euspen's 26th International Conference &
Exhibition, Krakow, PL, June 2026
www.euspen.eu

Fused Filament Fabrication System for continuous fibre reinforcement

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Abstract
Additive manufacturing offers significant potential for industrial applications due to its capacity to produce complex geometries while concurrently processing materials efficiently. In particular, the integration of continuous fibres in fused filament fabrication (FFF) enables the production of prototypes and functional components with significantly improved mechanical properties and customisable structures. However, the current state of the art is limited in terms of flexible fibre positioning, which limits targeted component reinforcement and optimisation of material properties. A modified FFF system, incorporating a double bowden extruder, an integrated cutting unit and automated build field calibration for flexible continuous fibre deposition, can be employed to create an open research platform for investigating and optimising fibre-reinforced additive manufacturing processes. The control of the process is facilitated by means of customisable G-code commands, which permit the definition of deposition parameters such as fibre orientation, layer height and feed rate in a flexible manner. Systematic experimentation of the fibre extrusion has been undertaken to demonstrate the influence of these process parameters on defect formation and fibre-matrix interaction during continuous fibre deposition.

fused filament fabrication, continuous fibre reinforcement, defect analysis

1. Introduction

Additive manufacturing is becoming increasingly important for the production of functional components, but still has limitations in terms of mechanical component properties, particularly in polymer-based processes such as fused filament fabrication (FFF) with which the influence of individual process parameters can be specifically investigated [1,2]. The objective of this study is to develop and conduct experimental research on an open FFF system for continuous fibre integration. One method of enhancing the mechanical properties of a material is to introduce fibres into the plastic matrix. While short fibre-reinforced materials achieve only limited reinforcement effects, continuous fibres aligned with the load enable a significantly higher increase in strength and stiffness [3]. In the FFF process in particular, continuous fibres can be specifically integrated into components due to the linear application of material and free path control [4]. Commercial continuous-fibre FFF systems, such as those provided by Markforged Inc., Watertown USA, allow the production of fibre-reinforced components but offer only limited flexibility regarding fibre placement strategies and process parameter modification. For research purposes, there is a need for open, flexibly adaptable systems with which the influence of individual process parameters can be specifically investigated.

2. System concept and modification

The starting point is a commercially available desktop FFF printer that has been extensively modified. A dual Bowden extruder system has been implemented to separately feed the matrix material and continuous fibre, keeping the print head mass low and enabling precise path guidance as shown in Figure 1.

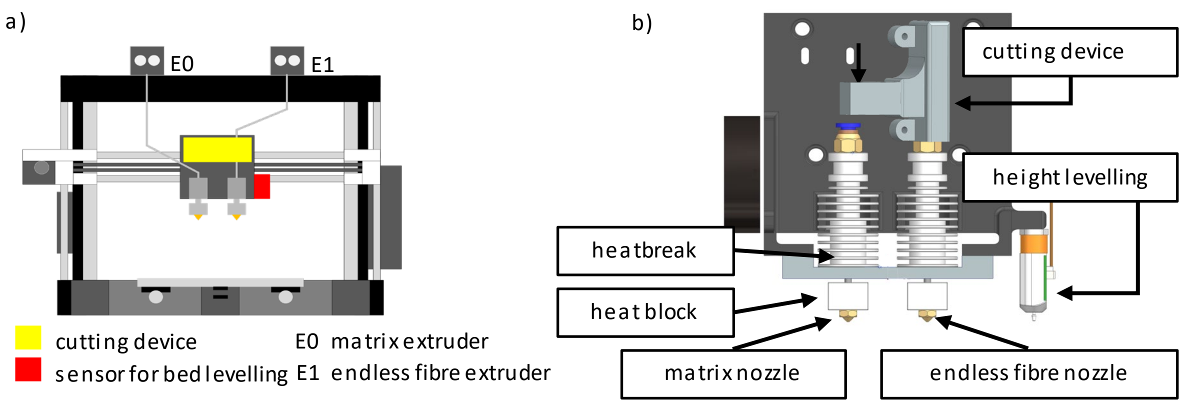

Figure 1. Modified FFF printing system with dual nozzles for matrix material and continuous fibre, including integrated cutting and calibration unit

The coated continuous fibre is fed into the print head via a specially developed cutting and feeding unit and applied to the surface of the matrix material. A multi-part cutting mechanism was developed to cut the continuous fibre while maintaining compatibility with the print head. The linear cutting movement is performed by an electromagnetic solenoid motor from HESCHEN, Foshan, China. A cutter blade is inserted at the front of the adapter. Due to the positioning of the cutting blade, the minimum fibre length is $l_{mF} \leq 105$ mm. This value corresponds to the distance between the fibre cutting device and the deposition point at the nozzle. As a result, fibre segments shorter than this distance cannot currently be produced by the system. This limitation restricts the use of short reinforcement segments and locally defined fibre placements within small component geometries. Consequently, reinforcement strategies must primarily rely on longer continuous fibre paths.

