

Performance of Polymer Additively Manufactured Tooling for Low-volume High Strength Steel Sheet Metal Parts

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ABSTRACT

Low-volume prototype tooling is a large expense in vehicle development. Often, these tools cost a similar amount to mass-production tooling despite the much shorter useful life. Much of this cost is associated with the precision machining needed to create the tool geometry. Additive manufacturing brings with it the ability to create complex geometries at or near the final part shape. When applied to metal forming tools, additive manufacturing has the potential to reduce the cost and lead time of tooling by reducing the machining time required for traditionally manufactured tools. This study investigates the performance of sheet metal forming tools made from different polymer additive manufacturing materials and processes through forming trials on 1.6 mm thick 590 MPa high-strength steel, comparing the tools and their manufactured parts to traditional hard steel tooling and parts produced thereon. Physical die trials show success in forming mass-production materials accurately and tool life adequate to support low-volume production. A modeling framework has also been developed to rapidly iterate on new materials for tool design and application to other sheet metal grades and gauges.

1. Introduction

The development of automobiles is an iterative process, involving design, analysis, and prototyping phases before new models enter into mass-production. The majority of mass-production vehicle structures consist of many individually formed sheet metal components, each formed by unique die sets. These mass-production die sets are typically made from hardened steel for longevity, allowing for 1,000-10,000's of parts before refurbishment. However, before mass-production tooling can be made, validation needs to be performed on prototype parts made on prototype tooling. Depending upon the grade and gauge of sheet metal used to make the stamped component, tooling used for prototyping these parts is typically made from machined steel or cast and machined zinc-aluminum alloys such as Kirksite or Zamak. Where the cost of mass-production die sets is amortized over the production volume of the vehicle, often consisting of multiple 100,000's of parts, the useful life of prototype tooling, which has a cost similar to that of mass-production tooling, may be less than 100 parts due to the small quantity of parts needed for development. Despite similar robustness and cost, prototype tooling has a much shorter useful life than mass-production tooling and is one of the

largest contributors to vehicle development cost.

This study investigates the ability to use Additive Manufacturing (AM) to create sheet metal forming tools that can create formed components equivalent to the same components formed on hard tooling with the ultimate objective of reducing the cost and lead time as compared to traditional hard tooling manufacturing methods.

2. Methods

2.1. Approach

This study endeavors to create parts of relevant sheet metal grade and gauge on AM tooling that match the forming strain and geometry of the same components formed using traditional hard tooling while understanding the toolset life as determined by deformation of the tools themselves. In order to obtain a common basis for comparison, the parts formed on the AM toolset are compared to parts formed on a steel toolset of identical geometry that was manufactured using traditional machining methods.

While metal AM processes are an obvious first choice for forming tools from a tool longevity perspective, material cost, process cost, post-processing time, and size envelopes inherent in current metal AM technology

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preclude metal AM as a viable alternative to traditional hard tooling manufacturing processes due to the required size of stamping dies and associated cost of the die sets. Instead, polymer AM processes are the focus of this research due to the lower overall cost of the parts they produce. Key challenges in successfully using polymer AM die sets for forming sheet metal components are managing the inherently lower yield strength and elastic modulus of the materials which impact part accuracy and tool longevity. If the tools are limited to low-volume production, as in prototype and service part production, tool longevity of polymer tools has been shown to be sufficient for thin gauge and/or low-grade alloys⁽¹⁾⁻⁽⁶⁾, but little research to date has investigated application to automotive-relevant gauges and grades.

Simulation is a key step in developing metal forming tools. A common assumption in metal forming simulation is the use of rigid tooling, which holds well when forming thin sheets of metal with steel dies. However, in switching from steel to polymer-based tooling, assumptions on negligible tool deflection and wear are no longer accurate. This study extends the authors' work⁽⁷⁾ on development of a modeling methodology that accounts for the elastic and plastic response of AM tooling during sheet metal stamping. The models not only accurately recreate tool behavior but serve as a basis for further exploration in using new AM materials and forming other grades and gauges of sheet metal.

2.2. Material Grade

All parts formed in this study were made from 1.6 mm thick High-Strength Steel 590 (HSS 590), a commonly used material for structural components in automobile designs. This material and gauge were selected because they represent a large portion of the Body-in-White (BIW) structure in modern unibody automotive construction while a majority of the remainder of a typical BIW consists of lower grade steel and aluminum sheet metals. For example, Fig. 1 shows the BIW composition of a 2021 Acura TLX⁽⁸⁾. HSS 590 comprises 35% of the BIW and when combined with lower grade steel and aluminum

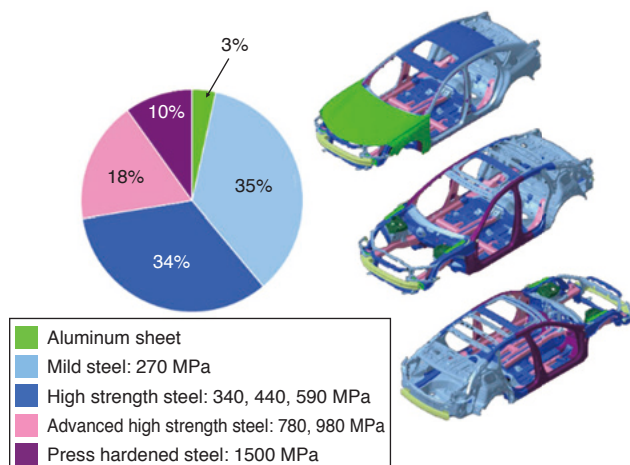


Fig. 1 Body-in-White sheet metal composition for 2021 Acura TLX

alloys, accounts for 90% of the BIW composition. If AM tools are capable of forming HSS 590 parts accurately and consistently, it is likely that such AM tools will also successfully form the lower-strength and thinner-gauge alloys as well.

