

# Some Investigations Regarding the Surface Treatment of Ultem\*9085 Parts Manufactured with Fused Deposition Modeling

M. Fischer<sup>1,2</sup>; V. Schöppner<sup>1</sup>

<sup>1</sup>Kunststofftechnik Paderborn (KTP), University of Paderborn, D-33102 Paderborn, Germany

<sup>2</sup>Direct Manufacturing Research Center (DMRC), University of Paderborn, D-33102 Paderborn, Germany

## Abstract

Fused Deposition Modeling (FDM) parts are typically subject to process-related rough or wavy surfaces, with stair-stepping effects whenever the parts produced have sloped or rounded part geometries; however, the level of optical quality frequently required demands that parts feature a smooth surface. In this paper, the results of a high-energy finishing process, which uses a disc finishing unit and is designed for parts manufactured with the material Ultem\*9085, are presented. The analysis discusses the surface-smoothing effect of various finishing materials with varying geometries, as well as the effect of finishing time and speed. Additionally, the efficiency of the surface treatment has been analyzed specifically at corners, edges and in cavities.

## Introduction

Additive manufacturing technologies have established themselves in recent years for prototyping in different industries. The only necessary basis of additive-manufactured parts is a 3D-CAD data file of the part in a .stl format [2], meaning that engineers or designers can build a new product without needing specific tools. Furthermore, the principles of additive manufacturing processes offer many new possibilities for part design and production. This is particularly exciting for newer industrial sectors, which are already using this new technology to produce end-use products in small batches or for creating complex part geometries which can only be produced using additive manufacturing technology. One such technology is Fused Deposition Modeling (FDM) from Stratasys.

For the FDM process, the .stl-file of the part is sliced into layers using the software program Insight. Required supporting structures and the tool path for the building process are also calculated by the software. The classical FDM process, the setup of which can be seen in Figure 1, is an extrusion process, using a melted filament which is then applied by a heated tip.

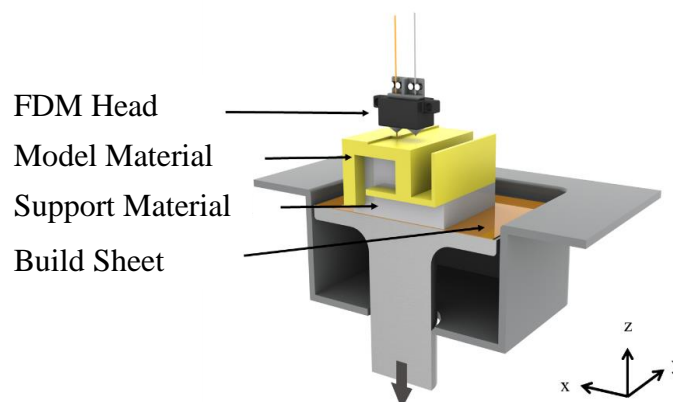


Figure 1: FDM Process

To create a layer, the polymer filament is melted in the heated tip of the FDM head and deposited on the building platform along the tool path determined by the software. After building the first layer, the building platform will be moved down one layer thickness and the next layer will be built on top of the first one. As a result of thermal influences, the new layer will fuse with the layer beneath and solidify. If necessary, a supporting structure can be built in specific areas. This support material can be removed during post-processing, either by breaking it off or by dissolving it in a warm-water bath. [2]

In addition to its advantages, such as flexibility and the possibility of producing complex part geometries, FDM nonetheless also poses challenges, especially concerning the quality of the part surface. As a result of the additive manufacturing process, FDM parts show rough and/or wavy surfaces with stair-stepping effects on slopes and rounded part geometries [4]. In order to produce parts with higher surface quality, the surface has to be treated after production. The manufacturer of the FDM manufacturing systems has therefore developed a special smoothing station, which uses the steam from a special solvent to smooth the surface of ABS parts [5]. One promising process for improving the surface of FDM parts manufactured with Ultem\*9085 is a mechanical grinding process; experimental investigations with a high-energy finishing process, based on a disc finishing unit, show promising results. The FDM parts for the following experiments were produced with Ultem\*9085 and a T16 tip on a Stratasys Fortus 400mc.

### Definition of the Surface Quality

Just as the mechanical qualities of additive-manufactured components are heavily anisotropic, based on the building direction, the surface quality of FDM parts also depends heavily on build direction and angle [6] [8]. The selection of production process parameters and of which sections of a part will be in contact with the support material, together with the stair-stepping effect on sloped or rounded part sections, leads to characteristic surface profiles for various build angles and measurement directions (see Figure 2). The surface quality of the part can be determined by, among other methods, the use of a mechanical contact profilometer. Using the two-dimensional profile thus obtained, reliable characteristic values can be identified according to DIN EN ISO 4287, such as the average height of the surface roughness profile,  $R_z$  [7] [14]. Figure 2 shows the  $R_z$ -value for FDM part surfaces produced with different build angles.

