Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Considering machine- and process-specific influences to create custom-built specimens for the Fused Deposition Modeling process

Christian Schumacher[1,2]; Volker Schöppner[1]; Jonas Guntermann[3]

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

Abstract

Compared to conventional polymer processing technologies the material selection in the Fused Deposition Modelling (FDM) process is restricted. To expand the range of materials the requirements for the material properties and the semi-finished products (filaments) must be clarified. For this, a machine- and process-independent rating of the processability is necessary. The established standards for the tensile strength test apply to specimens with nearly isotropic mechanical properties. The FDM process generates anisotropic parts. The properties are mainly influenced by the machine quality and the data processing. It is not possible to test a material for FDM independently of the machine and the data processing. In this paper, machine and process-specific influences are investigated. Considering these influences, a custom-built specimen is created to test the tensile strength of the welding seams for polyamide 6. This procedure allows a machine- and process-independent rating of the processability in terms of tensile strength for different materials.

Introduction

The Fused Deposition Modeling (FDM) process is one of the most commonly used additive manufacturing processes. In this method, the semi-finished product, a filament of a thermoplastic polymer, is melted and forced through a nozzle. The continuous positioning of this nozzle allows the polymer to weld together strand by strand and layer by layer to produce a component. The energy for the welding of the individual strands largely results from the thermal energy of the deposited polymer melt and, if present, through a heated chamber.

It is desirable to be able to use a similarly wide variety of materials with this method as, for example, in the profile extrusion or injection molding technology. Therefore, the processing suitability of any thermoplastic polymer should be estimated based on the material properties or characteristics in advance of the processing. This is currently not possible because, in contrast to conventional methods, there is a lack of knowledge about the required and desirable material properties for processing by the FDM process. By gaining a better understanding of the process, a knowledge base should be created to increase the variety of materials that are available. This work is conducted in cooperation with the company ALBIS PLASTIC GmbH and under the NRW "Fortschrittskolleg Lightweight – Efficient – Mobile" (FK LEM).

With the aim of material development, this paper sets out to identify test methods and test specimens with the aid of which the suitability of various materials for the FDM process can be quantified. To evaluate the suitability, characteristic data are defined. The aim here is to be able to test the effects of modified material properties, isolated from other influences. The machine quality and data processing should, wherever possible, not have any effect on the results. In order to enable the selection and/or development of such specimens and test methods, the FDM process must be adequately understood. Any influences that occur must be identified and taken into account when designing the test methods and test specimens.

In this paper, process-specific influencing factors on the product are described. Subsequently, a specimen is designed and the corresponding test method is presented for assessing the weld seam strength. Based on this, the influence on the weld seam strength of a change in viscosity in fused deposition modeling is tested and evaluated for PA 6. The materials and the determined material properties have been supplied by our research partner ABIS Plastic.

Influencing factors in FDM

In the FDM process – as in every manufacturing process – there are certain influencing factors that affect the production result. Through these and the process itself, production-specific structures are formed in the part. The influencing factors can be divided up according to [Klo16, p. 10–14] into material-related, process-related and machine-related factors. The following chapter discusses the main influencing factors, orientated to this subdivision.

Influences from the material and the semi-finished product

Process-specific demands are made on the material used in the FDM process and also on the plastic filament used as the semi-finished product. The influences exerted by the material or material properties on the production result in the FDM process are at present not sufficiently well-known and need to be investigated. A sufficient understanding of the process and experience from conventional plastics processing processes serve to derive fundamental preconditions for the materials used and the properties of the semi-finished product. For example, in the classic FDM process, the material is converted into the molten state and fused. This means that only a thermoplastic material can be used.

No dirt particles must be present in the semi-finished product because of the specified part quality and the diameter of the nozzle used in the FDM process. Large dirt particles can block the nozzle and bring the process to a halt. It must also be ensured that the material is dry enough during processing. Any moisture can outgas during processing, leading to pressure peaks in the plasticizing unit, uncontrolled delivery of the plastic melt and foaming of the material. The semi-finished product must also have a constant cross-sectional area over its entire length. The reason for this is that the amount of plastic delivered in the FDM process is calculated via the controlled feed distance of the semi-finished product and the cross-sectional area contained in the software. If the actual cross-sectional area deviates from that in the software, the amount of plastic melt delivered in the process will not agree with the calculated quantity of delivered plastic and the part will be faulty. For the same reason, but also to avoid bubbles and blisters in the discharged plastic melt and defects in the final part, the semi-finished product must not contain any pores or voids.

The semi-finished product used in this research project is produced under laboratory conditions from fine pellets, taking account of the previously derived requirements. The quality of the semi-finished product is monitored via a visual examination of the transparent melt during processing and of the extruded product. Furthermore, the diameter and ovality are controlled by an inline laser measuring system of type Accuscan 5010 from the firm BETA LaserMike with several laser curtains. Adequate drying is carried out before extrusion into the FDM semi-finished product and FDM processing.

Influences from the process/data processing

The building of a part through the laying of strands next to and on top of one another as well as the sequence, direction and method of strand deposition have an influence on the production result. The manufacturing process is defined by the process principle and the set production parameters. The translational accelerations and velocities of the tool that have to be reached in the process as well as the melting performance of the plasticizing unit are subject to machine-specific limitations. Influences that are process or machine-related are sometimes directly connected. With an adequate understanding of the FDM process, factors influencing the production result are easier to comprehend. The following section will therefore briefly explain the principle of action of the FDM process and the various process phases. After this, a list will be given of important influencing factors.