2.3. AM Processes and Materials

This study investigates two different AM processes using two different materials to create a sheet metal forming toolset. The two processes are Big Area Additive Manufacturing (BAAM), developed by Cincinnati Incorporated and Oak Ridge National Lab, and Fused Deposition Modeling (FDM) on a Stratasys F900 system. Both systems provide unique capabilities that make them attractive for printing forming tools.

The BAAM system has a large build volume, up to $2.4 \times 6.1 \times 1.8$ m, and a deposition rate of approximately 45 kg/hour⁽⁹⁾ which makes it attractive for printing toolsets for large automotive components in a single build. However, the BAAM system requires a finish machining process to achieve the final tool geometry due to its low print resolution. While BAAM does not eliminate the machining step, finish machining of a net-shape polymer is faster than machining the same geometry from a billet of steel, as done for traditional tool manufacturing. In comparison, the FDM system has a smaller build envelop, up to $914 \times 610 \times 914$ mm⁽¹⁰⁾, but much finer resolution, allowing for the use of printed components directly from the machine.

Both the BAAM and FDM systems have a wide variety of available polymer feedstock, allowing a tool designer to select a material that has sufficient mechanical properties and wear characteristics while minimizing the cost of the print. For this study, glass fiber filled polycarbonate (GF-PC) was selected for use in the BAAM systems due to its strength, stiffness, and toughness. For FDM tooling, Nylon 12CF, a carbon fiber filled nylon (CF-Nylon), was selected for its high strength and stiffness.

2.4. AM Material Characterization

AM materials exhibit high anisotropy in material properties due to the presence of reinforcement fibers and layer-wise fabrication which results in the formation of voids inside the material as well as inhomogeneous temperature histories. In FDM fabrication processes, the reinforcement fibers get aligned along the direction of material deposition due to extrusion forces. This results in the material having tetragonal symmetry, with every layer orientation being orthogonal to the previous layer. In tetragonal materials, the directions X and Y, as well as XZ and YZ are equivalent due to the internal symmetry⁽⁷⁾⁻⁽¹¹⁾⁻⁽¹⁵⁾. Since BAAM is a similar AM technology as FDM but at a larger scale, these same observations are assumed to apply. Here, the X-Y plane is considered as the printing plane and Z is the build direction. Due to the complex properties of AM materials, it is important to characterize them properly to make accurate models during the die design process.

The AM materials were characterized using uniaxial tension test along three principal and three diagonal

Table 1 Elastic modulus and yield strength of tested AM materials

Material	Direction	E [GPa]	YS [MPa]
CF-Nylon	X	2.7	26.4
	Y	2.6	28.5
	Z	2.2	30.0
	XY	7.0	67.9
	XZ	1.6	20.2
	YZ	1.8	17.1
GF-PC	X	4.0	56.6
	Y	3.9	58.3
	Z	2.8	57.7
	XY	3.6	54.4
	XZ	3.0	44.1
	YZ	2.7	47.7

material directions. Table 1 shows the results of mechanical characterization of the CF-Nylon and GF-PC materials. High anisotropy is observed in both elastic modulus and yield strength in BAAM and FDM materials due to the presence and orientation of reinforcement fibers and voids from printing.

2.5. Forming Trial Procedure

Draw forming, in which a flat blank is held between a blank holder and die while a punch is used to draw the material into the die, is a common forming process in automotive mass-production. In this process, the blank holder force can be varied to adjust how material flows into the die and the amount of plastic deformation the blank undergoes during the forming process. A common draw forming tool geometry, the Universal Formability Testing (UFT) tool seen in Fig. 2, was used as a basis for comparison between the baseline steel tooling and different AM materials to evaluate formed part accuracy, die life, and tool cost. The UFT tool consists of four parts: the die insert, primary die, blank holder, and punch.

For this study, the full steel toolset was used to make

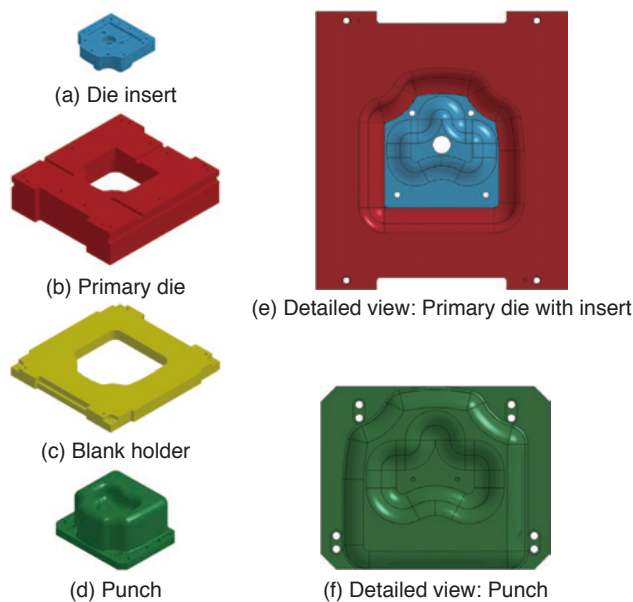


Fig. 2 Universal formability testing tool components

100 formed parts to serve as a component baseline, then an initial pilot study replaced the steel die insert with a 3D printed solid CF-Nylon insert. Upon successful completion of the pilot study, an additional forming trial was completed with a solid GF-PC AM toolset consisting of the UFT punch and combined primary die and insert.

