FUSED FILAMENT FABRICATION PRINTING FOR ACCELERATED PRODUCT DEVELOPMENT AND LOW VOLUME SERIES PRODUCTION

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Abstract

Advancements in materials and processes for additive manufacturing are bringing us closer to realizing the promise of accelerated product development and cost effective low volume manufacture with 3D printed structural thermoplastic parts. Resin suppliers continue to develop new, tailor-made materials for additive manufacturing processes. In parallel, improvements in manufacturing technology is delivering faster, more cost-effective and more accurate manufacturing processes. Combined, this results in the potential for 3D printed functional thermoplastic parts that can compete with traditional injection molding processes in both cost and performance.

This paper will highlight the obstacles and present solutions to realize accelerated product development through additive manufacturing of structural thermoplastic parts. We will explore two pathways to realize speed and cost savings for different volumes of produced parts. One approach is to use 3D printed components as prototypes in the product development process for injection molded parts, leading to lower cost and lead times. The second approach is the complete replacement of injection molded parts by 3D printed parts. Test data and case studies will be presented.

Background

As additive manufacturing technologies mature, adoption across industry sectors is increasing which is driving demand for broader applications of 3D printed parts. Within the spectrum of additive manufacturing technologies there are a multitude of different processes available to meet different application requirements. The range of resulting components extends from purely visual objects to functional structural components for low volume automotive applications like the one highlighted later in this paper.

Compared to metal 3D printing there are a number of possible additive manufacturing processes thanks to the relatively low process temperatures and ease of material handling of thermoplastic resins. Some of the most common technologies found are the Selective Laser Sintering process (SLS), where plastic resin powder is bound together using a laser and Stereolithography (SLA) where UV radiation is used to solidify a reactive photochemical. Another plastic additive manufacturing technology gaining traction in the market is the Multi Jet Fusion process from HP (MJF). In this process, a curing agent is selectively applied to a powder bed fusing the targeted particles together and building the workpiece up layer by layer. Given the ability to incorporate larger size and percentages of reinforcing materials, the FFF (Fused Filament Fabrication) process, in which an extrusion unit is used to place material strand by strand on a sheet, is of particular interest to those seeking to displace traditional injection molded parts. All processes highlighted above are characterized by a layered structure.

There is currently a broad range of commercially available materials for 3D printing of plastics. These include classic high-performance polymers such as PLA, PA, PP, PEEK and some more special materials such as PAEK or PEI. These resins offer acceptable stiffness, strength and heat resistance for many industrial applications. The specific application requirements will guide the user to select from these available materials. As noted above, in the FFF and SLS processes, fiber-reinforced materials can be used, which significantly improves the mechanical properties of the produced parts. The reinforcing materials used here are typically carbon fiber and glass fiber. Current developments in the field of material development are mainly focused on creating a homogeneous structure in the printing process.

For 3D printing applications we can segment prototyping into three main categories. These are classified according to the achievable mechanical or thermal performance. Those categories are dimensional, mock-up and functional. The intention of dimensional prototypes is to make geometric dimensions visible in real life. The mechanical performance is not relevant. For mock-up prototypes on the other hand, the mechanical performance is relevant but not critical, since there won't be ultimate load tests for those prototypes. Functional prototypes fulfill every requirement, both dimensional and mechanical. Those qualities make them suitable for small series application, as well. An example of a fully functional 3D printed component is a roof console from BMW, see Figure 1.

