MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (On-line)
Special Issue | HSM 2025
18th International Conference on High Speed Machining
October 15-16, 2025, Metz, France
DOI: 10.17973/MMSJ.2025_11_2025130

HSM2025-44835

INFLUENCE OF LAYER TIME ON THE MECHANICAL PROPERTIES OF THIN-WALLED PARTS PRODUCED FROM MODIFIED POLYCARBONATE REINFORCED WITH CARBON FIBRES BY A PELLET EXTRUSION MODELLING (PEM) PROCESS

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Abstract

Large-format additive manufacturing is a production technology that enables production of large-scale parts made from fibre-filled thermoplastic pellets. A kinematic structure, such a robot or a CNC portal machine, carries the extruder that plasticizes polymer granulates and extrudes material layer by layer (Pellet Extrusion Modelling - PEM). The technology is usually used in tooling manufacturing processes. One specific application of PEM technology is production of thin-walled lightweight structures using modified polycarbonate reinforced with carbon fibres. Thin-walled parts are used as a core in production of structural composite parts. The critical process parameter of PEM is layer time. It is a key technical parameter that affects the temperature of the bonding of two layers, which relates to the mechanical properties of the printed part. Ensuring the correct process window of a temperature during the bonding process is thus critical. For structural components where mechanical properties are inspected, the correct layer time must be chosen. This paper focuses on a study of temperatures during the bonding process of a structural thin-walled part printed via PEM technology. The layer temperatures during the cooling process before application of the next layer were investigated. The layer time was changed to monitor the thermal influence of this parameter. The specimens were prepared and the mechanical tests were carried out to present the effect of the layer time on the mechanical properties of the thin-walled 3D printed parts.

Keywords:

Large-format additive manufacturing, Pellet extrusion modelling, Layer time, Thin-walled parts, Modified polycarbonate, Structural composite parts, Tensile strength

1 INTRODUCTION

The growing significance of large-scale additive manufacturing processes such as Pellet Extrusion Modelling (PEM) is due to their ability to produce complex geometries with high productivity while reducing material waste and manufacturing time. PEM provides productive thermoplastic material extrusion. When reinforced with carbon fibres, the final part offers improved mechanical properties and structural integrity. However, ensuring strong interlayer adhesion remains a critical challenge. Layer time (deposition time) is defined as the time between the deposition of two successive layers. It is related to the temperature of the previously deposited layer when placing the subsequent layer. Layer time directly influences the mechanical properties of the final part [Ramirez de las Heras & Osinga, 2024].

The layer time in PEM determines the bonding quality between successive layers, which affects the final mechanical properties of the printed component. A prolonged layer time results in the deposition of the subsequent layer onto an excessively cooled surface, leading to weak interlayer bonding, delamination, and potential structural failures. Conversely, an excessively short layer time prevents adequate cooling, resulting in overheating, material collapse, or warping [Jo et al., 2022]. Optimising layer time is, therefore, essential to balance these opposing factors and achieve high-quality printed parts [Vanaei et al., 2020].

Several studies have demonstrated the impact of layer temperature on the mechanical performance of additively manufactured parts. Research indicates that depositing a new layer when the substrate temperature is slightly above the glass transition temperature (Tg) enhances interlayer adhesion and mechanical strength [Pignatelli & Percoco, 2022]. Furthermore, fibre reinforcement plays a crucial role in reducing thermal distortion, improving structural stability, and increasing the mechanical performance of the final print [Consul et al., 2020].

Mechanical analysis of parameter variations in large-scale extrusion additive manufacturing reveals strong anisotropy due to insufficient bond formation. The tensile properties of carbon fibre-filled polyamide have been investigated to determine the correlation between substrate temperatures and layer heights on mechanical strength. Findings indicate that sufficient transverse tensile strength is achieved between the extrapolated crystallisation onset and melt temperature, highlighting the importance of precise thermal control during the printing process. The proposed process window for satisfactory interlayer strength using infrared pyrometers was validated. Data were used for varying printing robot velocities [Tagscherer et al., 2022].

Additionally, non-isothermal fusion bonding has been identified as a crucial mechanism governing interlayer adhesion in extrusion-based AM. Studies suggest that fusion bonding efficiency is directly linked to the temperature range between the glass transition and degradation onset, making temperature regulation essential for enhancing mechanical integrity [Tagscherer et al., 2021]. The influence of short and continuous carbon fibre reinforcements on printed polymer composites has also been explored, demonstrating improvements in mechanical properties while highlighting challenges related to fibre alignment and anisotropic strength distribution [Adil & Lazoglu, 2023].