All forming trials utilized a 300 ton servo press programmed with a crank slide motion. The blank holder force was maintained at 200 kN for the duration of the draw phase and the total draw depth was set at 65 mm with a speed of 14 strokes per minute. These parameters were chosen based on prior experience with the sheet metal material and relevance to mass-production manufacturing. For all trials, the HSS 590 blanks were lubricated with the same mass-production relevant water-based lubricant and a subset of blanks was etched through an electrochemical process for post-forming strain analysis. The etching process applies a regular pattern on the surface of the sheet metal with known spacing. By measuring the pattern spacing after forming, a discrete strain map can be generated. An example of the etch pattern used is shown in Fig. 3(b).

Components with etched patterns were scanned with an ARGUS system to quantify and compare post-forming strain at up to five locations on final components for comparison across all forming trials. The geometric accuracy of the parts was also measured using an ATOS 3D scanner. Both strain measurements and geometric measurements were compared to parts formed on the steel baseline toolset. Each toolset was also scanned using an ATOS 3D scanner before and after the forming trial to quantify tool change due to wear or deformation.

2.6. Modeling and Simulations

FEA simulations of the stamping process described in Section 2.5. were performed on the commercial software ABAQUS/Explicit. For stamping with the steel toolset, all the tools were modeled as rigid parts. The blank was meshed with 3 mm shell elements having 7 Gauss

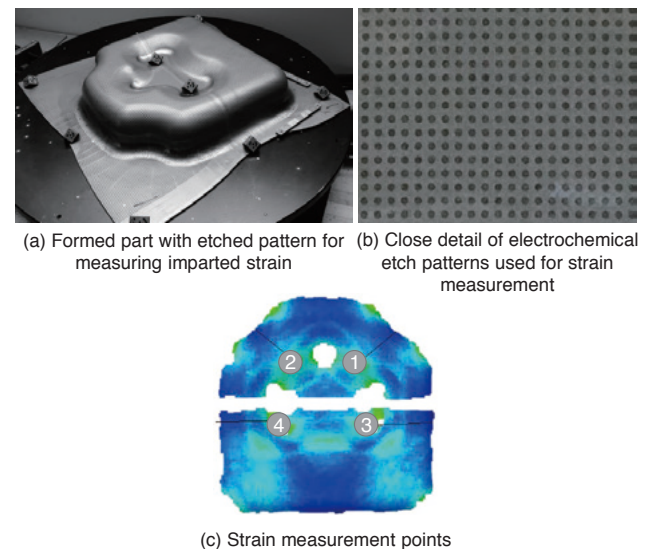


Fig. 3 Strain measurement of a steel tool-formed component

integration points through thickness. Element type and size were decided based on a mesh sensitivity analysis considering parameters such as the stresses and strains at critical locations. The die was fixed while the punch was given a displacement boundary condition with the same profile as in experiments. Preliminary forming simulations were first validated on the baseline trial. Stamped part strains and part thickness from simulations were compared with that from experiments to validate the simulation parameters.

For stamping simulations with polymer AM tools, the AM parts were modeled with 3 mm deformable linear tetrahedral elements as they are much softer than conventional steel tooling. To account for the tetragonal symmetry of AM materials with orthogonal printing orientation, orthotropic elastic material model along with von Mises yield function and isotropic hardening was used. Experimental testing data from Table 1 was used to calibrate the model coefficients⁽¹⁶⁾.

In all simulations in this study, a linear elasticity model, von Mises yield function, and isotropic hardening model were assumed for HSS 590 blank sheet. Hardening properties were obtained from uniaxial tension tests used for initial sheet metal characterization. Friction coefficient between the blank and tools was calibrated for steel tools as well as polymer tools by comparing the punch force vs. displacement data from experiments and simulations. A friction coefficient of 0.15 was found to be ideal for both steel and polymer tools.

Progressive plastic deformation of the AM tool parts due to repeated stamping was estimated through FEA simulations by a geometry update scheme. After each stamping simulation using ABAQUS/Explicit, an unloading simulation using ABAQUS/Standard was performed on the AM tooling to obtain the plastic deformation. The deformed tool shape along with the material state was used as the starting point for the next stamping simulation. This process was repeated until the plastic deformation reached saturation, and the additional plastic deformation was less than 5% from the previous stamping simulation.

Springback simulations were also performed on the formed part using ABAQUS/Standard. Final part shape after springback was compared with experiments as well as that from stamping simulation with steel tooling. Tool geometry after springback was also compared with experimental tool scans showing the plastic deformation of AM tooling post-stamping.

3. Experimental Results and Discussion

3.1. Steel Tool Baseline Trials

The steel toolset, including the punch, blank holder, primary die, and die insert were installed in the stamping press and formed a full 100-part trial using the HSS 590 material and the press parameters described in Section 2.4. Blanks #1, #15, #30, #40, #50, #60, #70, #80, #91, and #100 were etched for strain analysis. For brevity, only the top side average major strains and their standard deviations are shown in Table 2.

