Finishing of ABS-M30 Parts Manufactured with Fused Deposition Modeling With Focus on Dimensional Accuracy

M. Fischer[1,2]; V. Schöppner[1]

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

REVIEWED

Abstract

Fused Deposition Modeling (FDM) parts are prone to process-related rough and wavy surfaces with stair-stepping effects whenever the parts produced have sloped or rounded geometries. These stair-stepping effects can be reduced by using a smaller slice height, but complete elimination is not possible. In this paper, FDM parts manufactured with the material ABS-M30 are finished using mass finishing methods. The mass finishing is done with a trough vibrator, which is comparatively gentle to the parts in comparison to other mass finishing technologies. The analysis discusses the surface-smoothing effect of finishing time and intensity on various part sizes and build orientations. In addition, the dimensional accuracy of the parts after the finishing process is examined.

Introduction

Additive manufacturing processes make it possible to directly convert a 3D digital CAD model into a physical component. In contrast to formative or subtractive manufacturing processes, which create the desired shape by re-forming the initial material or by removing material from the initial form, additive manufacturing produces components by repeatedly adding volume elements to the part being built. This technology enables rapid production of prototypes and offers designers new creative freedom when developing end products. Fused Deposition Modeling (FDM), which belongs to the category of extrusion processes, offers one possibility of employing additive manufacturing. [1] [2]

The process steps necessary when using FDM units such as those from the company Stratasys can be divided into three areas: data preparation (creating a build file), job preparation (prepping the machine), and the building process itself on the FDM unit. The 3D CAD model, available as a .stl file, is sliced into layers using the build-preparation software Insight. This software also calculates any necessary supporting structures and the tool path parameters. Afterwards, the prepared data is sent by the software to the control center, which then determines the position of the part within the build chamber. The control center then sends the preprocessed and calculated data, packaged as one “print” job, to the FDM machine unit.

The initial building material is a spool of thermoplastic polymer thread which has been placed in the machine. This support material is distinct from the material which is used later to build the part; the extrusion head switches between the two materials during the build process. A schematic representation of the FDM process is shown in Figure 1.

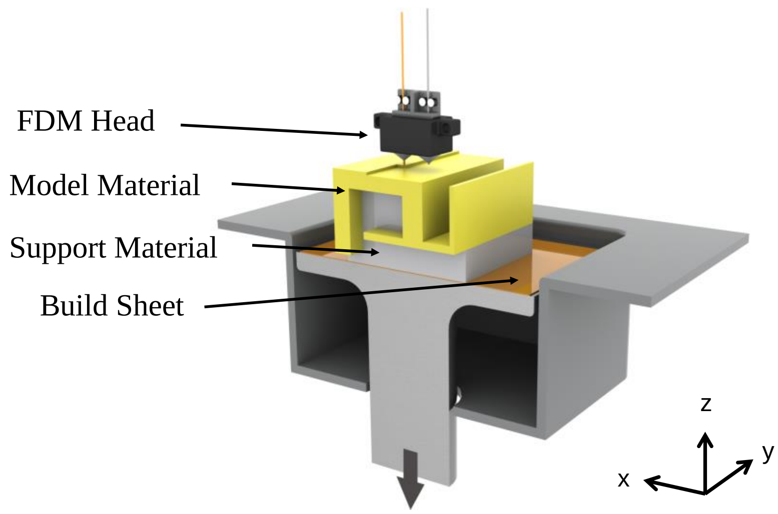


Figure 1: FDM Process

Both the part material and the support material are fed into the heated FDM extrusion head. In the extrusion head, the material is liquefied and pushed out through an extrusion tip. The material is applied at defined locations in 2-dimensional space by the extrusion tip and by the FDM head, which can move in the X and Y directions. After completing one part layer by applying multiple adjacent ribbons of melted material, the build platform is lowered in Z-direction to make space for the next layer; this process is repeated until all layers of the part have been built. Any support material can be removed after the build process, either by simply being broken off or by being dissolved in a lye solution. [2]

In addition to its many advantages, such as the production of complex part structures, and the ability to dispense with product-specific tools for small-series production, Fused Deposition Modelling nevertheless offers many process-related challenges as well. These include the geometric exactness of the parts produced, and in particular the quality of part surfaces. As a result of the layer-by-layer build process and the placing of adjacent polymer strands, parts produced using FDM exhibit rough and wavy surface structures with stair-stepping effects at edges and corners [4]. The FDM machine manufacturer Stratasys offers the possibility of producing parts from, among other materials, ABS-M30 with varying layer heights of 0.127 mm (0.005 in.), 0.178 mm (0.007 in.), 0.254 mm (0.010 in.), and 0.330 mm (0.013 in.) when using the Fortus 360mc, 400mc, or 900mc printer units. Each layer thickness requires a corresponding tip diameter, which must be consistent throughout the print job due to system constraints. The tip diameters decrease as the layer thickness decreases and have labels ranging from T20 (for up to 0.330 mm layer thickness), to T16, T12, and lastly down to T10 (for 0.127 mm layer thickness). By increasing layer thickness, the build time can be shortened; however, this also leads to more prominent stair-stepping effects, which in turn reduces the exactness of the surface structure. [3] [13]

In order to improve the visual aspects of parts, post-processing of the surface should be carried out on the part. Stratasys offers a chemical post-processing option for this purpose by the use of the Finishing Touch Smoothing Station, with which the surface of parts from the ABS family can be smoothed. Should chemical post-processing of the parts be undesirable, which is quite possible depending on the eventual application, mechanical finishing processes like vibratory grinding or abrasive blasting offer possibilities of improving part surface quality; this paper will examine the influence of vibratory finishing processes on the surface quality of ABS-M30 parts produced by FDM. In addition, there is a short discussion of abrasive blasting; however, this process is not discussed in detail here due to problems with reproducibility.

