

Investigation of the Processability of Different PEEK Materials in the FDM Process with Regard to the Weld Seam Strength

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Abstract

Due to the great popularity of the Fused Deposition Modeling (FDM) process, the material market is growing. In particular, processing of high-temperature materials such as PEEK is demanding. The aim of the investigations is to test different PEEK materials regarding their processability in the FDM process. An unreinforced PEEK, a thermally conductive PEEK as well as a carbon fiber reinforced PEEK are investigated. The processability is assessed with the help of the weld seam strength. The assessment of the weld seam strength is carried out by building tests. For this purpose, a special method developed at the DMRC is used. In addition, a welding width factor between the strands deposited on each other is calculated and compared. Finally, a welding factor is determined to enable the comparison between the different materials. With this procedure, the influences of varying nozzle and build chamber temperatures on the achievable weld seam strengths are evaluated.

Introduction

One of the most commonly used additive manufacturing processes is the Fused Deposition Modeling (FDM) [1]. Due to the great popularity of the FDM process, the material market is growing with new materials. There is a large number of plastics that can be processed using the FDM process. Additives can be mixed with the materials in order to influence the basic properties as well as certain material properties such as fire resistance, chemical resistance, fracture resistance or heat resistance. In principle, almost all thermoplastics are suitable for the FDM process. Especially PLA, ABS, polyimides or PA6, for example, are frequently used. The demand for new material concepts for the production of highly stressed components has driven forward the research of additive manufactured components made out of high-performance plastics. This can be seen as an example in investigations of polyether ether ketone (PEEK) as an application in gear technology [2] or for medical applications, where prostheses were manufactured using PEEK [3]. Due to the high material price of PEEK, it is important to aim for a waste-free production. Since FDM printers have no distribution systems or sprues compared to injection molding, they have an advantage in this field [4]. Therefore, in this publication the processability of different PEEK materials (injection molding grades) in the FDM process is investigated with regard to the weld seam strength.

State of the Art

The components are generated by a heated thermoplastic strand, which is applied layer by layer in a defined process. The thermoplastic filament is pulled into the FDM head by motors, plastified there and deposited through a nozzle onto the building platform or on an existing structure in a defined way through a nozzle [5]. The FDM process is an extrusion process [6]. The protected brand name FDM [7] is often synonymous with the term FLM (Fused Layer Modelling) or FFF (Fused Filament Fabrication) [8] [9]. The construction of an FDM machine consists of an FDM head and a building platform, which are located in a heated build chamber [8]. The filament is continuously fed into the FDM head and the material is melted by an electric heating element and extruded through a nozzle. After a layer has been applied, the molten material solidifies [9]. Due to the heat conduction into the previously deposited layer a thermal fusion results and a further component layer is formed [10]. The building platform is then lowered by one layer thickness and the next layer

is applied. This process is repeated until the component is completed [8]. Factors which influence the FDM build process according to [11] include the nozzle diameter, nozzle temperature, build chamber temperature, material viscosity and working pressure during material feed. The adhesion between the strands and layers in the FDM process is achieved by temperature-driven molecular diffusion [12]. A good bonding of the individual layers/strands is favoured by a high nozzle temperature, since the temperature increase results in an improved diffusion of the individual molecule chains into each other [13].

PEEK is a thermoplastic semi-crystalline material which belongs to the group of high-performance plastics [14]. The mechanical properties of the material include high tensile strength, flexural strength and stiffness. PEEK is used in many different fields. These include aerospace, military, machine and automotive, electrical and medical industries [15]. For this reason, the processing of PEEK is also of particular interest for the FDM process.

Experimental Approach and Testing Methods

Three different PEEK materials are studied in the investigations. An unreinforced PEEK (VESTAKEEP 1), a thermally conductive PEEK (VESTAKEEP 2) and a carbon fiber reinforced PEEK (VESTAKEEP 3).