Table 2 Comparison of experimental part strain and simulated strain for the steel baseline UFT toolset

Strain	Strain region			
	1	2	3	4
Exp. average	16.5%	14.7%	12.4%	13.7%
Standard deviation	0.07%	1.41%	0.42%	0.92%
Simulation	18.1%	15.9%	10.4%	11.5%

3.1.1. Formed part strain measurements

A formed part ready for strain analysis is shown in Fig. 3(a). Due to the high forces and friction inherent in the forming process, the etched pattern in some regions of some parts was worn off of the blank and unable to provide strain data. However, all etched blanks did provide strain measurements in multiple key locations. Four key locations were selected from the strain maps of the baseline tool-formed components and used as points of comparison for parts formed using AM toolsets. An example of a strain map and regions of comparison are shown in Fig. 3(c). Strain comparison results are shown in Table 2 for the top side of the formed component. As exhibited by the standard deviation, a maximum of 1.41% at strain region 2, strain was consistent across the entire 100-part trial for the steel tool-formed parts. To compare the accuracy of the AM toolsets, the same strain regions are investigated and compared to the range of strain values within ± 3 standard deviations ($\pm 3\sigma$) of the average strain of a particular region on the steel tool-formed baseline components. If the average strain of a part formed on an AM tool falls within this region, it indicates that it is within the expected variation of strain induced by a traditionally made toolset.

Since the steel die is considered the baseline for comparison of AM die sets, ATOS scans of the formed parts are compared to AM tool-formed parts in forthcoming sections. The ATOS scan gives a 3D measurement of the final part and is used to compare draw depth and overall shape profile in the drawn portion of the components.

3.1.2. Simulation and comparison

Stamped part strains and part thickness from simulations were compared with that from experiments as shown in Table 2 to validate the simulation parameters. Strains for all four regions match the average experimental values within 2.2%, indicating that the baseline simulation has sufficient accuracy for examining the effects of changing the properties of the forming tools. This maximum deviation of the baseline tool simulation will be used as a point of comparison for the accuracy of simulated AM toolsets.

3.2. CF-Nylon Tool Trials

Prior to printing a full AM die set, the insert portion of the UFT die was printed from CF-Nylon to prove concept viability. The insert was printed fully-dense to maximize

part strength as shown in Fig. 4. Aside from the insert, the punch, blank holder, and primary die were all the same steel UFT components used in the baseline trial.

The steel tool components and the CF-Nylon die insert were installed in the stamping press and formed a full 100-part trial using the HSS 590 material and the press parameters described in Section 2.5. Blanks #5, #40, #99, and #100 were etched for strain analysis.

3.2.1. CF-Nylon part accuracy

Part #5 and #100 were oriented such that the etching patterns and strain analysis was performed on the top surface. The strain measurements are summarized in Table 3. For measurement regions 1-4, the average strain data are within 2.3% of the same regions on the steel tool-formed baseline components. For strain regions 1, 2, and 4, these fall within $\pm 3\sigma$ of the baseline components, indicating that parts formed with the CF-Nylon insert are comparable to the parts formed on a complete steel die set. The consistency of strain measurements over the 100-part forming trial is also comparable to that of the measurements of the steel tool-formed components, with standard deviations between 0.14% and 0.37%, similar to the range of standard deviation observed in the baseline components, 0.07% to 1.41%. The similar strain levels and similar consistency of the parts as compared with those formed on the steel toolset indicate that a solid CF-Nylon insert is an acceptable choice from a part accuracy perspective.

Since the CF-Nylon insert was intended as a quick verification of the viability of AM forming tools, individual parts were not scanned via ATOS for a geometry comparison with the baseline steel tool-formed parts.

3.2.2. CF-Nylon tool geometry

The CF-Nylon insert performed well on the full 100-part forming trial and a second geometry scan was completed to quantify the overall deformation of the tool. Figure 5 shows the comparison of the pre- and post-trial geometry scans. Deformation is concentrated at the corners of the insert with the maximum occurring at the front protrusion, or “nose,” of the insert with the maximum deformation of 0.259 mm. Due to the lack of plastic debris observed during the forming trial and absence of scratches on the insert, this deformation is believed to be due solely

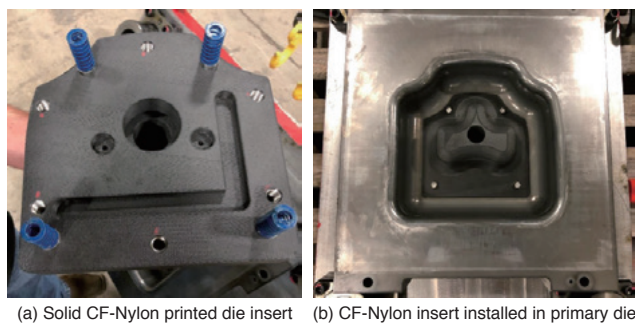


Fig. 4 CF-Nylon die insert

Table 3 Comparison of experimental part strain and simulated strain for the CF-Nylon insert with steel primary die

Strain	Strain region			
	1	2	3	4
Exp. average	16.6%	17.0%	10.6%	12.8%
Standard deviation	0.14%	0.37%	0.32%	0.18%
Simulation	15.8%	16.3%	11.8%	12.3%

to plastic deformation due to the compressive forces from contact with the blanks during forming.