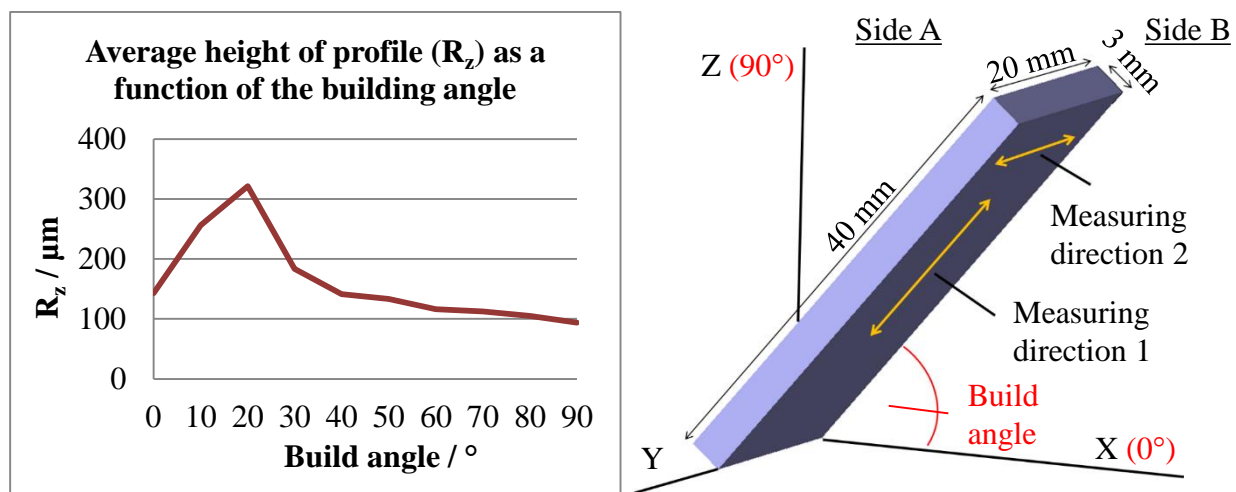


Figure 2: Average Roughness Height ( $R_z$ ) for Different Build Angles

The 0° build angle in Figure 2 represents a part surface produced parallel to the building platform of the FDM-unit. This surface is characterized by the inner structure of a single part layer. The 90° build angle represents part surfaces produced perpendicularly to the building platform, which are characterized by the seams between individual component layers. In addition, the choice of from which direction measurements are taken (see Figure 2, right) results in different surface profiles for the same build angle; for a 90° build angle, for example, the measurement in one case can be carried out parallel to the layers (Direction 2) and in another perpendicular to the layers (Direction 1). In general, small build angles lead to very rough surfaces, with R-values up to 300 µm, as compared to merely 100 µm for a 90° build angle [8].

### **Surface Treatment with Mass Finishing**

Mass finishing processes are chipping processes which are categorized among the production technology processes according to DIN 8580. Mass finishing units can be built based on a rotational or a vibrational principle [9]; the grinding principle is identical in both cases and is based on relative motion between the components and the grinding elements [9]. These grinding elements are available in a variety of materials and geometric designs. For a mass finishing process for FDM components made of Ultem\*9085, ceramic grinding elements have been found to be particularly suitable [10].

In a series of experiments, the effect of varying the length of the grinding process and of using differently-shaped abrasive media has been investigated, and detailed information about the effectiveness of different types of grinding elements was collected. These experiments were conducted on a disc finishing machine from the ECO 18 Series, produced by OTEC Präzisionsfinish GmbH, with a standard finishing speed of 250 rpm. For this, the grain types listed in Figure 3, which are differentiated both by their geometrical form (triangular, irregularly triangular, and cylindrical) and by their grinding action (very strongly, strongly, and medium abrasive) [11].



**Figure 3: Finishing Media**

In Figure 4, significant differences can be identified between the various abrasive media concerning their abrasive qualities. The average height of the surface roughness profile  $R_z$  was determined for surfaces with a build angle of 90° and was measured perpendicularly to the layers.