For the experimental investigation of different PEEK materials in the FDM process, the FDM printer must fulfill various requirements. Diverse challenges occur during the processing of PEEK materials in the FDM process. A high melting temperature of about 343 °C makes processing more difficult compared to thermoplastics with a lower melting point [2]. In addition, the semi-crystalline behavior leads to material shrinkage which results in warpage during processing. These challenges lead to different requirements for the FDM system. A heated build chamber is required in order to limit the shrinkage behavior of the material. Stresses caused by warpage can be compensated by keeping the temperature difference between the heated material and the build chamber as small as possible. In addition, nozzle temperatures above the PEEK melting temperature are required. Another requirement is a heated bed to ensure good adhesion of the first layer. The mechanical testing samples were printed using the Gewo HTP260. The technical data can be found in the following table.

Table 1: Technical data Gewo HTP 260

Technical data	Gewo HTP 260
Max. nozzle temperature / °C	450
Max. build chamber temperature / °C	260
Max. heating bed temperature / °C	270
Build envelope / mm	350 x 150 x 165

The aim of the experimental investigations is to investigate the processability of PEEK materials with regard to the weld strength. In order to assess the suitability of these materials for the use in the FDM process, the weld quality is determined. For this purpose, a method developed by [16] is used. The method is tested whether it is suitable for high-temperature materials. For this purpose, test specimens with single-stranded areas are built. The used component (see Figure 1) consists of three elements which are connected by a bridge to improve stability during the building process. In addition, the groove in the lower part of the component should prevent warpage of the components due to material shrinkage.