3.2.3. CF-Nylon simulation and comparison

Figure 6 shows the cumulative plastic deformation from simulation compared with experiment. It is observed that the highest amount of tool deformation occurs in the very first stamping pass and the cumulative deformation reaches a steady state value within the first 5 passes. Additionally, the simulated part strain closely matches that measured from the experimental trials as seen in Table 3.

Simulated part strain of components formed using the CF-Nylon insert have a maximum absolute deviation of 1.20% from the average measured strain in region 3, as shown in Table 3. This is less than the simulation

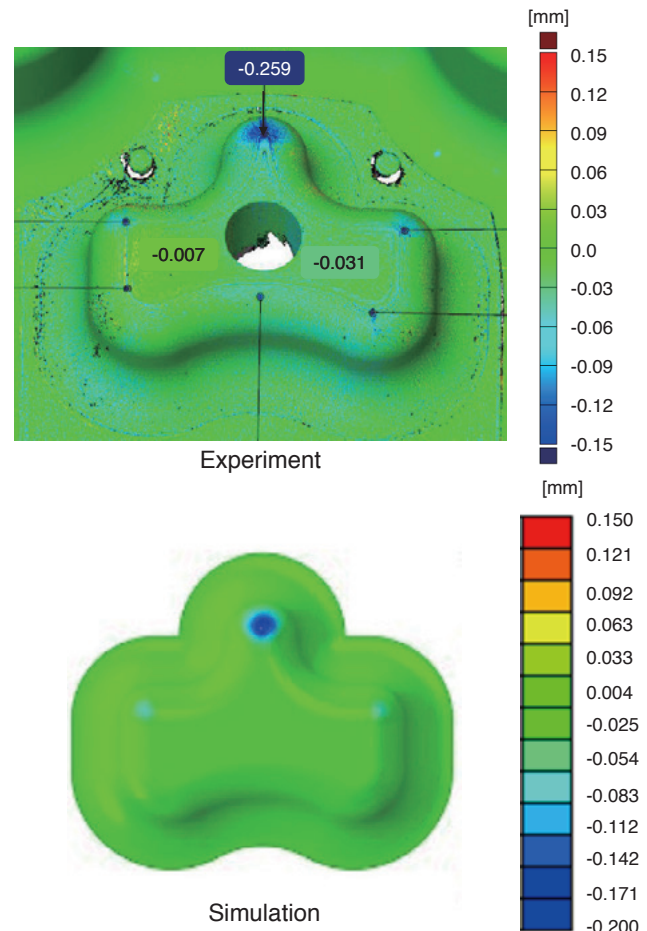


Fig. 5 Experimentally determined and simulated deformation in the CF-Nylon insert

deviation of the rigid tool simulation used in the baseline analysis, indicating that the model is accurately capturing the key behaviors relevant for using deformable AM tools.

3.3. GF-PC Tool Trials

A BAAM system was utilized to print a solid UFT die with integrated insert and a matching punch from GF-PC. Due to the size of the tools relative to the BAAM system, solid blocks were printed and machined to final dimensions as seen in Fig. 7. The insert and punch were installed with the steel blank holder for the UFT toolset in preparation for the forming trials. Similar to the previous forming trials, 100 sheet metal parts were formed using the GF-PC BAAM printed tool. Parts #1, #15, #30, #40, #50, #60, #70, #80, #90, and #100 were etched for strain analysis and were also scanned for geometry measurements.

3.3.1. GF-PC part accuracy

The etched patterns on the GF-PC formed components on regions 1-4 provide strain values seen in Table 4. These strains are lower than the strains exhibited by the same regions on both the steel baseline tool and CF-Nylon insert formed components. The maximum absolute deviation between the GF-PC average strain and that of the baseline components is 4.8% at region 1 while the strains at both regions 2 and 4 are 2.9% lower than their respective average values on the baseline components. This indicates that the material was not stretched as much during the forming operation with the GF-PC toolset as

Table 4 Comparison of experimental part strain and simulated strain for the GF-PC UFT toolset

Strain	Strain region			
	1	2	3	4
Exp. average	11.7%	11.8%	10.9%	10.8%
Standard deviation	0.61%	0.64%	1.61%	0.15%
Simulation	12.8%	13.7%	10.7%	10.6%

it was when using the other toolsets. Despite the reduced draw depth and resulting reduced strain levels, the standard deviation over the forming trial is 1.61%, similar to that of the baseline and CF-Nylon insert trials, showing that the GF-PC toolset does produce consistent components.

The difference between the parts from GF-PC tool compared to the steel tool baseline showed a much greater deviation than the part-to-part change during the GF-PC trial. A difference of approximately 1.5 to 2.2 mm was observed in the GF-PC part #1 vs. steel tool part #1 within the body of the part, as seen in Fig. 8. This is believed to be due to increased deflection of the AM tools due to the lower elastic modulus of the GF-PC material as compared to steel. The reduced draw depth is believed to be the cause of the lower strains, as compared to the steel baseline formed parts, measured in the formed parts, shown in Table 4.