Principle of action and process phases of Fused Deposition Modeling

The principle of action of FDM can be basically described by two functions. One function is the translational motion of the tool. The other function is the delivery of a flow of plastic melt by the tool (nozzle). The strand-shaped deposition of the plastic that is typical of the FDM process is attained by overlapping, in the plane, a translational motion of the tool while simultaneously delivering plastic melt.

One way of differentiating between various process phases in fused deposition modeling comes from the type of strand deposition. This can be interrupted during the process or carried out non-stationarily or stationarily (cf. [Bel02, p. 34-35, 147]). During an interruption to strand deposition, no plastic melt is deposited as a strand. Translational motions can be performed without the delivery of plastic. These are necessary in the FDM process to jump, for example, to another section of the part, or to begin a new layer. During strand deposition, a distinction can also be made between two other process phases. Non-stationary strand deposition is characterized by acceleration processes of the tool and/or the plastic delivery. Acceleration processes are necessary because of the existing mass inertia, e.g. with changes of direction. In addition to the translational motion velocity of the tool, the velocity of the plastic delivery can also be adjusted. At present, various techniques are being used and investigated in order to obtain a strand deposition that is as constant as possible despite changing translational tool velocities (cf. [GRS16, p. 154], [Bel02, p. 34], [HJ07, p. 652], [AJL+96, p. 10], [BJH+99, p. 445, 447-450], [Hen-ol]). During non-stationary strand deposition, the feed velocity of the plastic filament can be constant. If the delivered flow of plastic melt is not constant, the strand deposition is regarded as non-stationary. Stationary strand deposition is characterized by the attained constant target velocity of the translational motion and the delivery of plastic melt with a constant volume flow at constant feed velocity of the plastic filament.

Effects observed on the part

Through the influencing factors acting on the FDM process, part-specific structures are formed. Some can be seen even on the deposition of an individual strand while others only occur when several strands are laid together to create a strand package. A few examples are given below.

Starting and ending of the strand deposition

FDM parts contain numerous seams. Seams occur at all points of contact of deposited plastic strands. With seams formed through the starting or ending (or both) of a strand extrusion (cf. [Geb13, p. 71]), additional process operations can be performed, depending on the data processing and the available machine technology. The various process operations on starting or ending the strand deposition serve, for example, to produce well-fused seams that are as clean as possible. Other seams come about through the laying of the strands next to each other and on top of each other, and are usually not influenced by additional process operations.

Fig. 1 shows a seam created by the starting and ending of a strand deposition. In the deposition strategy, the strand deposition shown here is defined as the outer contour of a part. In Fig. 1, the outer face of the component is pointing upwards. The direction of motion of the tool during strand deposition as well as the translational motion of the tool afterwards are shown in the diagram with arrows.

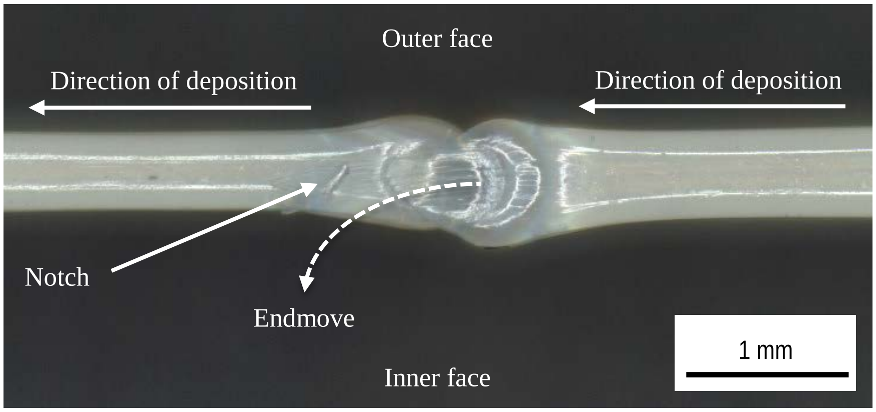

Fig. 1: Macrograph of a seam on the outer face (produced from ULTEM 9085 with a T16 nozzle on a Stratasys Fortus 400mc)

The notch in the deposited strand that can be seen in Fig. 1 results from an end-move of the tool after depositing the strand. With this motion, the nozzle is advanced over the already deposited plastic strand into the inside of the part in order to produce as clean a weld as possible on the outer face of the component.

Acceleration processes in strand deposition

When starting and ending a strand deposition or when changing direction during strand deposition, the tool, because of dynamic forces, must be accelerated and decelerated. In modern machines, the feed velocity of the filament is adjusted during non-stationary strand deposition to the translational motion velocity of the tool. The aim is to ensure that a strand of uniform thickness is deposited. Through various disruptive factors, such as the material-specific Young's modulus and machine-specific spring length of the material, this process is at present not very reliable. In Fig. 2 it can be seen that, in areas of non-stationary strand deposition, with acceleration and deceleration processes of the tool (cf. [TG15, p. 253], [HJ00, p. 1711]), non-uniform strand thicknesses are produced.