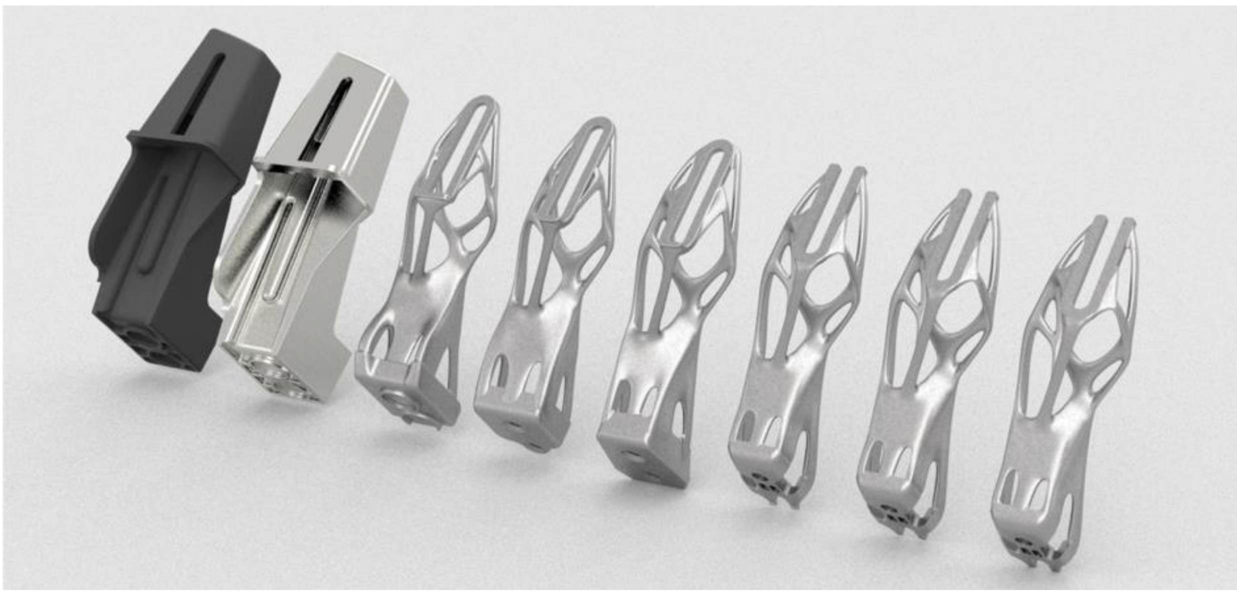


Figure 1: 3D printed Roof Console of a BMW i8 (3D Grenzenlos Magazin, 2018) (Lehmann&Voss&Co. KG, 2019)

Contrast of Injection Molding Development Process and Additive Manufacturing Development process with FFF Technology

Thanks to continuous advances in additive manufacturing processes we are closer than ever to realizing the promise of 3D printed parts replacing injection molding parts in series production applications. Given that the use of short fiber reinforced materials is very common in the industry (Schmid, 2015), the FFF or the SLS process should provide a natural platform to transition from injection molding to additive manufacturing of structural thermoplastics. Here, however, there are challenges due to different product development sequences.

In order to compare injection molded parts with 3D printed parts, we must first start with an analysis of the expected as processed material performance properties. Fundamentally, to achieve a printed part with similar dimensions (e.g. wall thickness, radii, geometry) as an injection molded part, you must be able to achieve equivalent material properties in that design space. Comparing data published by materials suppliers (shown in Figure 2) we see the relative material performance when injection molding as compared to additive manufacturing of filled and unfilled polyamide materials. For filled and unfilled materials, the FFF technology achieves comparable mechanical properties as compared to the reference technology Injection Molding (IM). In the case of the SLS processed material, we see significant drop in mechanical properties in both filled and unfilled states as compared to the IM reference. In the Multijet process, even when considering the limitation of unfilled resins, the mechanical properties fall well short of the injection molded reference injection molded material. Given our goals, this data makes it clear that FFF technology offers the best potential of displacing IM parts with equivalent performance 3D printed parts.

