FDM Part Quality Manufactured with Ultem*9085

A. Bagsik[1,2], V. Schöppner[1], E. Klemp[2]

[1] Kunststofftechnik Paderborn (KTP),Universität Paderborn, D-33102 Paderborn, Germany
[2] Direct Manufacturing Research Center (DMRC), Universität Paderborn, D-33102 Paderborn, Germany

Abstract

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). 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. 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, as well as reproducibility from job to job.
In this work the influence of the orientation and the structure of the manufactured parts based on the mechanical data are analyzed. Sample parts are generated with the given parameters of the native software based upon the CAD data. First, specimens were analyzed concerning their geometry and configuration. The dimensions and weight were measured. The mechanical tests conducted were the tensile and compression tests.

1 Introduction

FDM is one of the most used additive manufacturing processes to produce prototypes and end-use parts [1]. The parts are built up layer by layer by means of an additive process without a forming tool. 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].

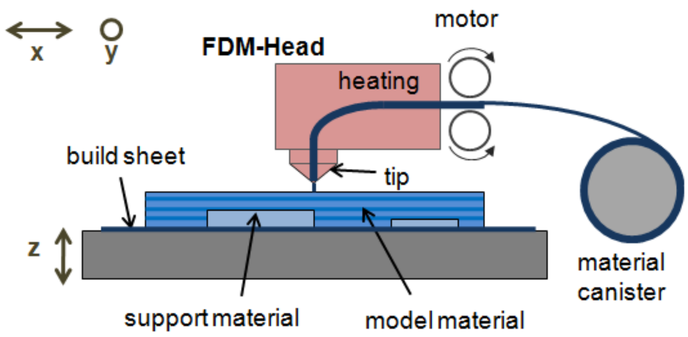

Figure 1: FDM-Process

The FDM head processes in the coordination 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.
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 (see Figure 2).

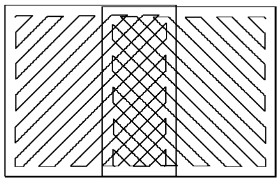

Figure 2: Raster Fill with Raster Direction at 90° to one another

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. Thus, the air gap between the rasters in the fill pattern can be adjusted smaller or larger, as well as the air gap between the raster fill and the contour. Other changeable parameters are the angle between the x-axis and the raster fill, the delta angle of the rasters between layers, the width of the toolpath, etc. A change of one parameter would impact the mechanical properties of a part [3,4,5,6].

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 typically used on FDM machines for the manufacturing of end products. The temperature of the building chamber for PEI is T_B=195°C. Thus, parts are built up at ambient temperature above the actual glass transition temperature of T_G= 181°C. The preset tip temperature is 380°C and above the normal extrusion temperature (330°C-360°C). This higher temperature allows a thermal fusion of two layers resulting in a permanent bond. However, the shear rate $\dot{\gamma}$ that effects the material in the tip during the FDM process has a value of $\dot{\gamma}=200s^{-1}$ which is in the lower range of an extrusion process (100-1000s-1). This value was calculated for a tip T16 with a tip radius of r=0,2mm.

2 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, two mechanical tests on specimens manufactured with FDM are presented: the tensile and the compression tests. There was no post-processing of test specimens.

Currently, there are no specific test standards for specimens manufactured via additive processes. Thus, the specimens were built up and tested according to the American standard (ASTM).