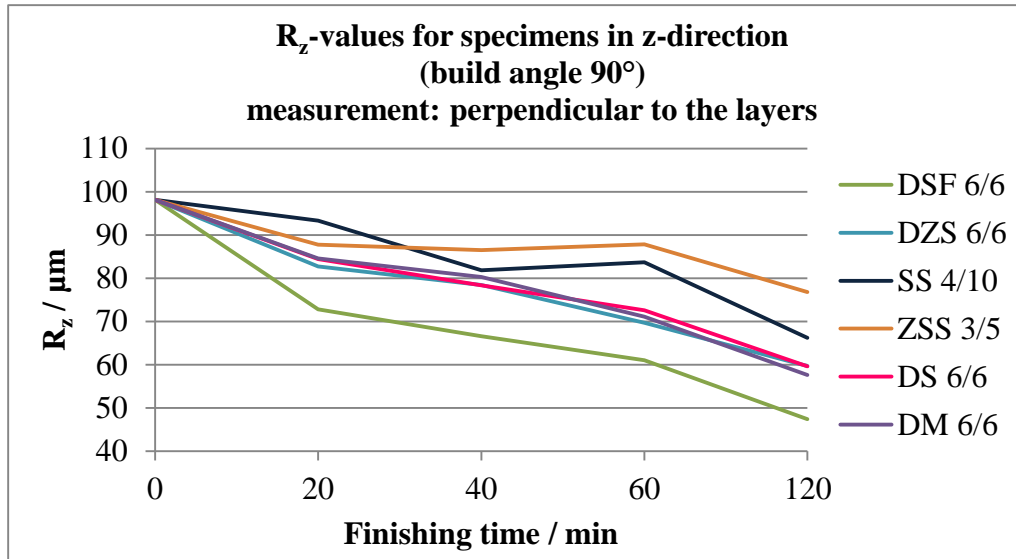


Figure 4: R<sub>z</sub> Values for Specimens with a Build Angle of 90°

The R<sub>z</sub>-value of the untreated specimens is ca. 98µm. Over the course of a 120-minute finishing process, the abrasive ZSS 3/5 displays the least reduction in surface roughness. The abrasives DZS 6/6, DS 6/6 and DM 6/6 show almost identical results with a 41% reduction in the surface roughness over the same period, resulting in an R<sub>z</sub>-value of 58 µm after 120 minutes. It should be mentioned here that, according to the manufacturer, the grit type DM 6/6 should be less abrasive than the DZS 6/6 and DS 6/6 [11]. The most effective abrasive medium in these experiments was the grit type DSF 6/6. After a finishing time of only 20 minutes, the average height of the surface profile had sunk by 26%, from 98 µm to 73 µm. After a 120-minute process, an R<sub>z</sub>-value of 47 µm was reached, meaning that the starting value had been effectively halved.

Above all, selecting the proper parameters for the FDM-process is necessary in order for the finishing treatment to be successful. This can be confirmed by comparing various abrasives and finishing times used on component surfaces which were constructed at a build angle of 0° (see Figure 5).

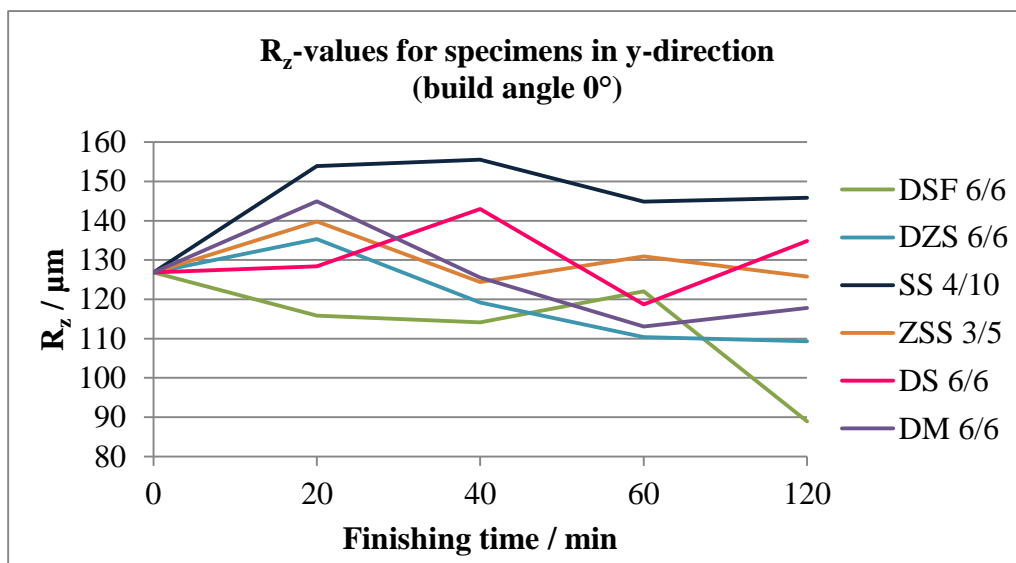
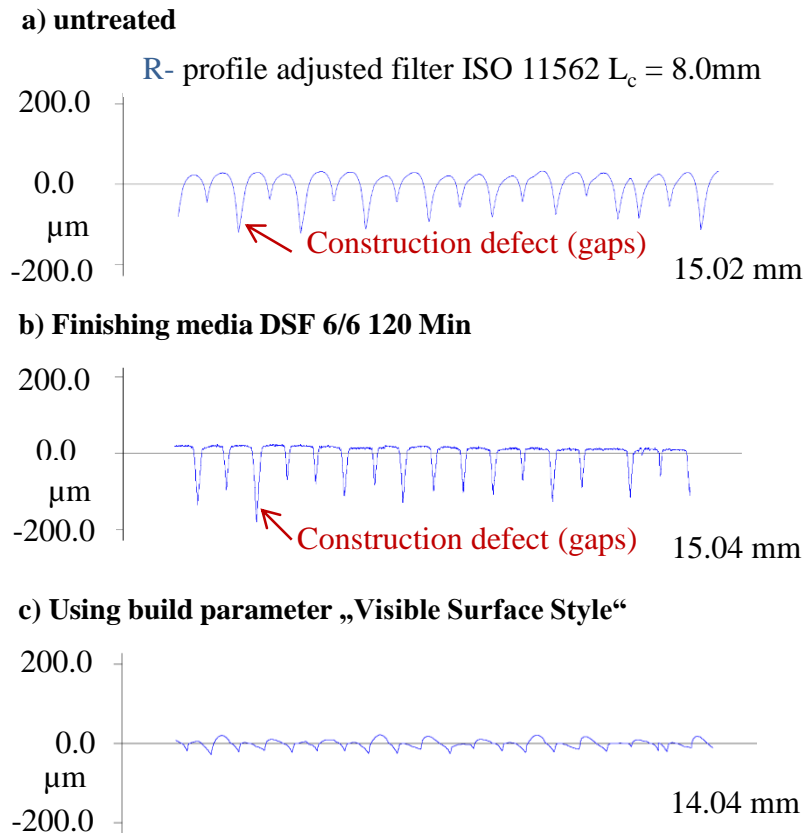