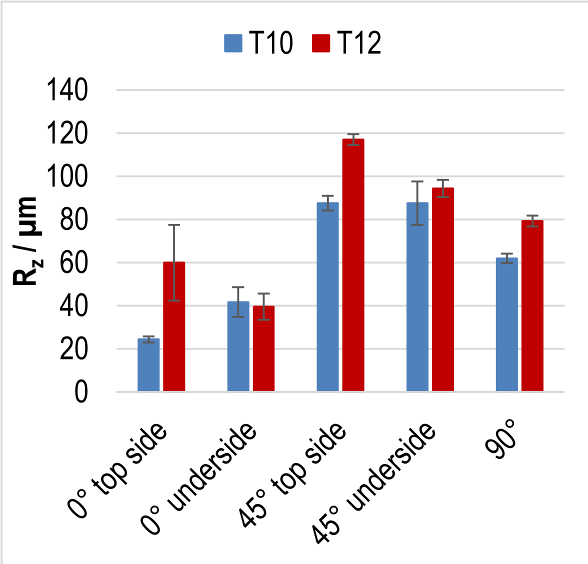
Materials and Methodology

FDM parts with layer thicknesses of 0.127 mm (T10 tip) and 0.178 mm (T12 tip) were produced for this purpose using a Fortus 400 mc 3D FDM printing unit from Stratasys. The following vibratory grinding process was carried out using an RMO 210/530 TE-30 trough vibrator from the company RÖSLER Oberflächentechnik GmbH. The abrasive blasting was performed with a blasting station from the manufacturer Normfinish, type JUNIOR EP 0275, with glass spheres (diameter 70-110µm) as the finishing media. Furthermore, the blasting tests were carried out by hand, meaning that results were strongly dependent up on the available work force; thus they should only be used for a general comparison. For the examination of the surface structure as well as the dimensional accuracy of the parts, a mechanical profilometer from Jenoptik (model: Hommel ETAMIC T8000) was used in addition to a Colibri Multi 3D optical measuring system from Fraunhofer Vision. [5] [10]

Surface Quality of FDM-Produced Parts of ABS-M30

Due to the production process, parts produced in a FDM process display notably anisotropic mechanical properties [6]. Analogously to this quality of the mechanical properties, the surface characteristics also exhibit differences with respect to the build and the measurement directions [8]. Differing surface qualities are obtained for different sections of the part, which depend on the build process parameters, contact to the supporting material, and the orientation of the part itself. Characterization of the surface quality can be done by various measuring processes, such as different optical or mechanical methods. One mechanical method is the use of a stylus-equipped contact profilometer; important characteristic values, such as the average surface roughness R_z, can hereby be determined for a two-dimensional surface profile according to DIN EN ISO 4287. [7] [14]

In the following, the test specimens of ABS-M30 are produced with the respective Standard Tool Path parameters according to the Insight 9.0 software and with the function “Visible Surface Style: Enhanced”. Further, specimens with a layer thickness of 0.127 mm (T10 tip) and those with a thickness of 0.178 mm (T12 tip) are considered separately for purposes of comparison. An overview of the measured average surface roughness values R_z is shown in Figure 2 for varying layer thickness and build orientation.



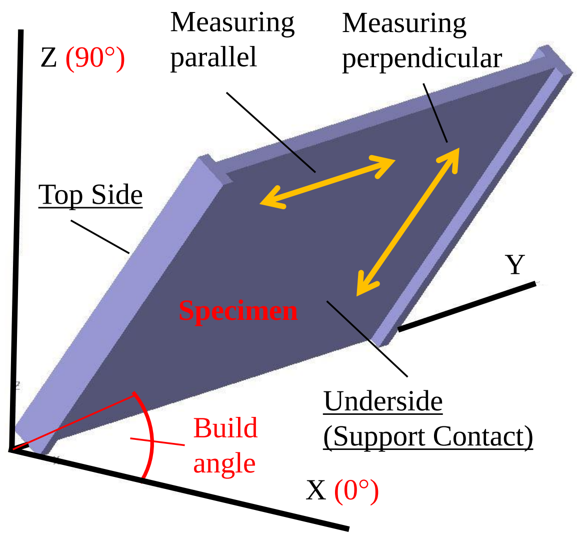


Figure 2: Average Height of Profile R_z for Different Slice Heights (0.127mm/T10 tip and 0.178mm/T12 tip), Build Orientations and Part Surfaces