2.1 Tensile Test

The tensile test is one of the main material tests and belongs to the quasi-static and destructive tests. It is used to describe mechanical and deformation properties of a specimen at a parallel tension with a given velocity. The specimens were built up with the geometry as per ASTM D638 specifications in the directions X, Y and Z (side, 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. The build directions of the specimens are presented in the following illustration:

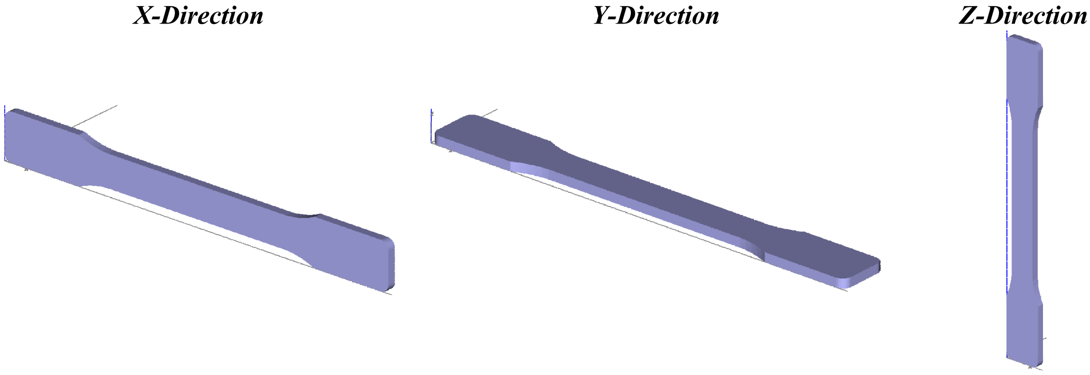

Figure 3: Build Direction of Specimen for Tensile Test (X, Y and Z)

2.1.1 Part Geometry

At first, specimens were analysed concerning their geometry and configuration. The different building directions of the specimens caused unequal results of width and thickness, which do not represent exactly the nominal size. In this work only the narrow section was measured due to its importance for the tensile test. All specimens, independent from their build direction, are larger in the width of the narrow section and in the thickness. Thus, this indicates an error of the native software to reflect the real geometry accurately. The most exact geometry is the specimen built up in X-direction. The different dimensions are shown in following Table 1.

Table 1: Dimension of Specimen for Tensile Test

Dimensions	***X***	***Y***	***Z***	***Nominal Size***
Width of narrow section b [mm]	12,94	12,72	12,83	12,7
Thickness h [mm]	3,22	3,47	3,31	3,2

Furthermore pictures of the reflected-light microscope give information about the inner structure of a specimen. For this, pictures were taken of the top as well as from the cross and longitudinal sections of the specimen. The first figure shows the top view of the specimen built in Y-direction with the filaments of the top layer lying next to each other. These rasters are not fused together, thus the air gap between the raster fill is not small enough. The layer below this top layer is also visible with an angle of 90° to the top layer. Consequently there are cavities in the part and these cavities are also visible in the cross section of the specimen (compare Figure 4 (2)).

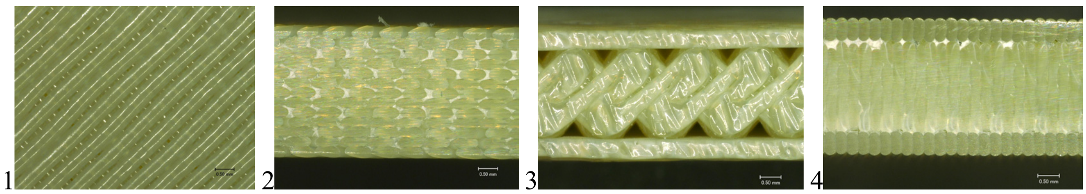

Figure 4: Reflected Light Mikroscope
(1) Top view and (2) Cross Section of Specimen Built in Y-Direction
(3) Top view and (4) Longitudinal Section of Specimen Built in Z- and X-Direction

Other pictures taken with the reflected-light microscope show specimens built in X- and Z-direction. The big cavities between the contour and the inner raster are striking. This is noticeable in the top view as well in the longitudinal section view. Due to the small thickness of specimen and the typical raster fill, the cavities appear to be larger.
As a result of unequal part structure and unequal results in the geometry of specimen, the weight of the specimen, depending on the built direction, varies (see Table 2).