Figure 5: R<sub>z</sub> Values for Specimens with a Build Angle of 0°

The lines in the diagram in Figure 5 provide no clearly information about the effectiveness of the different abrasive grit types, as the component surfaces feature construction defects. These defects are characterized by gaps between the strands of the grid pattern, and result in the surface profiles shown in Figure 6 a) und b).



**Figure 6: Surface Profiles**

In Figure 6 a), pair formation, consisting of 2 polymer filaments in the outermost building layer, can be noted; this pair formation causes gaps to appear between neighboring polymer strands. Optimization of the surface quality is therefore only possible by adjusting the process parameters. For this purpose, the FDM manufacturer Stratasys has introduced the process parameter “Visible Surface Style” in the newest version of their Insight software, with which the distance between strands can be independently varied for strands which are on the  $0^\circ$  component surface [13]. By choosing a negative distance between the polymer strands of the grid pattern, the existing gaps between the strands can be avoided and the surface profile in Figure 6 c) can be generated. For this profile, the height of the surface roughness  $R_z$  is, with an average value of  $40\ \mu\text{m}$ , significantly below the original value for untreated specimens.

The resulting average surface roughness for specimens constructed at a  $90^\circ$  build angle are displayed in Figure 7; the graph shows the surface roughness after being finished using the grit types DS 6/6 and DM 6/6 and at speeds of 200 and 250 rpm.

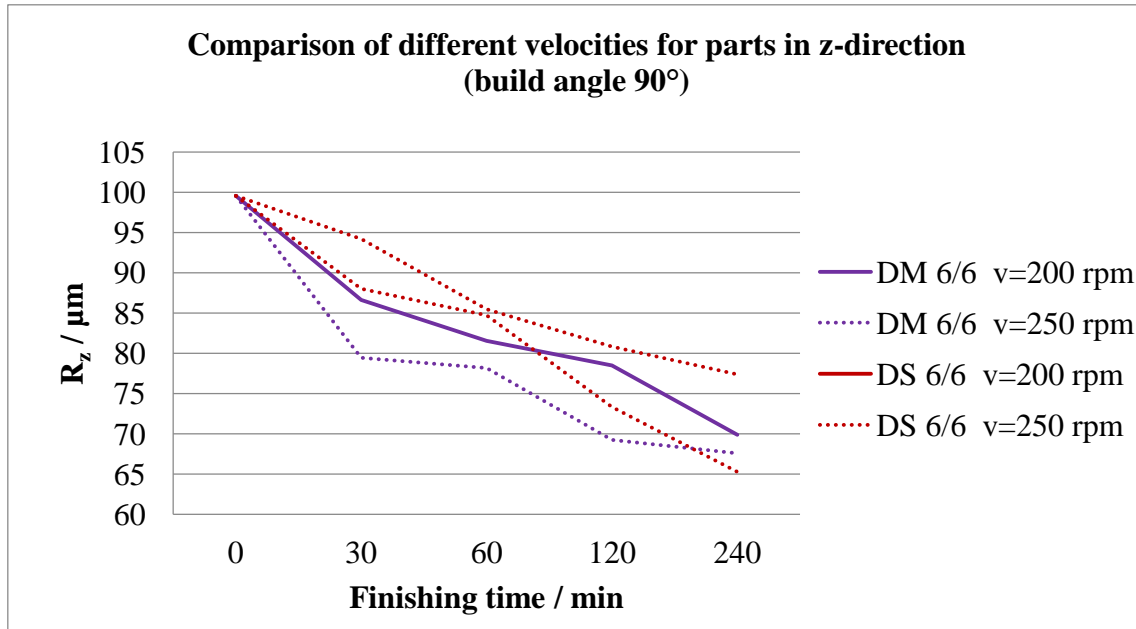


Figure 7: Finishing Media DM 6/6 and DS 6/6

Reducing the speed by 20%, to 200 rpm, results in a smaller reduction in the average surface profile height over time for both grit types; however, the effectiveness of the abrasives, as compared to the higher speed, is reduced by a maximum of 10%. Thus, even for components which require particularly gentle treatments due to delicate or fragile structures, positive finishing results can still be achieved at reduced speeds.

