TEMPERATURE CONTROL OF CONTINUOUS CARBON FIBRE REINFORCED THERMOPLASTIC COMPOSITES BY 3D PRINTING

Jing Pu[1], Peng Zhuo[2], Arthur Jones[3], Shuguang Li[4], Ian Ashcroft[5], Tao Yang[6], Kulsangcharoen Ponggorn[7]
[1] School of Aeronautic Science and Engineering, Beihang University, China
[1,2,3,4,5,6,7] Faculty of Engineering, the University of Nottingham, UK
[2] Composites Science and Technology Division, AVIC Composites Corporation, Ltd. China
[1]jing.pu@nottingham.ac.uk
[2]peng.zhuo@nottingham.ac.uk
[3]arthur.jones@nottingham.ac.uk
[4]shuguang.li@nottingham.ac.uk
[5]ian.ashcroft@nottingham.ac.uk
[6]tao.yang@nottingham.ac.uk
[7]ponggorn.kulsangcharoen@nottingham.ac.uk

Keywords: 3D Printing, FDM, temperature control, PEEK continuous carbon fibre,

ABSTRACT

This paper describes the design of a high temperature heating system for a 3D printing application of continuous carbon fibre reinforced thermoplastic composites FDM process. The purpose of this system is to use PEEK carbon fibre prepreg material as the printing material for continuous carbon fibre reinforced thermoplastic composites manufacturing. The challenge for this project is to make a traditional FDM 3D printer capable of heating up the temperature into the PEEK melting point. The system includes a section for providing the heating, a section for temperature measurement and a closed-loop feedback PID control system. More experiments will be carried out for this project to prove the feasibility of the design.

ABS	Acrylonitrile butadiene styrene	MOSFET	Metal-oxide-semiconductor field-effect transistor
AM	Additive Manufacturing	PC	Polycarbonates
CFRTP	Continues carbon fibre reinforced thermoplastic	PEEK	Polyether ether ketone
CMOS	Complementary metal-oxide-semiconductor	PID	Proportional-integral-derivative
FDM	Fused Deposition Modelling	PLA	Poly(lactic acid)
FFF	Fused Filament Fabrication	PWM	Pulse-wide modulation
FRC	Fibre Reinforced Composite	SLA	Stereolithography
ISR	Interrupt Service Routine	SLS	Selective Laser Sintering
LOM	Laminated Object Manufacturing		

1 INTRODUCTION

1.1 Background and Motivation

The amount of fibre reinforced composite (FRC) material used in aircraft is continuously increasing. However, there is still limited application of composites for key load carrying structural parts such as joints and lugs. The biggest challenge of FRCs for key load carrying parts is their geometric complexities, e.g. notches and holes, which undermine the structural benefit composites can bring about. The objective of this project is to address the goals of maintaining fibre continuity so that load can be transferred along fibres and structural weight can be minimised. The application of 3D printing as a solution to manufacture complex structure parts has been identified as the means to achieve the proposed objective. It is envisaged that structural parts can be manufactured without having to cut fibres in presence of holes or notches. One of the tasks of this project is to develop or adapt a 3D printer to facilitate the manufacturing process. This involves improved temperature control system so that the matrix material for the composite can be selected over a reasonably wide range.

1.2 Process

Additive Manufacturing (AM), also known as 3D printing, is a new manufacturing concept of advanced manufacturing [1-3]. This technology is used to manufacture objects by adding material to minimize the need for finishing material removal operations while achieving satisfactory geometric accuracy [4]. One of the advantages of 3D printing compared with traditional manufacturing techniques is that the process does not require templates, moulds or masks. In addition, 3D printing has unique ability to fabricate interlocking geometries, features embedded within a shell structure, and heterogeneously printed materials within a single layer or design, leading to new designs and functionalities [5]. For the printing materials of 3D printers, both metallic and plastic parts can be manufactured by different process, since our project is on the research of polymer composites, Table 1 below lists techniques relevant to polymers for 3D printing processes.