Table 2: Weight of Specimen for Tensile Test

Direction	***X***	***Y***	***Z***
Weight [g]	9,38	9,66	9,46

The weight of the specimens built in X- and Z-direction is particularly low. This effect is caused by the increased presence of the cavities between contour and inner raster.

2.1.2 Results from Tensile Test

The tensile tests were conducted with the universal testing machine Zwick (Typ 1446). 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.

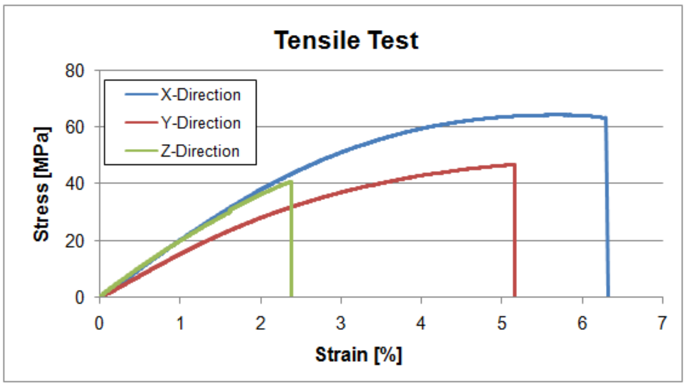

Figure 5: Compare of Stress-Strain Curves from different Build Directions

Test specimens built in X-direction obtain the maximum strengths. After reaching the maximum stress, the specimens break. The average tensile strength is listed with $\sigma_{M,X}$=63MPa; the elongation at break is listed with $\varepsilon_{B,X}$=6,4%. The tensile strength of samples built in Y-direction is lower than the tensile strength of samples built in X-direction. Test specimens built in Y-direction break after reaching the maximum stress. The average elongation at break is listed with $\varepsilon_{B,Y}$=5,0% and the tensile strength is listed with $\sigma_{M,Y}$=46MPa. The Young's Modulus between test specimens built Z- and X-direction seems to be similar, but the test specimens build in Z-direction accomplish lower strength values. The average tensile strength is listed with $\sigma_{M,Z}$=41MPa; the elongation at break is listed with $\varepsilon_{B,Z}$=2,3%.
The weld between separate layers is not strong enough to resist the tensile loading in Z-direction; therefore the strength values in this direction are smaller than the values in X-and Y-direction. Furthermore, the contact surface between the layers of specimen built in Z direction is the smallest (A=42,5mm²) of all directions. The tensile loadings for samples built in Z direction affect the welded layers crosswise, for samples built in X-and Y-directions they affect the structure in the layer direction.
A comparison of the different average strength values with the measured standard variances as a function of different orientations within the building chamber is listed in Table 3.

Table 3: Compare of Average Values from Tensile Test

Direction *(tested parts)*	***X*** *(12)*	***Y*** *(12)*	***Z*** *(40)*
Young`s modulus [MPa]	**2033,54** ± 64,73	**1461,41**± 194,40	**2092,26** ± 129,92
Tensile stress at break σ_B [MPa]	**61,34** ± 1,31	**45,67** ± 1,38	**40,71** ± 2,07
Tensile strength σ_M [MPa]	**63,25** ± 1,07	**45,87** ± 1,32	**40,75** ± 2,06
Tensile strain at break ε_B [%]	**6,35** ±0,28	**5,0** ± 0,45	**2,29** ± 0,19
Tensile strain ε_M [%]	**5,65** ± 0,08	**4,99** ± 0,44	**2,29** ± 0,19

In comparison, a specimen manufactured with the conventional injection-molding method has a more tough 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 [9]. Thus, the tensile strength of specimens manufactured with FDM has lower strength values and, due to their inner structure, a brittle fracture behaviour and therefore lower elongations.

2.1.3 Break analysis

The break characteristics were analysed in order to correlate the specific strength values with the present part structure. The fractures of specimens built in all three directions are shown in Figure 6.