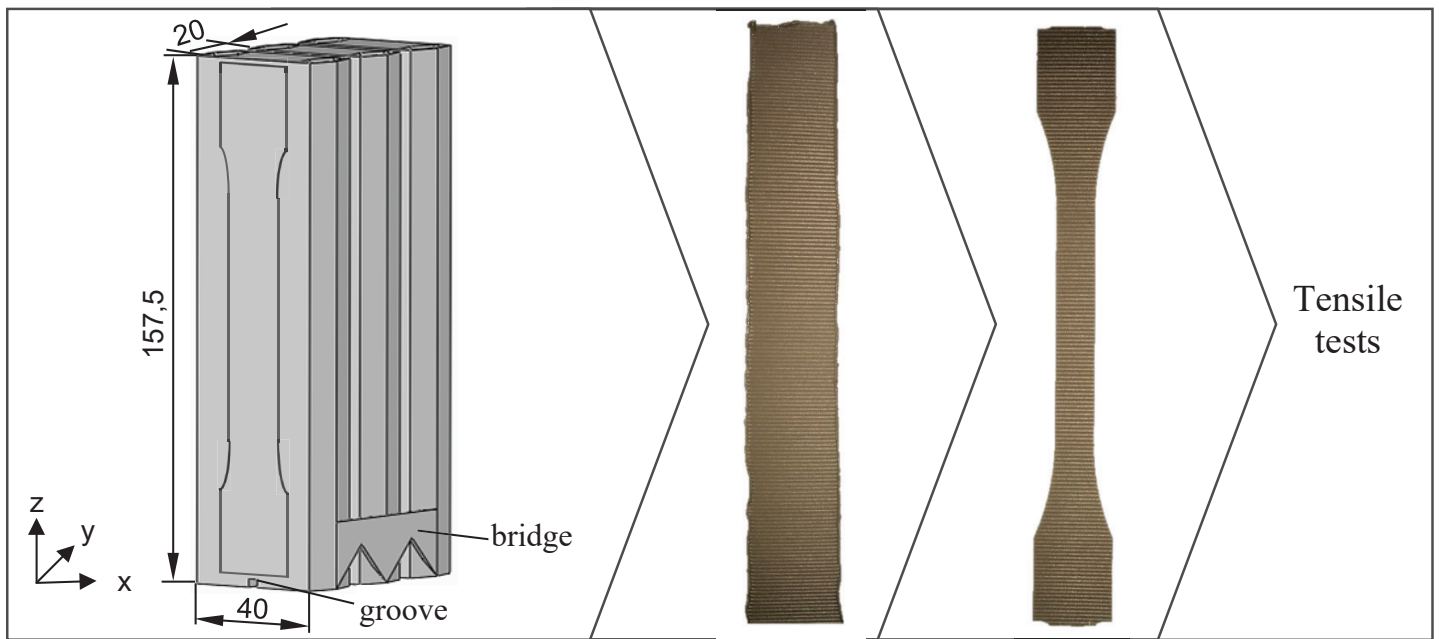


Figure 1: Process chain to determine the weld seam strength

After manufacturing the components, rectangular areas are cut out of the component and then the geometry of the tensile bar is milled out. The tensile bar geometry for determining the tensile properties was selected according to DIN EN ISO 527-3 with type 1B specimens. Afterwards, the weld strength between the single layers can be determined with the help of tensile tests.

In order to ensure comparability between the different materials, a welding factor is determined. The welding factor is the weld seam strength in relation to the tensile strength of the used filament (according to equation 1).

$$\text{welding factor} = \frac{\text{weld seam strength}}{\text{base material tensile strength}} \quad (1)$$

The weld seam strength is the maximum force resulting from the tensile tests in relation to the real weld area. To determine the real weld area, a small piece is separated from the tensile test specimen and embedded in resin. After grinding the surface, the width of the weld seam can be measured with the help of a microscope. With the weld seam width determined by using this method and the known weld seam length, the actual welding area is calculated. The following illustration (Figure 2) shows a schematic representation of the weld seam and a microsection taken from a section of a milled tensile bar.

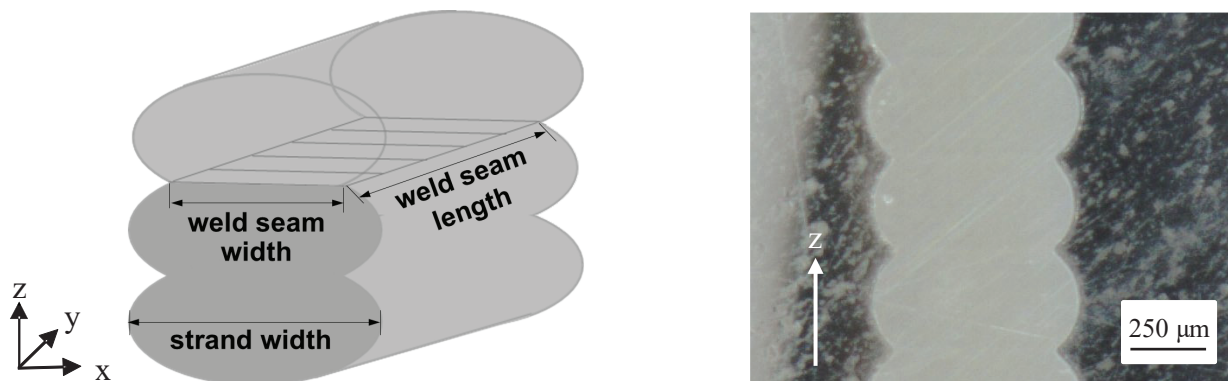


Figure 2: Left: schematic illustration of the weld seam / right: microsection of a weld seam

and would therefore heat the heating bed as well. The minimum nozzle temperature used is 430 °C and the maximum temperature is 450 °C. The temperature of the build chamber has been varied between 150 °C and 250 °C in order to cover a temperature range as wide as possible. Thus, an influence of the build chamber temperature on the weld seam strength of semi-crystalline materials can be detected. The combination of the individual test points is shown in the following table.

