due to its universal applicability, the restrainer is substractively made by milling from conventional tool steel grade 1.2312. The restrainer encloses a rubber pad of the outer dimensions of 115 x 115 mm² and is made from polyurethane, which can be adjusted in hardness according to the mixture ratio of the cast compounds. For the present investigation, 60 and 80 hardness Shore rubber pads are cast with a thickness of 20 mm. The forming die is additively manufactured. In the type I rubber pad forming process, the rubber pad is compressed and expands into the cavity of the die, thus stretch drawing the sheet metal.

2.2 AM Materials

Considering availability, FDM is a wide-spread additive manufacturing technology. A variation of thermoplastic filament materials is covered within this study in order to find a good applicability to sheet metal forming dies. Polyethylene terephthalate modified by glycol, PETG, is a common FDM material used in diverse applications (Szykiedans, Credo, and Osiński 2017). In general, strength, durability and reasonable workability are associated with this material. Stiff mechanical properties are also associated with Polylactic acid (PLA) (Rodríguez-Panes, Claver, and Camacho 2018) which, additionally, allows a biological decomposition after use (Musioł et al. 2018). In the present study, the following FDM processing parameters are adjusted in the additive manufacturing processes according to Table 1.

Table 1: FDM manufacturing parameters for pre-test specimens with 90° alternating printing path.

Parameter		**PLA**	**PETG**	**ABS**	Explanation
Nozzle diameter	[mm]	0.4	0.4	0.4	Diameter of extrusion nozzle
Fixed layer height	[mm]	0.1	0.2	0.2	Thickness of each layer
Fixed first layer height	[mm]	0.2	0.2	0.2	Thickness of first layer
Extruder Temperature	[°C]	210	250	245	Temperature of the nozzle during printing
Platform temperature	[°C]	55	90	70	Temperature of the printing bed
Printing speed	[mm/s]	45	45	40	Speed during printing
Infill density	[%]	100	100	100	Interior solidity of the model
Shell count		3	3	3	Number of shells to contour the cross-sectional area

For the feasibility study of AM-materials in sheet metal forming dies, the compressive properties of the materials described in Table 1 are investigated. Therefore, cylindrical test specimens are additively manufactured from the materials, (see Figure 4) and subjected to destructive compression tests, according to EN ISO 604:200.

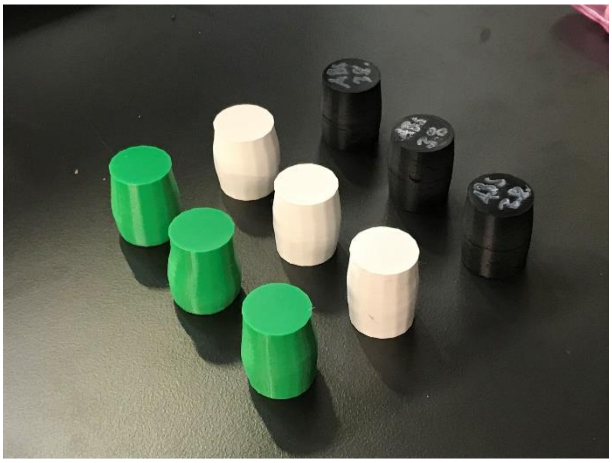

Figure 4: FDM Additively manufactured material variation, namely from left to right: PETG, PLA, ABS. Cylindrical specimen are utilized to test and compare the compressive mechanical properties.

Moreover, to gather information about aging influence, the materials are tested two days after their fabrication and, for the most promising materials regarding the application as forming dies, after 20 days under ambient conditions. Three repetitions have been conducted for each individual test setup from which a representative curve is displayed for each material in Figure 5.

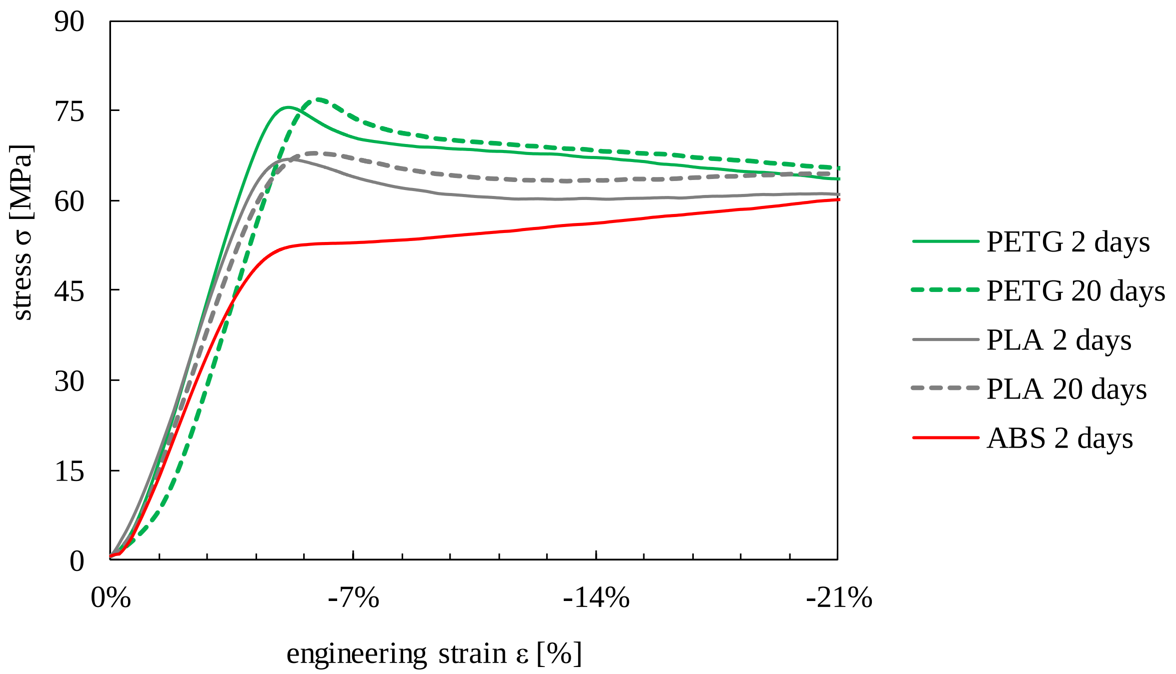

Figure 5: Mechanical properties of different AM polymers under compression with respect to the influence of ageing. Graphs are given as average of test repetitions.