Finite element analysis can be used for physics-based simulations of thermal behaviour and optimal layer time prediction. The glass temperature of the material used in the process - polycarbonate reinforced with carbon fibres - is 145°C. This temperature was used as a target temperature in the optimisation process. The upper limit was set to 165°C due to the risk of collapse. The lower limit was 125°C based on the required tensile strength. The best layer time for these conditions was determined to be 129 seconds. Through experimental analysis and numerical simulations, this research aimed to establish optimised layer time parameters that enhance optimal interlayer bonding [Jo et al., 2022].

As mentioned, studies have described optimal bonding of printed layers as one of the key challenges in PEM. This can be achieved by controlling the temperature profile of the deposited beads. Layer temperature control is a crucial factor for interface bonding for the following reasons:

• a high cooling rate causes poor interface bonding.

• a low cooling rate causes deformation of the fabricated parts due to gravity, etc.

Temperature control can be achieved via layer time optimization, but this has some limitations, especially in extruder performance and machine velocity. Another approach is in-process heating of the layer before depositing the next layer. The optical pre-deposition local heating method can be used to increase the inter-layer interface temperature and bond strength. Although this approach has been used in FDM printing technology, the principle can be transferred to PEM [Ravi, 2016].

2 TECHNICAL EQUIPMENT

An industrial robot with a pellet extruder was used in the experiments presented in this research. A KUKA KR 60 HA robot was equipped with a CEAD E25 extruder. The pellet extruder is controlled by a base unit, which controls temperatures, extrusion speed and automatic material. The maximum output of the extruder is 12kg/h with 4 heat zones and 1kW motor power. The KUKA robot is controlled by a CNC control system, namely the Sinumerik 840d sl with the option Run MyRobot /Machining. This control architecture allows continuous-path control of the robot via G-code programming. Programs for the robot are prepared via CAM Siemens NX AM Multi-Axis.

This study focuses on thin-walled structural parts, which can be used as a core for carbon fibre winding processes. These parts are used as a structural part for high-dynamic machines. In any case, the mechanical properties of the part play a crucial role in the durability and rigidity of the final product. There are many parameters which affects material and part properties. This study focuses on tensile strength as an elementary characteristic of the structural material.

Pellets produced by Airtech were used. The material was Dahltram® C-250CF - modified PC reinforced with carbon fibres. Due to this reinforcement, the final part was tested as a composite material.

3 THIN-WALLED STRUCTURAL PART

The final mechanical properties of the printed object depend on the wall thickness, bead parameters (height, width) and process parameters (temperatures, velocities). An overview of the process settings is shown in Tab. 1. Layer time was identified as a critical process parameter.

Tab. 1: 3D printing process settings

Nozzle Diameter	Layer Height	Layer Width	Material Constant	Layer Length
Ø 2 mm	1 mm	3 mm	2,18 cm^3/rot	1980 mm

The topology of a printed structural part with temperature measurement locations is shown in Fig. 1. The path of one layer is displayed. Each layer of the final part has the same path length and shape.

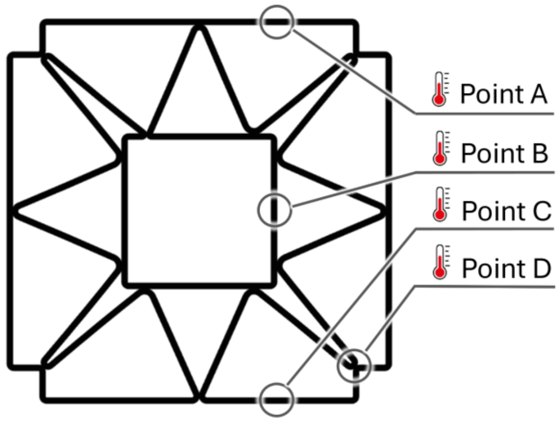

Fig. 1: Topology of a structural part and temperature measurement locations

The locations of temperature measurements are indicated in Fig. 1. The measurement points were selected to represent different thermal conditions across the thin-walled structure in critical areas (walls and corners) in order to determine how the layer time affects the temperature at these locations. A range of possible layer times was set to 20 seconds, 25 seconds and 30 seconds. The extruder's screw RPM and robot TCP velocity were calculated using equation (1).

$$RPM\ screw = \frac{v_{TPC}\ .\ LH\ .\ LW}{MC\ .\ 1000} \qquad (1)$$

The velocity of the robot's TCP v_{TCP} [mm/min] is calculated from layer length (1 980 mm) and the required layer time. The *RPM screw* [1/min] is calculated from the layer height *LH [mm]*, layer width *LW [mm]* and material constant *MC* [cm^3/rot].