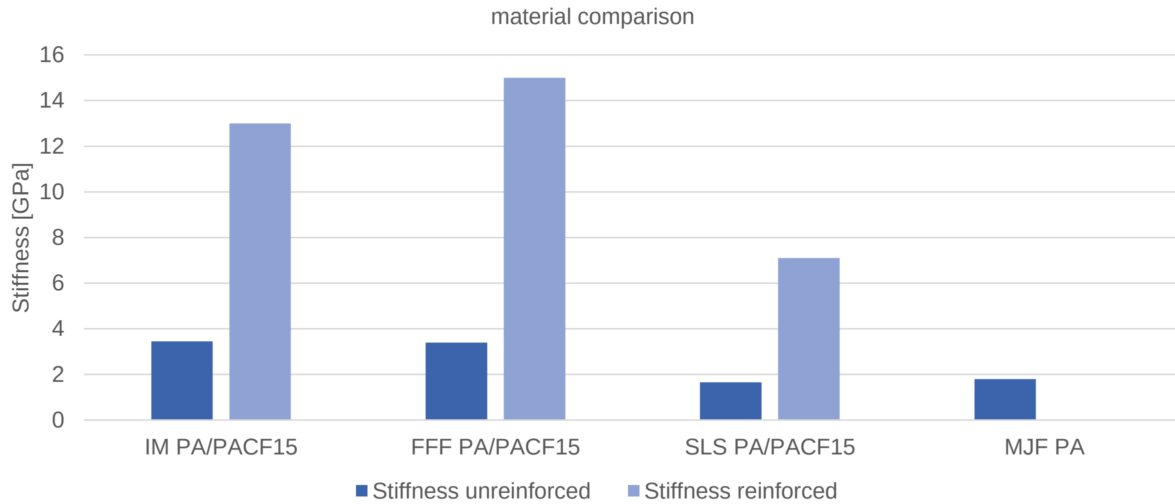


Figure 2: material comparison for Polyamide in different processes (Materialise, 2019) (3Faktur, 2019) (Kern GmbH, 2019) (Lehmann&Voss&Co. KG, 2019) (Polytron, 2019) (Rapidobject GmbH, 2019)

The design process for developing injection molded components is an iterative approach between component and process development. It is well understood that when developing an injection molded component, great attention must be paid to process-oriented design (e.g. mold flow analysis). For example, it is expected that the component geometry will likely change after the filling simulation results. Injection molding is a very mature process with material and technology suppliers having refined the product development tools (e.g. mold flow analysis, process parameter tool kits) over decades. In contrast, our research has shown a gap in the availability and quality of development tools for 3D printing. As we will show later in this paper, in the absence of a structured product development process and robust material application data 3D printed part performance will fall short of theoretical performance. To develop 3D printed parts capable of competing with IM parts we must therefore develop a product development process which has at least a sufficient level of fidelity to guide the user to produce capable repeatable performance.

When reviewing the typical product development process for injection molded parts show in Figure 3 below we can see that a large part of the development time is spent on the design and manufacturing of the IM tooling. Usually a prototype tool is developed in the first stage to develop and test the first functional prototypes. After testing the prototypes, the series tool is developed and manufactured. This process is very time-consuming and can take up to 12 months or even longer (Proto Labs GmbH, 2019).

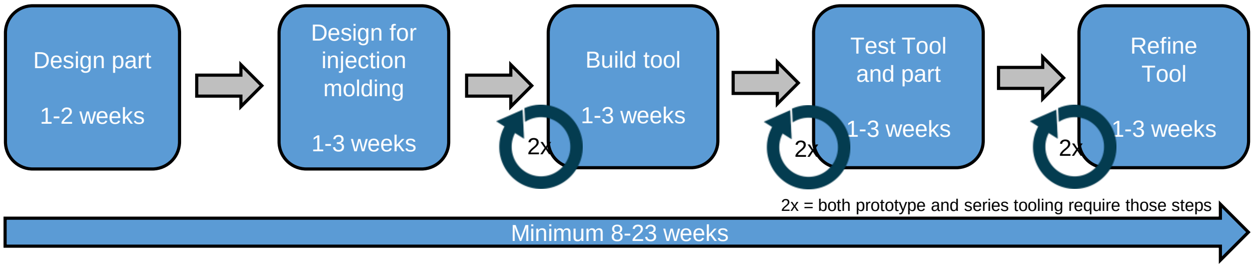


Figure 3: Product Development Process Injection Molding

As compared to the injection molding component development process, the development process for 3D printed components in the FFF process takes from a few days up to several weeks (Proto Labs GmbH, 2019). The FFF additive manufacturing development process is characterized by the ability to quickly transfer the component from digital geometry to production, see Figure 4. The level of complexity and duration of each stage of the process is greatly reduced. While the printing of each individual component itself takes longer as compared to typical cycle times for injection molded parts, due to the rapid adaptability of the component to test results and optimize design, many physical iterations are possible in the development process.

