OVERPRINTING OF LARGE-SCALE THERMOPLASTIC COMPOSITES IN FGF-PROCESS USING LOCAL PREHEATING

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ABSTRACT

The rise of large-scale systems for Fused Granular Fabrication (FGF) of thermoplastics opens up new possibilities for manufacturing thermoplastic composites. One promising approach is the overprinting of continuous fibre-reinforced laminates to increase complexity and functionality of high-performance structures. However, overprinting aerospace-grade materials like Polyether Ether Ketone (PEEK) requires high substrate and ambient temperatures. The large-scale systems lack the possibility to use heated build chambers and can therefore overprint only to a limited extent. This work investigates the possibility of equipping the printer system with local preheating for high-temperature substrates. Therefore, a heating concept using hot air heating is developed and evaluated regarding heating efficiency and the influence of heating on print quality. The study was performed on a modified desktop printer, with which temperature measurements and mechanical testing were carried out. Based on this study, a prototype of a local preheating for a large-scale FGF system was designed, suitable for multi-axis overprinting PEEK laminates. The heating capability of high-temperature substrates was evaluated. Results show preheating temperatures of over 200 °C and significant improvement of the material quality of printed PEEK. The developed prototype forms the basis for further process and technology development fur future composite manufacturing.

1 INTRODUCTION

Additive manufacturing through material extrusion, like Fused Filament Fabrication (FFF) or Fused Granular Fabrication (FGF), has become an established process for industrial applications. In aerospace, especially high-temperature materials like Polyether Ether Ketone (PEEK) or Polyethyleneimine (PEI) play an important role. The 3D-printing of such high-temperature thermoplastics poses a special challenge to the printer and the process management. Yang et al. [1] investigated the influence of process temperatures on printed PEEK's mechanical properties and degree of crystallinity. They showed that high ambient temperatures of up to 200 °C are required to achieve tensile properties close to the bulk material. Similar effects of the substrate temperature have been reported by Wang et al. [2]. Ambient temperatures up to 260 °C have been investigated by Hümbert et al. [3], whereby the trend for high temperatures was confirmed. Zanjanijam et a. [4] give an overview of the main process requirements for PEEK 3D-printing and concludes that the temperature difference between nozzle and bed/chamber temperatures is crucial for the process. Theoretical models support these experimental results. Sun et al. [5], [6] and Coogan et al. [7], [8] both successfully described the bond formation during material extrusion based on crack healing, where healing only occurs before the temperature has fallen short of the glass transition temperature T_g. High-temperature printers are equipped with closed, heated chambers and a heated print bed to achieve the required process temperatures.

In addition to the advances in high-temperature printing, FGF systems are increasingly being used for large-scale 3D-printing. Most activities focus on engineering materials, e.g. for mould production [9]. Velu et al. [10] showed first results on PEEK large scale 3D-printing. A unique opportunity of large-scale FGF printing is the overprinting of thermoplastic laminates to generate complex composites. Overprinting of PA 6 (polyamide 6) organo-sheets has been shown by Morales et al. [11]. The impact of process parameters on overprinting PA 6 has been investigated by Penter et al. [12] and Boros et al. [13]. First studies on overprinting of PEEK laminates have been shown by Caprais et al. [14], [15] and

Hümbert et al. [3]. All studies show that overprinting of thermoplastic laminates poses the same challenges on the process temperatures as regular 3D-printing. Especially for high-temperature materials, high substrate temperatures are required to ensure a sufficient bonding between the 3D-printed structure and the laminate

However, most systems for large-scale 3D printing do not allow for a heated chamber. Therefore, local heating concepts are necessary, which are carried along on the extruder. In order to solve this task, different concepts were presented. Kishore et al. [16] suggested infrared heating and achieved an increase in tensile strength of 200 % for acrylonitrile butadiene styrene (ABS). Han et al. [17] used a laser heat source to improve the properties of printed polyetherimide (PEI). Another approach is followed by the company Apium, which uses convection heating with a heated plate [18], [19]. Finally, hot air pre-heating has been demonstrated by Prajapati et al. [20].

