CONTINUOUS DIRECTED LASER PREHEATING OF BIG AREA ADDITIVE MANUFACTURING

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ABSTRACT

With the development of big-area additive manufacturing (BAAM) or large format additive manufacturing (LFAM), optimizations of the printing process are made to obtain controllable and stable mechanical performance. In this work, we propose a continuous laser preheating technology for LFAM to achieve higher interlayer bonding strength. Multiple laser diodes are used and built in a ring form to realize the continuous heating process. With multiple laser diodes around the nozzle, the preheating area can be retargeted continuously without rotating the extrusion head or laser source. Compared to the laser-heating source fixed in one direction, switching laser diodes can offer much more printing possibilities and flexibilities. A significant mechanical improvement by using a directed laser heating is achieved. The mechanical testing results showed that with 15W laser power, the flexural strength in the out-of-plane direction reaches up to 80% - 90% of that in the in-plane direction. The highest flexural strength is 86.5Mpa, which is 137% more than that of the specimens without laser heating.

1 INTRODUCTION

The demand for using additive manufactured parts for the structural component is increasing rapidly in recent years [1]. For the manufacturing of large-scale parts with short fibre-reinforced polymer composite (SFRP) materials, the commonly used technique is LFAM [2, 3]. Compared to the fused deposition modeling additive manufacturing technique on the desktop scale, LFAM uses pellets as the printing material, which are melted with heaters mounted on the barrel. The melted SFRP material is then extruded with a long screw driven by a powerful motor and finally shaped through a nozzle to the print platform. To ensure the printing on the large dimension, the extruder head is mounted on a portal frame or a 6-axis robot arm that can move with the slide rail on the side. [4]. Various thermoplastic materials can be used in LFAM: from standard thermoplastic materials such as Acrylonitrile Butadiene Styrene (ABS) to engineering plastic (e.g., Polyamide (PA)) and even advanced thermoplastic (e.g., Polyetheretherketon (PEEK)) [3, 5]. Due to the high-volume output, the LFAM is used to print large prototypes, toolings, moulds and non-structural parts in the automotive, aerospace, construction and shipbuilding industry [6].

However, with the problems, such as large warpage, poor interlayer bonding strength, voids and gaps, the quality of the printed parts cannot be fully controlled and thus, cannot achieve the desired performance [7].

One of the crucial factors that affects greatly the interlayer bonding strength is the substrate temperature during the printing process [8, 9]. According to the previous research, the interlayer bonding strength is significantly determined by interlayer bonding temperature, which is the temperature between the newly placed material of the current printing layer and the previously printed layer [10, 11]. As seen in Fig. 1, the strength in the Z direction, which represents the interlayer strength, in most cases is much less than that in the X direction, which represents the in-plane strength along the printing direction [3]. In critical states, when the temperature of the previous layer is much lower than the glass transition temperature (Tg) or melting temperature (Tm) of the polymer material, delamination between layers occurs [9]. Due to the different sequences of placing material, the substrate temperature on the local position before the next layer is placed can have a large difference. A large difference in local substrate temperature on the different areas of the part causes the inhomogeneous bonding strength of the printed part. To achieve a better interlayer bonding performance, different preheating approaches are proposed and researched, such as using, hot air [12], infrared light [13, 14], laser [15, 16] and hot end [17]. For heating of the thermoplastic material, the laser has offered contactless heating of the material, which has less influence on the original printing process and higher energy density compared with other heating methods. However, due to the high processing speed and changes in the printing direction frequently during the printing process, heating the substrate only in one or two locations is not sufficient to meet the requirement of the complex printing process, such as printing on curves or circles. Thus, we have proposed a method of using an active laser heating system with multiple heating sources to heat up the substrate continuously during the printing process without a standstill.