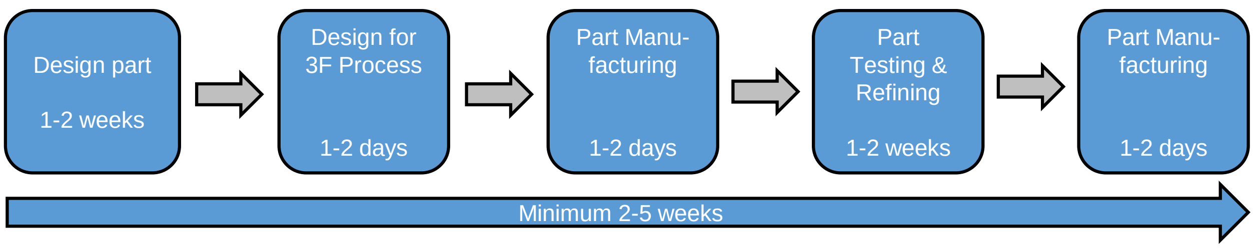


Figure 4: Product Development Process Fused Filament Fabrication (Carbon Inc., 2019)

Potential benefits of using FFF technology as replacement or assistance for Injection Molding Product Development

As already described before, the development process for injection molded parts is very time-consuming given the lengthy process of tooling development and fabrications. In Figure 5, we highlight two potential ways to shorten the development times in this development process using FFF technology.

The first option is to use 3D printed parts for prototype testing. This eliminates a number of process steps such as prototype tooling and prototype ramp up production. Additionally, 3D printing can be used to print and test a large number of different prototypes. In this way, in combination with CAE, you obtain a valuable tool for optimization during the development process. The time and resources (human, financial) saved through the elimination of prototype tool development can be used to accelerate product development process and further optimize the final part design.

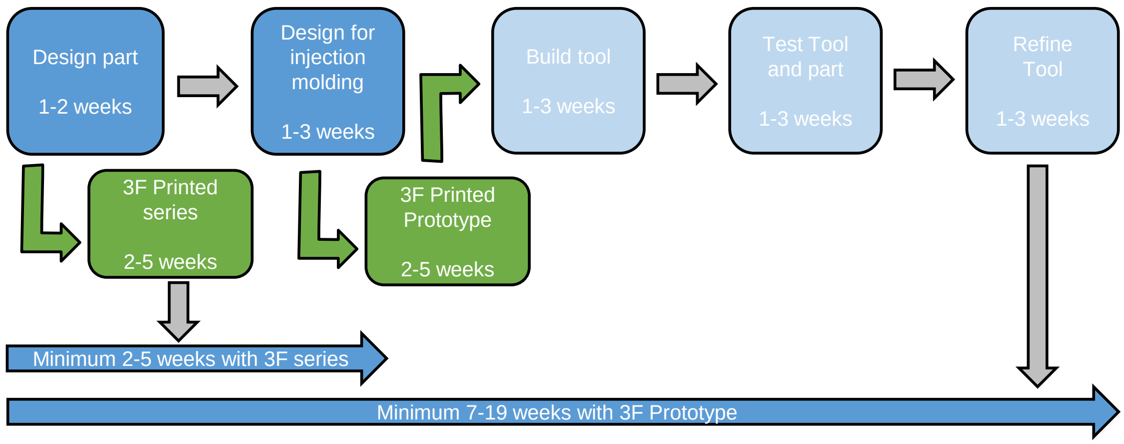


Figure 5: Shortcuts in the Product Development Process for Injection molded parts using the FFF technology

The second approach is to use 3D printed parts as a direct replacement for the injection molded series parts. This is particularly relevant for small quantities, as shown in Figure 6. Here it becomes clear that an economical production with 3D printing is possible, if the basic conditions enable it. This is where 3D printing becomes a general alternative. Although material and equipment suppliers strive to shift the break-even point even further in favor of 3D printing the challenge of ensuring that the printed part delivers equivalent mechanical performance as the reference injection molded part remains.