The robot TCP velocity and screw RPM for the different layer times are shown in the Tab. 2. The dry run (i.e. a program run without a printing process) revealed that the required layer time and velocity cannot be met over the whole path. The robot must reduce the velocity at the corners. One of the main reasons is the torque limits of the robotic joints based on the servo motor size. The drops in velocity at the corners was reduced by adjusting the Cycle832 setting in Sinumerik. The tolerance was set at 0.2 and the specified mode was set to Roughting. The priority was put on productivity rather than precision. This setting allows higher deviation from a nominal path. The velocity drops were reduced but not entirely eliminated. The result was that the required layer time could not be met. The measured and required layer time are shown in Tab. 2. The greatest difference in required and measured layer times (12%) occurred at the highest velocity (layer time of 20s).

Tab. 2: Process settings for different layer times

Layer Time Setpoint	Screw RPM	TCP velocity	Measured layer time
20s	8.2 $^{1}/_{min}$	5940 $^{mm}/_{min}$	22.4s
25s	6.5 $^{1}/_{min}$	4752 $^{mm}/_{min}$	26.6s
30s	5.5 $^{1}/_{min}$	3960 $^{mm}/_{min}$	30.3s

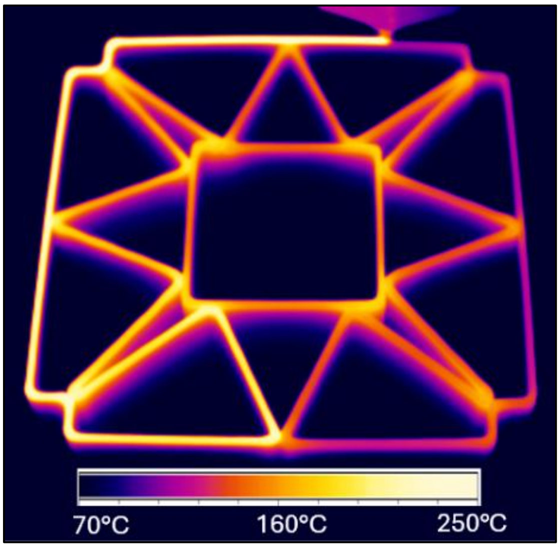

Fig. 2: Image taken by the infrared camera (layer time 25s)

Three objects were printed. Each of the objects was printed with a different layer time. The temperature was measured at discrete locations (shown in *Fig. 1*) using a Micro-Epsilon thermoIMAGER TIM 40 infrared camera. The emissivity was set to ε = 0,96.

An image taken by the camera is shown in Fig. 2. The CEAD E25 extruder has four heat zones. The temperature setpoints of each zone is shown in Tab. 3. The temperatures follow the recommendations of the pellet manufacturer (Airtech) and are adapted to the process. The heat zone 4 is the zone near the nozzle.

Tab. 3:Temperature setpoints of the extruder's heat zones

Heat zone 1	Heat zone 2	Heat zone 3	Heat zone 4
285°C	295°C	320°C	345°C

Based on the temperature measurements, it was determined that the object cools down unevenly across the points, and this depends on a particular location on the part. Fig. 2 shows the relative difference in temperature using various colours. To measure the temperature, specific locations were set. The temperature measurement locations are defined in the Fig. 1. These temperatures are the temperatures of the layer at the moment of depositing the next layer. The measured temperatures during the bonding of the layers for three different 3D printed objects with different layer time are given in Tab. 4.

Tab. 4: Measured temperatures at set locations

Layer Time	Point A	Point B	Point C	Point D
20s	125°C	140°C	137°C	185°C
25s	113°C	135°C	118°C	160°C
30s	102°C	117°C	108°C	150°C

The temperature of the resin at the nozzle output is 275°C ± 5°C, depending on extruder's RPM. The cooling of the part strongly depends on the layer time. To highlight the difference in temperature between different layer time settings, percentage relationships are shown in Tab. 5. Note that the reference temperature is the temperature for a layer time of 20s.