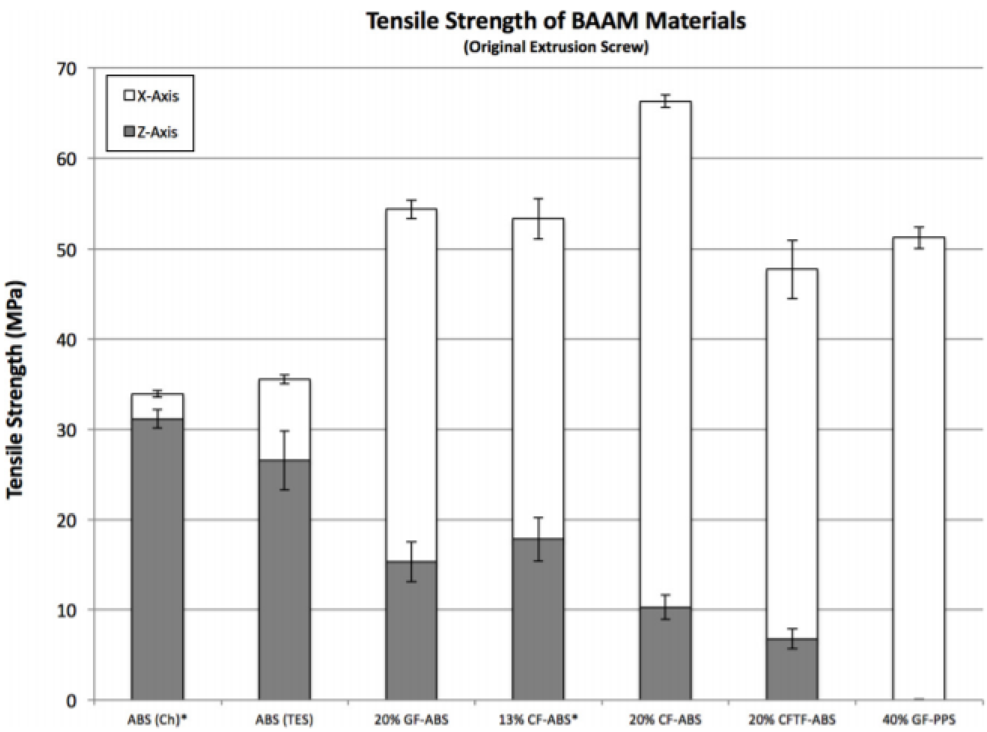

Figure 1: Tensile strength for various LFAM thermoplastics deposited in x and z direction [3].

2 MATERIALS AND METHODS

2.1 Material

Commercial 10% short carbon fibre-reinforced PA6 (AKROMID® B3 ICF 10 black (5118), Akro-Plastic GmbH, Germany) is used in the test. The raw material is in the form of pellets with the color of black. The datasheet of the material recommended a pre-processing a drying of the raw material for about 0-4 hours with the drying temperature of 80℃. The reported melting temperature in the data-sheet is 220℃. The recommended processing temperature of the extruder is about 270°C to 300°C. Under the conditioned testing condition (not dried before testing), the flexural strength is 100 MPa.

2.2 LFAM with in-situ continuous laser pre-heating

The used LFAM system is consists of a Pulsar pellet extruder from the Dyze Design, a Rexroth programmable logic controller (PLC) and a KUKA 6-axis industrial robot arm with a KRC4 controller. The machine data from the current state of the robot arm is sent from the KRC4 controller to the PLC. By using the machine data of the current state of the robot arm, the motor and the heaters of the extruder are controlled by the PLC control unit.

The laser heating system has multiple control channels, which are used to control the state and the power of the laser diodes. A simple example schematic diagram shown is in Fig. 2, the complete heating area is divided into multiple sections. The sections are activated according to the current printing direction. With this approach, the substrate can be heated along the printing path without stopping. It is especially essential when printing a circle or a long curve path, which requires the adjustment of the heating area continuously during the process. The data of the printing direction is sent to the controller of the laser heating system at a high frequency, which can achieve the real-time adjustment of the laser diodes and change of the heating area.