### Finishing Effects for Complex Part Geometries

For industrial applications, components frequently feature delicate structures and complex geometrical forms with cavities or indentations. The FDM process is suitable for producing complex structures that cannot be produced by traditional injection molding [3]. For a post-processing surface treatment, however, the complexity of the components presents several challenges. Among these are sharp edges and corners which may be rounded off after the finishing process due to the continuous material removal; these challenges also include deeper-lying surfaces, such as those within grooves, notches or other such indentations, which are more difficult for the grit to reach.

An examination of the effectiveness of various grit types for reaching indentations and cavities was carried out by applying a finishing process to specimens with 8-mm-deep grooves of varying widths. The grooves were open at one end. The abrasive effectiveness of the grit type DSF 6/6 is shown in Figure 8 for 8- and 10-mm-wide grooves, compared to its effectiveness on exposed surfaces.

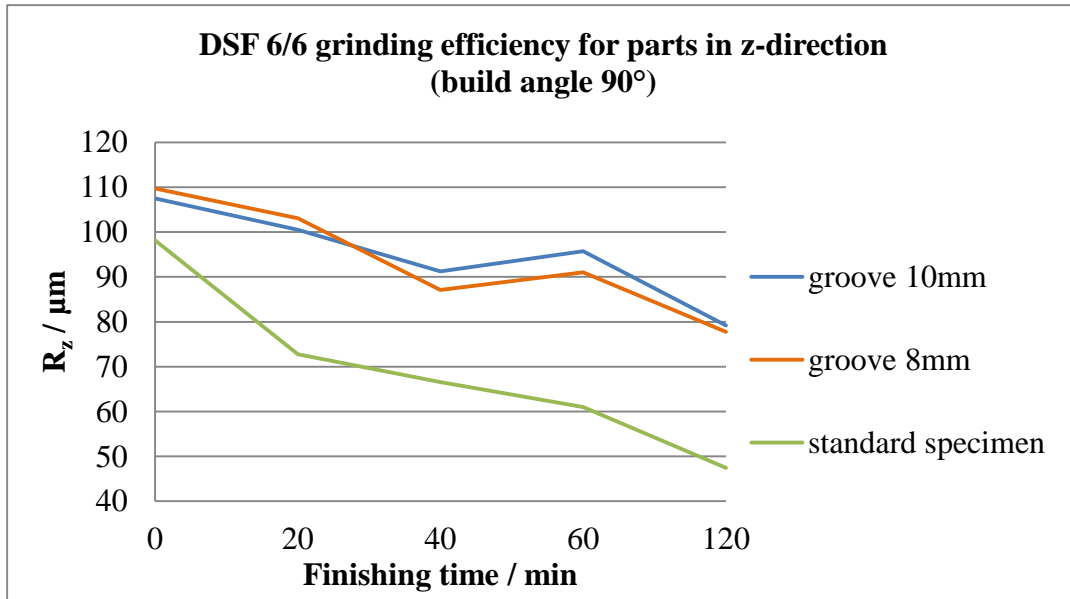


Figure 8: Grinding Efficiency for Parts with a Build Angle of 90°, Treated with DSF 6/6

Figure 8 allows us to see clearly that the grinding efficiency of the grit on an exposed surface is notably better than in indentations and cavities. Because of fluctuations in the construction process as well as the possible influence of edges in deeper areas of the groove, the reference values for the grooved specimens are, at 108  $\mu\text{m}$ , some 9% higher than the standard specimen value of 98  $\mu\text{m}$ . When examining the grinding efficiency for standard specimens, a 38% reduction in the average surface profile height can be observed after 60 minutes; for the same period of time, the average surface profile height is reduced by only 15% in indentations and cavities. After 120 minutes, the  $R_z$ -value is reduced by 52% for a standard specimen, while for a grooved specimen, the reduction is only 26%.

We can thus conclude that the grit does, in fact, work to reduce surface roughness in indentations and cavities; however, a more-than-50% reduction in efficiency, as compared to that for exposed surfaces, must be taken into account here. For indentations or hollows that have identical or smaller dimensions than the grain length of the chosen abrasive media, no finishing effect can be observed. In addition, the use of triangular grains leads to blockage buildup of the grit within grooves. The specimens shown in Figure 9 display grit blockages in grooves which are, in fact, 1.7 times wider than the grain length. Cylindrically shaped grains can also result in buildup within grooves; these blockages are generally shorter than twice the grain diameter.