Tab. 5: Measured temperatures shown as percentage relationships

Layer Time	Point A	Point B	Point C	Point D
20s	100% ↓	100% ↓	100% ↓	100% ↓
25s	90%	96%	86%	86%
30s	82%	84%	79%	81%

For example, the temperature drops for a layer time of 30s and Point C is by more than 20%. The temperature difference when choosing a slightly different layer time (just 10s difference) is significant. This is because it is a thin-walled structure and the part has a very limited temperature capacity.

4 EXPERIMENTAL PART FOR SPECIMENS

An experimental part was designed for preparing specimens for tensile strength testing. The intention was to reduce temperature variation to generate a consistent batch of specimens for tensile strength testing and to make it easier to cut specimens from straight walls. The original structural part did not have enough straight walls to prepare all the specimens. The experimental part has a box-shape. The part is shown in *Fig. 3*

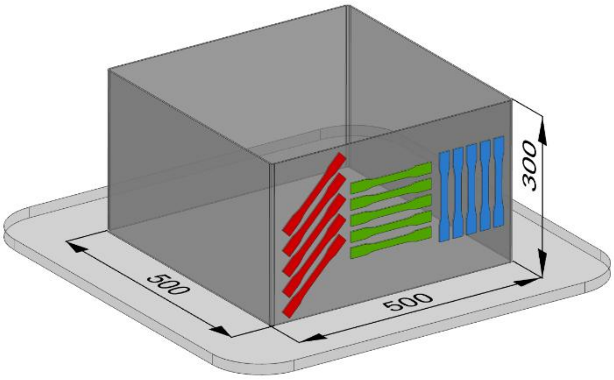

Fig. 3: Experimental part for cutting specimens

Both the structural part shown in Fig. 1 and experimental part shown in *Fig. 3* have a layer length of 1 980 mm. This means that the experimental part is a flat pattern of the original structural part. The flat pattern allows easier and more time effective cutting of the specimens for subsequent tensile strength testing.

The temperature was measured during the printing of the box. Point A in Fig. 1. has the same temperature of the layer before depositing the next layer as the experimental part. The temperatures for Point A and all the layer times are provided in Tab. 4.

Fig. 3 highlights specimens which were subsequently cut from the printed object. Different specimen orientations were chosen because a 3D printed object has a high anisotropy. Three objects were printed. The only change in the process parameters was the layer time, i.e. objects with a layer time of 20s, 25s and 30s were printed.

The specimens for each layer time have the following orientation: Longitudinal 0° (green), L/T 45° (red) and Transverse 90° (blue). This discreet choice of orientation should show and cover the anisotropy of the 3D printed object. Five samples were prepared for every specimen to account for statistical deviations.

4.1 Mechanical testing

Tensile strength testing was carried out. The methodology followed ASTM D638, which is a standard testing method for determining the tensile properties of plastics. It describes preparation of specimens with a dogbone shape, of a size according to the standard and loading characteristics with constant speed. An image taken during testing is shown in *Fig. 4*.

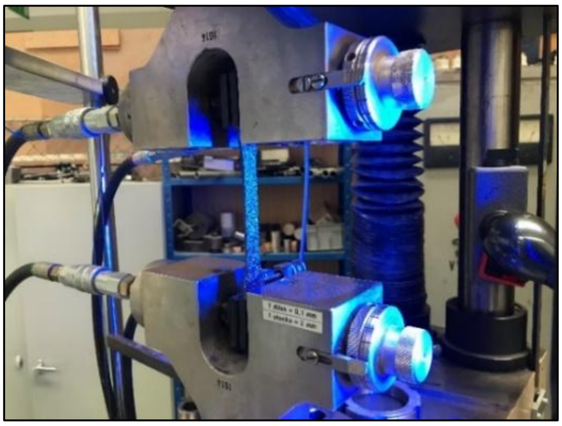

Fig. 4: Tensile strength testing of specimens on a universal testing machine TIRA TEST 2300

The recorded data were processed. Multiple material properties were calculated, such as modulus of elasticity and Poisson's ratio. *Tab. 6* shows the tensile strength testing results. The tensile strength for different layer times and modes is shown.