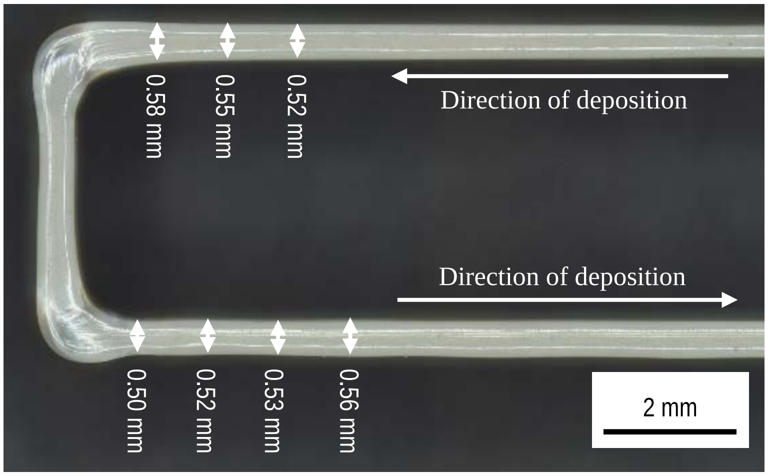

Fig. 2: Acceleration processes during strand deposition (produced from ULTEM 9085 with a T16 nozzle on a Stratasys Fortus 400mc)

Strand deposition around a radius

When depositing a strand around a radius, a compression or thickening occurs on the inside of the strand and a stretching of the material on the outside. There are also areas in which the travel distances of the tool overlap. Here, more material is deposited than necessary as a result of overlapping of the travel motions (cf. [HJ00, p. 1711]). The smaller the radius around which the strand is deposited, the more marked this effect becomes. Fig. 3 shows the deposition of a strand around a 90° angle. The deviation from the planned strand deposition plus a thickening of the inner radius and a lack of material on the outer radius can be seen.

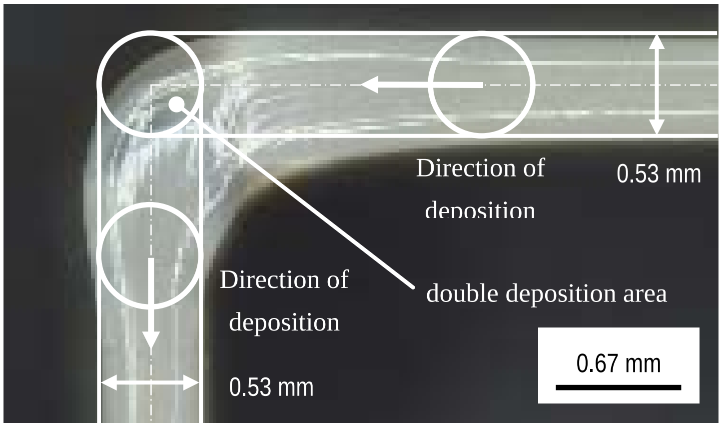

Fig. 3: Strand deposition around a radius (produced from ULTEM 9085 with a T16 nozzle on a Stratasys Fortus 400mc)

Layer gaps due to the strand deposition strategy

At present, depending on the particular layer, a constant width is used for the deposited strands while the track width is allocated to the strand width. If, in any particular area of the part, the deposited tracks of the inner screen are aligned parallel to the contour line, it is impossible to produce just any desired wall thickness. Depending on the settings for the strand deposition strategy, there are two possibilities for mapping the relevant area of the part. One possibility is to map the area of the part with a discrete wall thickness corresponding to many times the track width, in which case the finished part may not have the intended wall thickness. The other possibility is to deposit the strand for the contour in such a way that the outside measurement of the wall of the part corresponds to the intended size and to fill the inner areas by laying as many strands as possible next to one another. As long as the inner dimension cannot be mapped as a whole-number multiple of the track width, gaps will occur in this area of the part (cf. [HRE+13, p. 385]). Fig. 4 illustrates this effect with the aid of a cuboid produced by FDM with edge lengths of 5*5*25mm.

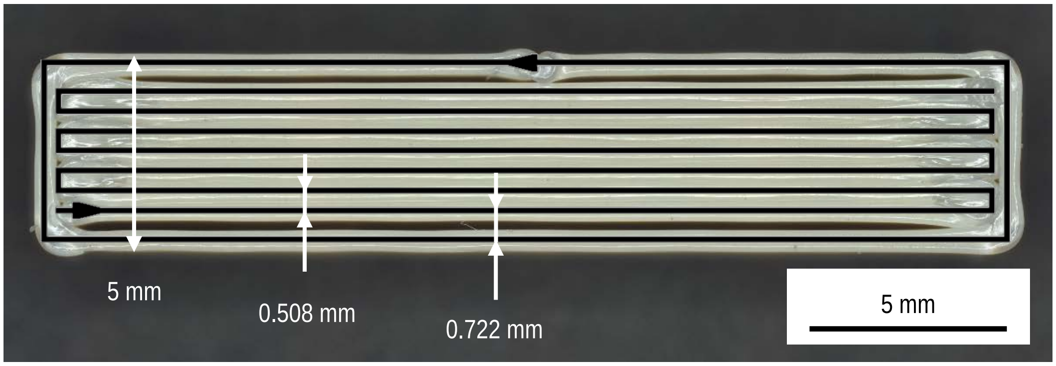

Fig. 4: Top view of a cuboid to visualize the strand deposition strategy (produced from ULTEM 9085 with a T16 nozzle on a Stratasys Fortus 400mc)

Twin formation and variable notch geometries

In FDM parts, it can be seen that strands lying next to one another group together to form pairs of twins. This means that both strands grow together to a certain extent and partially cover the same space. As a consequence of this, the resultant twin no longer has the full double width of a strand. A possible explanation for this behavior is that the strands group together in the molten state to reduce surface energy. This theory is supported by the sintering tests carried out by [BLS+04, p. 174ff]. The strands are deposited side by side, strand by strand. The first strand is deposited and solidifies at its respective position. Subsequently, the next strand is laid next to it in the molten state. The latter lies so close to the first, already solidified strand that the melt, under the compulsion to reduce the free surface, can pull slightly in the direction of the deposited strand and can solidify there. With the third strand, however, the gap to the second strand is so large that it can solidify in its intended position. This process repeats itself in the course of the build process.