Since thermoplastics reveal a hygroscopic behavior (Kakanuru and Pochiraju 2020) and (Chaitanya and Singh 2017), the specimens were kept in sealed bags after printing. Compared to the tests carried out with two days old specimens, the later tests reveal slightly higher strain-related mechanical properties after 20 days, which indicates a decrease in elastic stiffness. Therefore, the hereby presented polymers beneficially support their utilization as tool materials in a just-in-time production environment.

Two distinct mechanical behaviors are obtained from the resulting flow curves. A characteristic compressive yield stress maximum can be observed from the stress-strain curves of PETG and PLA while a continuously increasing stress over strain function without a local distinct yield stress maximum is obtained from the ABS polymer. With regard to their aging, the materials show slight variations in the mechanical properties. For each material, the compressive mechanical parameters are evaluated quantitatively in Table 2 from the repetitions of the two days old specimen. For ABS, yield stress is assessed at 5% compression, as no characteristic maximum is present from the tests because of the monotonous increase of stress over strain, cf. Figure 5, even if higher compression is tested.

Table 2: Mechanical material parameters under compressive load of the investigated additively manufactured polymer materials.

Material	**E_c [MPa]**	**σ_y [MPa]**	**ε_{cy} [%]**	**$\sigma_{5\%}$ [MPa]**
PETG	1880 ± 23	75.2 ± 0.3	5.0 ± 0.1	-
PLA	1688 ± 10	67.3 ± 0.4	5.2 ± 0.1	-
ABS	1497 ± 8	-	-	51.4 ± 0.5

For the application in forming tools, the three key material properties of interest are,

1) Stiffness, related to the compressive elastic modulus E_C will determine the relationship between the die geometry and the product and can be compensated in the design phase. In general, a stiffer tooling is related to higher forming accuracy.
2) Strength will give the maximum feasible load of the forming die. Therefore, a high strength AM material is favourable.
3) Brittleness will strongly increase the risk of tool breakage. As the effective gradients of contact pressure can be estimated from analytic considerations, local maxima in the practical application could overload the capacities of the material. On the other hand, with reasonable ductility, an overloaded tool would be rather partially deformed instead of break, which would cause initial run in effects.

With regards to the three aspects raised above, PETG and PLA show promising mechanical properties when subjected to compressive load. Moreover, considering the application as forming tools of small quantities, its vast availability makes PLA the favored material, which is selected for the application within the remainder of this investigation. According to the CAD geometry shown in section 2.1, the die is additively manufactured on a Creality Ender 3 Pro from PLA, see Figure 6. The parts are printed in multiple repetitions for the practical experiments (section 3.1) according to the parameters of Table 1.

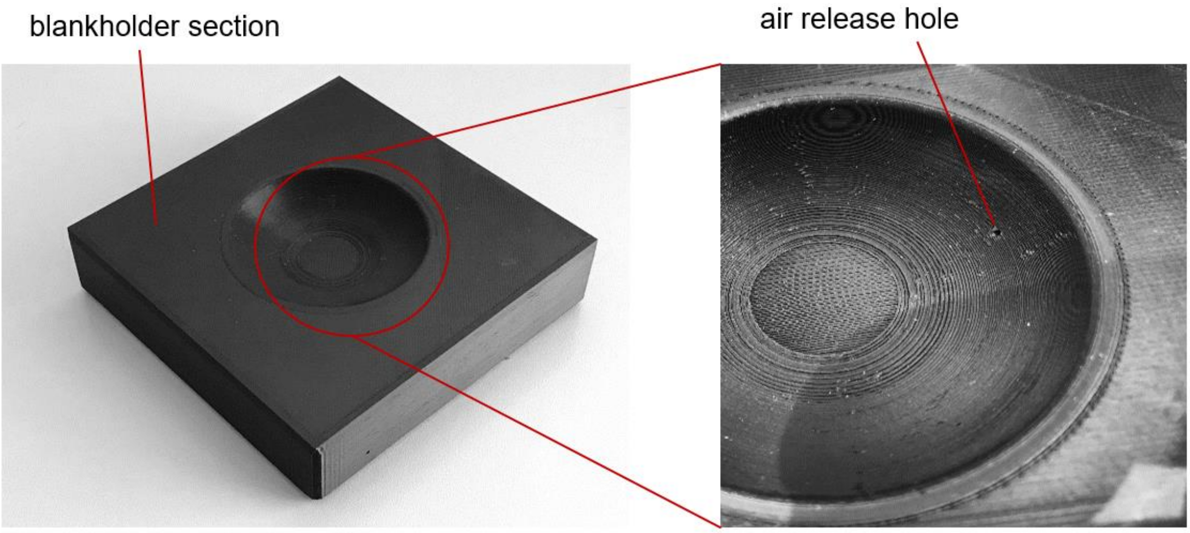

Figure 6: Additively manufactured forming die from PLA in a FDM printing layer resolution of 0.1 mm. a) Showing geometrical overview and b) detail for 0.1 mm printing resolution and air release hole.