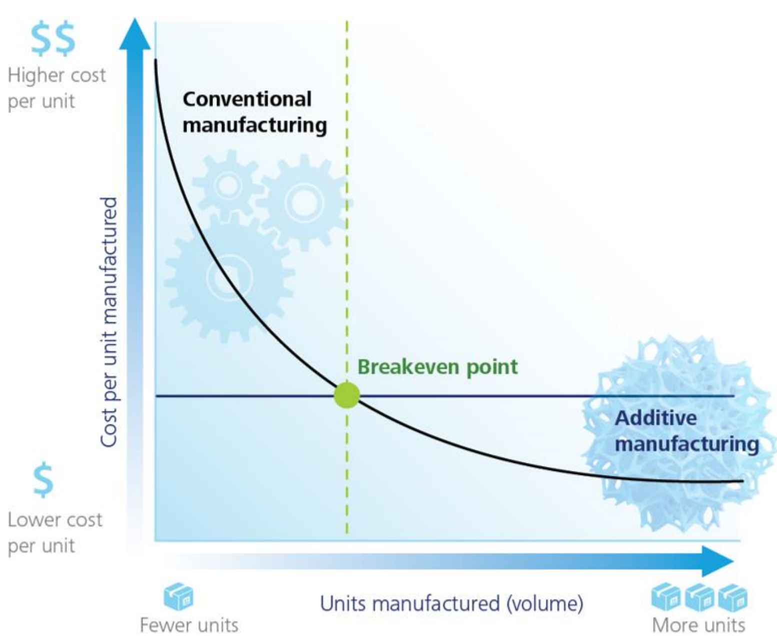


Figure 6: Breakeven point for additive manufacturing vs. injection molding (Lehmann&Voss&Co. KG, 2019)

The challenges for using Fused Filament Fabrication within the development process for plastic parts

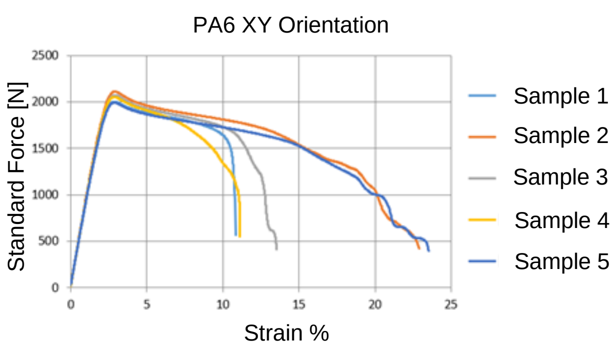
Earlier we highlighted data which showed FFF printed materials offering properties equal to or better than similar material when injection molded. Although this performance was better than the SLS and MJF printed parts at the same time we see that there is a difference between the expected results. This difference is further compounded when you factor in the multitude of FFF machine and material suppliers. Our research has shown that based on available material data, it is not possible to predict printed part performance as relevant data is often missing or cannot be realized in actual part printing with the information that is available.

Therefore, it is important to develop the comprehensive list of process parameters required to mitigate the risk of poor print quality and to develop data based models to accurately predict the structural behavior of the printed structure. When these tools are sufficiently refined and we are able to deliver precise and accurate results FFF technology may be viewed as a viable solution for series structural component applications.

Showcase of a Polyamide material with non-optimized process parameters

When purchasing materials for an FFF printer, it is common to get predefined parameters for the 3D printer. These parameters are e.g. extrusion temperature, extrusion speed, layer thickness, etc. However, previous investigations have shown that the information provided is not sufficient to produce quality parts with this data alone. Figure 7 shows the test results of a tensile test for a polyamide from the FFF printer using the parameters provided by the material supplier. It can be seen that the data actually measured are 21% worse than the values in the data sheet. In spite of following the guidance of the material data sheets, there was not sufficient information provided to insure that the printed sample delivered the performance predicted. Additionally, this doesn't begin to consider potential effects of more complex geometry as compared to the simple tensile test sample for this initial comparison.

PA6 Tensile Testing:



Mechanical data	
Young‘s modulus (datasheet)	3,2 GPa
Young's modulus (measured and recalculated)	2,53 GPa
Influence of Process on young's modulus:	21%

Figure 7: Test results for tensile tests of a Polyamide material with printing parameters from the material supplier

Methodical approach for material and process qualification using the “3F Twin Part method”

In order to solve the problem of printed part performance falling short of design and at the same time generate a model that predicts material behavior with sufficient confidence, we developed a methodical optimization process. This process can be segmented into three basic steps which are summarize in Figure 8.

