MECHANICAL PROPERTIES OF FUSED DEPOSITION MODELING PARTS MANUFACTURED WITH ULTEM*9085

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Abstract

In this work the influence of the orientation and the toolpath generation of manufactured parts based on the mechanical data are analyzed. Tensile Specimen are generated with the given parameters as well as with changing parameters of the native software based upon the CAD data. The parts then are built up with the "Fortus 400mc" from Stratasys. First tensile tests show different strength and strain characteristics that depend on the given structure and as a result of the build direction. The influence of the parameters was analyzed with a statistic test method by using the software Design Expert.

Introduction

Generative production techniques have the advantage of manufacturing parts via an additive process without needing a forming tool. One of these additive manufacturing technologies is "Fused Deposition Modeling" (FDM). It is one of the most used additive manufacturing processes to produce prototypes and end-use parts [1]. From a 3D-CAD data set, components and assemblies are manufactured out of thermoplastic material in only a few working steps. Native software automatically slices the data, calculates the support structures, and creates toolpaths. The parts then are built up layer by layer by means of an additive process. An extrusion head deposits the molten thermoplastic filament to create each layer with a particular toolpath. Due to the thermal fusion the material bonds with the layer beneath and solidifies. Thus a permanent bonding of two layers is formed [2].

This technology began as a process for creating prototype parts; recently it has found new utility in the production of manufacturing tools and as a manufacturing process for end-use parts.

In order to be used as a part for serial production, the components must possess the required mechanical properties. To this end, not only is the chosen material relevant, but a correct process control is also necessary. An interesting material for the aircraft and automotive industry is the material PEI with the trade name Ultem*9085. This material should typically be used on FDM-machines for the manufacturing of end products. The aim of the research is to determine the present mechanical data based on the process control and the toolpath generation.

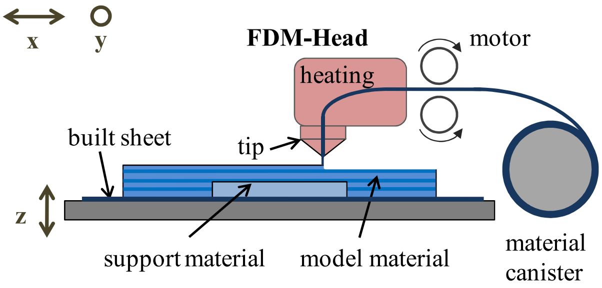

Figure1. FDM-Process.

The FDM head processes in the coordinate directions x and y and is very accurate. By lowering the platen in the z-direction, manufacturing layer by layer is possible. If necessary, an additional support material is used to provide a build substrate if the component part shows an overhang, offset or cavity. This additional material prevents the component part from collapsing during the building process. The support material itself can easily be removed after the building process by breaking it off or dissolving it in a warm water bath.

Process Parameters

The FDM technique has particular toolpaths to fill one part layer. The most used toolpath is the raster fill. First the perimeter of the layer is formed by the contour toolpaths, and then the interior is filled with a back and forth pattern and an angle of 45° to the x-axis. Alternating layers are filled with a raster direction at 90° to one another, like shown in Figure 2.

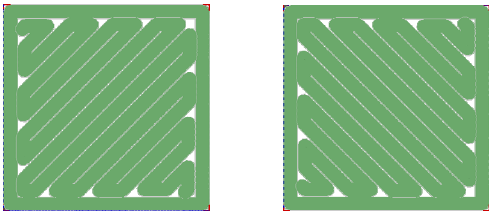

Figure 2. Raster Fill with Raster Direction at 90° to one another.

Other strategies to fill one layer are to generate all contours or only contours to a specified depth.

Furthermore, many parameters can be changed to generate a part.

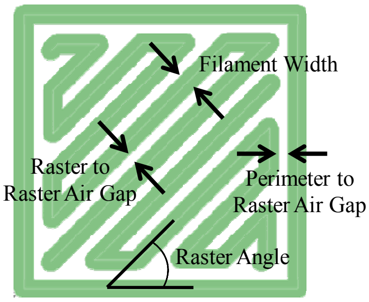

Figure 3. Parameter of Toolpath.