The schematic representation of the specimen in Figure 2 shows a complex relationship between the measuring direction, the side of the part which is measured, and the build orientation of the surface being measured. The layer-by-layer building technique, typical of FDM, is regarded here as a periodic profile, for which, according to DIN EN ISO 4288 surface measurements should be carried out perpendicular to the furrows created during production in order to obtain reliable measuring results. This entails measuring perpendicular to the layer structure, which is shown in Figure 2 as “Measuring Perpendicular”. In the bar chart in Figure 2, significant differences in surface quality with relation to build orientation and layer thickness are clearly visible for specimens of dimensions of 75x50x20 mm, which have not been post-processed. For a build orientation of 45° in particular, which is usually heavily beset by stair-stepping effects, smaller layer thicknesses of 0.127 mm result in a reduction in surface roughness of more than 20% in comparison to the same part when produced with a layer thickness of 0.178 mm. The R_z value from part sections which are in contact with the support material, in contrast, show no significant effects of varying layer thickness.

Surface Finishing through Vibratory Grinding

The term “vibratory grinding” derives from the principles behind the process, in which the grinding action is generated by relative movement, caused by machine vibration, between the part and the abrasive media. In DIN 8580 vibratory finishing processes are categorized with the primary category “Separation Methods” [9]. The implementation of the vibratory grinding principle can entail drum-based tumble grinding, classic vibratory grinding, centrifugal-force-based grinding, or wet grinding. For FDM parts made of Ultem*9085, experiments have already been carried out to which investigate the effects of disc grinding units, which operate on the basis of centrifugal force; increased wear on the edges and corners has been noted when using this option. [11]

The experiments carried out here were done to analyze the effectiveness (= reduction in roughness / finishing time) of a vibratory grinding process on ABS-M30 specimens for various grinding times and grinding intensity levels. The specimens as well as the ceramic abrasive media used are shown in Figure 3 below.

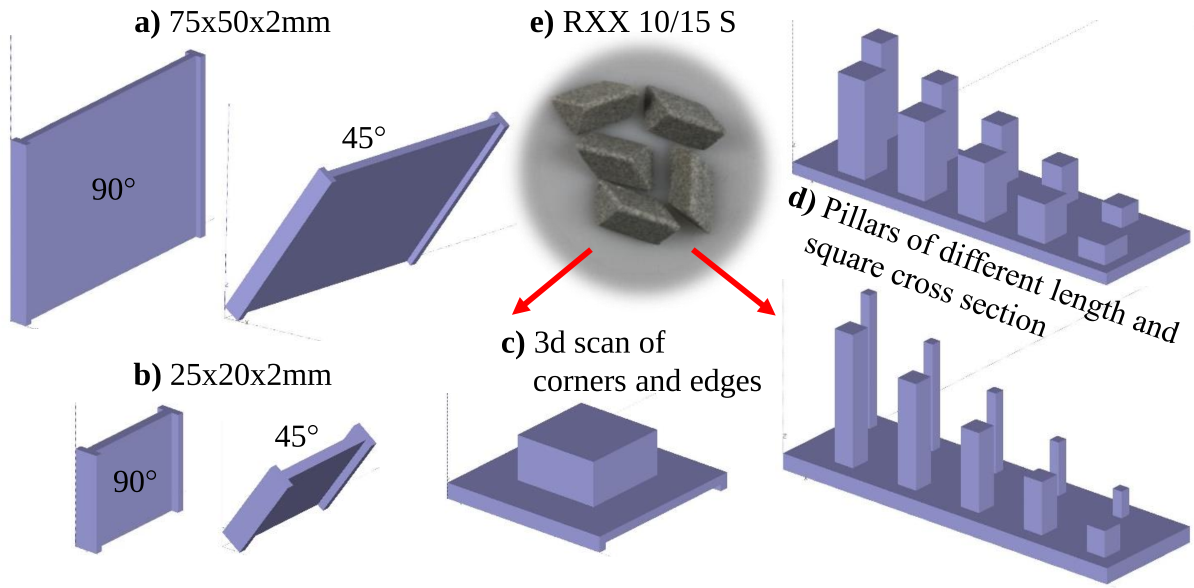


Figure 3: Finishing Media and Specimen Design

The use of two different-sized specimens (cf. Figure 3 a) and b)) with the same geometry should allow conclusions to be drawn about the influences of part size (particularly in the case of small parts) on the grinding process. The wear on corners and edges due to the grinding process will be analyzed later using three-dimensional measurements of the rectangular specimens (cf. Figure 3 c)). Each side of the specimen should be plane; the overhanging faces on the ends of the specimens are intended to prevent the parts from adhering to the wall of the grinding unit. The specimens with pillars of varying lengths and widths (cf. Figure 3 d)) are used to characterize the resistance of the parts against forces to which they are subjected during the grinding process. The grinding media used consist of diagonally cut, triangular-faced rod segments of ceramic; these segments, model type RXX 10/15 S, are from the company RÖSLER Oberflächentechnik GmbH and have face side dimensions of 10x15 mm (cf. Figure 3 e)).