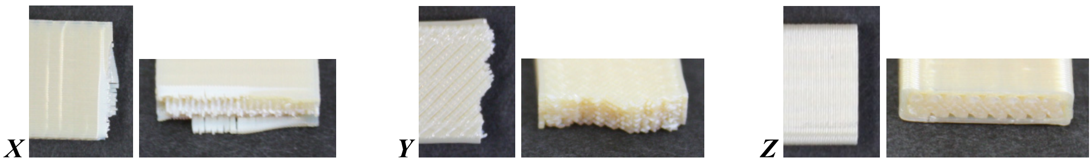

Figure 6: Fractures of Specimen built in X-, Y-, and Z-Direction

Specimens built in X-direction show a brittle fracture. Stress whitening could be observed exactly above the air gaps between the contour and the inside raster fill. Because of this damage on the contour, the specimens were weakened in strength and the inner raster fill broke. Thus, with the raster fill, the specimen has limited ability to elongate. The break characteristics of single samples are simplified shown in Figure 7.

Figure 7: Break Behavior of Specimen built in X-,Y- and Z-Direction

Specimens built in Y direction show a brittle fracture, too. Because the load affects the material beads crosswise, specimens built in Y- and X-direction should have similar tensile properties. However, the samples in Y direction have lower characteristic values. One reason is a notch on the outside contour, which is a result of seam lines due to the layer manufacturing. This notch causes all breaks at this point and initiates the total break of the specimen. Thus, the test specimen breaks more easily than the specimen built in X-direction. Furthermore, the contour surface of specimens built in X-direction is larger and the volume filled with the raster structure is lower than of the specimen built in Y-direction. The possibility to elongate more is consequently higher for the specimen built in X-direction.

As mentioned before, specimens built in Z direction break between two layers due to the fact, that the load affects the welded layers in the layer direction. Therefore the fracture has a smooth surface.
Hence, the tensile properties depend much on the given structure and as a result of the build direction. This experiment 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.

2.1.4 Reproducibility Analysis

Reproducibility from job to job is an important topic in the direct manufacturing process. To be used as a part for serial production, the components must possess the required mechanical properties consistently for every job and at each position in the build chamber. This aspect includes not only the geometry characteristics, but also the mechanical data, which was analysed for the FDM process.
The maximum standard variance in dimension of the specimen is ±0,05mm (errors in measuring accuracy are not taken into account). The standard variance of the relevant dimensions b (width) and h (thickness) of the specimen for the tensile test has a maximum difference of ±0,05mm. Consequently, the reproducibility of dimensions is rather good. Furthermore, the mechanical data from the tensile test also proves repeatable. The standard variance of tensile strength and tensile strain at break of the specimens are not changing that much.
One factor that could influence the reproducibility of the FDM process is the abrasion of the tip, due to the high material temperature and the small tip diameter. Therefore the tip should be changed regularly. Otherwise the built parts would show optical defects as the extruded filament would not be exactly deposited at the start and end of one layer of the contour.
Not only does the part geometry get worse, but the mechanical data also drops. The average data of specimens for tensile test built up with an old and a new tip was compared. The specimens were built up with the same parameters in Z direction and were conditioned and tested at room temperature (23°C and 50% relative humidity).
The mechanical properties of specimen built up using a new tip are higher by of 7% for the maximum tensile strength and 17% for the tensile strain at break. Furthermore, the standard variance of specimens built up with the old tip is much higher at 5,23MPa for the tensile strength. In comparison, the standard variance of specimens built up with a new tip is 0,42MPa. Hence, for accurate geometry and higher mechanical properties without a large variance and to ensure the reproducibility from job to job, a regular change of the tip is necessary. Additionally, the tips have to be calibrated after every change to ensure an exactly defined deposition of the filament.