2.3 RUBBER PAD MATERIAL

Polyurethane (PUR) rubber pads are cast with varying components to achieve a variation in shore-A hardness. A variation of mixing ratios of Sika PUR resin U1404 is applied according to the manufacturer's instructions to obtain three different degrees of shore-A hardness (40,60 and 80), which are applied to the rubber pad forming process during the pretests. The required mixtures are cast directly in the restrainer with a thickness of 20 mm each to achieve good geometrical correspondence for the process. After seven days, the cured rubber pads are extracted from the restrainer and implied to the forming process.

2.4 SHEET METAL MATERIAL

A standard automotive body deep drawing sheet metal of DC03 grade and thickness of 0.7 mm is introduced to the AM-RPF process. Blanks of 80 x 80 mm size are cut for the practical experiments. For comprehensiveness, the mechanical parameters of this sheet metal material are evaluated by uniaxial tensile tests, which are summarized in Table 3.

Table 3: Tensile mechanical properties of the hereby utilized 0.7 mm DC03 sheet metal.

R_e [MPa]	R_m [MPa]	n [-]
181 ± 3	310 ± 1	0.105 ± 0.01

2.5 FORMING EXPERIMENTS

The experimental procedure according to the test assembly shown in Figure 3 is structured in two parts. First, it is of interest how the loaded rubber pad forms the sheet metal in the cavity of the die as a function of applied forming force. Therefore, the applied press load is raised in successive steps of 25 kN and the geometry resulting from each step is evaluated. In addition, the RPF process is tested with a variety of hardness of the rubber pad in between 40, 60 and 80 degrees Shore-A hardness. The hardness is expected to show a compliant increase of the required forming force. Harder rubber pads generally require significantly higher press force but are sufficient to suppress the formation of wrinkles (Del Prete, Papadia, and Manisi 2011; Elena Loredana Deladi 2006; Thiruvarudchelvan 2002).

In the second approach, a fresh die is introduced to the AM-RPF process under application of the before evaluated suitable forming parameters with regard to forming force and rubber pad hardness. Repetitive forming iterations are conducted to provide information on geometric stability of the AM die with respect to the areas of highest contact stress, i.e. the blank holder area and, in particular, the drawing radius. Surface scans provide statistical information about manufacturing accuracy and any attrition of the additively manufactured tooling.

2.6 MEASURING DEVICE

The metrology system gom ATOS Core 200 is used to measure the 3d printed forming dies. The optical measurement of this system bases on the principle of photogrammetry to scan the topological parameters of an object. These data can be integrated subsequently into further analyses, such as the deformation measurement by gom ARAMIS. Both systems are available at the Centre for Smart Production Design Siegen (SmaPS) at the University of Siegen, where the present study was conducted.

The system has been validated by the manufacturer according to the technical guideline VDI 2634. The calibration parameters utilized for the present experiments are listed in Table 4.

Table 4: Calibration parameters of the optical metrology system gom ATOS core 200.

Parameter	***Value***	***Unit***
Ambient temperature	20.0	°C
Warm up time	15	minutes
Focal length	12.5	mm
Grey value compensation factor	0.08	-
Number of calibration points	1911	-
Nominal edge length of calibration plate (square type CP40-200)	250	mm

The calibration deviation was 0.052 pixel and thus under the maximum value of 0.100 pixel. The results of the projector calibration were a gap of 0.038 pixel in accordance to a maximum value of 0.250 pixel. The gom ATOS Core 200 measuring head is therefore reliable for the following measurement procedure.

The software for the measurement process is gom Scan 2019. For the measurement analysis, gom Correlate 2020 is used.

III. RESULTS

3.1 EMPIRICAL DETERMINATION OF PROCESS PARAMETERS

The experiments confirm the feasibility of operating AM tools in the female type RPF process for forming products from sheet metal of automotive body grade and thickness. For this study, the process parameters that are necessary to form a spherical dome geometry from DC03 sheet metal in the rubber pad forming process are determined in an empirical approach. Initially, the applied press force is increased successively by 25 kN steps in order to investigate the filling of the cavity throughout the rubber pad forming process. As a softer pad in general would reveal the advantages of a lower necessary process force for the RPF process, a 40 Shore polyurethane pad is initially utilized (see Figure 7). At a process force of 175 kN, full geometrical definition of the desired product shape is achieved without any changes by increasing press force. No wrinkles appeared despite the relatively soft rubber material.