3. Method

The verification of the newly developed printer is carried out in several stages. Once the basic functions of the printer have been tested, the focus is on the production of test specimens from PLA-Basic from BAMBULAB, Shenzhen, China, as the matrix material with integrated continuous glass fibre filament from MARKFORGED INC., Watertown, USA. This initial test series analyse the influence of process and structural parameters on the quality of fibre deposition, such as the fibre deposition angle ϕd in the component plane, as well as the interaction between matrix extrusion and fibre transport. A systematic statistical evaluation with repeated trials will be part of future investigations. A similar study was conducted for the continuous carbon fibre filament from MARKFORGED INC., Watertown, USA. Fibre deposition angles $\phi d_a = 30°$, $\phi d_b = 60°$, $\phi d_c = 90°$, $\phi d_d = 120°$, $\phi d_e = 150°$ and $\phi d_f = 180°$ were investigated [5]. As part of this work, defects are to be detected for the same fibre deposition angles ϕd using microscopy and analogies and deviations from the aforementioned study are to be found. Ultimately, a recommendation is to be derived as to the maximum fibre deposition angle ϕd_{max} at which processing without cutting is feasible.

The samples were evaluated visually and by means of microscopic analysis in order to identify typical defects such as fibre breakage, delamination, insufficient impregnation and positional deviations. A VHX-5000 digital light microscope from KEYENCE, Osaka, Japan, was used for all microscopic examinations.

4. Results

The experimental investigations visbile in Figure 2 show that the fibre deposition angle has a significant influence on process stability and defect formation during continuous fibre integration. At small deposition angles, there is an increase in fibre kinks, local detachments and irregular embedding of the continuous fibre in the matrix. These defects are due to increased deflection of the fibre in the print head and unfavourable relative movements between the nozzle and the fibre. As the fibre deposition angle increases, the stability of the fibre deposition improves significantly. For deposition with as few defects as possible, an optimal range of up to $\phi d_{max} \leq 60°$ has been identified, although initial changes in the cross-section of the fibre have already been observed. If the aim is simply to avoid the formation of fibre folds, deposition up to $\phi A_{max} \leq 90°$ is possible.

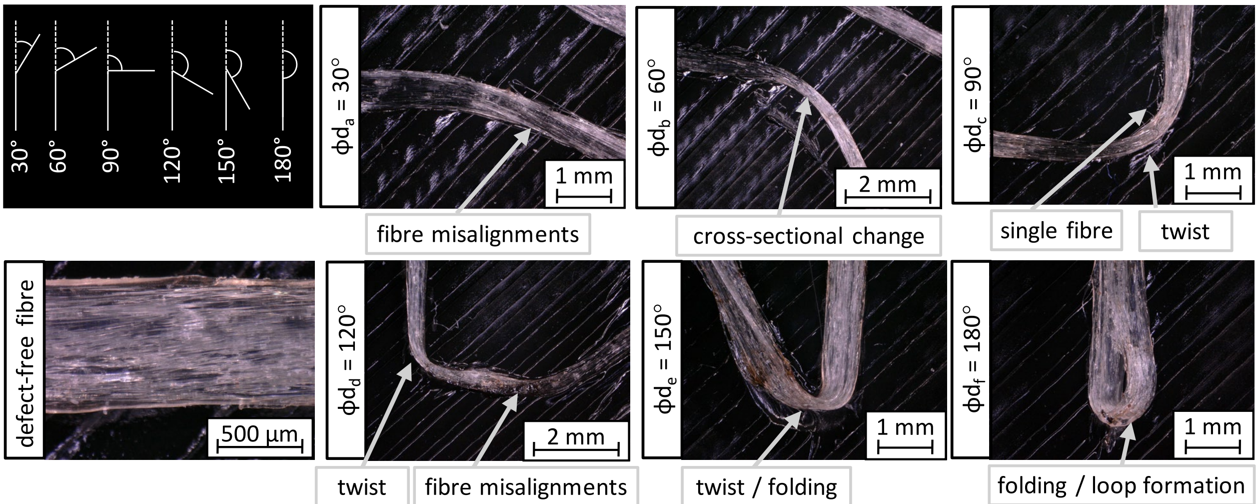

Figure 2. Microscopic images of continuous fibre deposition

5. Conclusion and outlook

The flexible G-code-based control system allows specific process windows to be identified in which reproducible and defect-free continuous fibre integration is possible. The developed system thus enables systematic investigation of the interactions between process parameters and component quality. The experimental results show that the system is particularly suitable for investigating process-related defects and optimising fibre-matrix interaction. Future work will focus on quantitative mechanical testing and the integration of more complex reinforcement strategies and additional fibre-matrix combinations.

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