In the following, the surface roughness of specimens produced with 90° and 45° build orientations will be examined under different FDM build conditions and for various grinding process parameters. Due to the build-angle-dependent surface structures resulting from the process itself, the results are continually differentiated based on build orientation. Figure 4 shows the R_z values for specimens built with a 90° build orientation and with a surface area of 75x50 mm, in relation to the layer thickness, grinding time, and grinding intensity.

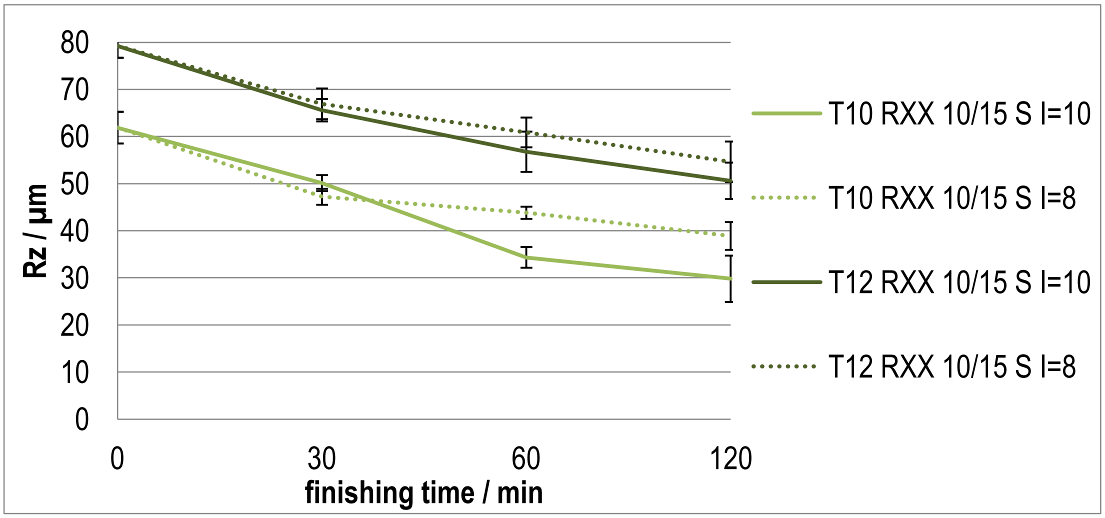


Figure 4: Specimen Size 75x50x2 mm with 90° Build Orientation: Comparison of Different Layer Thicknesses and Finishing Intensity

Due to the lower layer thickness, the curves representing the T10 series show smaller roughness values. The parallel curves in Figure 4 show a constant effectiveness of this vibratory finishing process on parts with different layer thicknesses. Increasing the grinding intensity, which can be set at levels between 1 and 10 on the trough grinding machine with the help of a potentiometer, appears to result in a slightly better finish. After a grinding time of 120 minutes on intensity level 10, the average height of the surface roughness profile could be reduced by up to 50%, from 62 µm to 30 µm.

The results of a series of tests similar to those described above for specimens with the dimensions 25x20 mm are shown in Figure 5 below.

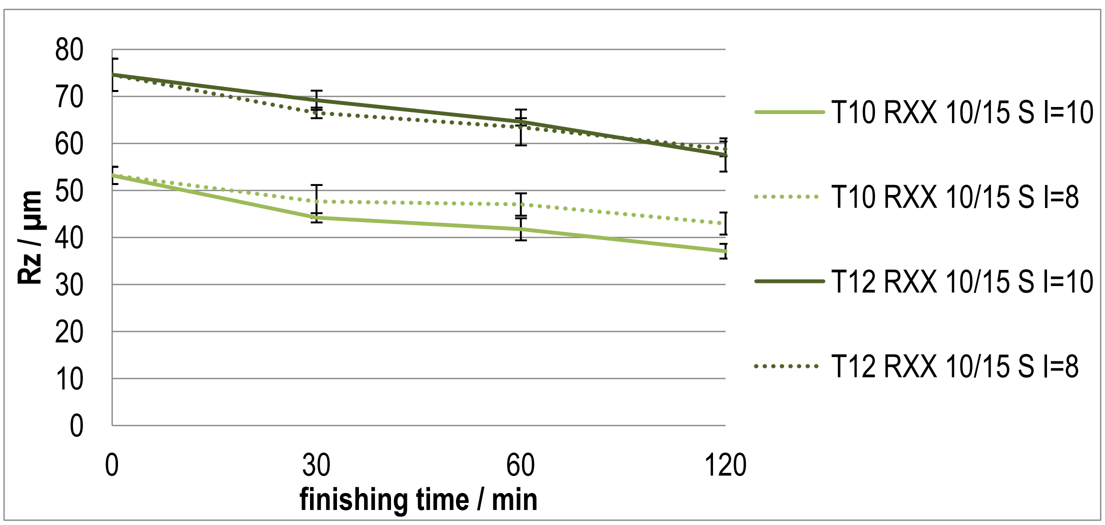


Figure 5: Specimen Size 25x20x2 mm with 90° Build Orientation: Comparison of Different Layer Thicknesses and Finishing Intensity

The relationship between the intensity level and different layer thicknesses has shown itself to be constant in this case as well. However, it is noteworthy in comparison to the larger specimens represented in Figure 4 that, here, the finishing process is less effective throughout the entire finishing period. Taking into consideration the somewhat lower initial values, the surface roughness is reduced by only 30%, from 53 µm to 37 µm, for parts with a layer thickness of 0.127 (T10 tip) and an intensity level of 10. One speculative reason for this difference could be the lower resistance of the smaller part to the grinding pressure of the finishing media, because smaller parts tend to move with the flow of the finishing media in the processing bowl. The influence of the finishing process on the amount of material separated from the specimen can be seen in Figure 6.