2.2 Compression Tests

The compression test is used to analyze the material behavior of specimens (prisms or barrels) at a single-axis compression stress. For the compression test a prism was used according to ASTM D695. The test specimens were built up due to the symmetry in the two directions XY and Z with a contour and an inner part raster. The generation of the toolpath was made with the preset parameters of the native software. The geometry and orientation of the specimens are presented in the following illustration:

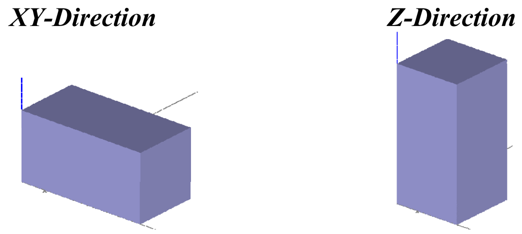

Figure 8: Build Direction of Specimen for Compression Test (XY and Z)

Specimens first were analyzed concerning their geometry and configuration. The weight was measured as well. Like the tensile specimen, the specimens for the compression test have different dimensions and different weights due to the different building directions (see Figure 4).

Table 4: Dimension of Specimen for Compression Test

Dimension	***XY***	***Z***	***Nominal Size***
length l [mm]	25,4	25,6	25,4
width b [mm]	12,68	12,71	12,7
thickness h [mm]	12,86	12,71	12,7
Weight [g]	4,77	4,82	-

The compression tests were conducted with the universal testing machine Zwick (Typ 1474). Tests were conducted at room temperature (23°C and 50% relative humidity), with a velocity of 1,3mm/min and a 50kN load cell was used. The specimens were loaded until they broke.

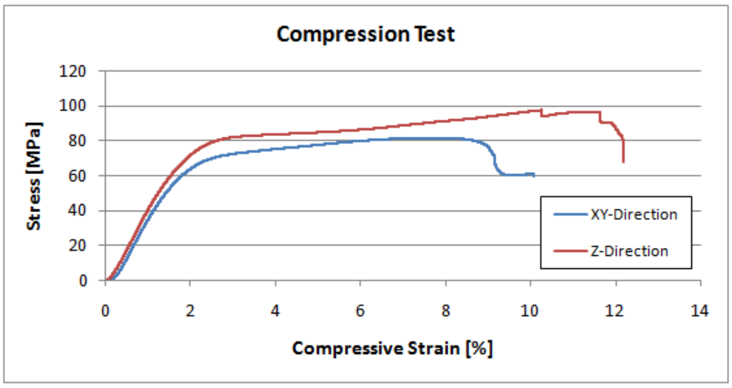

Figure 9: Compare of Stress-Strain Curves from different Build Directions

The compressive strength of specimens built up in XY-direction is lower than that of specimens built up in Z-direction. The XY-specimens break after reaching maximum stress and the average compressive strength is $\sigma_{B,XY}$=83MPa and the compression strain at break is listed with $\varepsilon_{B,XY}$=9.5%. In comparison, specimens built in Z-direction have an average compressive strain at break of $\varepsilon_{B,Z}$=12% and the compressive strength is listed with $\sigma_{M,Z}$=97MPa.
All specimens undergo shear strains between the layers due to the additive build up. XY-samples affect a load crosswise. Some specimens broke incompletely and showed cracks on one side only (compare Figure 10). These specimens could be compressed even further and achieved a higher stress and a higher strain after passing a minimum. The results where this phenomenon occurred were manually cancelled.

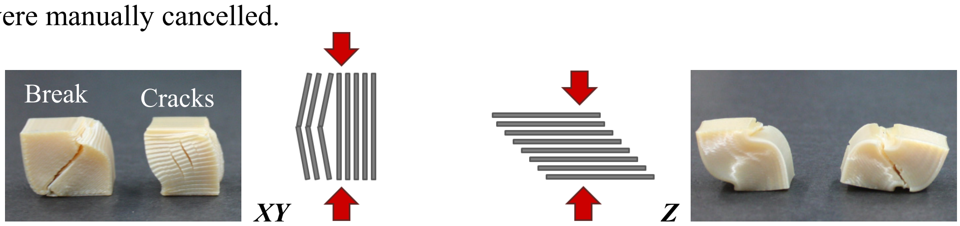

Figure 10: Break Behavior of Specimen built in XY- and Z-Direction

The break of the Z-specimen occurs after reaching a maximum stress and after the compression stress has reduced in steps. As the pressure loads on the layers, the single layers slide along one another until the specimen finally breaks.
A comparison of the different average compressive strength values with the standard variances as a function of different orientations within the building chamber is listed in Table 5.