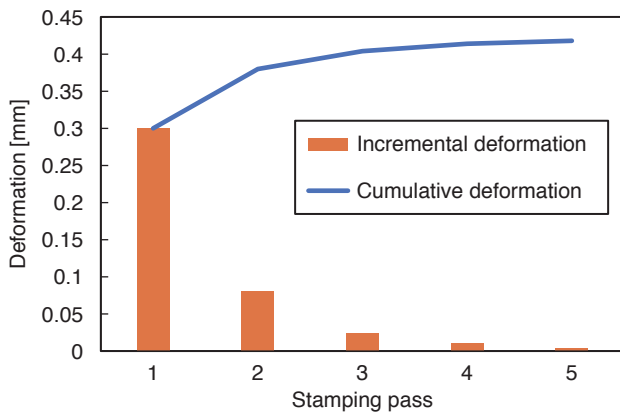
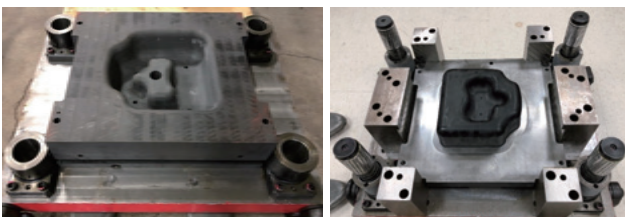


Fig. 6 Cumulative deformation from FEA of CF-Nylon insert over repeated part stampings



(a) Solid GF-PC printed die (b) Solid GF-PC printed punch

Fig. 7 Solid GF-PC die and punch

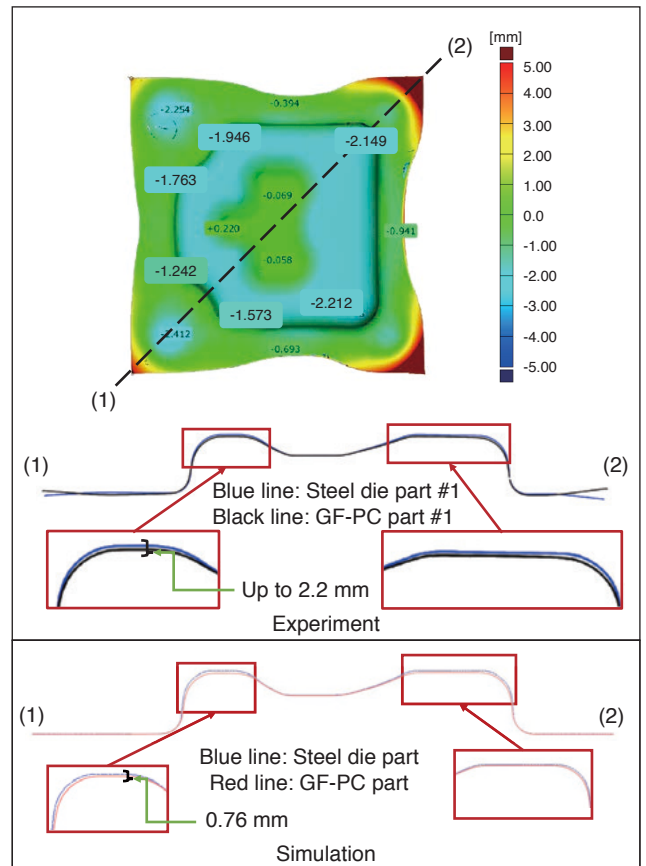


Fig. 8 Draw deviation between steel tool-formed part #1 and GF-PC tool formed-part #1

3.3.2. GF-PC tool geometry

The GF-PC die and punch were ATOS scanned before and after the forming trials. The pre- and post-trial scans were compared to each other to determine the amount of deformation incurred over the trial. The comparison shows a maximum deviation of 0.158 mm in the pre- to post-trial comparison occurring at the tool nose where maximum load occurs, as seen in Fig. 9. This is approximately half of the deformation observed in the CF-Nylon insert in the same region, indicating that this toolset could likely form many more components.

3.3.3. GF-PC simulation and comparison

As seen in Table 4, simulated part strains match well with those from experiments, with a maximum deviation of -1.90% at region 2. The model also captures the generally reduced strain in the key regions of the GF-PC formed components as compared to baseline parts. This indicates that, like the CF-Nylon insert simulation, the model has sufficient detail to account for the role of a deformable tool in the forming process.

Maximum deviation of 0.76 mm was found between parts stamped using steel vs. GF-PC tools after the springback simulation on the blank, shown in Fig. 8. This deviation is smaller than that found experimentally, up to

2.2 mm, which could be due to the lack of a sophisticated blank material model which would require additional testing to calibrate. Accurate prediction of springback was not considered to be a major goal of this study.

The simulation was also able to accurately capture the deformation of the GF-PC toolset. As shown in Fig. 9, the simulated die exhibits a deformation of 0.130 mm in the nose region of the insert, the same region in which the GF-PC tool exhibited a 0.158 mm deviation from its pre-trial geometry. This indicates that the yield criteria used for the AM material and the stresses generated in the model accurately reflect those experienced during the forming trials.

4. Performance Comparison

By comparing the performance of the AM die sets to each other, a viable approach for using polymer AM tooling for low-volume applications can be developed. In terms of overall durability, the solid CF-Nylon insert and solid GF-PC tools set are still usable forming tools after the initial 100-part trial. The maximum deformations of 0.26 mm and 0.16 mm exhibited by the CF-Nylon insert and GF-PC die, respectively, are not substantial enough to merit refurbishment or reprinting of the tool before forming additional components. Further, FEA simulations indicate that both tools accumulate a majority of their deformation while forming the first few parts. This is also consistent with findings in the broader literature⁽⁴⁾, indicating that both tools are able to accurately form several more parts beyond the initial 100-part trial. The observed lack of plastic particles during the trials and accuracy of the FEA model deformation indicate that plastic deformation of the AM material is the dominate mode as opposed to wear, the physical removal of the polymer surface by abrasion by or adhesion to the sheet metal. These findings indicate that the polymers used in these two AM tools are sufficiently strong and durable, thus further suggesting that non-reinforced polymers may also be viable options for AM tools, another avenue for cost reduction potential.