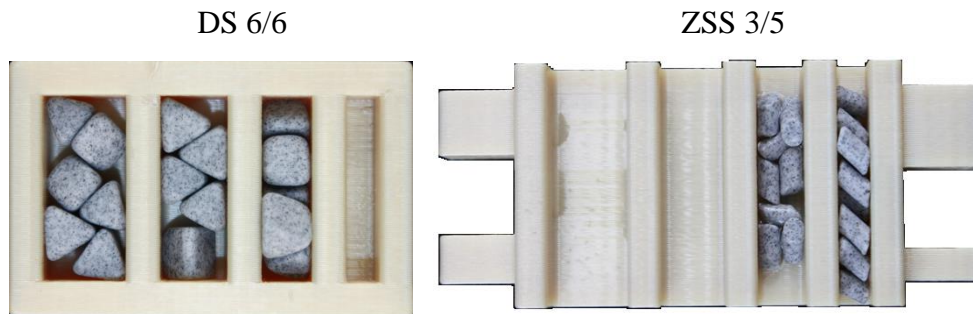
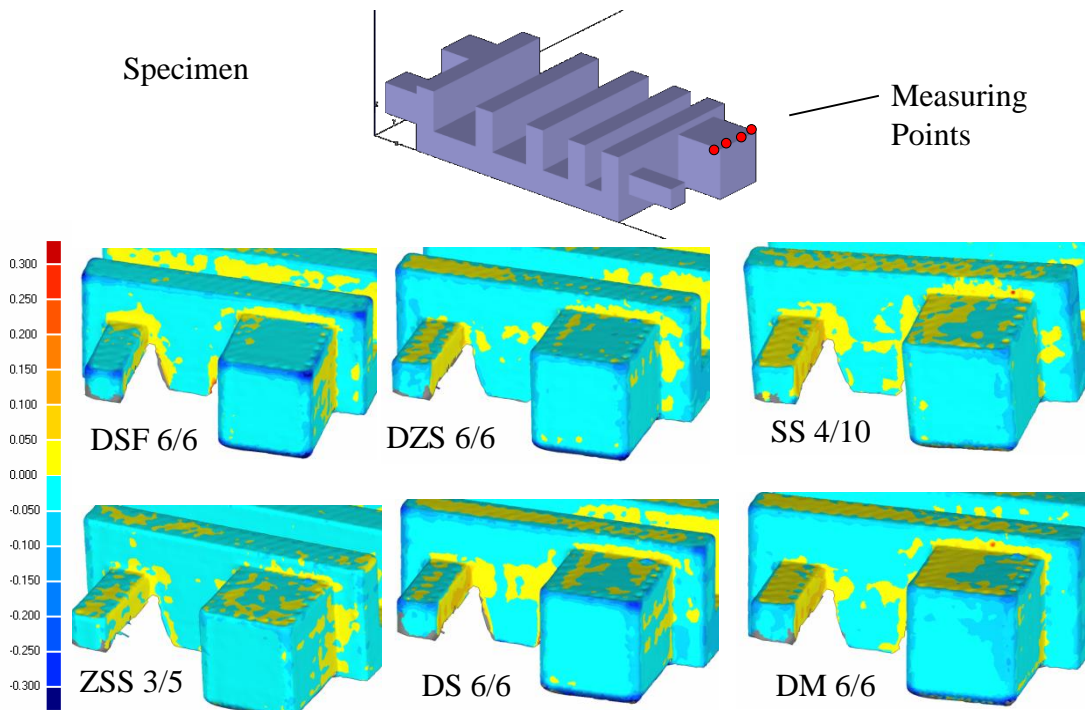


Figure 9: Buildup Effects in Grooves

The use of grooved specimens in which the grooves were closed at both ends displayed a significant reduction in effectiveness of the finishing process as compared to open-ended grooves. As a result of the groove being closed at both ends, the flow of grit in the lower part of the groove is so far reduced as to effect only a 10% reduction in the average surface roughness  $R_z$  after a 120-minute finishing process. This value is also only applicable for 10mm-wide grooves; narrower grooves exhibit almost no detectable change in surface roughness.

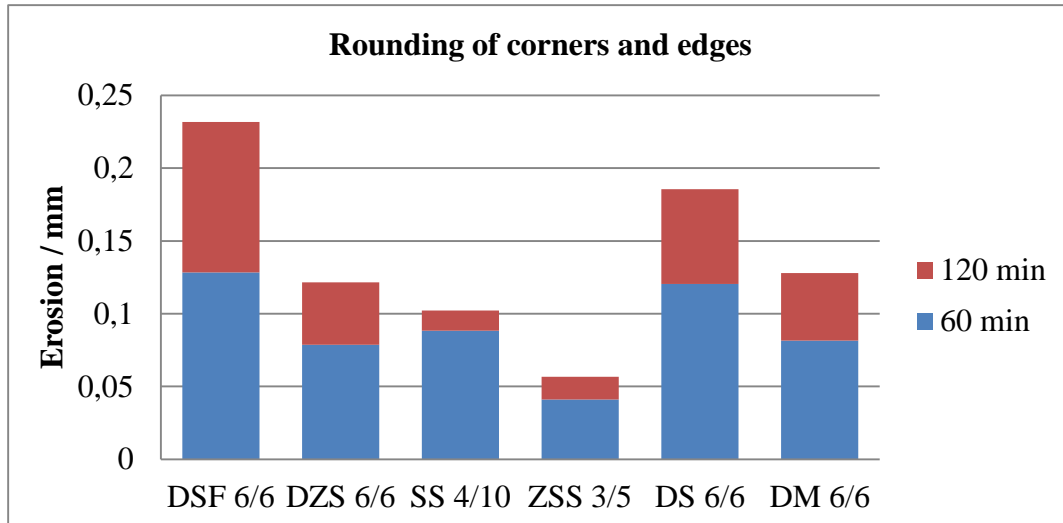
In contrast to indentations or cavities, sharp edges and corners are in danger of increased material removal. In order to investigate the influence of the chosen grit type on increased material removal at edges and corners, components with rectangular recesses were added to the finishing process. The parts, shown in Figure 9, were produced by an FDM process lying flat on the building platform. This building orientation results in areas at the top of the recesses (red dots in Figure 10) with comparatively sharp edges for an FDM-produced component.