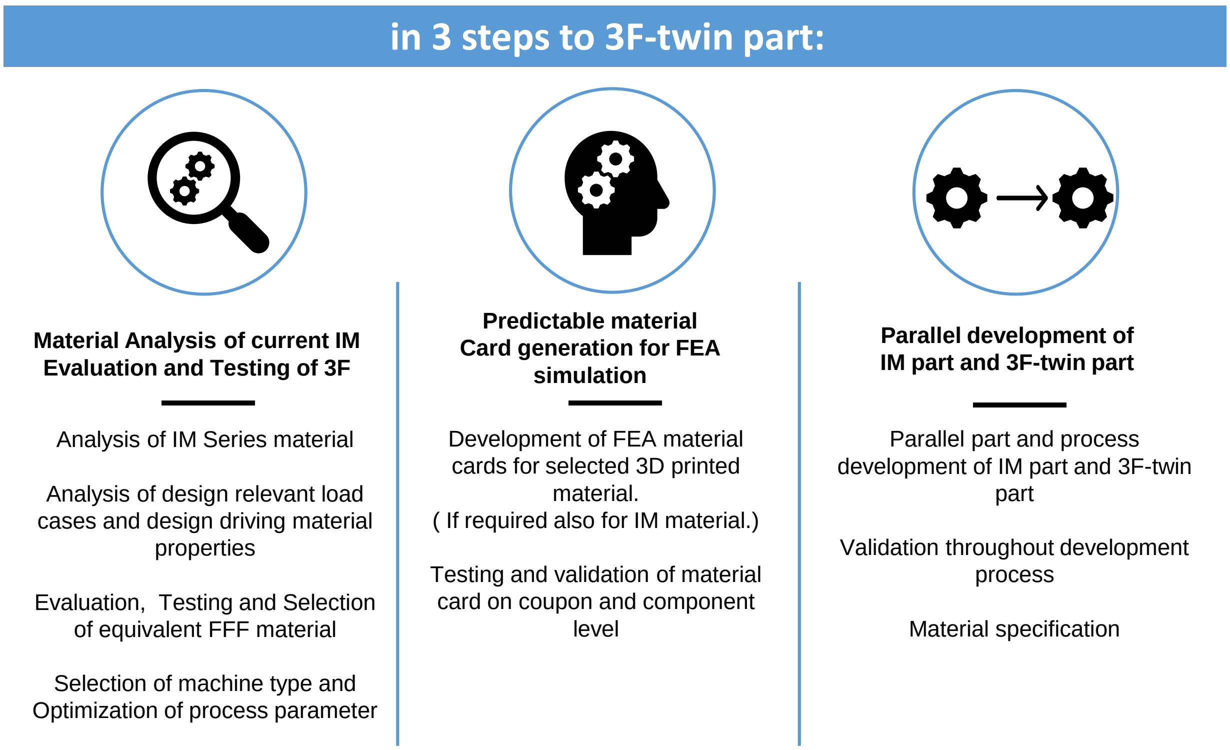


Figure 8: 3F Twin Part Process

The first section describes the material and requirements analysis for the selected reference part. Both relevant material properties and relevant component properties must be isolated and analyzed. Based on these investigations, an appropriate FFF material can be selected. In the further procedure this material is tested and, if necessary, the process is optimized. For this purpose, various printing parameters and possibly the material preparation will be iteratively improved.

In the second step, relevant values for the determination of a material card are obtained by standardized tests. This material card is used to analyze the structural behavior of the selected component. Only by a valid determination of the material card the necessity for a geometrical adjustment can be identified in advance. In order to validate the material card for more complex geometries, tests are carried out on sample geometries. This is necessary because further variations in the mechanical properties can be expected due to the more complex layer structure. It is important to highlight that this material card has a comprehensive set of printing parameters and material preparation guidelines that accompany it.

In the third step, the validated material card is used to compare the reference part with a twin part from the 3D printer. Some geometric values, such as wall thicknesses or rib geometries, can still be changed if the installation space permits. The goal of the applied CAE is to achieve equivalent mechanical behavior for the relevant loads. When a material card is available for a FFF material, this step can be repeated as many times as required for other components. This is only valid for a production with the specified printing parameters.