To illustrate this effect, the part shown in Fig. 5 on the left was produced by the FDM process. The strand deposition strategy was selected so that all strands are aligned in the direction of the symmetry axis. The formation of twins can be seen irrespective of whether the strands lie exactly above one another or with a gap (cf. Fig. 5 right). It can also be easily seen in Fig. 5 that, in the production of a strand package, depending on the strand deposition strategy and shape of the part, very different notch geometries are formed inside a part.

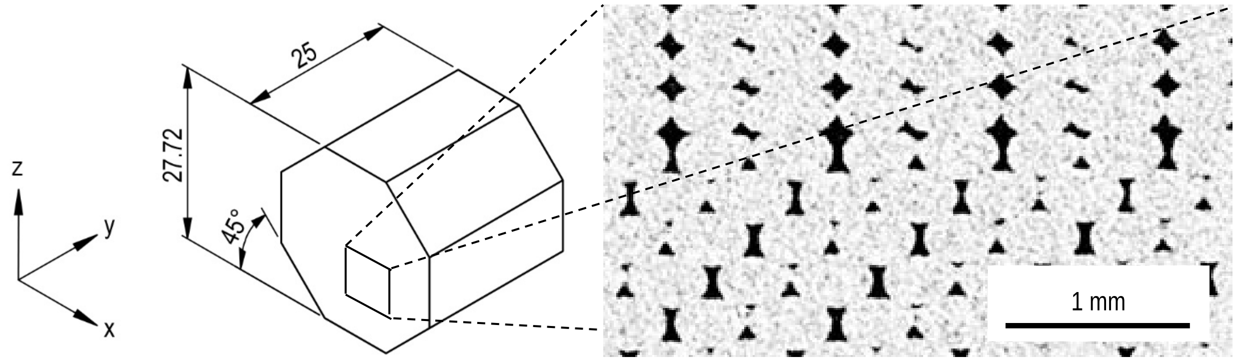

Fig. 5: Formation of twins and notch geometries in the strand package (produced from ULTEM 9085 with a T16 nozzle on a Stratasys Fortus 400mc)

Influences from the machine (kinematics, tool and build environment)

There are a variety of FDM machines on the market. In some cases they differ considerably in their concept, design and construction. Without taking the machine-specific influences into account it is not possible to determine characteristic data for evaluating the processing properties of different materials. Basically, an FDM machine can be divided up into three sub-assemblies: the kinematics, the tool and the building environment. With the help of these criteria, the most important influences are explained below.

Kinematics – machine vibrations and positioning accuracy

In the FDM process, the kinematics have the task of moving the tool in relation to the building platform or the partially manufactured part. The positioning, track and repetition accuracy as well as the possible travel speed of the tool have a major influence on the deposition of the strands and differ significantly depending on the machines [Geb13, p. 80], [TSG14, p. 194]. It is essential that the strands are positioned very accurately next to one another and on top of each other in order to ensure reproducible weld seams and thus attain the specified strength data in the final part. In particular, depending on the machine stiffness and damping properties, vibrations occur in connection with the highly dynamic movements of the tool. As a result, the positioning and track accuracy are reduced after a period of vibration. This can also be seen in the production result and is illustrated in Fig. 6. The deposited strand was measured in the diagram at equidistant intervals. Deposition of the strand around the 90° change of direction and the acceleration processes taking place induces vibration of the machine construction. Following the change of direction this can also be recognized in the strand deposition in the form of thickness fluctuations. These effects on strand deposition and machine vibration gradually decline.

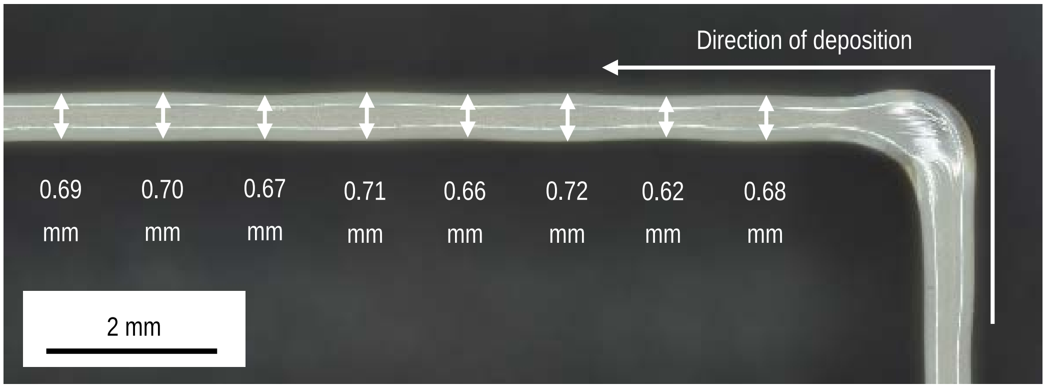

Fig. 6: Macrograph of a strand deposited around an angle of 90° (produced from ULTEM 9085 with a T16 nozzle on a Stratasys Fortus 400mc)

Depending on the machine concept and quality of the machine calibration, the deposition of melt strands cannot be accurately performed directly on the build platform in the first layers of a part. This can lead to the width-to-height ratios (b/h ratios) of the deposited melt strands not corresponding to the original settings for the process. This in turn influences the density of the component, the width of the weld seams and the strength data of the part. Two error patterns can occur. If the first layer is set too low through the machine, the strands will be deposited with an excessive b/h ratio. The melt strands are squeezed on and the resultant weld widths are larger than with a correctly set layer height. If the layer is set too high, the b/h ratio is lower than intended. The strands are deposited on the platform and not squeezed on. The resultant weld widths ($bs_{1,1}$ and $bs_{1,2}$ in Fig. 7) are smaller than with a correctly set layer height.