Table 2: Overview of the test points

		Build chamber temperature		
		150 °C	200 °C	250 °C
Nozzle temperature	430 °C	X		X
	440 °C		X	
	450 °C	X		X

The tests are carried out with the following building parameters. The VESTAKEEP 1 is processed with a 0.4 mm nozzle. The layer height is 0.25 mm and the strand width is 0.5 mm. Both the VESTAKEEP 2 and the VESTAKEEP 3 show insufficient material extrusion with a 0.4 mm nozzle. The nozzle also clogges during processing. For this reason, the nozzle diameter for the thermally conductive and carbon fiber-reinforced material has been adjusted to 0.6 mm. This modification leads to an adjustment of the layer height to 0.375 mm and the layer width to 0.75 mm. The printing speed is 30 mm/s for all three materials. The filaments are dried before processing

Results and Material Comparison

With the help of the test method [16], the three different PEEK materials are evaluated and finally compared with each other. Figure 3 shows the analysis of the weld seam strength of VESTAKEEP 1.

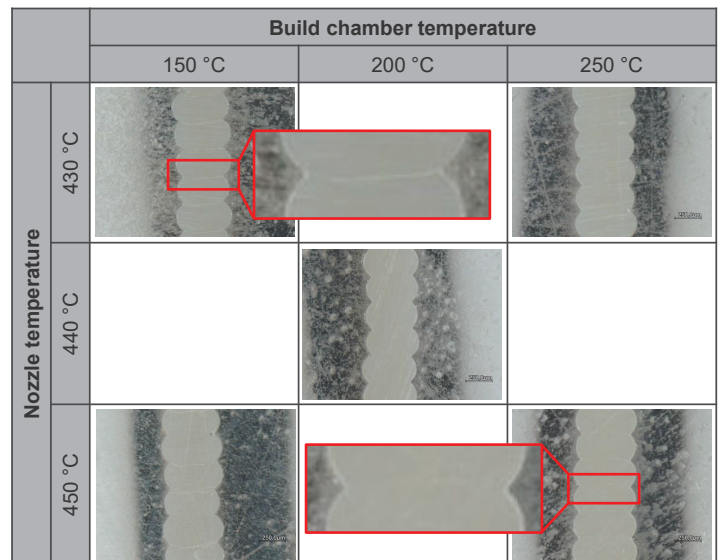
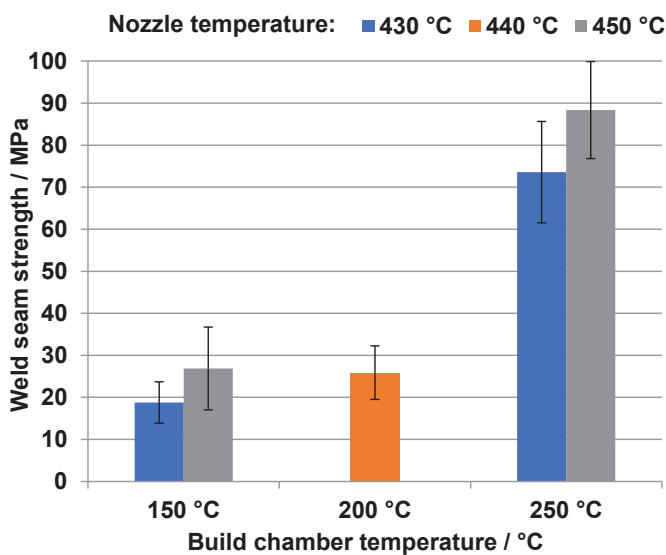