While AM material strength may be reduced, there is a limitation on minimum ductility. A low strain to failure for a given AM material may lead to tool fracture if the yield stress is locally exceeded where a more ductile material may be able to withstand minor deformation. With this in mind, when selecting an AM material for a sheet metal tool, strain to failure is a more critical material property than overall strength. Since each forming application will have unique stress and strain demands on the tools due to their unique geometry and grade and gauge of sheet metal, specific values for these properties cannot be provided from this study, however, this research shows that an FEA forming simulation that accounts for deformable tools provides a good indication of the stresses and strains that the tool will ultimately experience and can be used as a starting point in material selection.

In comparing the formed parts to those formed by the baseline steel UFT tool, the primary metric is the overall draw depth. The GF-PC toolset showed a global draw

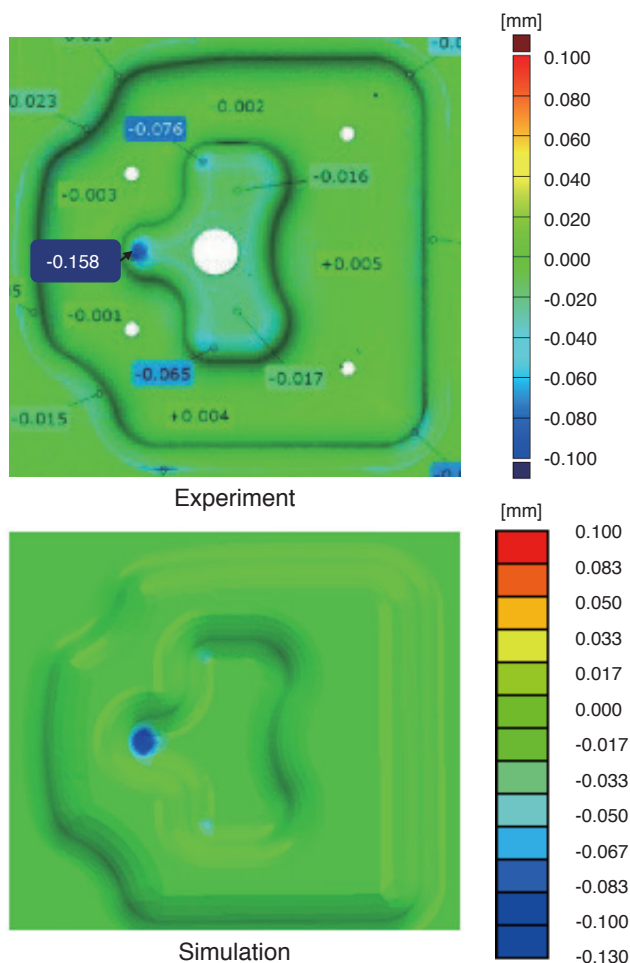


Fig. 9 Measured and simulated deformation comparison for GF-PC die

reduction of approximately 2 mm in the finished parts. Since the press stroke was the same in all trials, this draw depth deficit is due to elastic deformation of the punch and die themselves. This is a consequence of the lower elastic modulus of the GF-PC material (≤ 4 GPa) as compared to the steel UFT tool (200 GPa). This deviation is consistent across the entire GF-PC part run. One approach to remedy this would be to program a deeper draw into the press to account for elastic die deformation.

The imparted strain for finished sheet metal parts is compared for the AM tool-formed parts and baseline steel tool-formed parts. Where Tables 2, 3, and 4 compare the individual strain points for each tool, a higher-level analysis is performed by considering the average of strain over multiple parts for points 1-4 and determining if they fall within $\pm 3\sigma$ of the respective points on the baseline steel tool-formed parts. The average part strains for all measured regions are compared in Fig. 10 with error bars defined by $\pm 3\sigma$ for each region of each toolset's respective parts. As shown in Tables 2 and 3 and Fig. 10, parts formed with the CF-Nylon insert exhibit average strains falling within $\pm 3\sigma$ of the average strain in the steel-formed parts for all four locations. The solid GF-PC toolset exhibits average strains falling within $\pm 3\sigma$ of the average strain in the steel-formed parts for three out of four locations. This deviation is likely due to the reduced global draw depth; increasing the draw depth to better match that of the baseline components would likely bring the average strain measurements of all four regions within the standard deviations measured for the baseline components.