Type	Process	Materials
Extrusion	Fused Deposition Modelling (FDM) Fused Filament Fabrication (FFF)	Thermoplastics
Light polymerized	Stereolithography (SLA)	Photopolymer
Powder bed	Selective Laser Sintering (SLS)	Thermoplastics
Laminated	Laminated Object Manufacturing (LOM)	Plastic film

Table 1. Polymer related 3D printing process [6]

The 3D printing technique applied in this research is the extrusion-based Fused Deposition Modelling (FDM) process, since theoretically the technique is capable of processing continuous fibres combined with thermoplastic matrix material. FDM is a filament-based technology where a temperature-controlled head can extrude a thermoplastic material layer by layer onto a substrate (see Figure 1).

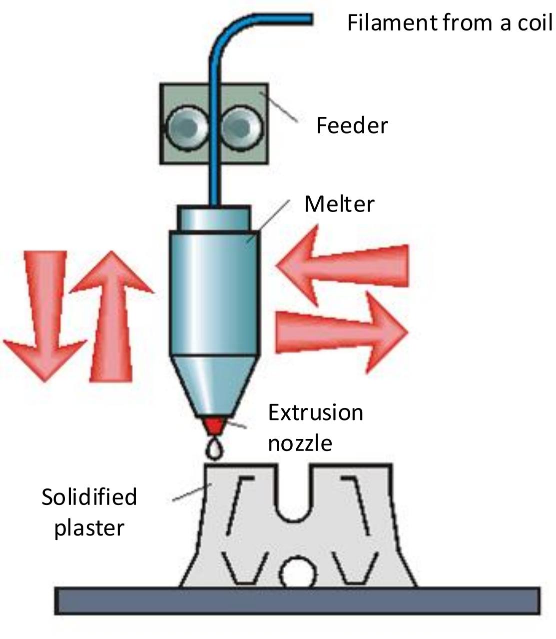

Figure 1. Fused Deposition Modelling [6]

FDM 3D printers are most commonly used for manufacturing polymer composites. The FDM 3D printing process achieves a controlled extrusion of thermoplastic filaments as follows: Filaments are melted into a semi-liquid at nozzle and are extruded onto the substrate layer by layer where layers are fused together and then solidify into final parts [7]. From the properties of the FDM 3D printer, the temperature control of the print head is one of the most important controlling factors of this process. It should be controlled at a temperature sufficiently close to the melting point of the polymer so that the polymer being extruded should turn soft, but not melted into a liquid.

1.3 Material

Fibre reinforced composite materials have advantages of high specific stiffness and strength. They have received enormous attention and been widely used for aerospace and military applications. The 3D printing technique has already been applied for the production of aircraft components. However, the majority of these are made of metallic materials or particulate short-fibre reinforced composites. Continues carbon fibre reinforced thermoplastic (CFRTP) are not widely used in 3D printing. The favourable mechanical properties and light weight are the reasons why composites have been chosen for this research [8-10].

As a semicrystalline thermoplastic, the Polyether ether ketone (PEEK) is of excellent mechanical and chemical resistance properties to a much higher temperature than other thermoplastics. In the aerospace industry, PEEK material is considered as one of the best materials for constructing airframe structures. The reasons include that it can provide significantly higher toughness and long term resistance to fatigue, it can be recycled more easily at the end of life, which makes the product life-cycle more environment friendly. Another significant benefit is that PEEK composites show particularly high resistance to fuel, hydraulic liquid corrosion, potentially reducing the maintenance requirements of the main rotor hub. For instance, for the H160, a medium duty twin-engine civil helicopter made by Airbus, already has a rotor hub manufactured by PEEK resin matrix composites. This technology is designed by Porcher Industries, and its carbon fibre PEEK prepreg has already met the quality requirements of the safety critical application and received the green light for production by Airbus Helicopters [11].