Table 5: Compare of Average Values from Compression Test

***Direction** (tested parts)*	***XY** (10)*	***Z** (10)*
Compressive stress at break σ_B [MPa]	**57,47** ± 4,59	**69,51** ± 4,65
Compressive strength σ_M [MPa]	**82,65** ± 5,69	**96,79** ± 4,43
Compressive strain at break ε_B [%]	**9,47** ± 0,97	**12,02** ± 0,42
Compressive strain ε_M at compressive strength σ_M [%]	**7,98** ± 1,25	**10,12** ± 0,60

The plastic deformation of Z specimen begins at a compression of about $\varepsilon_{irr,Z} \geq 1,5\%$. The applied deformation remains at this compression in the part. Specimens built in XY-direction show a irreversible deformation at a given compression value of $\varepsilon_{irr,XY} \geq 2,0\%$.

3 Summary and Outlook

In this paper the mechanical properties of FDM samples generated with the given parameters for the FDM "Fortus 400mc" depending on the build direction were analyzed. The mechanical tests conducted were the tensile test and the compression test. The results show that the geometry of the sample parts, independent from their build direction, does not conform to the nominal geometry. This indicates an error of the native software to represent the real geometry accurately. Furthermore, the sample parts show different break behaviors due to their typical layer build-up and thus different mechanical properties. In relation to the reproducibility, good results were achieved as long as the tip is changed regularly.

The test presented in this paper can only offer a first insight into the relation between the mechanical properties and the given parameters in the process. Further tests will be conducted with a variation of the process parameters to optimize the mechanical properties. These changing parameters are, for example, the width of the filament, the raster angle, and the air gap between the raster and the contour as well as between the raster itself. The parts built in Z-direction should show particularly higher mechanical properties at a tensile load.

4 References

1. Wohlers Associates/ Last access 28.06.2010: http://www.wohlersassociates.com/JanFeb10TC.htm
2. Alphacam- FDM Technologie / Last access 28.06.2010: http://www.alphacam.de/rpd/fdm
3. Es-Said, O.S.; Foyos, J.; Noorani, R.; Mendelson, M. ; Marloth, R., *Effect of Layer Orientation on Mechanical Propertiwes of Rapid Prottyped Samples*; Materials and Manufacturing Processes, Vol. 15, No. 1, 2000, pp. 107-122
4. Ahn, S.-H.; Montero, M.; Odell, D.; Roundy, S.; Wright, P.K., *Anisotropic Material Properties of Fused Deposition Modeling ABS*; Rapid Prototyping, Vol. 8, No. 4, 2002, pp. 248-257
5. Galantucci, L.M.; Lavecchia, F.; Percoco, G., *Study of compression properties of topologically optimized FDM made structured parts*; Manufacturing Technology 57, 2008, pp. 243-246
6. Sood, A. K.; Ohdar, R.K.; Mahapatra, S.S., *Parameteric appraisal of mechanical peoperty of fused deposition modeling proccessed parts*; Materials and Design 31, 2010, pp. 287-295
7. Hellerich, W.; Harsch, G.; Haenle, S., *Werkstofffführer Kunststoffe / Eigenschaften Prüfungen Kennwerte*; 8. Auflage, Carl Hanser Verlag München Wien 2001
8. GE Plastics - Ultem Profil / Last access 28.06.2010: http://www.plastoplan.com/download/ge_plastics_pdf_downloads/gep_Ultem.pdf
9. SABIC Innovative Plastics, Prospector- Ultem*9085 Resin