To illustrate the problem, Fig. 7 shows individual strands deposited on top of each other. On the left is a strand deposited with a correct layer height and a b/h ratio of 2. Fig. 7 right shows a strand deposition, which, with the same plastic delivery (i.e. the cross-sectional areas A_1 and A_2 are identical), results from the layer height being too high. The b/h ratio and the weld seam width are much smaller.

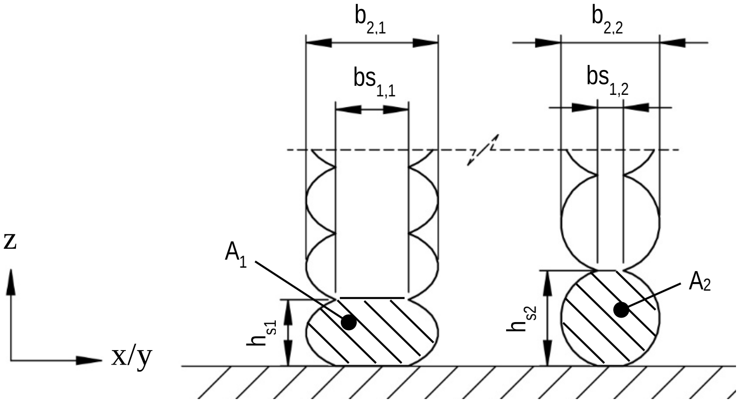

Fig. 7: b to h ratio and weld seam width with identical strand cross section

Through the process-specific deposition of a high-viscosity plastic melt to produce a porous part, the production process nevertheless has self-regulating properties. For example, the faults described above average out over several layers. It can be seen in Fig. 8 that, despite the initially excessive layer height, the target layer thickness is reached after only a few layers. The strands of the described part are deposited alternately with 0° and 90° orientation.

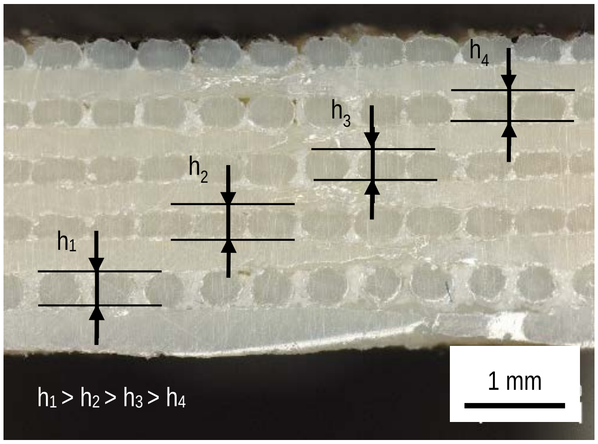

Fig. 8: Macrograph of the first layers of the part (produced from ULTEM 9085 with a 0.4 mm nozzle on an FDM laboratory machine)

Plastic filament extruder

The plastic filament extruder shown schematically in Fig. 9 constitutes the tool in the FDM process. It conveys the semi-finished product, i.e. the plastic filament, plasticizes it and forces the plastic melt through a nozzle onto the build platform or already produced areas of the part [TSG14, S. 192], [AJL+96, S. 5]. Basically, the plastic filament extruder consists of the feed unit and plasticizing unit. Depending on the machine, the construction of this tool varies considerably. There may be differences e.g. in the concept for conveying the filament, the length and design of the plasticizing zone and the arrangement of the filament feed unit and the plasticizing unit.

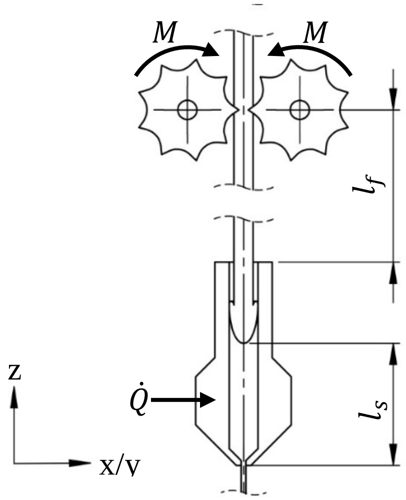

Fig. 9: FDM filament extruder

Because of the principle of the process, the plastic filament is stretched under pressure because the counterpressure created in the plasticizing unit counteracts the force of the filament feed. Depending on the construction of the plastic filament extruder, the length l_f between the plasticizing unit and the feed unit can vary considerably. Depending on the material being used, the stiffness of the processed plastic can also vary (cf. [YHG+97, p. 692f]). In the area of non-stationary strand deposition, this leads to a material delivery that is difficult to coordinate from a material and machine point of view (cf. [HJ07, p. 651-652, 657-658]). If the compressive stress in the plastic filament is too high or if the length l_f is too large or if the material stiffness too low, it is even possible that a buckling of the filament will occur. A differently designed plastic filament extruder will exert an effect especially when starting and ending the strand deposition or when changing the speed of the plastic delivery. Through the compressive stress present in the filament, the material will still be forced out of the nozzle even if the feed velocity is reduced to zero, because the plastic filament is under stress and the tension is released like a spring (cf. [AJL+96, p. 10].

