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INFLUENCE OF NOZZLE TEMPERATURE, BED TEMPERATURE, AND PRINTING SPEED ON THE TENSILE STRENGTH OF 3D-PRINTED PLA SPECIMENS

Faisal Dakhelallah Al-Shalawi[a], Azmah Hanim Mohamed Ariff [a,b*], Mohd Khairol Anuar Mohd Ariffin [a], Collin Looi Seng Kim[c], Dermot Brabazon[d]

[a]Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[b]Research Center Advanced Engineering Materials and Composites (AEMC), Faculty of Engineering, Universiti Putra Malaysia, Serdang 43400, Malaysia
[c]Department of Orthopaedic, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[d]Advanced Manufacturing Research Centre, and Advanced Processing Technology Research Centre, School of Mechanical and Manufacturing Engineering, Dublin City University, Dublin, Ireland

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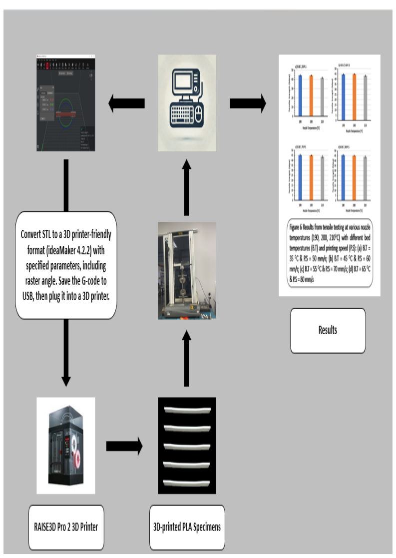
*Corresponding author
azmah@upm.edu.my

Graphical abstract



Abstract

Additive Manufacturing (AM), or 3D printing, revolutionises modern manufacturing by reducing material waste and enabling the creation of complex geometries through layer-by-layer construction from digital files. Its environmental efficiency and versatility, particularly with materials like biodegradable Polylactic Acid (PLA), align with global sustainability goals and cater to diverse industries, from healthcare to aerospace. As ongoing research enhances PLA's properties and sustainability, AM's adoption across various sectors is poised to expand, solidifying its role as a transformative technology. This investigation examined the impact of nozzle temperature on the tensile strength of PLA specimens produced by a 3D printer, considering different bed temperatures and printing speeds. The experiment involved varying the nozzle temperature (190°C, 200°C, 210°C), bed temperature (35°C, 45°C, 55°C, 65°C), and printing speed (50 mm/s, 60 mm/s, 70 mm/s, 80 mm/s), while maintaining all other variables constant. The specimens were printed using a raster angle of (90°, 0°, 0°) and a grid infill pattern. The tensile strength of the specimens was assessed using a tensile testing machine. The recorded tensile strength values of the PLA samples produced through 3D printing exhibited a decrease with increasing nozzle temperature, bed temperature, and printing speed. However, the measured tensile strength values remained approximately consistent. There was an elevation in tensile strength at a nozzle temperature of 200°C, bed temperature of 45°C, and printing speed of 60 mm/s. It may be deduced that the examined parameters do not exert a substantial influence on the tensile strength of the specimens. Consequently, it is advisable to undertake further investigation to scrutinise the implications of these parameters on other aspects of the material properties.

Keywords: Additive manufacturing, polylactic acid (PLA), nozzle temperature, bed temperature, tensile strength.

1.0 INTRODUCTION

Additive Manufacturing (AM), also known as 3D printing, represents a revolutionary technology that is transforming the landscape of modern manufacturing. This process involves constructing objects layer by layer from digital files, significantly reducing material waste and enabling the creation of complex geometries that are often unattainable through traditional subtractive methods such as cutting or drilling. The innovative nature of AM is proving essential across various industries, facilitating rapid prototyping, product customisation, and streamlined production processes [1,2,3,4,5,6].