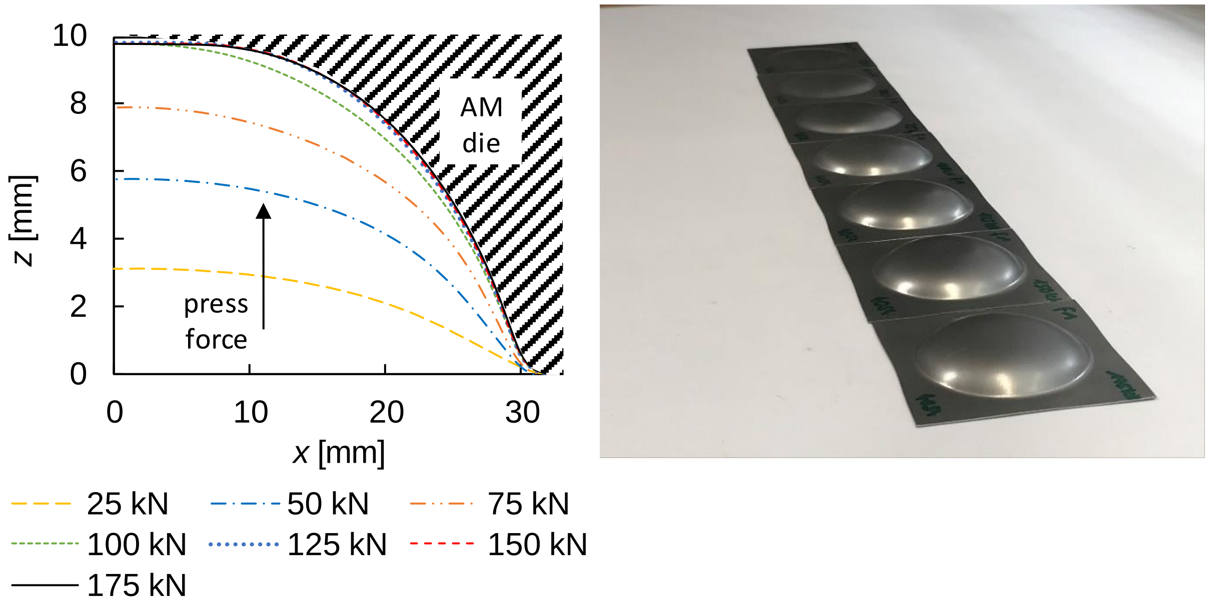

Figure 7: Results from the optically measured shapes of the formed pieces as a function of process parameters. A successive increase of process force shows the geometrical definition of the part in the rubber pad forming process. While the apex of the dome was reached after 100 kN, larger forces are required to calibrate the radius of the dome-shaped part.

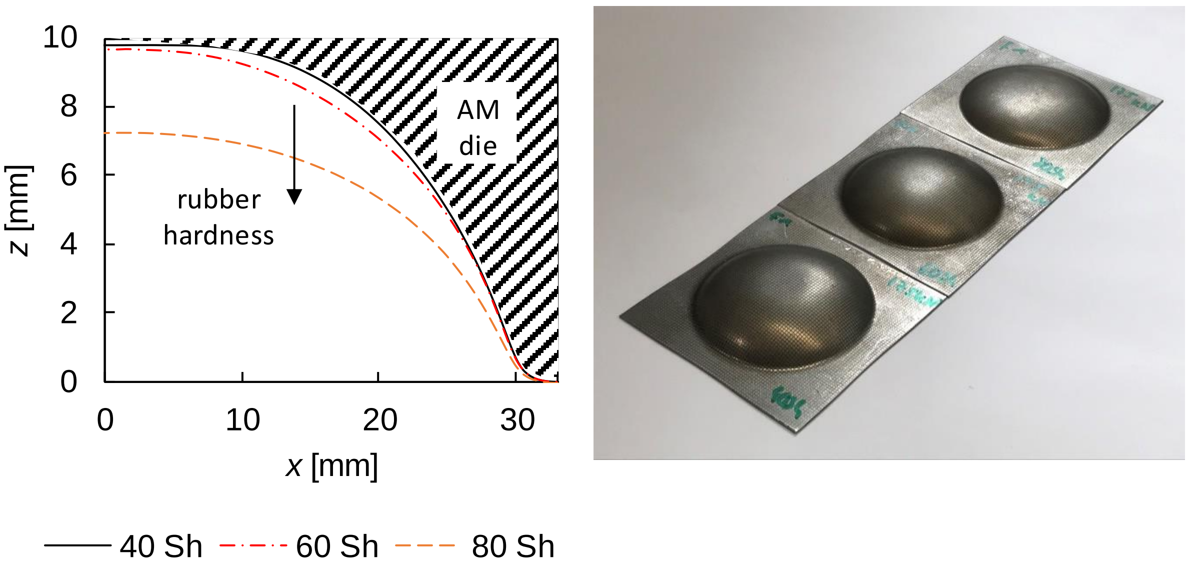

Figure 8: Results from the optically measured shapes of the formed pieces as a function of process parameters. Variation of shore hardness of the rubber pad, each at the same press force of 175 kN.

After reaching full process feasibility on the 40 Shore rubber pad, additional tests are performed on the 60 and 80 Shore hardness pads at the same press force of 175 kN (see Figure 8). Harder pads, in general, offer the opportunity to suppress wrinkles (Thiruvarudchelvan 2002) and are associated with higher durability (E.L Deladi 2006). The experiments demonstrate, that the cavity is filled incompletely by the harder rubber pads, thus higher process forces would be necessary if an operation of these pads was desirable.

3.2 SERIAL PRODUCTION OF SMALL BATCH SIZE

In addition, a batch size of 64 parts is formed in a sequence on a second, identical and unused AM tool from PLA. The afore mentioned empirical parameters of the RPF process are used throughout the series, i.e. 175 kN of forming force and 40 Shore-A rubber pad hardness. Within an exponential approach, the utilized die is scanned by the gom ATOS core system after zero up to 64 parts to evaluate the influence of any plastic deformation or attrition of the tool on the products.

The CAD file of the tooling is compared with the PLA die in its unused state (i.e. subsequently to additively manufacture) by an optical scan in Figure 9. The analysis indicates the distortion of the geometry. The highest shrinkage of the solid infill pattern indicates deviations at the radius inlet of the cavity of approximately 0.12 mm.