While concepts for local preheating have been presented, no suitable system is available for complex structures in large-scale additive manufacturing. Additionally, there is little data on the effect of overprinting high-temperature thermoplastics. Thus, this work aims to develop a compact preheating system suitable for overprinting PEEK laminates using multi-axis 3D-printing. Since a small design is crucial for multi-axis printing. The system is based on hot air heating. First, the heating concept is developed and verified with the help of a desktop printer. For this purpose, both thermal and mechanical measurements are carried out. Then the concept is transferred to a robotic FGF system.

2 MATERIAL AND METHODS

2.1 Material and Printer

The 3D-printing is performed using Ensinger TECACOMP PEEK 150 CF30, a PEEK compound filled with 30 % carbon fibres. The material is available as filament and pellets. Material properties are summarised in Table 1.

Density [g/cm^3]	1.38
Young's modulus [MPa]	17500
Ultimate strength [MPa]	190

Table 1: Material properties of TECACOMP PEEK 150 CF30 [21].

The desktop printer used to develop the concept is a Leapfrog Creatr, an FFF printer using 1.75 mm filament. For the processing of high-temperature materials, the hot-end was replaced with an E3D V6 hot-end, capable of 450 °C.

The robotic FGF system is a Weber DXR FGF system. The system consists of a KUKA KR70 industrial robot carrying a single screw extruder. The extruder has three heating zones, each up to 450 °C, enabling the processing of high-temperature materials.

The process parameters for printing PEEK with both printers are summarised in Table 2.

Parameter	FFF printer	FGF printer
Nozzle Temperature [°C]	410	430
Bed Temperature [°C]	110	200
Speed [mm/s]	15	15
Nozzle diameter [mm]	0.4	2.0
Layer height [mm]	0.2	0.5

Table 2: Process parameters of PEEK 3D-printing.

2.2 Heating Concept Study and Design

The concept study aims to prove the concept of hot air heating and find suitable air temperatures and print speeds for PEEK. The concept study was carried out using a modified desktop FFF printer in order to test different setups on a reasonable budget. The printer was equipped with a hot-end suitable for PEEK printing. Additionally, an external air heater was mounted to the printhead, allowing for different air temperatures and nozzle geometries of the air outlet. Using this test setup, temperature measurements of a PEEK laminate were carried out to evaluate the achievable preheating temperature of the substrate when overprinting. Additionally, geometrical shape tests, as well as tensile test specimens, were printed to identify the effect of the heating on the print quality and the material properties of printed PEEK.

Based on these results, a preheating for the robotic FGF system was designed. To validate the design, the temperature measurements were performed using the same method as with the desktop printer.

2.4 Thermal and Mechanical Testing

Thermal measurement of the substrate's surface temperature was carried out using five thermocouples attached to the surface. In the concept study, various travel speeds ranging from 5-20 mm/s were tested, and temperature was measured using five thermocouples placed at a constant distance of 20mm along a straight line. The temperature was measured without extruding material as the print head and local heating were moved along the line. Thermocouple measurement was conducted at 5 Hz, and the mean of the five measurements was calculated to determine the maximum temperature and the duration of time the temperature remained above T_g. For the validation of the large-scale system, only 15 mm/s and 30 mm/s were measured. Additionally, heated and non-heated print bed were compared. During the measurement, the nozzle was kept at the regular printing temperature listed in Table 2. In both cases, the heater was operated at its maximum power to find the maximum attainable temperature. The distance between the nozzle and thermocouple was 0.3 mm. The thermocouple setup is shown in Figure 1.