One of the most significant advantages of AM is its environmental efficiency when compared to traditional manufacturing methods. Traditional manufacturing typically results in substantial material waste and high energy consumption due to extensive machining. In contrast, AM optimises material usage by adding only the necessary material to create the final product, thereby reducing waste and energy consumption. This efficiency not only translates to cost savings but also aligns with global sustainability goals, making AM an appealing choice for environmentally conscious industries [7,8,9,10]. Furthermore, this shift towards a more sustainable manufacturing approach is gaining traction worldwide, driving industries to adopt AM technologies more widely [11].

The versatility of AM is further demonstrated by its ability to utilise a wide array of materials, each offering unique properties. Commonly used materials in AM include various plastics, metals, ceramics, and composites. Polylactic acid (PLA), a biodegradable thermoplastic, stands out for its environmental friendliness and ease of use. Metals such as titanium and aluminium are employed for high-strength, lightweight components, while ceramics and composites provide enhanced thermal and mechanical properties for specialised applications. This versatility allows AM to cater to diverse industries, from aerospace and automotive to healthcare and consumer goods [12,13]. The ability to select from such a broad range of materials ensures that AM can meet the specific needs of different sectors, further cementing its role as a transformative technology [14].

Generative design is another pivotal aspect of AM, employing algorithmic techniques to optimise designs based on specific constraints and performance requirements. This approach enables the creation of highly efficient structures that often surpass traditional design capabilities in terms of weight, strength, and material efficiency. Generative design algorithms can rapidly explore numerous design possibilities, providing engineers with superior, material-efficient solutions. Integrating generative design with AM allows to produce highly optimised parts, which is particularly beneficial in industries requiring advanced and complex components [15,16]. By harnessing the power of generative design, AM not only pushes the boundaries of what is possible in manufacturing but also paves the way for more innovative and efficient solutions [17].

In the medical field, AM has brought significant advancements, especially in orthopaedics. Customised implants and prosthetics tailored to the specific anatomy of individual patients enhance fit, comfort, and functionality. For instance, 3D printing has enabled the creation of patient-specific orthopaedic implants, such as hip and knee replacements, which can significantly improve recovery times and outcomes compared to traditional implants. Additionally, AM produces complex surgical instruments and models that aid in pre-surgical planning and training, further enhancing surgical precision and success [18,19]. The ability to produce customised medical solutions quickly and efficiently underscores the transformative potential of AM in healthcare [20].

Polylactic acid (PLA) has emerged as a key material in 3D printing due to its unique properties and advantages. Derived from renewable resources like corn starch or sugarcane, PLA is environmentally friendly compared to petroleum-based plastics. Its ease of processing, low melting point, and minimal warping make PLA particularly suitable for desktop 3D printers widely used in educational and home settings. Furthermore, PLA's biocompatibility extends its application to the medical field, as illustrated in Figure 1, including the creation of custom implants, surgical guides, and drug delivery systems [21,22]. The adoption of PLA in various applications highlights its versatility and environmental benefits, making it a popular choice in the growing AM industry [23].

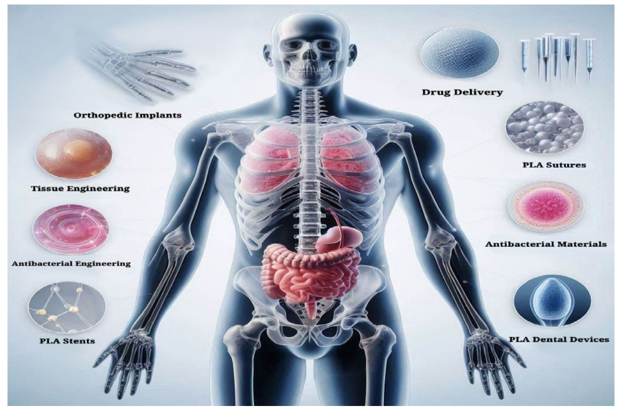


Figure 1 The medical application of PLA

The lifecycle of PLA begins with its production from renewable resources, as shown in Figure 2. Raw materials are fermented to produce lactic acid, which is then polymerized to form PLA. This bioplastic is processed into filament or pellets for use in 3D printing. After its useful life, PLA products can be industrially composted, breaking down into carbon dioxide, water, and biomass, thus significantly reducing plastic waste in the environment. This closed-loop lifecycle aligns with sustainable manufacturing principles, making PLA an attractive material choice for eco-conscious industries and consumers [24,5,6]. The sustainable nature of PLA production and disposal not only reduces environmental impact but also promotes a circular economy [9].