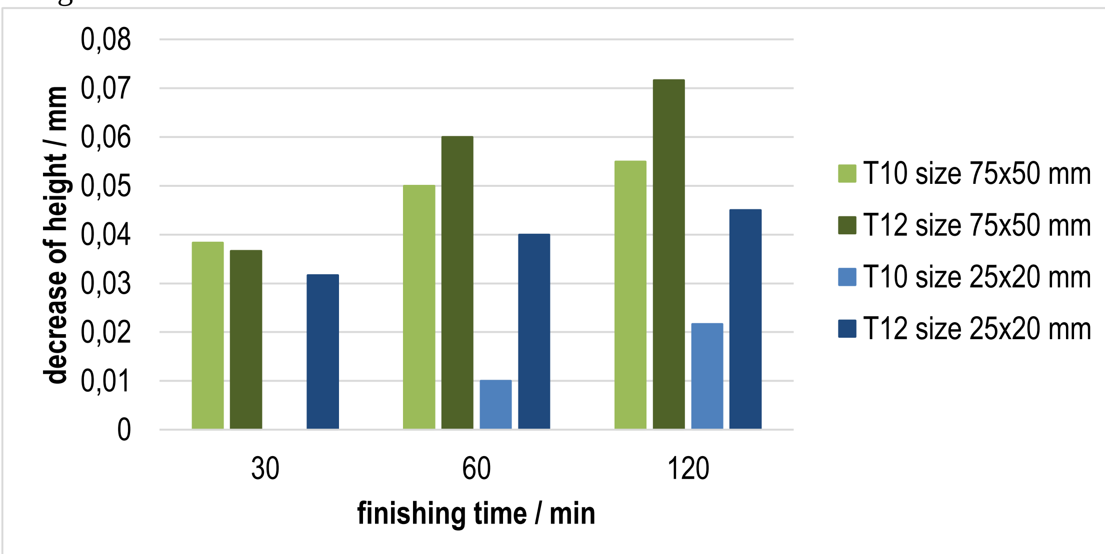


Figure 6: Material Removal for Specimens Built at 90° Build Orientation Using the Finishing Media RXX 10/15 S at Intensity Level 10

The material removal levels shown in the graph above were determined by measuring the specimen thickness with hand-held calipers after varying grinding times. The amount of material removed is the difference between untreated specimens and the specimens which were subject to the finishing process for a defined length of time; due to processing, material was removed from both sides of the finished specimens. As already noted when considering the grinding effectiveness, specimens with larger surface areas appear to exhibit more material removal than those with less surface area. Material removal from the larger T12-specimens was ca. 0.07 mm after 120 minutes. In this case, the part measured had a desired thickness of 2.00 mm; directly after production, this value was determined to be 2.07 mm, meaning that with material removal during finishing, the desired thickness was obtained. The T10-specimen with dimensions of 75x50 mm had a post-production thickness of 2.02 mm; in this case, after only 30 minutes of finishing, measurements showed material removal of some 0.04 mm, meaning a deviation downwards from the desired mass to 1.98 mm. This example serves to demonstrate that the length of the finishing process must be determined in relation to the initial and to the desired dimensions of the finished product in order not to negatively impact dimensional accuracy.

Figure 7 shows the change in average surface roughness R_z as a function of grinding time for parts with layer thicknesses of 0.127 mm and 0.178 mm.