1.4 Research Approach

There has been considerable scientific research conducted on manufacturing high-strength products and prototypes with 3D printed carbon composites. However, 3D printing with PEEK and other advanced reinforced polymers has still been technically challenging. Traditionally, thermoplastics such as PC, ABS and PLA, are commonly used in FDM 3D printing process due to their low melting temperature. By contract, PEEK with its high melting temperature forms a challenge for this process. Arevo Labs has solved this problem by optimizing polymer formulations with an innovative extrusion technology in order to make it suitable for the 3D printing process [12]. But it still hasn't proved the feasibility of producing carbon fibre with PEEK. The MarkOne, reported as the first commercial carbon fibre 3D printer using continuous fibre, uses carbon fibre with nylon matrix. However, the technology used there is not compatible with the PEEK filament fusion systems [13].

The melting temperature of the PEEK prepreg is close to the melting temperature of pure PEEK material. PEEK melts at a relatively high temperature (343˚C/649.4˚F). The original heating system of the print head used in this research (Velleman K8400) cannot reach the temperature required to extrude PEEK carbon fibre filaments. In order to overcome this problem, this project is to make a modification of the current 3D printer such that it can meet the high temperature requirement, and also to control the temperature in the required range. The objectives of this study are to design and implement a heating system to operate the equipment at the melt temperature of PEEK carbon fibre filaments.

In the subsystem of temperature control, the modification involves with metal-oxide-semiconductor field-effect transistor (MOSFET) driver module with aims to provide higher capacity of driving the heating element, the implementation of the amplifier circuit board to transmit an analogue signal from the thermocouple which has wider temperature detection range, and the corresponding closed-loop

PID control system parameters which can adjust the heating temperature in the required range of PEEK material.

In sections 2 and 3, the current equipment is described together with the proposed modifications. The effect of the modifications is discussed in Section 4 and the conclusions drawn from study can be found Section 5.

2. DESCRIPTION OF 3D PRINTING EQUIPMENT

In this project, the Velleman K8400 printer is chosen. This 3D printer is designed for printing plastic materials. Since this printer is open-source, it allows modifications to be made to meet different requirement that we want to achieve. The mainboard is a VM8400MB Atmega 3D printer board, which contains an Atmega 2560 microcontroller chip along with USB interface, and is equivalent to the open-source Arduino Mega 2560 microcontroller but with various peripheral devices integrated into the board. It uses Marlin firmware which is an optimized firmware for RepRap 3D printers and is compatible with the Arduino programming platform. Currently, it gives control of the print head *x* and *y* axes movement, the print bed *z* axis movement, two extruders, two heating elements on two nozzles and two fans. The overall view of the Velleman printer and the mainboard can be seen in Figure 1.