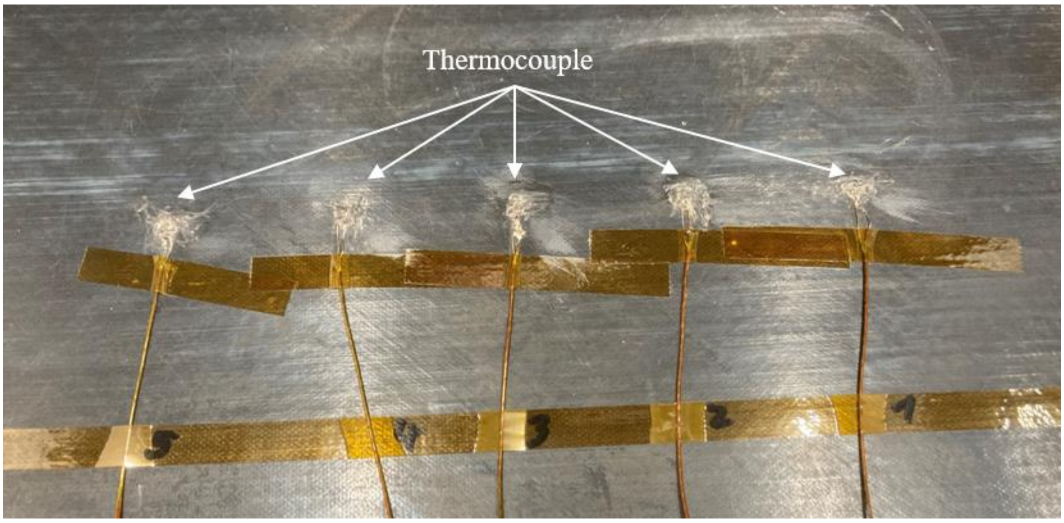

Figure 1: Thermocouple setup for temperature measurement.

Geometrical shape tests were printed in the form of small calibration cubes (20 x 20 x 20) mm^3 with an infill density of 20 %. Goal of the shape test is the evaluation of log-time exposure of hot air on the printing quality of small structures. Cubes were printed at 250 °C, 350 °C, 450 °C and 550 °C. Other printing parameters are listed in Table 2.

Tensile testing was performed to evaluate the effect of local heating on the material properties of printed PEEK. The tests were performed according to DIN 50125 [22] with a specimen thickness of 2 mm and a width of 5 mm. Specimens were printed flat on the print bed with an infill density of 100 %.

The tests were performed using different air temperatures between 250 °C and 550 °C. Other printing parameters are listed in Table 2. For each configuration, five specimens were tested. Results are presented as the mean value of those tests and the standard deviation. The tests are performed using a universal test machine Zwick RetroLine 1475.

2.5 Heater

For the concept study, the heater WR 3M from Weller [23] was used. The heater provides a temperature range from 50 °C to 550 °C at a maximum airflow of 15 l/min with a maximum power of 400 W.

For the large-scale FGF system, two heaters LE Mini from Leister [24], were used. Each one provides a heating power of 800 W and a maximum temperature of 750 °C.

3 RESULTS

3.1 Heating Concept Study

The modified printhead of the desktop printer is shown in Figure 2 on the left. The hot air is provided by a single air heater. In order to provide a symmetric airflow around the nozzle, an adapter is mounted on the air heater (Figure 2 on the right). The adapter is equipped with an exchangeable ring nozzle, allowing the testing of different outlet geometries.

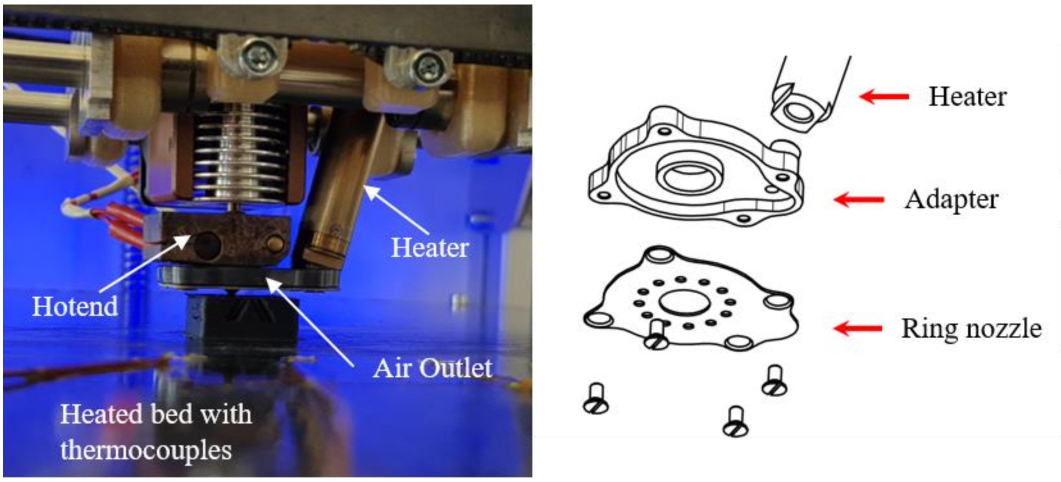

Figure 2: Modified printed for the concept study. Left: Print head assembly; right: Rong nozzle for symmetric air outlet.