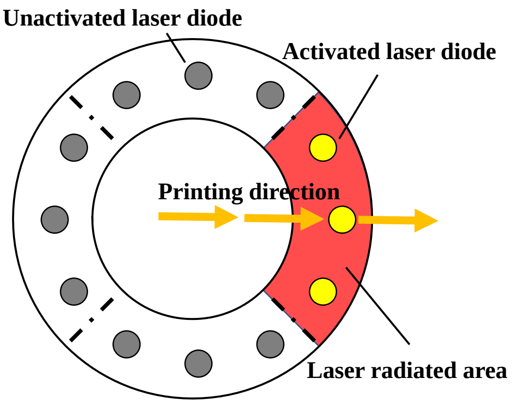

Figure 2: Activating of the laser diodes according to the printing direction.

With the activating of multiple laser diodes at the same time, the heated area between two laser spots is covered by overlapped laser spots without interspace. Thus, the area of the placed material is completely heated. With a wider printing path, the number of simultaneously activated laser diodes is increased to generate a wider heating area and vice versa. A homogenous heating temperature distribution can be obtained by adjusting the power of each activated laser diode. The mentioned laser power in this paper is the total power of all activated laser diodes in use, which represents the power emitted from the laser diodes.

As seen in Fig. 3, the laser is directed to a small local area in front of the nozzle. The objective is to heat only the material of the substrate, which will next have contact with the newly placed material. Heating of the small local area can guarantee the interlayer bonding temperature during the printing process and offer more flexibility to adapt to the different printing paths.

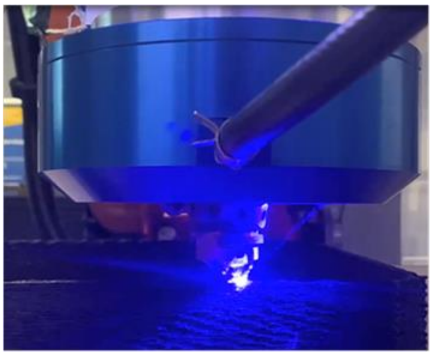

Figure 3: Directed laser preheating with multiple diode laser.

2.3 Three-point-bending test

To distinguish the difference between the specimens with and without the laser pre-heating, the specimen is so printed that the substrate has a long time exposed to the surrounding before the next layer is placed on. The printing path is shown in Fig. 4(a), the layer height is 2mm and the width of the printing path is 6mm. The internal paths are used for the manufacture of the specimen and printed with a speed of 30mm/s with double paths. The outside path with a lower printing speed of 15mm/s is used to ensure a longer cooling time for the material of the internal path. A continuous printing process has minimal influence on the heat convection coefficient with the environment and guarantees the printing quality of the specimen. Without printing the outside path, the substrate temperature before laser heating is 80°C higher. The four sides of the printed specimens are heated by using four different laser power levels with the same amount of laser diodes, which are 0W, 9W, 15W and 21W. The 10% short carbon fibre-reinforced PA6 pellets mentioned in Section 2.1 are dried for four hours and then used to print.