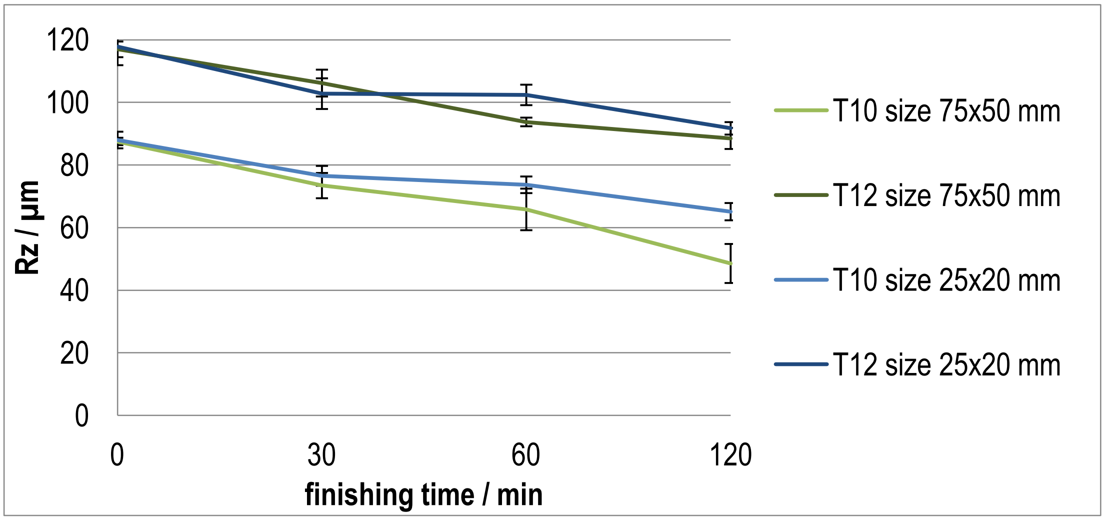


Figure 7: Average Height of Profile R_z in Relation to Finishing Time for Specimens with 45° Build Orientation, Using the Finishing Media RXX 10/15 S with Finishing Intensity Level 10 (measurement on top side, perpendicular to the layers)

For layer thicknesses of 0.178 mm (T12 tip), there are no significant differences apparent in the results for small and large parts (cf. Figure 7). In consequence of the pronounced stair-stepping effects affecting parts with a build orientation of 45°, the surface roughness could only be reduced by 20%, even after a 120-minute finishing process, from 118 µm to ca. 90 µm. For 45°-oriented specimens with a layer thickness of 0.127 mm (T10 tip), the initial R_z value (i.e., before finishing) of 88 µm is already below that of T12-specimens after a 2-hour finishing process. In this series of experiments, specimens with larger surface areas also showed themselves more responsive to the finishing process; after a finishing time of 120 minutes, an average R_z value of ca. 49 µm was observed. This translates to a reduction in surface roughness of more than 40% compared to the initial state. The results of material reduction from the 45°-oriented specimens are shown in Figure 8 below.

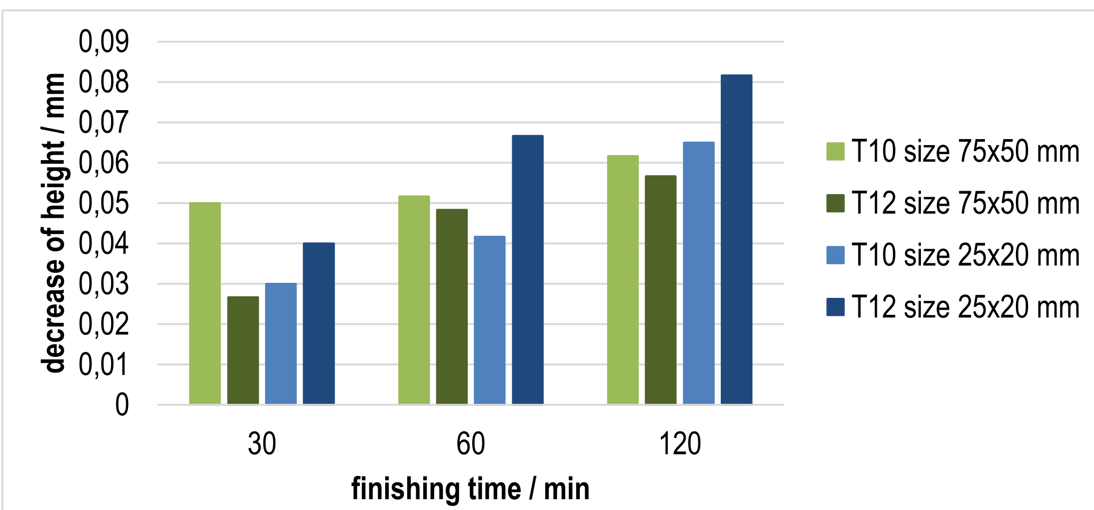


Figure 8: Material Reduction for Specimens with 45° Build Orientation Using the Finishing Media RXX 10/15 S with Finishing Intensity Level 10

Figure 8 shows increasing material removal as the length of the finishing process increases. Almost all of the specimens exhibit similar removal rates according to the respective finishing times. The poorer finishing effect seen in Figure 7 for parts with higher layer thicknesses cannot, therefore, be explained by lower levels of material removal; instead, it can be attributed to the more pronounced stair-stepping structure, which creates deeper furrows in the surface of the part produced.

A comparison of vibratory finishing and abrasive blasting with glass spheres (diameter 70-110µm) is presented in Figure 9.