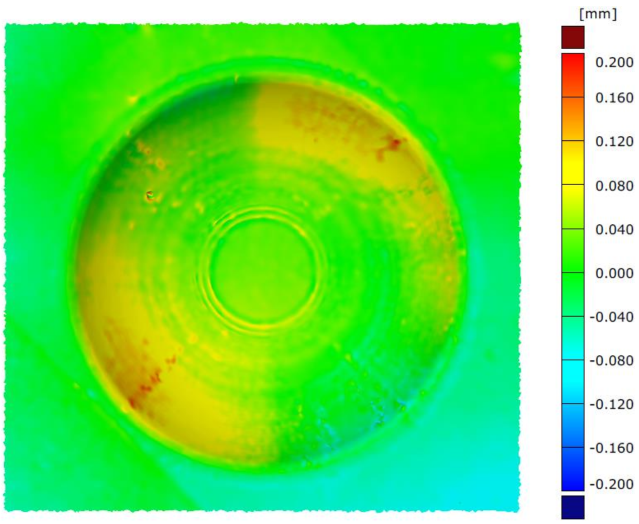

Figure 9: Spatial correlation comparing the CAD geometry and the unused die from PLA directly after its additive fabrication by FDM. Symmetric deviations of up to 0.12 mm are obtained within the tool cavity and related to thermal shrinkage of the fabrication method.

Even though shrinkage is common for FDM printed parts, since the cooling process lowers the specific volume, PLA reveals less shrinkage, compared to ABS and therefore better geometric accuracy (Rosli et al. 2020), (Abeykoon, Sri-Amphorn, and Fernando 2020).

After this initial comparison, the die is investigated after punch stroke one and 64 respectively. For this purpose, best-fit comparisons are carried out with the gom software. Figure 10 depicts the spatial deviation for the unused die and the worn dies.

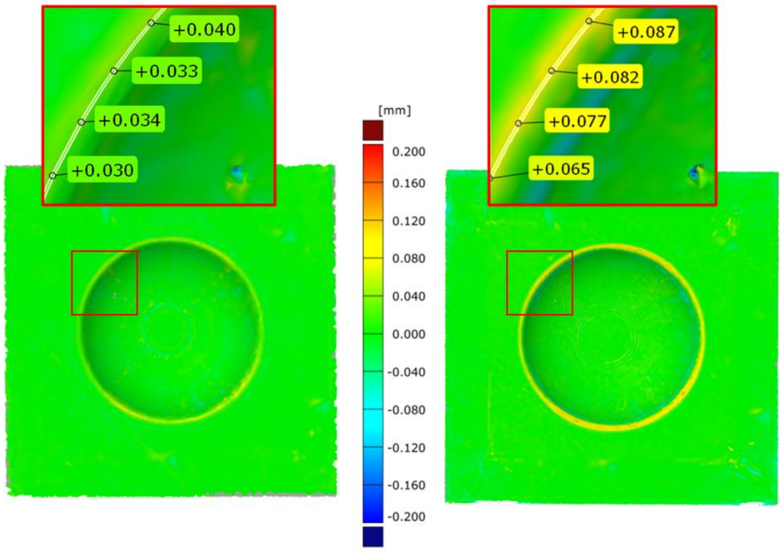

Figure 10: Optical surface correlation of the unused die subsequently to fabrication and of the die after the first (left) and the 64th press stroke (right). Top brackets indicate equidistant deviation flags at the radius inlet, which will be used for further statistical evaluation. By qualitative manners, the spatial deviation in the drawing radius of the PLA die increases over forming cycles.

A systematical circular deviation at the drawing radius can be observed, which most likely results from a permanent deformation and/or wear of the die material. By qualitative and quantitative means, this deviation increases over the number of press strokes and is therefore evaluated in a detailed statistical approach in the following section.

Following the same approach, the ejected blanks are examined up to 64 parts and each compared to the as-manufactured state of the tool surface. Figure 11 indicates the spatial deviation showing the first and the last blank part of the batch, which are correlated with the die surface.

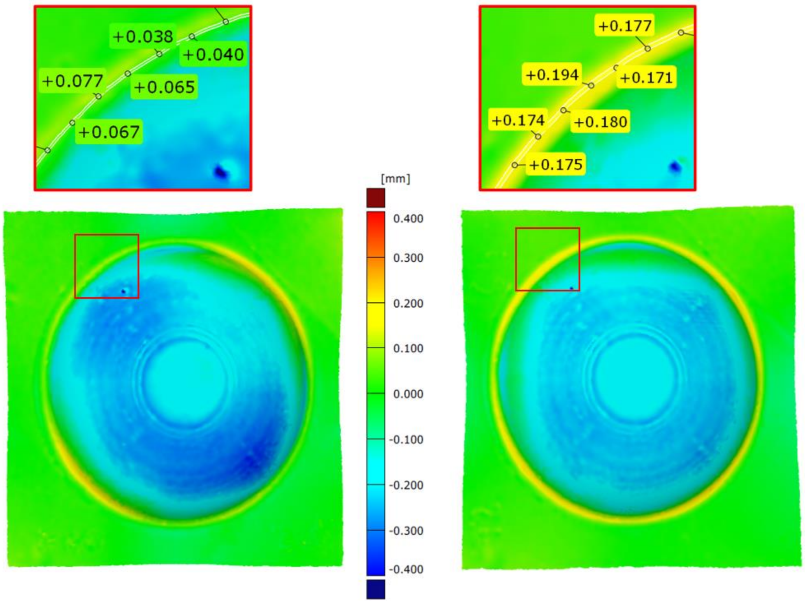

Figure 11: Optical surface correlation of the unused die subsequently to fabrication and of the first (left) and the 64th sheet metal part (right). Top brackets indicate equidistant deviation flags at the radius inlet, which will be used for further statistical evaluation. Over forming cycles, the spatial deviation in the drawing radius of the part increases accordingly to the deviations observed from the die.