The maximum substrate temperature achieved at different print speeds is shown in Figure 3. The maximum temperature achieved was 235.7 °C at 5 mm/s. Increasing the print speed greatly reduces the temperature. The same applies to the time above T_g. The time above T_g describes the period between exceeding T_g and the first time the temperature falls below T_g.

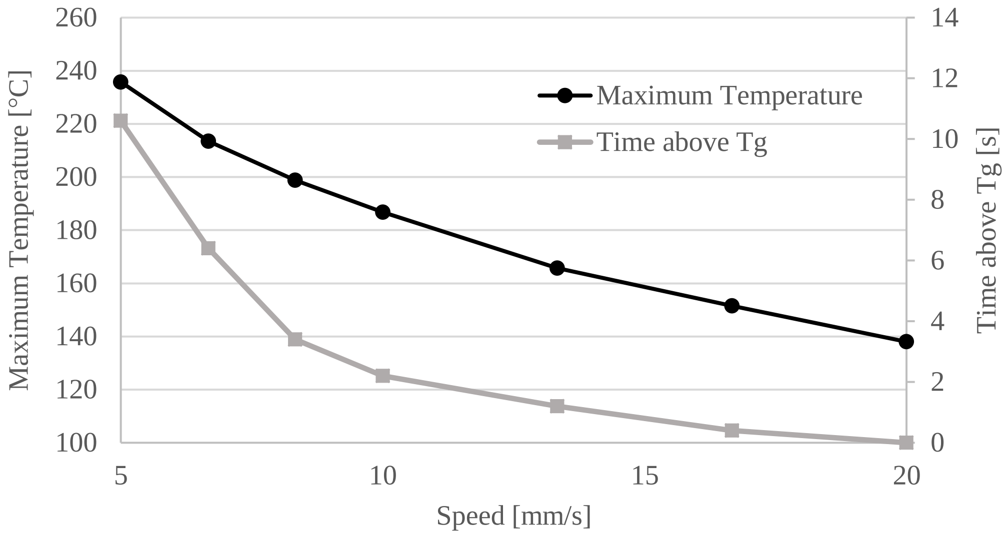

Figure 3: Maximum temperature and time above T_g at different print speeds.

In order to evaluate the effect of hot air temperature on the printing quality, calibration cubes at three different air temperatures (250 °C, 350 °C, 450 °C, and 550 °C) were printed. The results are shown in Figure 4. At 250 °C, delamination of printed layers occurs. Surface quality and geometrical tolerances are best at 350 C air temperature. At high air temperatures, collapsing of walls as well as sagging of the top layers, can occur.

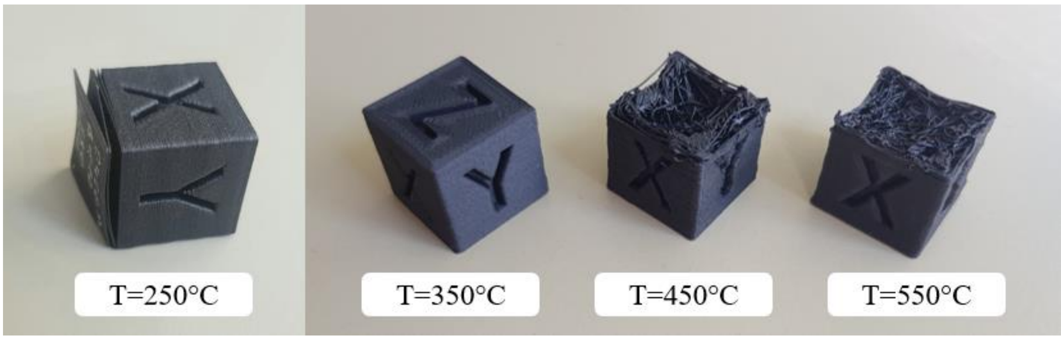

Figure 4: Printed calibration cubes.