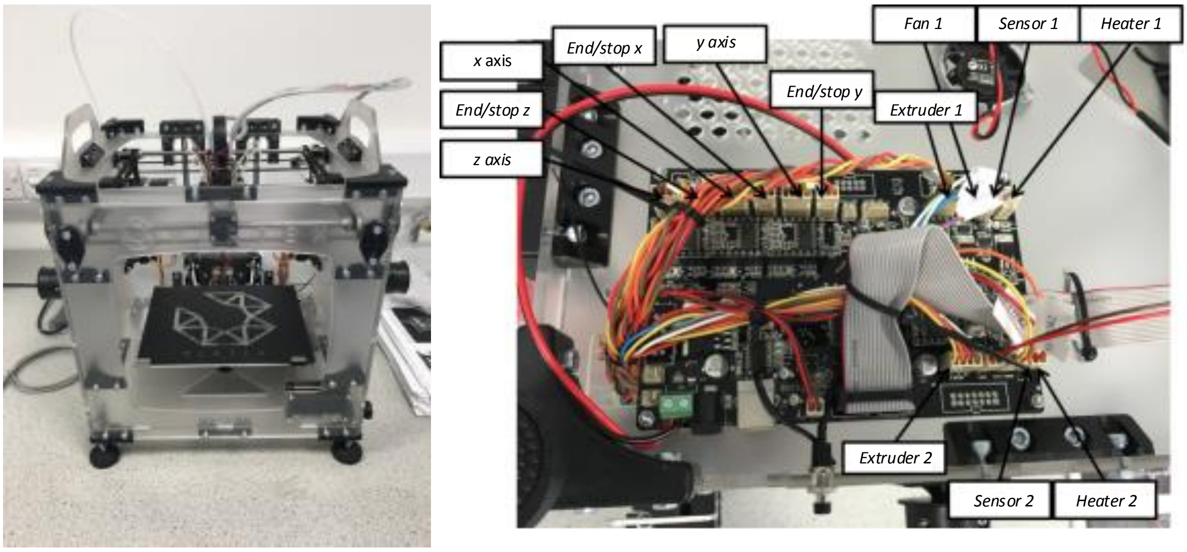

Figure 1. Velleman K8400 printer and mainboard

3. MODIFICATIONS

The high temperature control system modification design consists of three parts: firstly to design a MOSFET driver module with a higher current capacity, because high current capacity allows for higher capacity of the heating element; secondly to develop a sensor system for temperature monitoring, and thirdly to use a closed loop feedback control system with proportional-integral-derivative controller (PID controller) for temperature control.

3.1 Heating System

The open source 3D printer for this project is designed for heating up to 250˚C. In the firmware set up, the original maximum temperature achievable is 275˚C. In order to achieve the objective for the high temperature experiment, the MOSFET driver module board has been modified in order to have a higher current capacity. The modified MOSFET driver module is made by breadboard. The circuit wires are thicker to allow for the higher current to go through. As can be seen in Figure 2, in order to provide the necessary power, an external power supply is connected to the MOSFET and its driver transistor, while a separate supply is used for an additional CMOS logic circuit used to provide the inverted logic signal to the driver circuit. The power to the heater is varied by using Pulse-width modulation (PWM) for which the pulses are software-generated within the existing Marlin code. The

MOSFET driver module has been tested with our heating element, the temperature can be safely heat up into 400˚C without load.

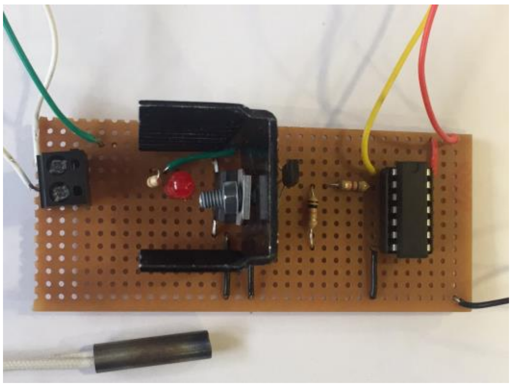

Figure 2: New circuit board of the MOSFET module

3.2 Temperature Sensor System

In this temperature control system, Marlin can control the temperature of extruder, detect the extruder temperature and give this value as the feedback to the system. The existing temperature control system uses a thermistor, for which the signal conditioning circuit is built into a monolithic temperature setpoint controller board. Our project requires the usage of thermocouple since the detecting range of the thermistor is not sufficient for the high temperature requirement. Hence, a K type thermocouple [14] is used but this requires interfacing to the Atmega processor. In order to achieve this, a commercial thermocouple amplifier AD597 is used to generate an analogue signal of 10mV/˚C for connection to a 5V (maximum) analogue input on the Atmega 2560.

A change of settings for the temperature sensor in the firmware configuration is required. In the experiment, the heating temperature range also needs to be modified in the configuration

3.3 Feedback Control System

The system uses a PID controller to control the heating element. A PID controller applies a correction based on proportional, integral, and derivative terms to continuously calculate the error difference between a desired setpoint and a measured variable. The default values of parameters are set in the configuration. In the future experiment, the values of each term parameters will be modified to tune the PID controller.

4 DISCUSSION

Temperature control is one of the most crucial parts in the FDM 3D printing process. The traditional thermoplastics used in FDM 3D printing all have low melting temperatures. However, PEEK has a high melting temperature and therefore forms a challenge for this process. Hence, not only the temperature detection system is being enhanced, the capacity of the heating up system also should be enlarged.

In this study, a modified heating system with higher current capacity has been designed. This heating system will also be powered by an external power supply. Furthermore, a temperature sensor with wider detection range has been chosen and an appropriate modification for the system has been designed. Additionally, the PID control system for closed loop temperature control has been tuned. The heating element and the modified MOSFET driver module of the 3D printer have been tested. Testing the modified head in isolation from the printer will be done before incorporating the head into the printer for system testing.