Figure 3: Analysis of the weld seam strength VESTAKEEP 1

The diagram on the left side of Figure 3 shows the evaluation of the weld seam strength (the tensile strength in relation to the actual welding area). The unreinforced PEEK shows strength-increasing influences of the nozzle temperature and the build chamber temperature. The weld seam strength at the low nozzle temperature of 430 °C increases from 19 MPa to 73.5 MPa due to an increasing temperature of the build chamber. The difference of the weld seam strength is also significant at a nozzle temperature of 450 °C. In this case the weld seam strength is increased from 27 MPa at 150 °C build chamber temperature to 88 MPa at a build chamber temperature of 250 °C. In summary, the results show that a build chamber temperature of 250 °C is recommended in order to achieve high weld seam strengths. The analysis of the microsections (on the right side of Figure 3) shows that a phase boundary occurs between the strands at a build chamber temperature of 150 °C. The phase boundary indicates that the heat supply was too low and that the strands could not be sufficiently welded together. This explains the low weld seam strength compared to the weld seam strength at a higher build chamber temperature. At 200 °C, this phase boundary is not visible. The significantly lower strength compared to 250 °C build chamber temperature probably indicates an incompletely formed molecular compound. At 250 °C, there are also no phase boundaries between the strands detectable.

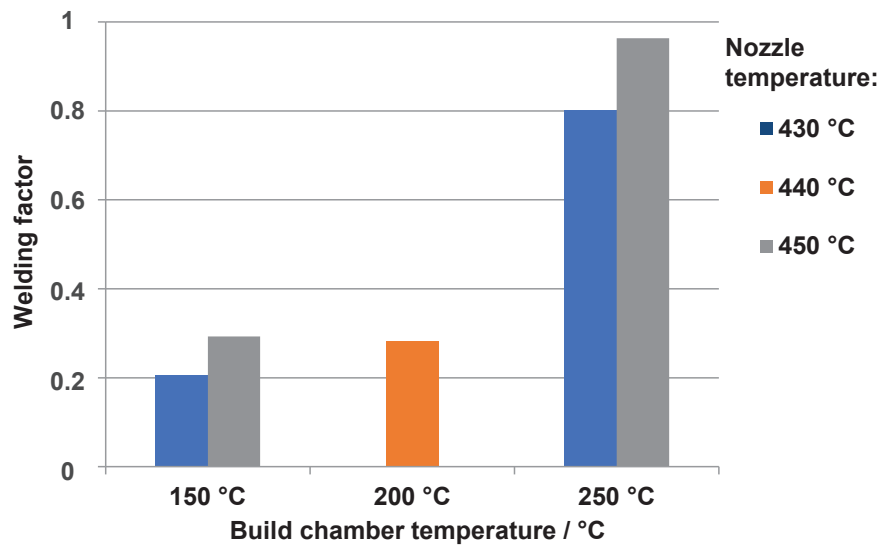


Figure 4: Comparison of the welding factor VESTAKEEP 1

The comparison of the welding factors in Figure 4 shows that high welding factors can be achieved, especially at a build chamber temperature of 250 °C. In relation to the base material strength of the filament, a welding factor of 0.8 is obtained at the low nozzle temperature of 430 °C. At a nozzle temperature of 450 °C, the weld seam strength is even close to the base material strength. This shows a good processability of the material with regard to weld seam strength.

The thermally conductive PEEK shows an increase in weld seam strength from a build chamber temperature of 200 °C to 250 °C (Figure 5). The highest weld seam strengths are achieved at a build chamber temperature of 250 °C. An increase of the nozzle temperature from 430 °C (60 MPa) to 450 °C (61 MPa) does not significantly increase the strength.