Some of these parameters are the width of the filament and the angle between the x-axis and the raster fill. Other changeable parameters are the air gap between the raster in the fill pattern, which can be adjusted smaller or larger, as well as the air gap between the raster fill and the contour, etc. In some publicized papers [3,4,5,6] was shown, that a change of one parameter would impact the mechanical properties of a part.

Material

Polyetherimide (PEI) with the trade name Ultem*9085 is an amorphous and transparent polymer [7]. This material is desirable due to its mechanical properties, relatively low density compared to traditional materials, and flame, smoke, and toxicity properties [8] that allow its use in aircraft cabins. The material PEI is used on FDM machines for the manufacturing of end products.

Mechanical Properties

The mechanical behavior of a part is the reaction of a material to a mechanical stress. The applied force causes deformation of a component depending on the direction of the applied force and the mechanical properties and size of the component geometry. In this paper the tensile properties of specimens manufactured with different toolpath parameters are presented. There was no post-processing of test specimens. Tests were performed according to the American standard ASTM D638, at an ambient temperature of 23°C and a relative humidity of 50%. The velocity was 5 mm/min and the specimens were loaded until they broke. A load cell with 5kN was used for this test.

The specimens were built up with the geometry as per ASTM D638 specifications in the directions X, Y and Z (on its edge, flat and up) with a contour and an inner part raster fill. The generation of the toolpath was made with the preset parameters of the native software with a raster fill and an angle of 45° to the x-axis. The build directions of the specimens are presented in the following illustration.

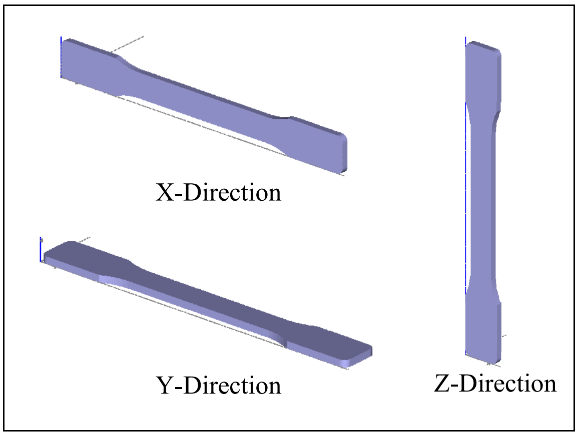

Figure 4. Build Direction of Specimen for Tensile Test (X, Y and Z).

First tensile tests show different strength and strain characteristics for each build direction. The results were published in [9]. Test specimens built in X-direction obtain the best strengths and elongations before the specimen break. Specimen build up in Y-direction accomplish lower strength values and specimen build in Z-direction has the lowest tensile strength. The tensile loadings for samples built in Z direction affect the welded layers crosswise, thus the weld between separate layers is not strong enough to resist the tensile loading. For samples built in X- and Y-directions the tensile loadings affect the structure in the layer direction. Furthermore, the sample parts show different break behaviors due to their different inner part structure. Hence, the tensile properties depend on the given structure and as a result of the build direction. This result reflects not only the material characteristics in general, but also reflects the material characteristics as a function of the inner building properties and toolpath generation.

Results from Parameter Variation

To analyze the influence of the toolpath parameters for the material Ultem*9085 a parameter variation test was accomplished. The three build directions in X, Y and Z were considered.

Varied parameters were the raster angle between the x-axis and the raster fill the thickness of the filament with a thin and a thick value. Furthermore the air gap between the raster in the fill pattern and the air gap between the raster fill and the contour were changed. The values used are shown in the following Table 1.

Table 1. Parameters for the Variation Tests.