Finally, the effect of air temperatures on the mechanical properties of printed PEEK has been tested using tensile test. The results are shown in Figure 5. Printed specimens at 250 °C air temperature showed significant delamination and could not be tested. Starting at 300 °C air temperature, the local heating improves the ultimate strength. The highest strength of 106 MPa is reached at the highest air temperature of 550 °C. Additionally, an effect on the standard deviation can be observed. While specimens without heating show strong scattering of results, the deviation is significantly reduced at high heating temperatures.

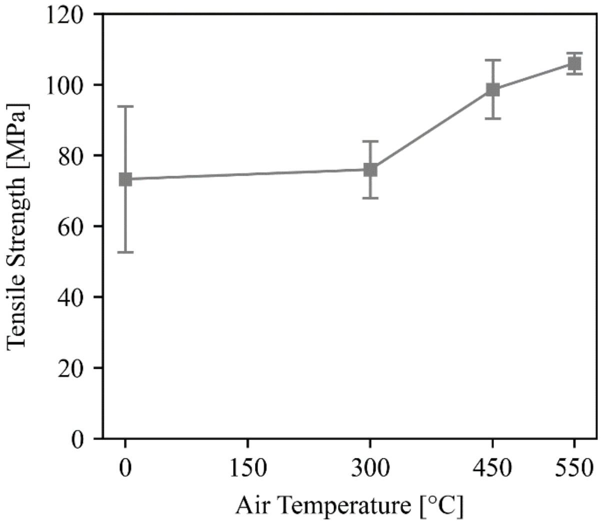

Figure 5: Tensile strength at different air temperatures

3.2 Heating Design for Large-Scale FGF

Based on the results of the concept study, local heating for the large-scale FGF system was designed. Since the concept study showed the need for higher heating power, especially for the larger system, two heaters with 800 W each and a maximum temperature of 750 °C were used. The heater was equipped with a power control and an air adjustment to realise different heat flows. Furthermore, the design was focused on a compact geometry to prevent the heating from severely restricting the freedom of movement of the robotic system. The CAD design and the entire assembly during temperature measurements are shown in Figure 6

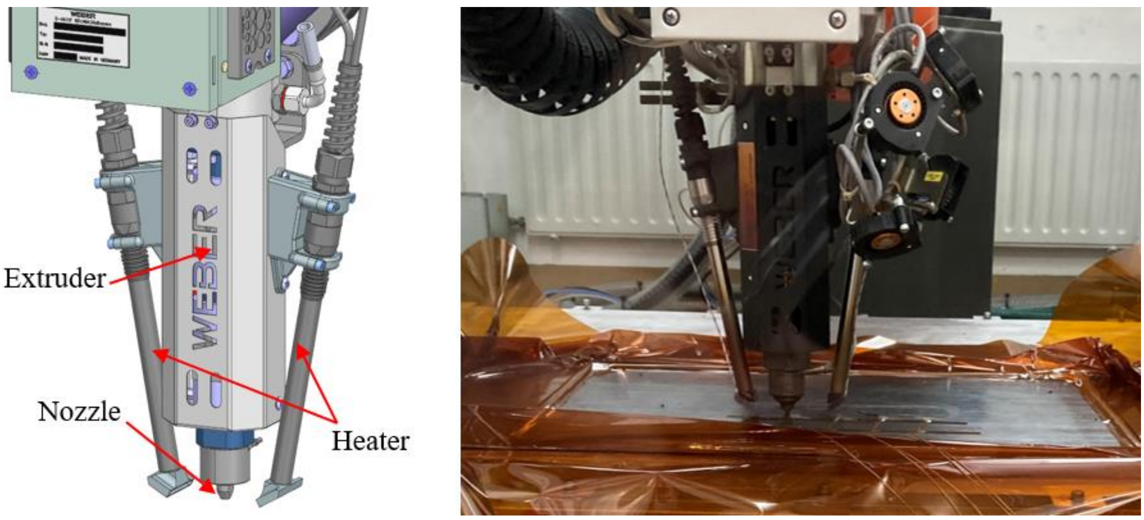

Figure 6: CAD design of the heater(left) and the entire assembly during temperature measurements (right).

The maximum temperature was measured at two speeds, with and without a heated print bed. The results are shown in Figure 7. Similar to the setup of the desktop printer, increasing the print speed reduces the preheating temperature. Using the non-heated print bed, the maximum substrate temperature was 135 °C. With the heated print bed at 200 °C, the preheating reaches 273 °C. For both print bed temperatures, doubling the print speed reduces the maximum temperature by about 20 °C.