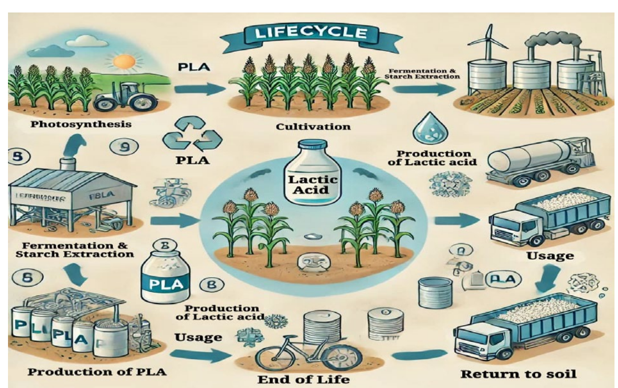


Figure 2 The lifecycle of PLA

Incorporating biomaterials into PLA can significantly enhance its properties, broadening its range of applications. Adding materials such as cellulose nanofibers or hydroxyapatite can improve PLA's mechanical properties, making it stronger and more resilient. These enhancements are particularly valuable in biomedical applications where customised mechanical properties are essential, such as in orthopaedic implants and bone scaffolds [10,11]. By enhancing PLA with biomaterials, researchers and engineers can develop more robust and versatile products, further expanding the potential uses of AM in various fields [12].

PLA's potential in the biomedical field through 3D printing is extensive. Custom bone scaffolds can be designed to mimic the porous structure of natural bone, providing a conducive environment for cell growth. PLA's biocompatibility ensures that it does not elicit adverse immune responses when implanted, making it ideal for long-term medical applications. Moreover, PLA can be used to create biodegradable stents that support blood vessels or other tubular structures while gradually degrading and being absorbed by the body, thus eliminating the need for a second surgery [13,14]. These applications highlight PLA's significant role in advancing medical technology and improving patient outcomes [15].

Despite its numerous advantages, PLA faces challenges in large-format AM due to its low thermal resistance and brittleness. Addressing these limitations often involves blending PLA with other materials or incorporating additives to enhance its mechanical and thermal properties. Such advancements aim to broaden PLA's range of applications, making it suitable for more demanding industrial contexts [16,17]. Continuous research and development efforts are essential to overcome these challenges and fully realise PLA's potential in large-scale manufacturing [18].

The future of AM, particularly with PLA, looks promising as ongoing research focuses on enhancing its properties and sustainability. Innovations such as incorporating natural fibres aim to create PLA composites that retain biodegradability while offering superior performance. These efforts ensure that PLA remains a competitive and eco-friendly option in the evolving landscape of additive manufacturing [19,20]. As these innovations progress, they will likely open up new possibilities for PLA applications, driving further adoption of AM technologies across various industries [21].

The primary aim of the present study was to conduct a comprehensive comparative analysis to ascertain the influence of nozzle temperature (190°C, 200°C, 210°C), bed temperature (35°C, 45°C, 55°C, 65°C), and printing speed (50 mm/s, 60 mm/s, 70 mm/s, 80 mm/s) on the tensile and strength of PLA specimens manufactured using a 3D printer. This investigation sought to identify the optimal conditions that yield the highest tensile strength values, thereby enhancing the material properties and performance of PLA in additive manufacturing applications.