Similar to Figure 10, the sheet metal part left hand side of Figure 11 indicates the surface of the part obtained from the first press stroke while the right image displays the deviation plot of a blank after 64 punches. By qualitative means, an increasing deviation over the batch can be stated at the floor radius from flange to dome. Highly concentrated contact pressures in this area are caused by the drawing process. Moreover, a deviation area within the tool cavity between die and sheet metal is caused by elastic springback and indicated by blue hues. From the plots, an average offset of 0.3 mm is obtained for springback.

3.3 Quality Assessment

3.3.1 Blanks

To evaluate the mechanical integrity of AM tools within a sheet metal drawing process in the context of a small batch size, a statistic evaluation for the blank parts is carried out. For this purpose, cutting planes are established with the help of the gom system to aggregate multiple measurements to obtain a statistic key figure system. The statistic values base on equidistant measurement points with a distance of 2.72 mm in circumference direction around the drawn cavity. This circle of measurement points is examined at the height of 0.3 mm above the flange level so the drawn radii of the formed blanks are intersected. The calculated spatial distance of the blank parts is correlated to the unused, as-manufactured die scan. The results from these metrological evaluations are presented in Figure 12.

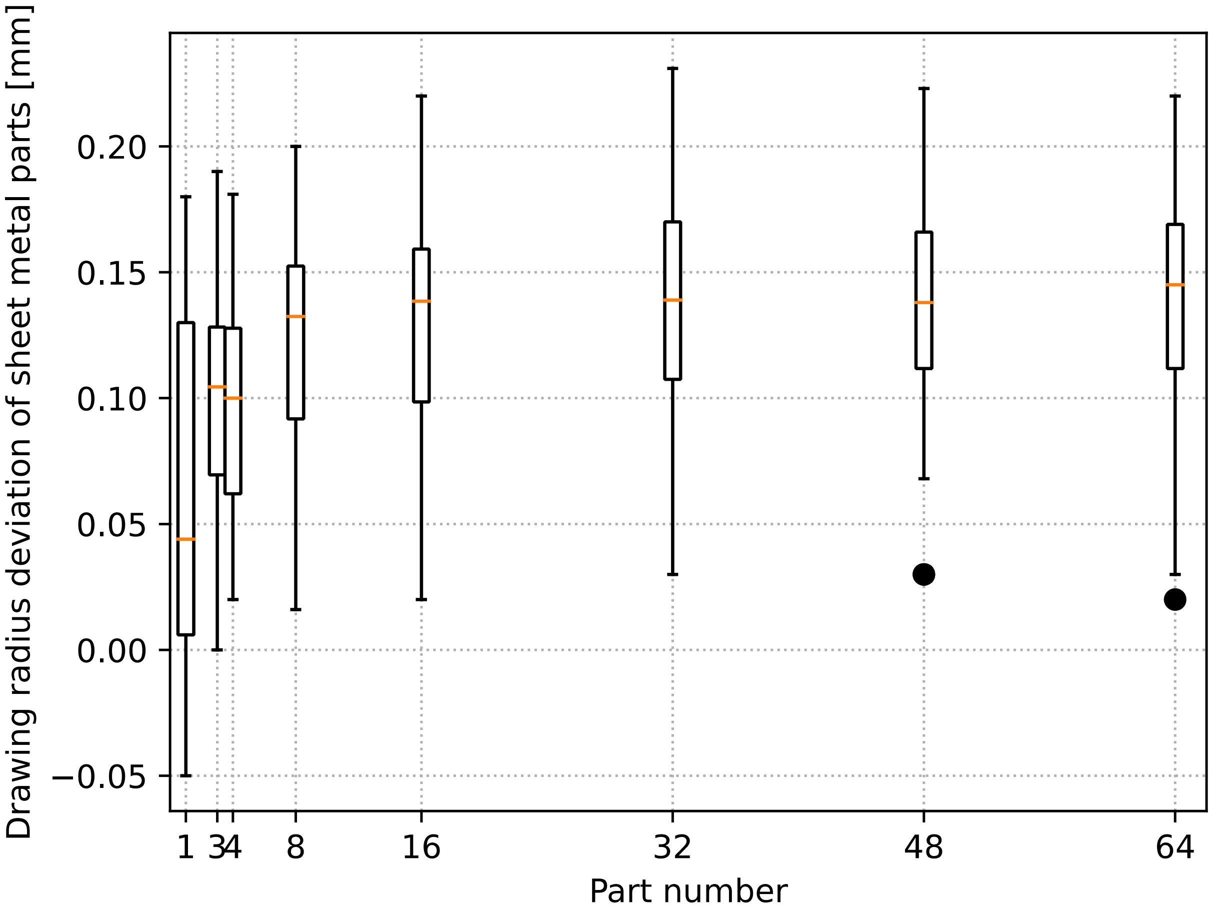

Figure 12: Spatial deviation within the drawing radius for comparing the parts produced by the AM-RPF process to the as-manufactured unused die. Statistical evaluation of a small batch series of metal parts indicates degressively increasing median deviations up to 0.15 mm, which asymptotically stabilize roughly at the 16th part.

In Figure 12, the median of the shape deviation initially strongly increases from the first part starting at 0.041 mm up to 0.103 mm at the third part. After that, the values of the median asymptotically converge towards a constant value of 0.15 mm.

3.3.2 Tool

Similar to the evaluation of the sheet metal parts, a quantitative evaluation is conducted for the die surface after representative strokes to ensure the similarity of the deformation in the drawing radius. The measurements are obtained from a cutting plane 0.3 mm above the flange level delivering a circular evaluation with equidistant points that describe the spatial deviation in between the unused die and its surface after each respective number of strokes (cf. Figure 10). Figure 13 visualizes the statistical examination of the optical measurements from the die throughout the production of the small batch series.