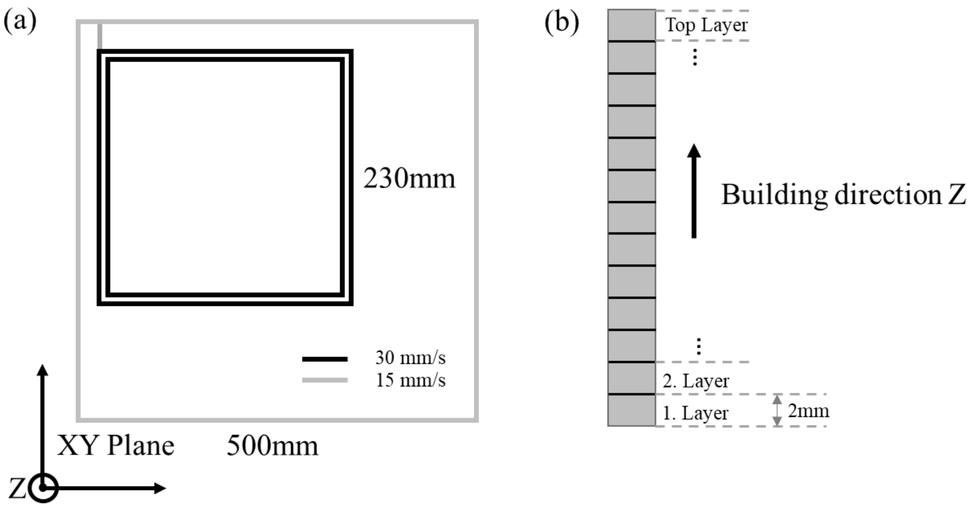

Figure 4: (a) Printing path and the speed of the specimen box. (b) Orientation of the bending test specimen.

The interlayer bonding strength is tested with three-point-bending test. The specimens are so prepared that the long direction of the specimen is the building direction (Z direction), which can represent the bonding quality between layers, as shown in Fig. 4(b). The three-point-bending tests are conducted under norm DIN EN ISO 14125. The dimensions of the specimen under the norm are length 80(+10) mm, width 10(±0.5) mm, and thickness 4(±0.2) mm. The testing specimens are cut out from the printed parts of internal paths.

3 RESULTS AND DISCUSSION

3.1 Temperature of the substrate heated by laser

To obtain the thermal reaction of the laser pre-heating, a thermal camera (FLIR A325sc) fixed on the side is used to measure the temperature of the substrate during the printing process. The temperature of the substrate heated by different laser power with the same printing speed (30mm/s) is measured. The used laser power changed from 0W to 30W and is radiated on a 6mm*2mm area. A picture captured by the thermal camera is shown in Fig. 5(a), the temperature measured at position 2 is the temperature of the substrate before the new material is laid on and the temperature at position 1 is the temperature of the substrate heated by laser. The result of the temperature reaction of the substrate is shown in Fig. 5(b). The showed temperature is the average temperature of 10 measuring points, which are distributed on the same line of the printed material and heated by the same laser power. Because the temperature is measured during the printing process, the residual temperature of the substrate is much higher than the surrounding temperature before the laser radiation. Without laser heating, the temperature of the substrate is about 100°C. With full power 30W, the temperature of the substrate is already above 300°C, which can lead to the degradation of the PA6 polymer. An obvious tendency can be observed that with higher laser power, the substrate temperature is higher and has an approximately proportional relationship.

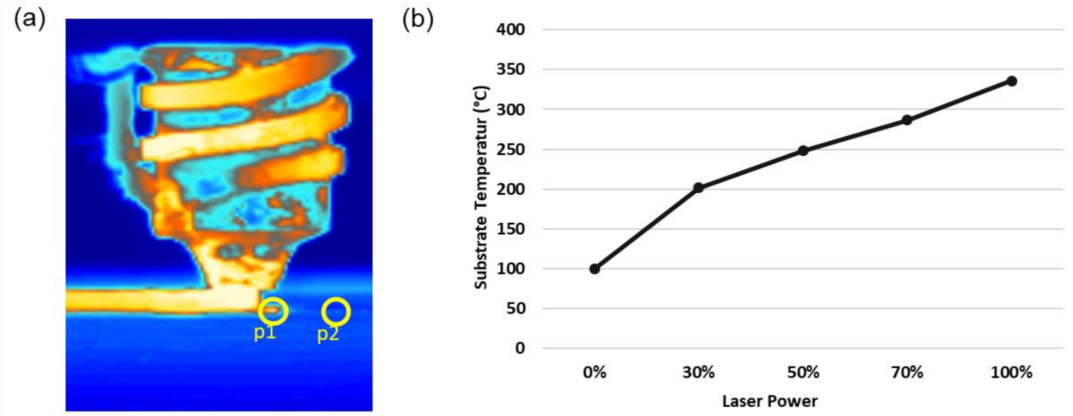

Figure 5: (a) Measurement points of the substrate temperature. (b) Average temperature of the substrate with different laser heating power.