2.0 METHODOLOGY

PLA filaments with a diameter of 1.75 mm, manufactured by Polymaker Industries (Shanghai, China), were meticulously selected to fabricate the test specimens for this study. These filaments are renowned for their superior quality and consistent performance, ensuring reliable and reproducible results in additive manufacturing processes. The 3D printer utilised for this purpose was the RAISE3D Pro2, a versatile and robust machine that supports a wide range of polymers, including PLA, PC, and ABS filaments, thus providing a comprehensive platform for exploring the properties of various materials. The specific properties of the PLA filaments are detailed in Table 1, highlighting their optimal printing conditions and characteristics, while Table 2 offers an in-depth overview of the technical specifications and capabilities of the RAISE3D Pro2 printer.

Table 1 The properties of PLA filament

P. S	P. T	B. T	Colour	Fan
40-60 mm/s	190-230 ˚C	25-60 ˚C	White	On

Table 2 The properties of RAISE3D Pro2 3D printer

Filament Diameter	P. S	Max B. T	Layer Height	Nozzle Diameter
1.75 mm	30–150 mm/s	110˚C	0.01-0.25 mm	0.4 mm

In fabricating the PLA tensile specimens, the study adhered rigorously to the ASTM D638-I standards, ensuring that the results were both reliable and comparable to other studies in the field. The experimental design incorporated variations in three critical parameters: nozzle temperature (190°C, 200°C, 210°C), bed temperature (35°C, 45°C, 55°C, 65°C), and printing speed (50 mm/s, 60 mm/s, 70 mm/s, 80 mm/s). By systematically varying these parameters while maintaining all other variables constant.

The samples were printed using a raster angle of 90˚, 0, 0 and a grid infill pattern, as described in Table 3. This particular configuration was chosen to ensure uniformity in the internal structure of the specimens, thereby facilitating a more accurate assessment of the mechanical properties.

Table 3 The constant printer parameters of specimens

Fill Pattern	Infill Density	Layer Height	Nozzle Diameter	Raster Angle	Infill Pattern Type
Line	100%	0.15 mm	0.4 mm	(90, 0, 0)	grid

To manage the experimental workflow efficiently, the specimens were divided into various combinations of the three processing parameters, as outlined in Table 4. The G-code necessary for the printing process was generated using the built-in G-code generator software. This code was then transferred to a USB drive, which was subsequently inserted into the liquid crystal display (LCD) interface of the 3D printer, thereby initiating the printing procedure.

Each combination of processing parameters resulted in the production of five dog-bone specimens, ensuring a sufficient sample size for statistical analysis. The tensile tests were conducted using the INSTRON 3366 machine, which boasts a maximum load capacity of 10 KN and a testing speed set at 5 mm/min, thereby providing precise and reliable measurements of the mechanical properties of the specimens.

The dimensions of the specimens conformed to the ASTM D638-I standards, ensuring that the results could be directly compared with those obtained in other studies adhering to the same standard. Figure 3 illustrates the standard dimensions of the specimens, while Figure 4 shows the 3D printing PLA specimens after testing. Figure 5 provides a visual representation of the experimental process, from the initial setup to the final testing phase.

Table 4 Sets of processing parameters

Specimens	Parameters
S_1	190 N.T, 35 B.T, 50 P.S
S_2	200 N.T, 35 B.T, 50 P.S
S_3	210 N.T, 35 B.T, 50 P.S
S_4	190 N.T, 45 B.T, 60 P.S
S_5	200 N.T, 45 B.T, 60 P.S
S_6	210 N.T, 45 B.T, 60 P.S
S_7	190 N.T, 55 B.T, 70 P.S
S_8	200 N.T, 55 B.T, 70 P.S
S_9	210 N.T, 55 B.T, 70 P.S
S_{10}	190 N.T, 65 B.T, 80 P.S
S_{11}	200 N.T, 65 B.T, 80 P.S
S_{12}	210N.T, 65B.T, 80P.S