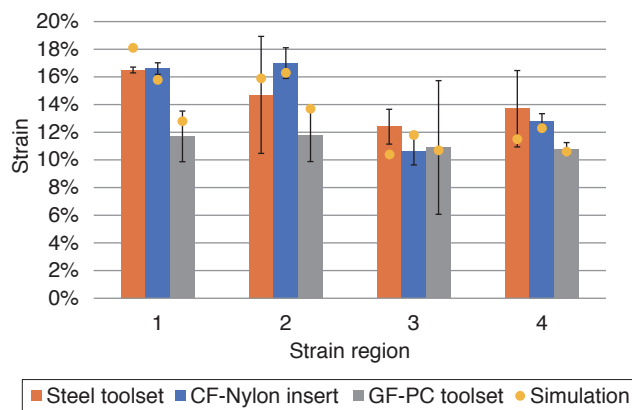


Fig. 10 Strain comparisons of parts formed on AM toolsets and their respective simulated strains

5. Conclusions

The die trials in this study have shown that polymer AM tools are capable of forming relevant grades and gauges of automotive sheet metal at volumes appropriate for prototyping. Part strains are consistent across the entire run for both AM toolsets and deviate less than 3% from those on the baseline components for all of the strain

comparison regions on the CF-Nylon toolset-formed components and three out of four regions on the GF-PC toolset-formed components. Solid AM polymer tools perform well in terms of tool longevity and part accuracy. Both CF-Nylon and GF-PC materials have sufficient strength for forming applications as demonstrated by the minimal wear accumulated over the forming trials. It is noted that the lower stiffness of polymer dies does result in an effectively reduced draw depth in the finished parts, though this can likely be remedied through increasing the draw depth of the press stroke or increasing the stiffness of the AM toolset itself.

The modeling methodologies developed to incorporate deformable die geometries accurately model the strains induced in the formed parts, predict final part deviation due to reduced tool stiffness, and predict the deformation accumulated in the toolsets. The demonstrated simulations will serve as useful framework in designing future AM die sets and performing virtual investigations on the suitability of AM for applications with more demanding geometries, different sheet metal grades, or thicker gauge materials. Whether the ultimate application for polymer AM tooling is in full die sets or inserts in larger traditionally constructed tools, there are large cost savings in low-volume tooling enabled by this agile tooling concept.

References

- (1) Schuh, G., Bergweiler, G., Fiedler, F., Bickendorf, P., Colag, C.: A Review on Flexible Forming of Sheet Metal Parts, IEEE Int. Conf. Ind. Eng. Eng. Manag., p. 1221-1225, (2019)
- (2) Hahnlen, R.: Application Space of Additive Manufacturing in the Automotive Industry, CAR Industry Briefing: Accelerating Additive Manuf. to Meet Future Mobility Needs, (2020)
- (3) Hahnlen, R., Hoffman, B.: Additively Manufactured Forming Tools for Low Volume Production, EWI Forming Center Workshop on Adv. Sheet Metal Forming Technol., (2020)
- (4) Schuh, G., Bergweiler, G., Bickendorf, P., Fiedler, F., Colag, C.: Sheet metal forming using additively manufactured polymer tools, Procedia CIRP, Vol. 93, p. 20-25, (2020)
- (5) Junk, S., Wagner, R., Tränkle, M., Côté, S.: Rapid Tooling in Metal Forming Processes using 3D-printed Tools, Proc. 5th Int. Conf. on Adv. Res. and Rapid Prototyping, p. 405-408, (2012)
- (6) Park, Y., Colton, J. S.: Failure analysis of rapid prototyped tooling in sheet metal forming - Cylindrical cup drawing, J. Manuf. Sci. Eng. Trans. ASME, Vol. 127, No. 1, p. 126-137, (2005)
- (7) Athale, M., Park, T., Hahnlen, R., Pourboghra, F.: Experimental characterization and finite element simulation of FDM 3D printed polymer composite tooling for sheet metal stamping, Int. J. Adv. Manuf. Technol., Vol. 121, p. 6973-6989, (2022)
- (8) https://www.steel.org/wp-content/uploads/2021/06/GDIS-2021-_Track-1_05_Lucas_-Honda-Acura-TLX.pdf

- (9) <https://additivemanufacturing.com/2015/10/17/ci-baam-system-has-fabtech-covered-by-land-sea-and-air/>
- (10) <https://www.stratasys.com/en/3d-printers/printer-catalog/fdm-printers/f900-printer/>
- (11) Zou, R., Xia, Y., Liu, S., Hu, P., Hou, W., Hu, Q., Shan, C.: Isotropic and anisotropic elasticity and yielding of 3D printed material, *Comp. Part B: Eng.*, Vol. 99, p. 506-513, (2016)
- (12) Dizon, J. R. C., Espera, A. H., Jr., Chen, Q., Advincula, R. C.: Mechanical characterization of 3D-printed polymers, *Additive Manf.*, Vol. 20, p. 44-67, (2018)
- (13) Penumakala, P. K., Santo, J., Thomas, A.: A critical review on the fused deposition modeling of thermoplastic polymer composites, *Comp. Part B: Eng.*, Vol. 201, 108336, (2020)
- (14) Biswas, P., Guessasma, S., Li, J.: Numerical prediction of orthotropic elastic properties of 3D-printed materials using micro-CT and representative volume element, *Acta Mech*, Vol. 231, p. 503-516, (2020)
- (15) Ziemian, C., Sharma, M., Ziemian, S.: Anisotropic Mechanical Properties of ABS Parts Fabricated by Fused Deposition Modelling, *Mechanical Engineering, InTech*, p. 159-180, (2012)
- (16) Park, T., Chung, K.: Non-associated flow rule with symmetric stiffness modulus for isotropic-kinematic hardening and its application for earing in circular cup drawing, *International Journal of Solids and Structures*, Vol. 49, No. 25, p. 3582-3593, (2012)

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