**Figure 10: 3D Measurement of the Part Geometry**

The colored images in Figure 10 are the result of a three-dimensional measurement using a 3-D scanner; they show sections of the specimens after a finishing time of 120 minutes with the various finishing media. Based on a comparison of the measured dimensions before and after the finishing process, the amount of material removed has been expressed by gradations in color: the darker the color, the more material has been removed. The grit types DSF 6/6 and DS 6/6 in particular exhibit increased material removal in the corners; these grit types also displayed the highest grinding efficiency. For the grit type ZSS 3/5, which showed the lowest abrasive effectiveness, the material removal observed in the corner areas is very slight. Figure 11 shows the amount of material removed along a series of measurement locations (upper edge in Figure 10) after 60 and 120 minutes finishing time.





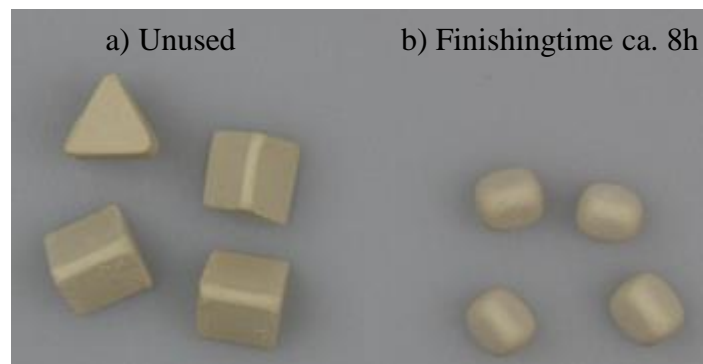
**Figure 11: Rounding of Corners and Edges after 60 and 120 Minutes**

The measured values in Figure 11 show significantly more material removal for the grit type DSF 6/6 in comparison to the DM 6/6 grit. The evaluation of the average height of the surface profile for the different grit types in Figure 4 showed only slight differences in grinding efficiency between these two types; therefore, the choice of which grit type to use for this finishing process should always be guided by the differentiation between required part quality and geometrical exactness.

### **Summary and Outlook**

The use of grinding processes offers one possibility of smoothing FDM-components produced using Ultem\*9085. Mass finishing processes offer the advantage of a high degree of automation and can be used, after suitable adjustment of the process parameters, for parts with varying geometrical forms [12].

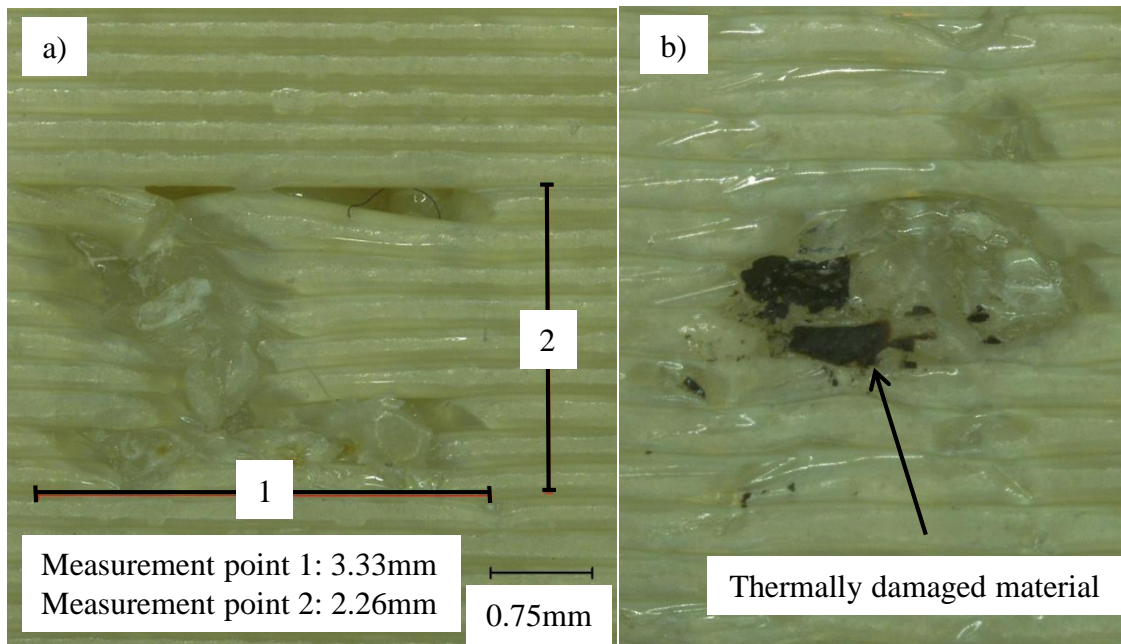
The use of grains with a triangular prismatic shape and with roughly the same side length for the base and the height have proved to be particularly effective for processing FDM-parts of Ultem\*9085. Additionally, increasing finishing times result in a continual decrease in the surface roughness  $R_z$  values. However, significant rounding on edges and corners can be observed here both for increasing finishing times and when using aggressive abrasive materials. In particular, the use of the strongly abrasive grit type DSF 6/6 in a disc finishing system leads to serious wear on the grains themselves after several hours of use (see Figure 12).