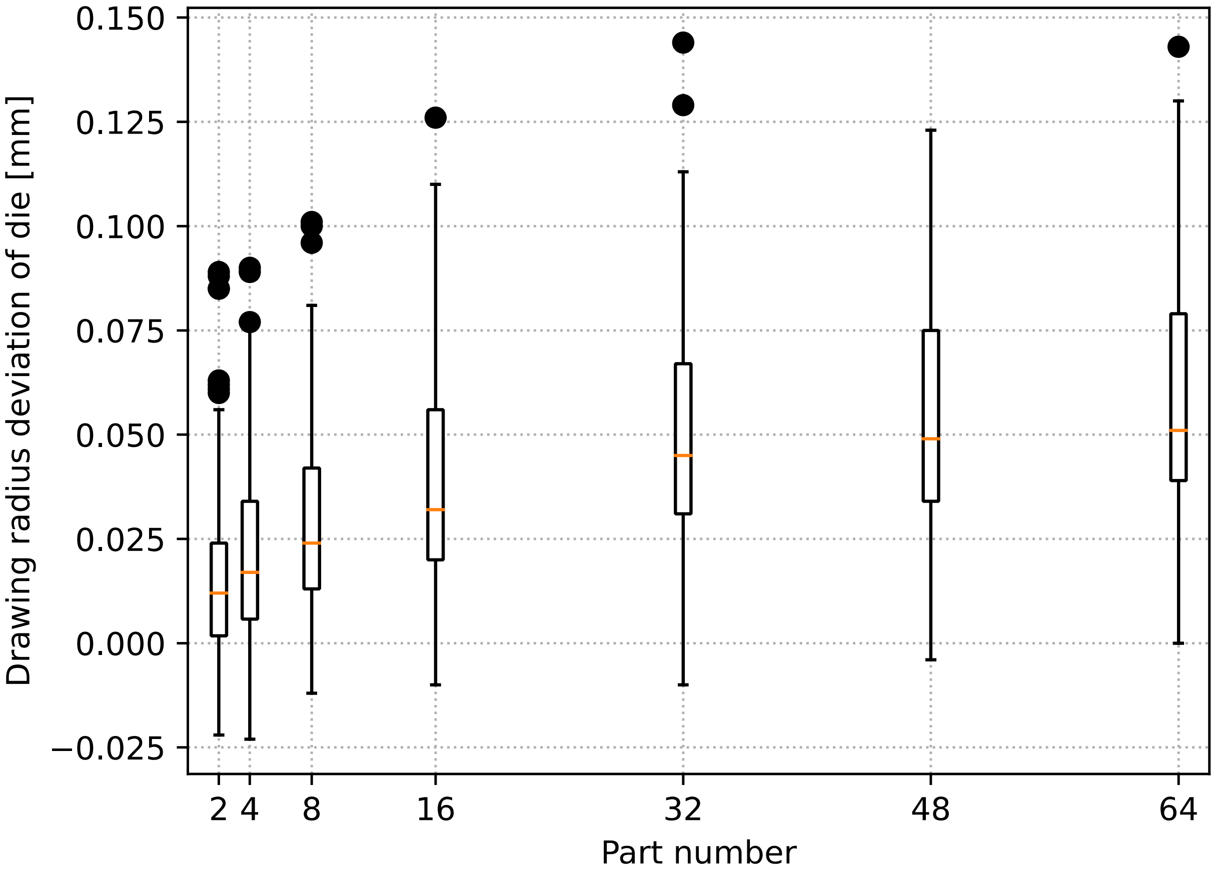

Figure 13: Spatial deviation within the drawing radius 0.3mm above flange plane. Comparison of the as-manufactured unused die to the die throughout the strokes of the AM-RPF process. Statistical evaluation of a small batch series of metal parts indicates degressively increasing deviations up to 0.05 mm.

For the medians of the optical scans of the die surface as a function of part number, a similar trend can be observed. Asymptotically reaching a deviation of 0.05 mm in median, the absolute values of the deviation are approximately three times smaller compared to the blanks. In contrast to sheet metal forming in conventional dies from tool steel, this observation can be explained by the large difference in the elastic moduli and yield strengths of the herein used polymer-based die in relation to the formed sheet metal blanks.

IV. DISCUSSION

The small batch series of sheet metal parts produced for the current study demonstrates the feasibility of the presented AM-RPF process. The major influences on the formation of geometry are demonstrated with regard to applied press force and rubber pad hardness. Due to the local contact pressure distribution caused by the forming operation, an early running in of the drawing radius of the die is observed, which is interpreted as initial plastic flattening of the comparably soft polymer material. With a degressive trend, the deformation stabilizes with the 16th part. In a use-case, this effect could be compensated by a larger drawing radius to equalize the peak of contact stress or even by metallic inserts, such as described by (Nakamura et al. 2020). The selected material PLA – being one of the most common polymers used in the FDM manufacturing process – shows suitable mechanical properties under compressive load, with regard to its elastic modulus as well as to its yield point. Comparable properties are also obtained from the compression tests on PETG, while the mechanical properties of ABS are rated as too weak for the current application. Moreover, PLA has revealed reasonable integrity to withstand the applied press force of 175 kN without breakage, even if heavily loaded areas like the drawing radius can potentially deform. Further research on higher batches and the material's wearing behavior when in repetitive sliding contact to metals would thus be rewarding to extrapolate the applicability of the considered process. Moreover, a preliminary experiment on a polyjetted material with considerably higher strength (Keyence AR-H1) of σ_y = 106 MPa resulted in die breakage after 90 kN press load in the presented AM-RPF process due to the material's brittleness. However, when considering a wider spectrum of available polyjetting materials, the general suitability of this AM process for forming tool manufacturing could be of interest.