Fig. 10 shows a component that has the seam in every layer at the same place and is always touched at the same xy position by a part being built next to it. As a result, the plastic emerging uncontrolled from the nozzle conglomerates on the side wall of the part and builds a kind of stairs.

Fig. 10: Building defects on the outer wall through uncontrolled delivery of material

Oven / Building environment

In an industrial environment, as is realized in facilities of the firm Stratasys (cf. [Str00]), the established procedure is to place the strands deposited by fused deposition modelling into a heated environment such as an oven. This has several advantages. On the one hand, it means the shrinkage of the individual strands can be reduced, and, on the other, the weld seam strength is increased. Different machines have a different homogenous temperature distribution in the oven and produce a different amount of convection there.

Determining the weld seam strength

The FDM process can be regarded as a constantly repeating welding process. To be able to produce parts that can be subjected to stresses and loads, it is necessary for the strands deposited by the FDM process and fused to one another to enter into a firm bond. The weld seam strength is therefore an important criterion for the suitability of a material for processing by fused deposition modeling.

Designing the test method and specimens

To evaluate and be able to compare the suitability of different materials for processing, it is necessary to design a test method and a test specimen that allow a representative weld that can be reproducibly produced by the FDM process. If at all possible, the weld seam strength should be dependent only on unambiguous process parameters and the material used. Because of the previously described effects, however, some areas of the part are formed that cannot be reproducibly produced by all machines and materials and can therefore not be compared with one another. For this reason, the area to be evaluated in the specimen should not contain any of these influencing factors.

To limit the testing of the weld seam strength to an FDM weld that can be easily produced and is also reproducible, the specimen should have a wall thickness of exactly one strand width. This eliminates all influences that occur in the strand package and also allows full visual examination. An exact description of the strand geometry through the production of simple sectional views, is also possible. In addition, care is taken to ensure that the area to be examined is located only in areas of stationary strand deposition, also that machine vibrations have already ceased and the area does not contain any radii and seams. Translational tool movements with motions that do not deliver any plastic are selected in such a way that the nozzle is not moved directly above already deposited strands and thus no additional energy is introduced into the part e.g. by heat radiation.

Taking into account a design suitable for production for the FDM process, such as adequate part stiffness, the structure shown in Fig. 11 was designed and produced by the FDM process. The first layers of the structure are not in the testing area so as to avoid the influence of any inaccurately set initial layer height. Interruptions to the structure of the first layers make it possible to gradually build up relatively high part stiffness with short strand depositions. As a result, materials with high shrinkage in the FDM process can also be used to produce this structure.

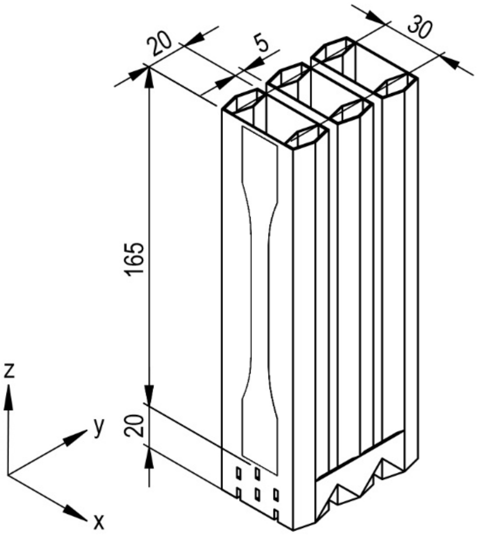

Fig. 11: Tensile bar in the Z direction

Tensile test specimens of Type 1B to [DIN527-3] were subsequently cut from the structure produced by the FDM process (cf. Fig. 11). The tensile test was carried out on a tensile testing machine according to the specifications in [DIN527-3]. In order to unambiguously describe the geometry, it is also possible, in addition to the outer dimensions of the specimen, to produce a sectional diagram (cf. Fig. 12) to show the strand geometry.

Material comparison PA6

With the help of the developed test method, two types of PA6 were then compared with each other. They differ only in their viscosity. The type described below as PA6 NV has a low viscosity while the PA6 HV has a high viscosity. Tests were carried out with different process temperature pairs using otherwise constant process conditions in the area of stationary strand deposition (see Table 1). The filament is dried before FDM processing.

Table 1: Build parameters

Parameter	FDM laboratory machine
Nozzle temperature [°C]	250, 300, 350
Oven temperature [°C]	25, 75, 125
Nozzle diameter [mm]	0.4
Layer height [mm]	0.25
Strand width set for the data processing [mm]	0.5
Speed in the area of stationary strand deposition [mm/s]	50

For every tested pair, a photomicrograph was produced to determine the strand geometry. Fig. 12 shows as an example the photomicrograph for the material PA6 NV at a nozzle temperature of 300 °C and an oven temperature of 75 °C.