**Figure 12: Erosion of the Finishing Media**

The grinding efficiency of the grit in indentations or cavities, such as grooves, must be considered a critical factor. In doing so, possible restrictions on the movement of the grains should first and foremost be prevented; above all, better grinding efficiency can be achieved in open-ended grooves, rather than in grooves which are closed at both ends. The ability of the grit to enter these cavities depends, of course, on the size of both the grains and the cavity; at the same time, however, blockages of the grains tend to build up, meaning that, even in cavities which are theoretically wide enough, only limited grinding efficiency is possible.

A surface comparable to, for example, those resulting from an injection molding process will be difficult to achieve, if not impossible, merely by using finishing processes. The process parameters of the FDM process have a substantial influence on the surface quality; in addition, manufacturing defects also contribute to irregularities in the part surface, as can be seen in Figure 13.



**Figure 13: Manufacturing Defects on the Part Surface**

Manufacturing defects, which are characterized by irregularities in the surface structure of FDM components, typically cause cavities in the part. As these cavities cannot be closed by a finishing process and as material removal from the rest of the surface is both economically inefficient as well as technically impractical, additional methods of improving surface quality require further consideration. Here, coating as well as combination coating-finishing processes offer highly promising possibilities of smoothing the surface of FDM-produced Ultem\*9085 parts.

## References

- [1] T. Wohlers: „Wohlers Report 2013 – Additive Manufacturing and 3D Printing State of the Industry“, Annual Worldwide Progress Report, 2013
- [2] A. Gebhart: „Generative Fertigungsverfahren / Rapid Prototyping – Rapid Tooling – Rapid Manufacturing“, Carl Hanser Publisher, München 2007
- [3] B. Wendel: „Prozessuntersuchung des “Fused Deposition Modeling““, Dissertation, Friedrich-Alexander-University of Erlangen-Nürnberg, 2009
- [4] A. Bruschetto, V. Giordano, F. Venaioli: „3D roughness profile model in fused deposition modelling“, Rapid Prototyping Journal, Vol. 19 No. 4, pp. 240-252, 2013
- [5] Stratasys – Smoothing FDM Parts  
<http://stratasys.com/applications/finishing/smoothing-fdm-parts>
- [6] A. Bagsik, V. Schoeppner, E. Klemp: “FDM Part Quality Manufactured with Ultem\*9085”, 14<sup>th</sup> International Scientific Conference on Polymeric Materials, September 15. – 17.2010, Halle (Saale)
- [7] Jenoptik – Poster Surface Parameters  
[http://www.jenoptik.com/cms/jenoptik.nsf/res/Poster\\_Surface\\_parameters\\_EN\\_10037103.pdf/\\$file/Poster\\_Surface\\_parameters\\_EN\\_10037103.pdf](http://www.jenoptik.com/cms/jenoptik.nsf/res/Poster_Surface_parameters_EN_10037103.pdf/$file/Poster_Surface_parameters_EN_10037103.pdf)
- [8] B. Vasudevarao, D. P. Natarajan, M. Henderson, A. Razdan,: „Sensitivity of RP Surface Finish to Process Parameter Variation“, Proceedings of Solid Free Form Fabrication, Austin TX, USA, pp. 252-258, 2000
- [9] Klaus-Peter Müller: Praktische Oberflächentechnik; Vieweg Publisher, Braunschweig 2003
- [10] Stratasys – Mass-Finishing  
<http://stratasys.com/applications/finishing/mass-finishing>
- [11] Otec – Media  
<http://www.otec.de/en/media.html>
- [12] Rösler – Vibratory Finishing  
<http://www.rosler.info/anwendungsgebiete/gleitschlifftechnik/entgraten/>
- [13] Stratasys – Insight Software 8.0
- [14] DIN EN ISO 4287: Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Tastschnittverfahren – Benennungen, Definitionen und Kenngrößen der Oberflächenbeschaffenheit