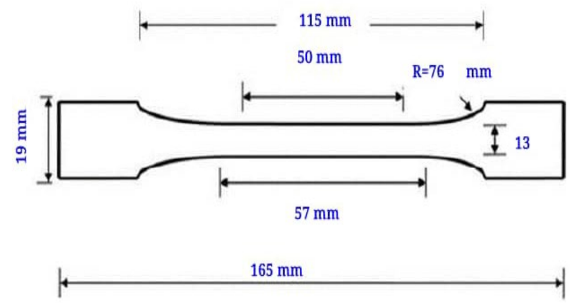


Figure 3 The specimen dimensions

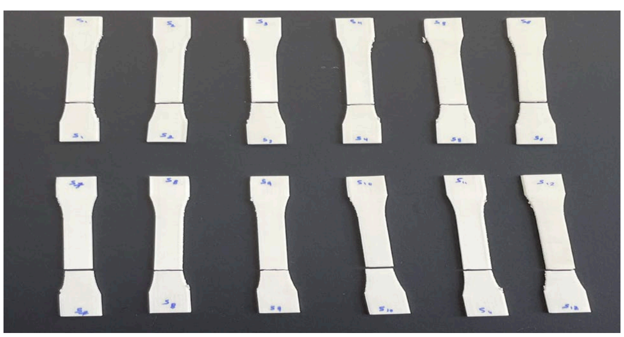


Figure 4 The specimens of 3D printing PLA after testing

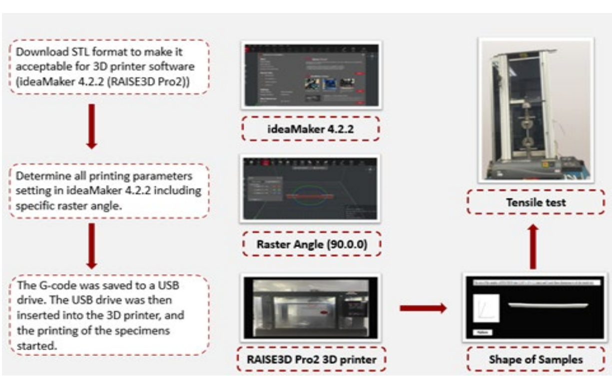
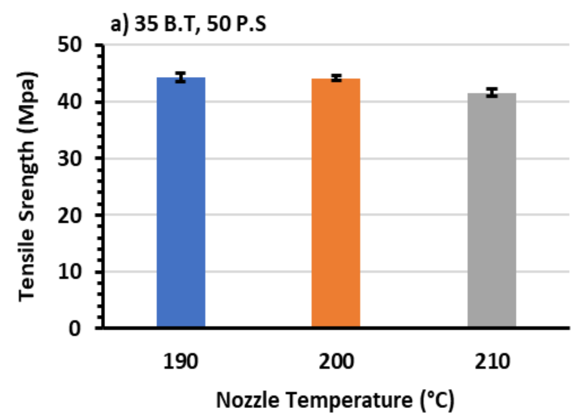
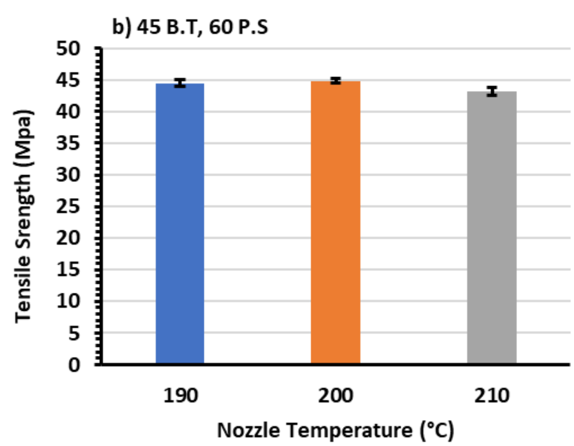