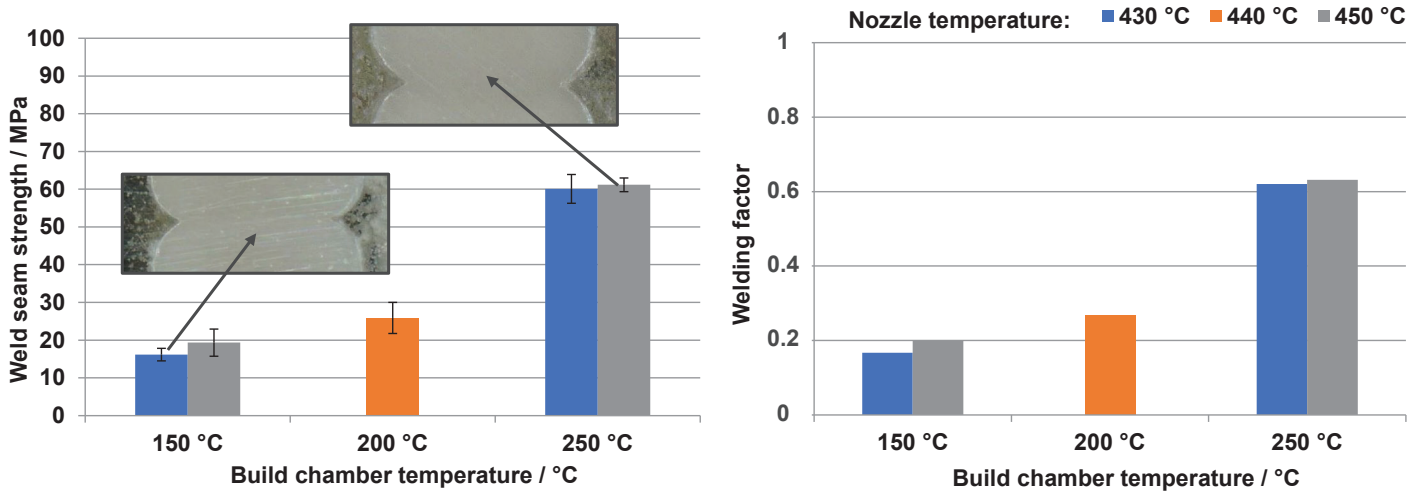


Figure 5: Analysis of the weld seam strength (left) and the welding factor (right) VESTAKEEP 2

The comparison of the weld seam formation shows that, in contrast to the VESTAKEEP 1 (Figure 3), no phase boundaries are formed between the strands at a low build chamber temperature of 150 °C. All test points have no phase boundaries. This can be explained by the increased thermal conductivity which supports the bonding of the strands. Nevertheless, the thermally conductive particles have a reducing influence on the weld seam strength, which can be seen in the lower strengths compared to VESTAKEEP 1. The base material strength of the filament is slightly higher than the base material strength of the VESTAKEEP 1. The resulting welding factors are shown in the right part of Figure 5. At a build chamber temperature of 250 °C, no significant difference of the welding factor between the nozzle temperatures can be detected for the thermally conductive material.

In the case of carbon fiber reinforced PEEK, at the minimum build chamber temperature of 150 °C no weld seam strength of the tensile test specimens can be determined. A preparation of the test specimens was not possible and the specimens broke while milling the tensile specimen geometry. This leads to the conclusion that at this temperature setting the weld seams cannot form sufficiently.