Raster Angle	0°	30°	45°
Filament Thickness	***thin*** 0,016-0,02 inch		***thick*** 0,026-0,030 inch
Raster to Raster Air Gap	-0,001 inch	0 inch	+0,001 inch
Perimeter to Raster Air Gap	-0,005 inch	-0,0025 inch	0 inch
		Negative Air Gap	***Positive Air Gap***

Specimen built up with the raster to raster (R/R) air gap at -0,001 inch and the perimeter to raster (P/R) to air gap at -0,005 inch show an overfilling by using a certain parameter set. Thus this parameter combination will not be considered in this paper. The results from three parameter sets for each raster angle were analysed in detail; a negative air gap with P/R= -0,0025inch and R/R= -0,001inch, a positive air gap with P/R= 0,000inch and R/R= +0,001inch and a standard parameter set of 0,00inch for the P/R and R/R (normal). The measured data is shown separated for the thin and thick filament geometry and presented in system diagrams.

First the results for the tensile strength σ_M are presented for specimen built up in X-direction (built up on its edge).

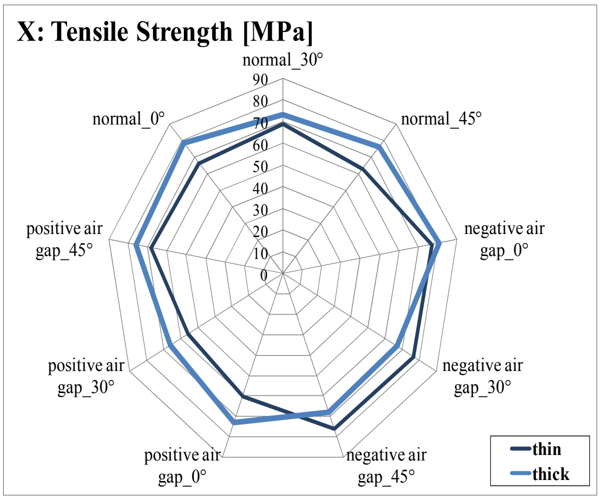

Figure 5. Tensile Strengths of Specimen built up in X-Direction.

Specimens built up with a thin filament achieve, in compare to a thick filament, lower mechanical strength properties for nearly all parameter sets except for the negative air gap and a raster angle of 45° and 30°. The lowest strengths are recorded for a positive air gap and a raster angle of 30° and 0° with a data under 60MPa. The highest mechanical data are measured at a negative air gap and an angle of 0° between the x-axis and the raster fill with a data of 81MPa.

The analogical results for the tensile strain at break ε_B are presented in the following Figure 6 and are more complex.

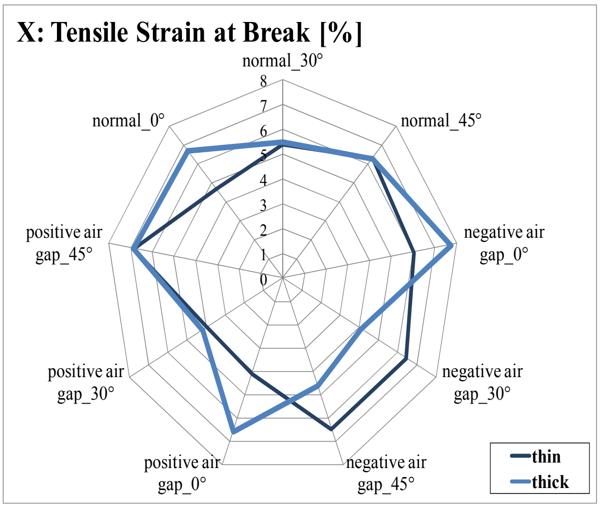

Figure 6. Tensile Strain at Break of Specimen built up in X-Direction.

Analogue to the strength properties, specimens built up with a thin filament achieve only better tensile strains for a negative air gap and a raster angle of 45° and 30°. In compare to the thick filament geometry the elongation is lower for the thin filament at all parameter sets with an angle of 0°. With the data under 4% the lowest elongation is presented for the thick filament geometry at a raster angle of 30° and a negative air gap. The highest tensile strain at break is recorded at a negative air gap and 0° raster angle for the thick filament with a data of 7,7%.