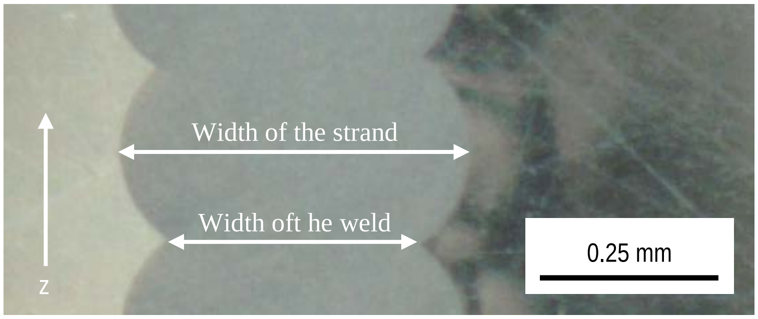

Fig. 12: Width of the weld and the strand, nozzle temp. 300 °C, oven temp. 75 °C, PA6 NV

To compare the materials with each other, a weld width factor is determined for all process points. This is defined according to Equation 1:

$$\text{Weld width factor} = \frac{\text{Width of the weld}}{\text{Width of the strand}} \quad (1)$$

Evaluation of the viscosity on the weld seam strength

Fig. 13 shows the weld width factors for all parameter pairs for the materials PA6 NV (left) and PA 6 HV (right). The non-plotted test points with the material PA6 HV and a nozzle temperature of 250 °C could not be produced. The material has such a high viscosity that reliable melt delivery is not possible. One striking aspect is that the weld width factor with the PA6 NV is dependent on the process temperatures, but that this effect was not observed with the PA6 HV.

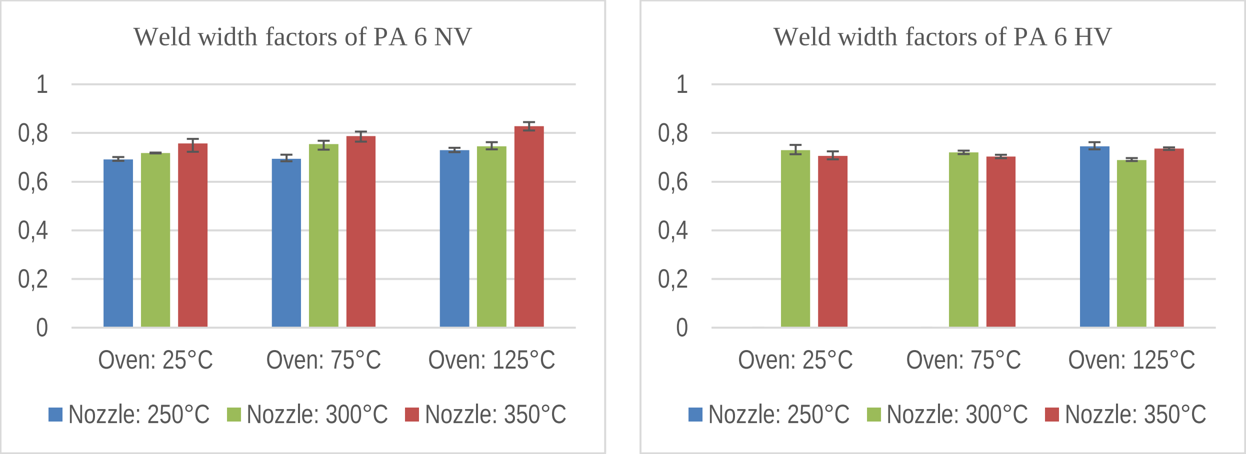

Fig. 13: Weld width factors of PA6 NV and PA 6 HV

To compare the welding seam quality of various materials, the tensile strength is shown in Fig. 14 related to the width of the weld (cf. Fig. 12). In this view, fracture-mechanical effects such as notch factors are neglected. With the test points that have not been plotted, production or testing of the specimens was not possible.

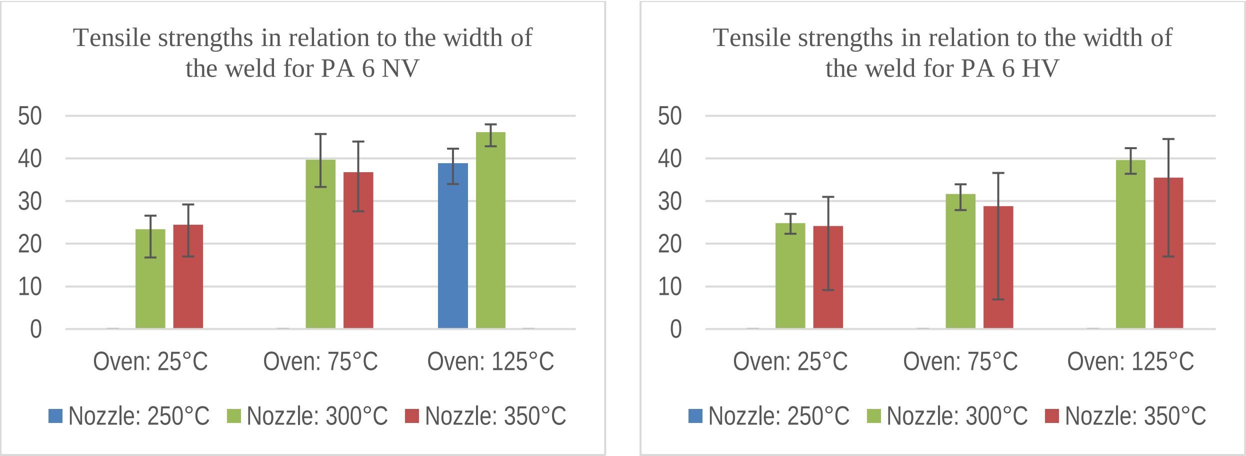

Fig. 14: Tensile strengths of PA6 NV and PA 6 HV

Suitable process temperatures can be selected with the help of the building results and the measured tensile strengths. Under the condition that the process must be reliable and reproducible, only a nozzle temperature of 300 °C proved suitable. At a nozzle temperature of 250 °C, there is a risk that the melt delivery is halted because the material viscosity is too high or it is blocked by non-molten material. As long as a reliable melt delivery is possible, the attainable weld seam strengths are also low because of the low energy input. At a nozzle temperature of 350 °C, the material already becomes thermally damaged, causing production defects. The results of the tensile tests at a 350 °C nozzle temperature therefore have a high degree of scatter. An oven temperature of 125 °C is not suitable for the production of parts as the material turns yellow with time at this temperature. Because an oven temperature of 75 °C provides for the introduction of more energy into the welding seam and the material does not become thermally damaged or discolored at this temperature, a nozzle temperature of 300 °C and an oven temperature of 75 °C have emerged as optimum.