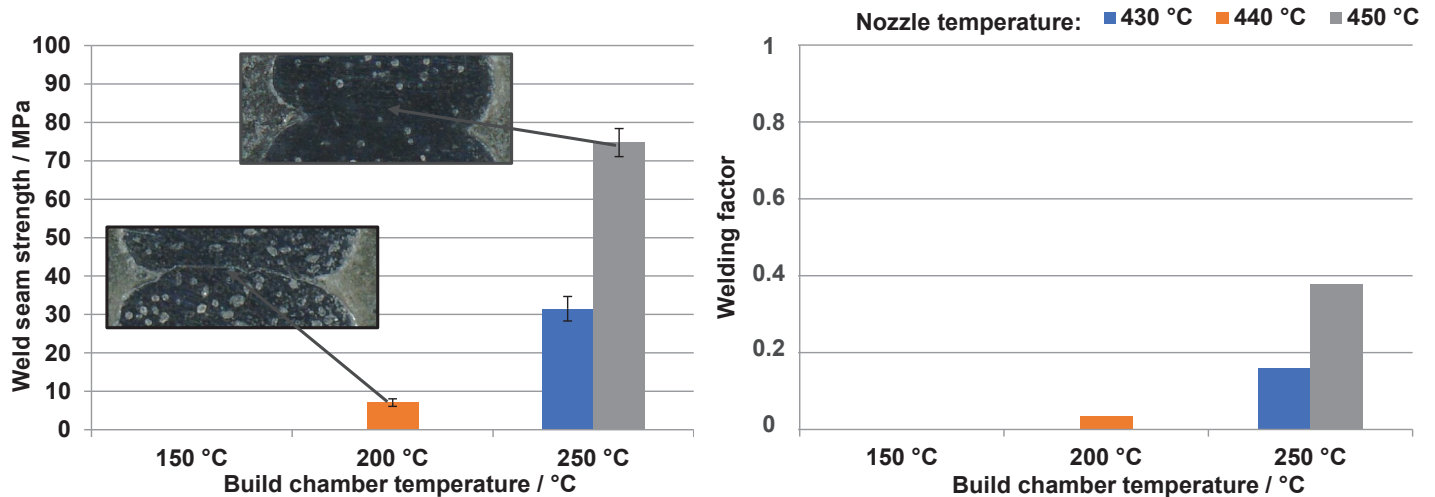


Figure 6: Analysis of the weld seam strength (left) and the welding factor (right) VESTAKEEP 3

Figure 6 shows the weld seam strengths and the welding factors of the VESTAKEEP 3. The low weld strength at a build chamber temperature of 200 °C confirms the poor weld seam formation at the minimum temperature combinations. It is significantly lower than the weld strength of the other PEEK materials. The insufficient weld seam formation can also be demonstrated by the microsections shown in the left diagram. At the build chamber temperature of 200 °C, phase boundary lines are formed between the strands, which explains the low weld strength and the low welding factor at this test point. Only at a build chamber temperature of 250 °C no phase boundaries between the strands can be observed. Therefore, a build chamber temperature of 250 °C is

necessary to ensure a complete formation of the weld seams. The base material strength of the filament is more than twice as high as the base material strength of the other two PEEK materials. The increase in strength is due to the carbon fibers. The welding factors calculated from the weld seam strength and base material strength are accordingly lower than the VESTAKEEP 1 as well as the VESTAKEEP 2. The welding factors can be improved by increasing the temperature in the build chamber. While the weld seam strength at the nozzle temperature of 450 °C is higher than the weld seam strength of the thermally conductive PEEK, the high base material tensile strength results in smaller welding factors of VESTAKEEP 3.

Conclusion and Outlook

In summary, it can be concluded that the different PEEK materials can be processed in the FDM process. In addition, it was shown that the method developed by [16] can also be applied to high-temperature materials such as PEEK. An increased build chamber temperature shows a positive influence on the weld seam strengths. In any case, the weld seam strength is increased at the same nozzle temperature by increasing the temperature of the build chamber. An increase in the nozzle temperature also causes an increase in strength. All in all, the highest weld strengths are achieved at the maximum nozzle temperature of 450 °C and the maximum build chamber temperature of 250 °C. While the base material strengths of the VESTAKEEP 3 are higher in comparison to VESTAKEEP 1 due to the additives (fibers are oriented in the deposition direction of the strand), the weld seam strengths are lower compared to the unreinforced PEEK. As a combination of this effect, the welding factors of the reinforced/modified PEEKs are lower than those of the VESTAKEEP 1. The highest welding factors can be achieved with the VESTAKEEP 1. A reduction in the strength of the materials due to a high nozzle temperature cannot be determined.

For further analysis of the processability, investigations of the shrinkage and warpage behavior have to be carried out. In addition, it will be investigated how the process parameters affect the shrinkage and warpage behavior in order to determine optimized parameters for the materials. Furthermore, the materials should be optimized and adapted.

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