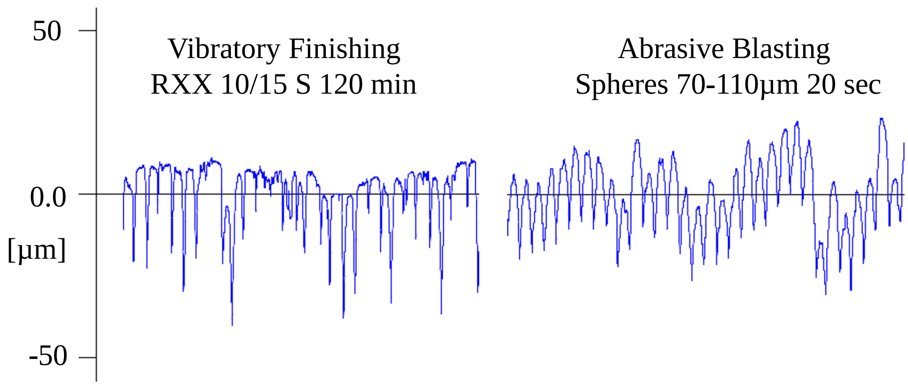


Figure 9: Surface Roughness for Parts With 90° Build Orientation (measurement perpendicular to the layers on top side, size 75x50x2 mm, T12 tip)

After a finishing time of only 20 seconds (abrasive blasting), the measured R_z value (51µm±4µm) is similar to the value after 120 minutes of mass finishing (51µm±4µm). At first this seems to be a promising result, but after analyzing the surface profiles after finishing (cf. Figure 9), it was observed that the blasting process not only grinds the part surface, but also removes material within surface troughs, resulting in no absolute change in overall roughness profile height. The vibratory finishing process smooths only the top of the filaments; therefore the results of abrasive blasting have to be taken with a grain of salt when focusing on smooth part surfaces.

Due to the nature of the process, vibratory grinding leads to mechanical stress on the parts. The analysis of FDM tensile testing specimens made of Ultem*9085 which had been finished on a disc grinder was not able, despite testing some specimens to destruction, to offer reliable conclusions about the influence of the finishing process on the characteristic mechanical values. Therefore, in order to attempt to characterize mechanical loading during the finishing process, specimens were created specifically for the test which featured several pillar-structures of varying length and with varying cross-sectional areas. The specimens were oriented in the build chamber such that these pillars were produced in the critical upright build direction (the Z-direction). [11]

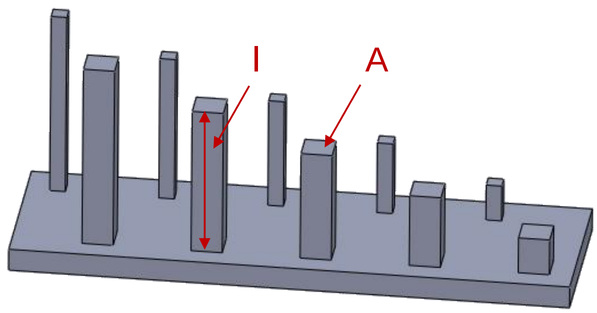


Figure 10: Analysis of Part Destruction after Grinding Pillar-Specimens

Based on the varying cross-sections and lengths of the pillars, the number of pillars broken off after a finishing process offers one possibility of drawing conclusions about the intensity of the mechanical loading for different grinding media, intensity levels, or grinding times. From a mechanical perspective, the pillars, as attached to the base, can be seen as cantilever beams. In a collision with the grinding unit components or other elements, the force applied to the pillar tip can be simplified as a bending moment in the support. Using the bending moment equation for a simple cantilever beam with a rectangular cross-section, a stress factor of A^2/l^3 can be determined with the following relationship: [11] [12]

$$\frac{A^2}{l^3} = \frac{4c_B}{E} \tag{1}$$

Here, A is the cross-sectional area (mm^2), l the length of the pillar (mm), E the Young's Modulus (N/mm^2), and c_B (N/mm) the spring constant of the cantilever. Figure 11 shows the percentage of intact pillars for 4 specimens after finishing in terms of this stress factor.

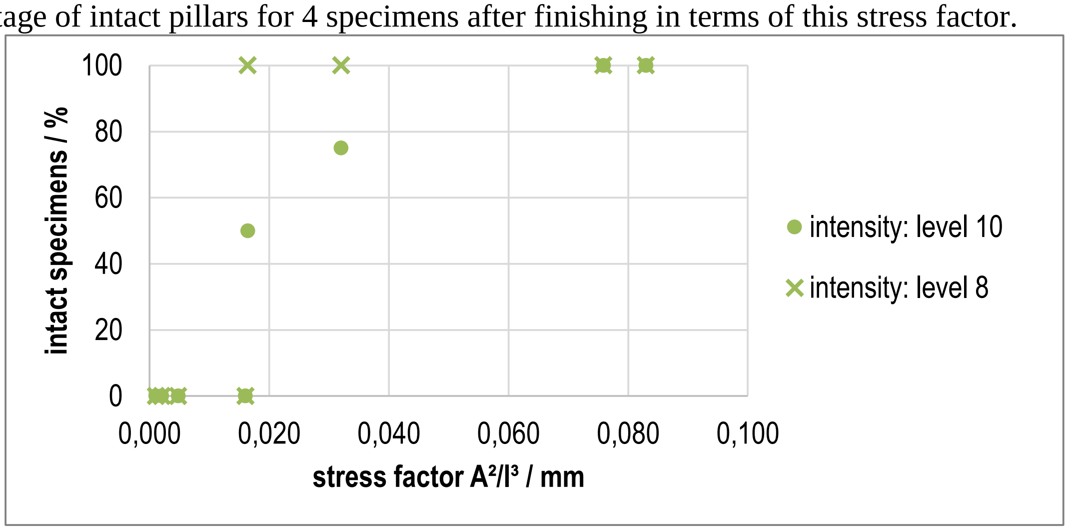


Figure 11: Intact Specimens Built with a T10 Tip after 120 Minutes Finishing Time with Grinding Media RXX 10/15 S