With the help of the base material strengths determined on injection-molded specimens (see Table 2) and the performed tensile tests, a weld seam factor can be given. This relates the strength of the welding seam in the FDM process to the strength of the base material. Overall, it can be said that the PA6 NV material has a better weld seam strength than PA6 HV and also has a better weld seam factor. The tests thus show that, under the aspects of high weld seam strength, preference should be given to a low-viscosity PA6 type.

Table 2: Weld seam factors

Material	Base material strength [MPa]	FDM weld strength [MPa]	Weld seam factor
PA 6 NV	76.1	39.69	0.52
PA 6 HV	75.2	31.70	0.42

Conclusion

Taking account of the machine and process-related influences affecting the FDM process and the effects on the final product, a test method and a test specimen were produced. Through the specific design of the specimen and the simple and virtually complete documentation of the specimen geometry by producing a sectional view, a virtually machine-independent comparison of different materials is possible. The testing of different material types while varying one key material property at a time makes it possible with this procedure to evaluate the effect of this property on the examined characteristic. In this way, this paper demonstrates that, for a high weld seam strength in the FDM process, preference should be given to a low-viscosity material when using PA6.

References

[AJL+96] Agarwala, M. K.; Jamalabad, V. R.; Langrana, N. A.; Safari, A.; Whalen, P. J.; Danforth, S. C.: Structural quality of parts processed by fused deposition. Rapid Prototyping Journal, Vol. 24, 1996, p. 4–19

[Bel02] Bellini, A.: Fused Deposition of Ceramics: A Comprehensive Experimental, Analytical and Computational Study of Material Behavior, Fabrication Process and Equipment Design, Drexel University, Philadelphia, 2002

[BJH+99] BOUHAL, A.; JAFARI, M. A.; HAN, W.-B.; FANG, T.: Tracking control and trajectory planning in layered manufacturing applications. IEEE Transactions on Industrial Electronics, Vol. 462, 1999, p. 445–451

[BLS+04] BELLEHUMEUR, C.; LI, L.; SUN, Q.; GU, P.: Modeling of Bond Formation Between Polymer Filaments in the Fused Deposition Modeling Process. Journal of Manufacturing Processes, Vol. 62, 2004, p. 170–178

[527-3] Kunststoffe - Bestimmung der Zugeigenschaften - Teil 3: Prüfbedingungen für Folien ud Tafeln, 2003

[Geb13] GEBHARDT, A.: Generative Fertigungsverfahren - Additive Manufacturing und 3D Drucken für Prototyping ; Tooling ; Produktion. Carl Hanser Fachbuchverlag, s.l., 1. Aufl., 2013 - ISBN 978-3-446-43652-7

[GRS16] GIBSON, I.; ROSEN, D.; STUCKER, B.: Additive Manufacturing Technologies - 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer New York; Springer, New York, NY, 2., Softcover reprint of the original 2nd ed. 2015, 2016 - ISBN 978-1-4939-2112-6

[Hen-ol] HENSCHKE, MARTIN, DR.-ING.: Advance-Algorithmus. Unter: http://www.dr-henschke.de/advance.html, 06. Mai 2017

[HJ00] HAN, W.; JAFARI, M. A.: Coordination control and deposition planning for improving deposition accuracy in layered manufacturing processCybernetics evolving to systems, humans, organizations, and their complex interactions - SMC 2000 conference proceedings. IEEE International Conference on Systems, Man, and Cybernetics, 8-11 Oct. 2000, Nashville, TN, USA, IEEE Service Center, Piscataway, NJ, 2000

[HJ07] HAN, W.; JAFARI, M. A.: Coordination Control of Positioning and Deposition in Layered Manufacturing. IEEE Transactions on Industrial Electronics, Vol. 541, 2007, p. 651–659

[HRE+13] HOSSAIN, M. S.; RAMOS, J.; ESPALIN, D.; PEREZ, M.; WICKER, R.: Improving Tensile Mechanical Properties of FDM-Manufactured Specimens via Modifying Build Parameters, 2013

[Klo16] KLOKE, A.: Untersuchung der Werkstoff-, Prozess- und Bauteileigenschaften beim Fused Deposition Modeling Verfahren. Shaker Verlag, Vol. Band 4, Aachen, [1. Auflage], 2016 - ISBN 978-3-8440-4489-8

[Str00] STRATASYS, I.: High Temperature Modeling Apparatus

[TG15] TURNER, B. N.; GOLD, S. A.: A review of melt extrusion additive manufacturing processes - II. Materials, dimensional accuracy, and surface roughness. Rapid Prototyping Journal, Vol. 213, 2015, p. 250–261

[TSG14] TURNER, B. N.; STRONG, R.; GOLD, S. A.: A review of melt extrusion additive manufacturing processes - I. Process design and modeling. Rapid Prototyping Journal, Vol. 203, 2014, p. 192–204

[YHG+97] YARDIMCI, M. A.; HATTORI, T.; GUCERI, S. I.; DANFORTH, S. C.: THERMAL ANALYSIS OF FUSED DEPOSITION, 1997, p. 689–698