In the following diagram the tensile properties are presented for specimen built up flat (Y-direction). The following Figure 7 illustrates the tensile strengths σ_M for the particular parameter sets.

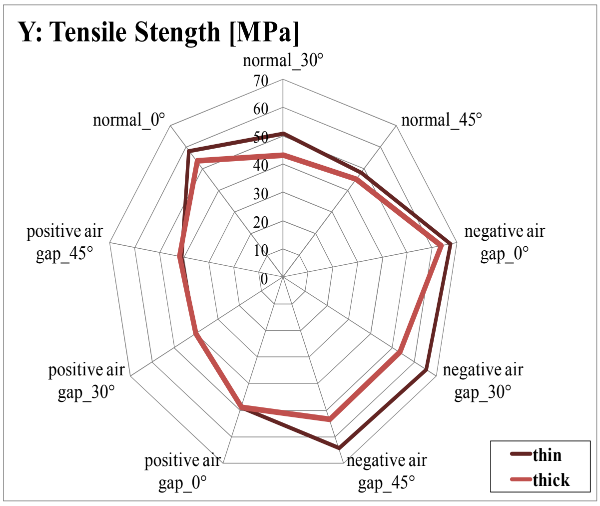

Figure 7. Tensile Strengths of Specimen built up in Y-Direction.

Y-specimens built up with a thin filament achieve higher mechanical strength properties for nearly all parameter sets than in compare to thick filament geometry. For the positive air gap the tensile strength are for each raster angle at the same level for the thin and the thick filament. For this parameter set the lowest strengths are recorded for the raster angle of 30° and 45° with a data at 40MPa. The highest mechanical data are measured at a negative air gap and an angle of 0° with a data of 67MPa.

The following Figure 8 presents the analogical results for the tensile strain at break ε_B.

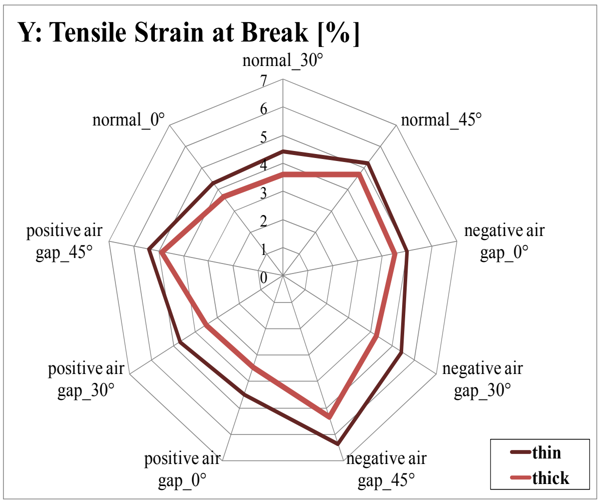

Figure 8. Tensile Strain at Break of Specimen built up in Y-Direction.

For all parameter constellations specimens built up with a thin filament achieve higher tensile strains at break. But specimen with a thick filament geometry show the same parameter dependency with the lowest data at a normal and positive air gap for the raster angle of 0° and 30° and the highest elongation at a negative air gap and a 45° raster angle. The data for this parameter constellation and a thin filament geometry is 6,35%.

The next diagram illustrates the tensile properties for specimen built up in Z-direction. These specimens achieve the lowest strength properties related to the buildup directions. The measured data for the particular parameter sets are presented in Figure 9.