Tab. 6: Tensile strength for different layer times

Layer Time	Strength Mode L	Strength Mode T	Strength Mode L/T
20s	101.5 MPa	34.8 MPa	39.3 MPa
25s	98.6 MPa	26.2 MPa	35.4 MPa
30s	96.8 MPa	19.5 MPa	24.2 MPa

There is a significant difference in tensile strength in Transverse mode. For 20s, the tensile strength is 34.8 MPa and for 30s it is 19.5 MPa. There is a 44% drop in tensile strength caused by different layer time setting.

Fig. 5 shows the results in a diagram. The average tensile strength of every tested batch of specimens is depicted. The standard deviation is also shown. The only process parameter, that was changed, is layer time. The specimens had different orientations in relation to the laying direction: Longitudinal, Transverse and L/T 45°. The temperatures in Fig. 5 refer to the temperature of the layer before the deposition of the next layer, for each layer time (bonding temperature).

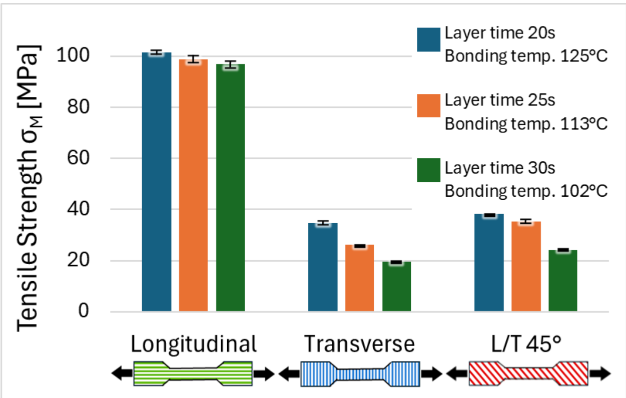

Fig. 5: Tensile strength for different layer times

5 DISCUSSION

Layer time relates to the temperature of interlayer bonding. This study points out the importance of temperature control in 3D printing PEM processes. Contemporary systems include standard temperature control of the extruder's heat zones. The temperature of the bonding of layers on the printed part is not considered in control. Temperature control of a printed part enables greater tensile strength, because the optimal layer time can be achieved.

There is a significant temperature inconsistency in the cooling down of a printed part. The temperature depends on the printed object's topology and shape. Temperature control is needed for velocity control of the TCP and extrusion to achieve an optimal temperature and layer bonding.

Future research will focus on temperature control of a 3D printed object during the printing process. This makes it possible to print the object with the correct process temperature window and to achieve optimal interlayer bonding in advanced topologies. This significantly influences the object's mechanical properties.

6 SUMMARY

This study focused on the mechanical properties of thin-walled structural parts printed via 3D printing technology PEM. The material properties are important parameters for structural parts during the design process. The main phenomenon, which influences the mechanical properties of a 3D printed object, is interlayer bonding. This is related to the temperature and printing velocity, which is described by a process parameter called layer time. Interlayer bonding temperatures were analysed during printing with different layer time settings.

The structural thin-walled part was printed and temperatures were measured. The experiment was designed and the box-shaped experimental part was printed. The experiment investigated the relationship between layer time and interlayer bonding via tensile strength testing. The specimens were cut out from a box-shaped object. Tensile strength testing followed ASTM D638. The experiment was analysed and the final results were presented.

For printing thin-walled structural parts via PEM technology the layer time is a crucial process parameter. Three different loading modes were chosen. In the worst loading mode (Transverse) a lower tensile strength was achieved. Comparison of different layer time settings for the transverse loading mode showed a 44% drop in tensile strength caused by the higher layer time (lower temperature of a layer before laying next layer). This study quantifies the influence of layer time on the final strength of the printed object.

7 ACKNOWLEDGMENTS

The presented research was supported by the European Union under the project "ROBOPROX - Robotics and Advanced Industrial Production", reg. no. CZ.02.01.01/00/22_008/0004590, and by the European Union within the project RICAIP, which received funding from the EU's Horizon 2020 research and innovation program under grant agreement No. 857306 and was co-funded by the EU within the project CZ.02.1.01/0.0/0.0/17_043/0010085 „Research and Innovation Centre on Advanced Industrial Production". The contribution of Ph.D. students in the team of authors was also supported by the Grant Agency of the Czech Technical University in Prague through grant no. SGS24/129/OHK2/3T/12.

8 DATA AVAILABILITY

The source data for this article are accessible via doi: 10.5281/zenodo.16892586.

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