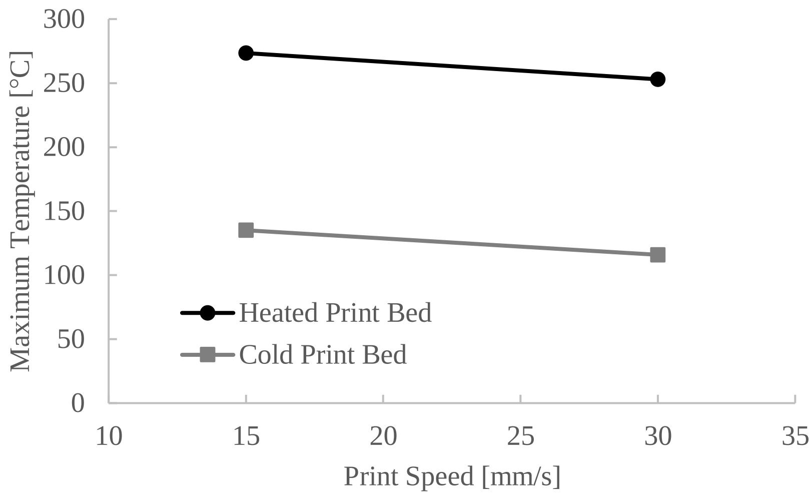

Figure 7: Maximum temperatures with heated and non-heated print bed measured with the large-scale system.

4 DISCUSSION

The concept study on the desktop printer showed effective preheating of the substrate. However, previous studies indicate that temperatures above 200 °C are required for sufficient bonding when overprinting PEEK laminates [3]. Using the desktop printer, this requirement is only met at print speeds below 10 mm/s. This result indicates that higher temperatures, combined with increased heating power, would further improve the print quality. At the same time, low air temperature can even reduce the print quality. At 250 °C, the airflow acted as cooling and introduced poor layer adhesion and high residual stresses, causing the specimens to fail before testing. A specimen at 250 °C air temperature is shown in Figure 8.

Figure 8: Specimen printed at 250 °C air temperature.

Moreover, the results have shown that a constant heating power is not suitable for all applications. Using local heating, the heat input per volume of printed material depends on the part's geometry. Therefore, small parts need less heating power to prevent overheating, while larger parts require more power to reheat the cooled surfaces. Regarding overprinting, different heating settings for the first layer and the following layers will be required.

The local heating system on the large-scale FGF printer showed significant preheating. However, using a non-heated print bed, the requirement of 200 °C was not met. For successful overprinting of PEEK laminates, a heated substrate in terms of heated tooling is still required. This represents a significant constraint on the process. Particularly with large, curved laminates, a heated tooling is expensive and not always feasible.

In addition, the heaters on opposite sides create a strong turbulence of hot air with cold ambient air. Optimising the heater nozzle can therefore lead to considerable improvements. A ring design, as in the concept study, would be ideal, but also severely restricts the robot's freedom of movement in multi-axis pressure.

5 CONCLUSION

In this work, the concept development and design of a heating system for local preheating of substrates in 3D-printing is presented. The aim of the heating system is to provide sufficient substrate preheating for overprinting of high-temperature thermoplastic laminates without restricting the freedom of movement when used on multi-axis systems. A concept study for hot air heating using a desktop FFF printer was performed to find suitable air temperatures and process parameters to achieve this goal. Subsequently, the concept was transferred to a large-scale robotic system and evaluated.

The concept study proved the concept of hot air heating for material extrusion. The heating did not only preheat the substrate but also increased the mechanical properties of printed PEEK. At the same time, investigations showed that sophisticated power management is required to adapt the heating power depending on the printing parameters and geometry to prevent overheating.

The heater prototype developed for the robotic FGF system was able to reproduce the results from the concept study. In combination with a heated printed, effective preheating was shown. However, the goal of 200 °C preheating temperature was not met without a heated print bed. Overall, the study showed great potential for hot air preheating, forming the basis for further process development. Especially the design of the air nozzle and the airflow design needs to be improved in follow-up investigations.

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