3.2 Flexural strength

The interlayer bonding performance is represented by the testing result of the three-point-bending test, which is described in Section 2.3. The result of three-point-bending test is shown in Fig. 6. By using of the laser power at 50% (15W), the reached highest flexural strength is about 86Mpa, which is 137% more than that of the specimens without laser preheating. Furthermore, the reached strength at 50% (15W) laser power is about 80% to 90% of the value in the material data sheet, which is the flexural strength of the material along the fibre direction mentioned in Section 2.1. However, with 70% (21W) laser power, the average heated temperature of the substrate is 286°C and at some locations of the substrate is even above 300°C. This causes the degradation of the polymer, which is harmful to the mechanical performance of the material. Thus, using 70% (21W) laser power has showed a decreased flexural strength.

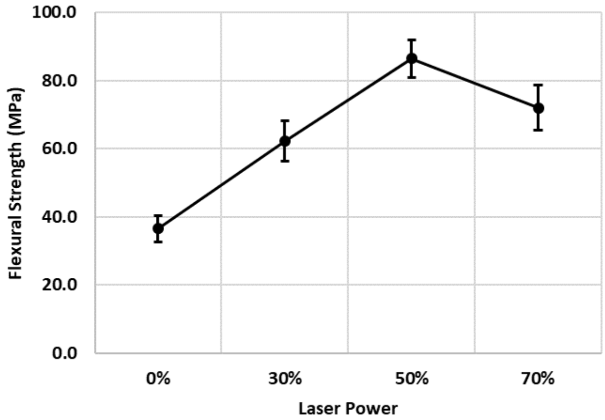

Figure 6: Flexural strength of the specimen with different laser heating power.

The relationship between the substrate temperature and flexural strength is shown in Fig. 7. The same tendency is observed in the relationship between the flexural strength of the specimen and the laser power. From an average temperature of the substrate of 100°C to about 250°C, the flexural strength is increasing with the increased substrate temperature. At the point around 290°C, the flexural strength is decreased because of the overheating of the material and leading to the degradation of the polymer on some areas of the substrate.

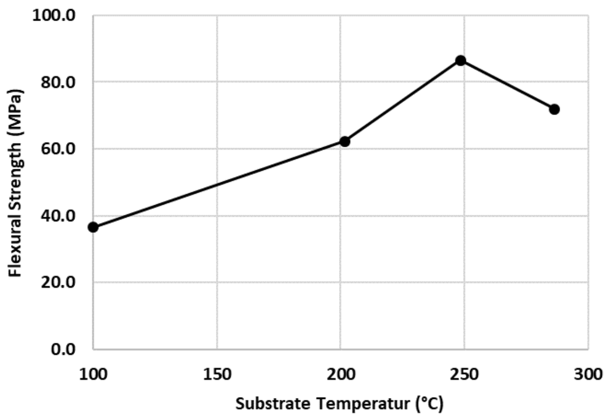

Figure 7. Flexural strength of specimen at different laser heating temperatures of the substrate.

4 CONCLUSIONS

The proposed laser preheating method with multiple heating sources and the developed directed in-situ laser preheating system is able to continuously heat the substrate of the printed structure without change of the original printing process and adjustment of the kinematic or adding other rotating kinematic in the LFAM process. The testing specimens are printed in one continuous process without interruption of the printing process. With maximum laser power of 30W, the temperature of the 10% short carbon fibre-reinforced PA6 substrate can be heated from 100°C to 336°C. In the four researched laser powers, the highest flexural strength is obtained at 15W laser power, which is about 86Mpa. Compared to the specimens manufactured without laser heating, a significant increase of 137% in the flexural strength of the building direction (z-direction) is obtained with a substrate temperature of 248°C.

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