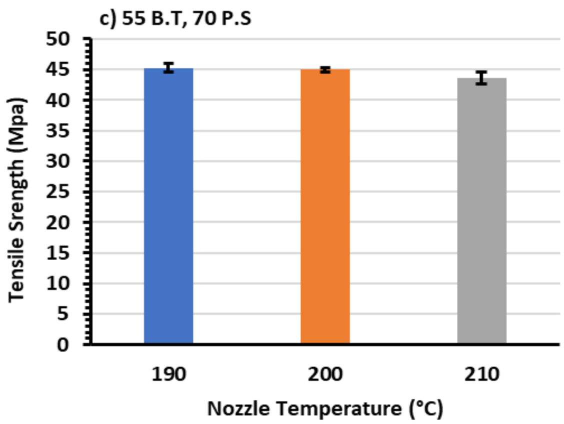
Figure 5 The experiment process steps

3.0 RESULTS AND DISCUSSION

The outcomes of tensile testing for diverse nozzle temperatures, bed temperatures, and printing speeds are demonstrated in Figure 5. It is noteworthy that the dimensional quality of the 3D-printed component is notably influenced by both the nozzle temperature and printing speed [22]. The average tensile strength values of the PLA samples manufactured through 3D printing indicate a diminishing trend with escalating nozzle temperature and printing speed [22,23], as illustrated in Figure 6 (a), (c), and (d). Nevertheless, the recorded tensile strength values remained approximately close. The utmost tensile strength values were observed at 190°C in Figure 6 (d). Conversely, Figure 6 (b) reveals that the average tensile values increased at 200 °C and subsequently declined with the elevation of nozzle temperature [23]. Furthermore, the lower standard deviation is discerned at N.T, B.T, and S.P, with values of 200 °C, 55 °C, and 70 mm/s, respectively, as indicated in Figure 6 (c).







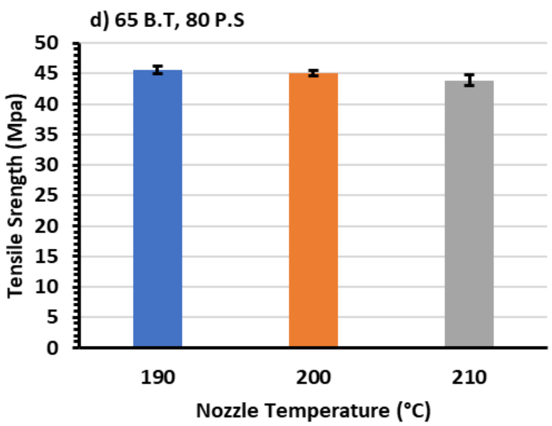


Figure 6 Results from tensile testing at various nozzle temperatures (190, 200, 210°C) with different bed temperatures (B.T) and printing speed (P.S): (a) B.T = 35 °C & P.S = 50 mm/s; (b) B.T = 45 °C & P.S = 60 mm/s; (c) B.T = 55 °C & P.S = 70 mm/s; (d) B.T = 65 °C & P.S = 80 mm/s

4.0 CONCLUSION

Additive Manufacturing (AM) is a groundbreaking technology that constructs three-dimensional objects through the meticulous addition of material, layer by layer. This innovative approach not only minimises waste and optimises material usage but also enables the creation of intricate geometries previously unattainable with traditional methods. A pivotal material in this domain is polylactic acid (PLA), renowned for its remarkable rigidity, transparency, and processability. The use of materials such as PLA further enhances this technology's sustainability and versatility, making it suitable for a wide range of applications. Furthermore, PLA's glossy finish and versatility as a printable biopolymer have solidified its utility in a variety of medical applications, including tissue engineering, orthopaedics, and regenerative medicine. The experimental parameters under investigation appear to have a negligible effect on the specimen's tensile strength, as evidenced by the minimal variation in recorded tensile strength values. Consequently, it is advisable to undertake further research to explore the influence of these parameters on other material properties of 3D-printed PLA specimens, particularly considering various raster angles and alternative infill pattern types. This extended investigation could yield valuable insights into the comprehensive mechanical performance of PLA in additive manufacturing applications.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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