Showcase of a Polyamide material with non-optimized process parameters

In this section we will share results of the latest benchmark analysis. In this example, previously generated process parameters and material card data was used to produce test components to demonstrate that when properly configured, FFF parts can be printed and deliver predictable capable structural component performance.

Figure 9 shows that the material card obtained can be used very well for the calculation of more complex geometries. In this example, a sample geometry was calculated with an isotropic and orthotropic material map. The deviations are very small, which shows that the material has very good adhesion in the Z-direction. With this material card it is possible to start the development of real components.

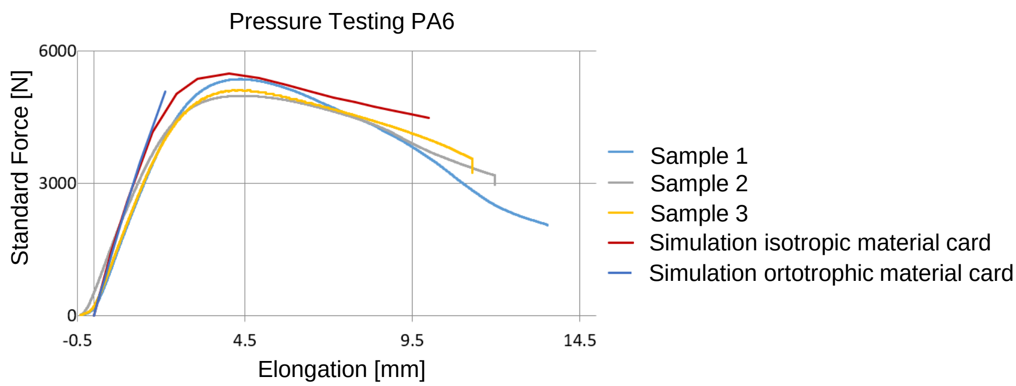
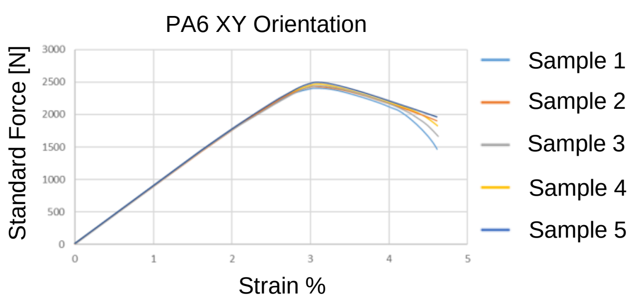


Figure 9: Results for CAE in comparison to Tests

Utilizing the optimized FFF process parameters associated with the material card, significantly better mechanical properties can be expected. Figure 10 shows this very clearly. The deviation of the young's modulus compared to the data sheet values is only 8%. This is an improvement of 13% as compared to the baseline results measured (see Figure 7). For this specific example, improved drying of the filament and changes in print head speed settings have made it possible to achieve this. Further Optimization, for example with an even better humidity control within the printing process, may result in even better properties.

PA6 Tensile Testing with optimized parameters:



Mechanical data	
Young‘s modulus (datasheet)	3,2 GPa
Young’s modulus (measured and recalculated)	2,94 GPa
Influence of Process on young’s modulus:	8%

Figure 10: Test results for tensile tests of a Polyamide material with optimized printing parameters

Summary and Next Steps

The test data demonstrates that with a sufficiently comprehensive material and process optimization process, FFF printed components can serve as a replacement for, or as a means to accelerate the development of, injection molded components. Similar to the comprehensive tools and databases developed for injection molding, the influences of production, design and material must be considered ahead of production to insure precise and accurate results.

As the database of comprehensive material cards for FFF materials is developed the FFF product development process will be further compressed. This knowledgebase, which continues to grow, will allow designers to skip the first two steps of the process and go directly to simulation driven design, production and validation.

In order to provide further confidence, actual series industrial components will be printed in the near future using the 3F Twin Part process. These components along with the associated test data will be used as a further demonstration of the capability of the 3F Twin Process.

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