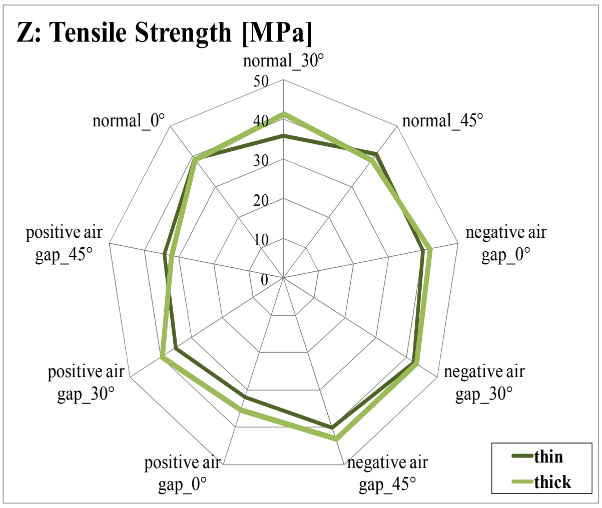

Figure 9. Tensile Strengths of Specimen built up in Z-Direction.

Z-specimens built up with a thick filament achieve for nearly all parameter constellations higher mechanical strength properties. But the tensile strength level is similar for both filament thicknesses. For the negative air gap these specimens achieve the best strengths for all raster angles. The highest mechanical data are measured here at an angle of 30° and 45° and a thick filament with a data of 43MPa. The lowest data was recorded for a thin filament, a positive air gap and raster angle of 30° at 32MPa.

The mechanical strength properties of these specimen build up in Z-direction depend more on the quality of the weld between two layers or in this case on the contact surface of the filaments from two layers. Thus the mechanical data do not change that much by changing the toolpath generation.

The following Figure 10 shows the analogical results for the tensile strain at break ε_B.

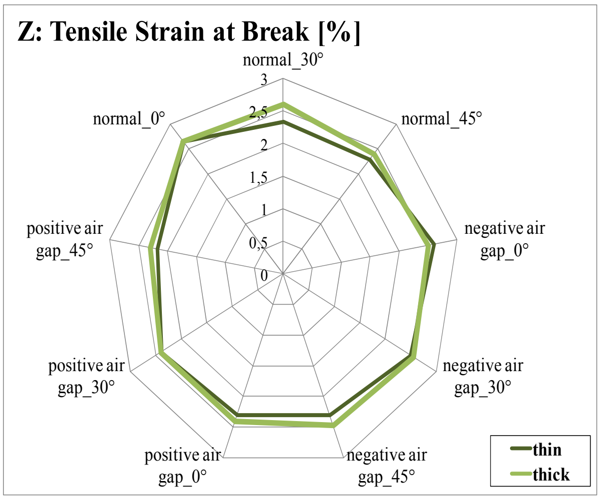

Figure 10. Tensile Strain at Break of Specimen built up in Z-Direction.

The level of tensile strain at break is similar for both filament geometries. But as presented for the strength properties, specimens built up with a thick filament achieve slightly higher elongations. The highest strain is recorded for thick filaments, a normal raster air gap and a 0° raster angle with s data at 2,65%. The lowest strain was achieved for a thin filament, a negative air gap and 45° at 2,2%.

Conclusions

In this paper the mechanical properties of FDM samples built up with the FDM process were analyzed depending on the build direction. Therefore the samples were generated with different parameters for the toolpath generation and the mechanical tests conducted were the tensile test. The results show that the mechanical strength properties depend on the given inner part structure as a result from the build direction and the toolpath generation.

The best results were achieved for all directions by using a negative raster air gap. With thick filaments better mechanical data can be achieved for the X and Z build direction, while a thinner filament improves the strength properties for Y-specimen.

In comparison, a specimen manufactured with the conventional injection-molding method has a different plastic behavior for the material Ultem*9085. The strength values of this specimen are 84MPa for the tensile strength at yield and 72% for the elongation at break [10]. Thus, the tensile strength of specimens manufactured with FDM nearly the same strength values, but due to their inner structures a brittle fracture behavior and therefore lower elongations.

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Key Words: Additive Manufacturing, Fused Deposition Modeling, Ultem*9085, Mechanical Properties.