Following this study, there will be future experiments with the newly designed temperature control system. Since the current extruder thermal isolator is made by PEEK material, new material with higher melting point will be chosen for the extruder. The heating element will also be tested under load. As the next step to be added, a rotation table equipped with a low speed motor will also be used as a platform for testing the modified head away from the printer. As a test of the process capability and quality of the modified 3D printer and process, a number of specimens will be manufactured. These specimens will be subjected to a series of mechanical tests to find the mechanical properties. Results of these tests will be collected and analysed, and compare with a control group.

5 CONCLUSION

The overall aim of this project is to be able to process a matrix material with better mechanical properties for carbon fibre reinforced thermoplastic composites. For this reason PEEK has been selected as matrix rather than materials such as nylon, which due to its low melting point are easier to process, but have less good material properties. In this work we presented a modification for the heating system. In addition, an appropriate temperature detection system has been chosen for this project. Future related mechanism design to enhance the capability of our 3D printer will also be involved before experiments and fabricating process will commence. The expected outcome will hopefully show that correct temperature control will facilitate the 3D printing continuous carbon fibre reinforced PEEK composites for key load carrying parts for aero-structures.

ACKNOWLEDGEMENTS

The first and second authors sincerely wish to thank Chinese Scholarship Council (CSC) for the financial and infrastructural supports under all their supervisors.

REFERENCES

[1] Wong, K. V., & Hernandez, A. (2012). A review of additive manufacturing. ISRN Mechanical Engineering, 2012.

[2] Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: a literature review. The International Journal of Advanced Manufacturing Technology, 1-13.

[3] Frazier, W. E. (2014). Metal additive manufacturing: a review. Journal of Materials Engineering and Performance, 23(6), 1917-1928.

[4] Levy, G. N., Schindel, R., & Kruth, J. P. (2003). Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. CIRP Annals-Manufacturing Technology, 52(2), 589-609.

[5] Gibson, I., Rosen, D., & Stucker, B. (2014). Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Springer. ch. 3, sec. 7.5, pp. 10,57

[6] "Major RP Technology", https://uni.edu/~rao/rt/, accessed on 18 May 2017.

[7] Wang, X., Jiang, M., Zhou, Z., Gou, J., & Hui, D. (2017). 3D printing of polymer matrix composites: A review and prospective. Composites Part B: Engineering, 110, 442-458.

[8] Williams, G., Trask, R., & Bond, I. (2007). A self-healing carbon fibre reinforced polymer for aerospace applications. Composites Part A: Applied Science and Manufacturing, 38(6), 1525-1532.

[9] Cerneels, J., Voet, A., Ivens, J., & Kruth, J. P. (2013, September). Additive manufacturing of thermoplastic composites. In Composites Week@ Leuven (pp. 1-7). KU Leuven.

[10] Van Der Klift, F., Koga, Y., Todoroki, A., Ueda, M., Hirano, Y., & Matsuzaki, R. (2016). 3D printing of continuous carbon fibre reinforced thermo-plastic (CFRTP) tensile test specimens. Open Journal of Composite Materials, 6(01), 18.

[11] "Carbon fibre reinforced PEEK prepreg Spheriflex rotor hub developed with Airbus Helicopters", http://www.porcher-ind.com/medias/dossier-presse/pdf/porcher-dossier-presseEN_11.pdf, accessed on 19 May 2017.

[12] "Arevo Labs announces Carbon Fiber and Nanotube-reinforced High Performance materials for 3D Printing Process", http://www.solvay.com/en/media/press_releases/20140324-Arevo.html, accessed on 19 May 2017.

[13] "3D Printing High-Strength Carbon Composites Using PEEK, PAEK", https://www.designnews.com/design-hardware-software/3d-printing-high-strength-carbon-composites-using-peek-paek/143795958032579, accessed on 19 May 2017.
[14] "Thermocouples - Using Thermocouples in Temperature Measurement", http://www.omega.com/prodinfo/thermocouples.html, accessed on 19 Nov 2016.