Compared to conventional forming tools from steel, the elastic constant of the herein objected polymers is a hundredfold smaller. Therefore, springback compensation strategies are required for the purposeful design of drawing dies from polymer materials and should be considered for ongoing research. As obtained from the additive manufacture, a shape deviation of 0.12 mm is observed comparing the cavity of the die to its CAD model, which is explained by thermal distortion aspects of the FDM process. By incorporating models to describe the residual stresses, as described by (Li et al. 2018), thermal shrinkage due to the FDM fabrication process could be compensated. From the correlation of the optical surface scans of the formed sheet metal parts to the die in its state directly after fabrication, a uniform shape deviation of 0.3 mm is obtained and related to elastic springback of the part after release of press force. In the light of these results, the deviation caused by thermal distortion (0.12 mm) and the observed trend from the running in effect of the drawing edge (0.15 mm) could be improved. However, the main influence on deviation between CAD and product lies at the elastic springback of the sheet metal itself. Springback compensation strategies are well established for sheet metal forming (Takalkar and Babu 2018) and can be incorporated for future additively manufactured dies.

From an economical point of view, sheet metal forming in additively manufactured dies from polymers could be a rewarding approach for on-demand production of diverse product variants in smaller batch sizes. Conventional drawing tools from steel are costly, primarily due to the aspects of raw material prices for tool steel and therefore related to large and inflexible batches, exclusively. Taking the CAD volume of the die, i.e. 0.349 dm^3, as a basis, the resulting die costs are twice the price from conventional tool steel, then from PLA or PETG. Moreover, significantly higher fixed costs are related to the machinery of subtractive manufacturing techniques (drilling and milling machines, lathes etc.) compared to additive manufacturing. While the herein utilized 3D printer is located at the private client end, professional FDM machines, which deliver much shorter manufacturing cycles, still cost a fraction of professional subtractive manufacturing equipment. The rubber pad forming process, in particular, allows to save half of the geometry specific tooling, which is substituted by the elastomer (in this case: the stamp is omitted). Thus, the economical niche of small batches is considered worthy for the application of the approach presented in this study. Restricted availability within a modern production environment – related to optimized occupancy of expensive equipment – will further limit and delay the availability of any subtractive manufacturing facilities. Therefore, due to its lower fixed invest, 3D printing capacities will be faster and easier available for tool manufacture. In addition, tools from polymers weigh roughly a fifth of steel tooling which might be another advantage if potential and kinematic energy consumption related to the process cinematics are considered as well as transportation, equipping and storing processes. Concluding these aspects, 3D printed forming tools can potentially undercut the invest and lead time for conventional steel tools up to factor 10 and therefore be implemented for producing smaller batch sizes (Schuh et al. 2019).

V. CONCLUSIONS

Modern production environments are driving the demand for flexible and intelligent production technology, as customer-specific variants are increasingly required (Wang et al. 2017). Resource-efficient use of materials affects both the products and the manufacturing processes - but especially the tooling technology used for production when smaller batch sizes become more relevant. Instead of conventional subtractive methods, additive manufacturing techniques can be used to achieve an economical use of lighter and cheaper materials for tools. Compared to steel-based solutions, polymers offer the chance to reduce investment and mass of tooling technology. The fused deposition modelling (FDM) technology is an established process of additive manufacturing (AM), with which complex geometries can be implemented on low-cost production machines. Presently, the extent to which highly stressed forming tools can be manufactured from common 3D printing materials has only been investigated in a few exemplary approaches (Schuh et al. 2019). The main focus was on costly, unconventional or non-recyclable materials (Durgun 2015), concept studies (Schuh et al. 2020) or specific steel inserts at the highly stressed areas (Nakamura et al. 2020).

This paper investigates the suitability of a conventional PLA plastic as a material for an additive stretch forming die. Due to its bio-based structure and its possibilities for industrial composting (Durucan and Brown 2001; Musioł et al. 2016), a resource-saving approach for producing and potential recycling of forming tools for smaller batch sizes is suggested. The forming tools produced in this way are combined with rubber pad forming (RPF) since this process variant requires only one (positive or negative) instead of two shape-dedicated tool parts compared to deep drawing. The rubber pad forming process in additively manufactured plastic matrices (AM-RPF) is used as an example to produce and evaluate a small series of sheet metal parts. The tools were produced on a Creality Ender 3 Pro 3D printer and then tested in RPF. A 60 mm diameter dome is produced from a 0.7 mm thick DC03 type automotive body sheet metal in a series of 64 parts as a demonstrator. In addition to that, the influence of the force and rubber pad hardness on the produced geometry is investigated. Immediately

after the 3D printing and, further on, after an exponentially increasing number of press strokes, the PLA drawing die was measured using optical area scans and, likewise, the corresponding sheet metal parts. Therefore, a method for measuring the geometrical quality and accuracy of sheet metal products that are manufactured by additive manufacturing of forming tools is suggested.
The results show that additively manufactured dies from PLA plastic can be used to form conventional car body sheet metals, despite the high process forces involved in this manufacturing operation (17 metric tons press force). An initial flattening was observed at the drawing radius of the die, which is reflected in a form deviation in the radius of 0.15 mm in the manufactured sheet metal parts. Thermal distortion could be minimized during 3D printing of the die, so that the surface deviations in the cavity of the drawing die are at a maximum of 0.12 mm. The presented process demonstrates that forming tools can be produced from inexpensive, recyclable plastics by additive manufacturing. Combined with the RPF process, the shape-dedicated part of the entire tooling can be reduced, so that drawing tools are economically available even for the production of very small lot sizes.

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