For a stress factor $A^2/l^3 > 0.016$ mm (meaning larger cross-sections in relation to length), there was no destruction registered for any of the specimens finished at intensity level 8. For higher grinding intensity (Level 10), part damage could be observed in the specimens starting at a stress factor of 0.032 mm. Thus, when using the abrasive media RXX 10/15 S, higher grinding intensity has a negative effect on part stability.

The influence of grinding time and intensity on the dimensional exactness as registered by three-dimensional measurements on a rectangular specimen is shown in Figure 12.

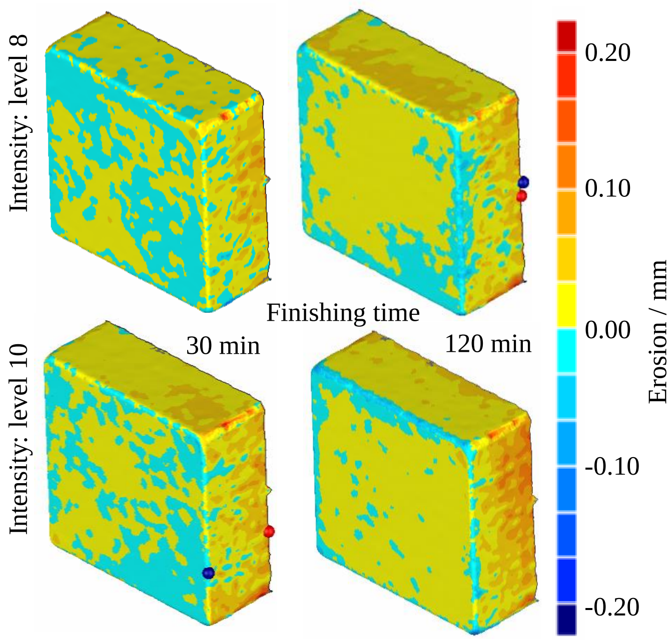


Figure 12: 3D Scan of Specimens Built with T10 Tip, Finished with RXX 10/15 S

The color changes seen on the specimen scans in Figure 12 represent local geometrical deviations from the desired dimensions in comparison to unfinished specimens. No measureable difference between intensity levels was observed here on the large surfaces when finishing parts with a layer thickness of 0.127 mm while using RXX 10/15 S. An examination of specimens with a finishing time of 120 minutes reveals increased material removal from the long edges related to higher intensity. At a mere -0.03 mm, however, this difference is very slight. At the corners of the specimens, scattered chamfering and rounding up to 0.1 mm was observed for finishing times of 120 minutes, which is significantly higher than average material removal levels. When using larger abrasive media, similar abrasive effects can be observed; however, corners and edges are much more rounded in this case.

Summary

An analysis of the surface structure of unfinished FDM parts made of ABS-M30 revealed smaller differences in surface roughness than initially expected for differing layer thicknesses of 0.127 mm (T10) and 0.178 mm (T12 tip). In particular for areas where the part is in contact with the support material, the process used exhibited no measureable difference between different layer thicknesses. The difference in resolution is, however, of great importance for part surfaces produced with a build orientation of 45°; here, an increase in average surface roughness R_z of more than 20% could be observed. Vibratory grinding has shown itself to be an especially mild finishing process with regard to rounding of edges and part damage. Lower grinding intensity is especially advantageous in order to minimize edge and corner rounding. When using the ceramic grinding media RXX 10/15 S, lower intensity levels result in a reduction in grinding effectiveness compared to the highest intensity level; this reduction is, however, slight. Thus, using lower grinding intensity not only offers advantages with respect to dimensional accuracy, but is no less advisable in terms of grinding effectiveness.

Acknowledgements

The authors want to thank all industry partners of the DMRC as well as the federal state of North Rhine-Westphalia and the University of Paderborn for the financial and operational support within the project "Analysis of the FDM Part Quality manufactured with ABS M30 with the focus on the toy industry".

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] I. Gibson, D.W. Rosen, B. Stucker: Additive Manufacturing Technologies; Springer, New York 2010

[4] A. Bruschetto, V. Giordano, F. Venaiali: „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", 14th 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

[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] M. Fischer, V. Schöppner: „Some Investigations Regarding the Surface Treatment of Ultem*9085 Parts Manufactured with Fused Deposition Modeling", Proceedings of Solid Free Form Fabrication, Austin TX, USA, pp. 805-815, 2013

[12] H. A. Richard, M. Sander: Technische Mechanik. Festigkeitslehre, Vieweg+Teubner (2008)

[13] Stratasys – Insight Software 9.0

[14] DIN EN ISO 4287: Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Tastschnittverfahren – Benennungen, Definitionen und Kenngrößen der Oberflächenbeschaffenheit