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Fatigue Analysis of Polylactide Manufactured by Fused Deposition Method of 3D Printing

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Abstract

Nowadays, 3D printing technology has gained popularity in various industrial sectors, especially in the field of developing new products. This technology allows for the layer-by-layer construction of 3D prototypes. This research primarily focuses on the fatigue performance of 3D-printed components made of Polylactide (PLA). PLA is a versatile material and has a diverse range of applications in packaging, medical, household items, etc. The specimens were made following the ASTM D638 standard using the Fused Deposition Modeling (FDM) technique. A fatigue test was carried out to investigate fatigue performance by fluctuating the loads and speed of the rotating beam fatigue tester. The finding reveals that materials break under variable strains at a stress magnitude is less than the material's ultimate tensile strength. Furthermore, it was discovered that the degree of the stress triggering fatigue failure reduces as the number of stress cycles increases. Fatigue failure is characterized as a time-delayed fracture due to cyclic stress. The finding reveals that PLA has a low fatigue strength of 19.62N.

Keywords: *3D Printing, Fatigue Test, Fused Deposition, Polylactide, S-N Curve*

1.0 Introduction

The earlier Additive Manufacturing (AM) technique known as 3D printing was developed in the 1980s to produce models and prototypes[1]. 3D system manufactured the first SLA (Stereo Lithographic) machine in the 1990s. Due to technological advancement, 3D printing has gained popularity in making prototypes and engineering parts[2]. Among the methods for fabricating additive layers, 3D printing offers outstanding advantages such as design flexibility, and cost-effectiveness[3]. Another aspect of this technology is to create a physical 3D object from digital data[4]. It demonstrated that sophisticated and complicated parts could be produced. Furthermore, this technique has been applied in the field of medicine. Since the turn of the twenty-first century, 3D printing technology has been used in several industries, including jewellery, manufacturing, automotive, aerospace, and medicine. The first 3D-written robotic craft in history was created in less than seven days in 2011. In the same year, the first 3D-printed car in history was also produced[5]. The productivity was increased via 3D printing. Compared to traditional methods of creating items, such as implants and prosthetics, which require milling, forging, and a lengthy transit time, 3D printing technology saves time[6]. Additionally, a 3D printer may produce an object at a minimal cost[7]. A 3D item can be produced at the lowest cost, with the initial object costing the same

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as the finished one. 3D printing plays a crucial role in industries where demand is for lesser manufacturing quantities or those who make intricate parts or goods that need regular modifications with high quality. Due to its ability to use raw materials more effectively and generate less waste, 3D printing may result in lower prices[8]. A 10-milligram pharmaceutical tablet could likely need to be specially made as a 1-milligram pill on demand. A portion of the capsules will also be made available in dosage bureaucracy, where they may be more affordable and easily administered to patients. 3D printing makes it feasible to create with unique geometry that would be difficult or impossible to produce using conventional procedures. Thus, this can enhance the performance of engineering components in terms of fostering originality and innovation in 3D printing design[9].

Of the various commercial polymers available for AM, polylactide (PLA) is undoubtedly the most widely utilized. PLA is best suitable for tooling tools such as jigs and fixtures, low-load bearings, gears, linkages, mechanisms and biomedical devices. The performance of such parts is investigated by static and fatigue tests[10]. The examination of a material's reaction to periodic loads is known as fatigue analysis, and it is crucial for guaranteeing the durability and structural soundness of printed parts. Many initiatives to enhance the mechanical properties of 3D printed parts have been undertaken recently. Vălean *et al.*,[11] investigated fatigue analysis of polylactic acid and PLA reinforced with short carbon fibers. The finding reveals that 3D printed parts reinforced with carbon fibers present both lower fatigue properties. Up to 90% of in-service part failures in the industrial sector are attributed to fatigue. Fatigue was an enigmatic event since it broke suddenly and did not manifest any evident plastic distortion.

Fatigue properties, failure modes, and performance constraints of PLA employing experimental research and theoretical modeling which will help in assisting in the development of 3D printed parts for increased robustness and dependability. This gave rise to the false belief that tiredness was just a technical issue. In the 20th century, material and design advancements appear to have been more important in addressing fatigue than technical concerns[12]. Wear and tear on 3D printed parts is a subset of the material and manufacturing sciences. There are two instances when fatigue on a 3D-printed component has been discovered. Kargar and Ghasemi[13] used a dog bone specimen that meets the UNI EN ISO 527-1 (1997) standard which stipulates a 10 mm by 4 mm cross-section with an 8 mm gauge length. To avoid data overload in the equipment, the maximum number of cycles for conducting tests is set at 10,000. The print orientation and design will often affect the material characteristics of a quickly prototyped component[14]. Additionally, an instance of 3D printed fatigue for Tango Black Plus elastomer material has been reported. The interface specimen and the specimen without an interface make up the comparative specimen. Every specimen undergoes an elongation ratio of around 20%, 30%, 40%, 50%, and 60%. Since it shows the maximum elongation before it breaks, a maximum of 60% was selected. Other methods, like the commercialization of Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), and Fused Deposition Modeling (FDM) occurred in the early 1990s. Fused Deposition Modeling (FDM). Technology was first launched by Stratasys in 1991, and it has since spread to become the most popular AM technique. FDM creates things layer by layer by extruding semi-molten thermoplastic materials using a liquefier nozzle onto a platform. Several open-source, entry-level FDM machines that can handle a range of thermoplastic materials have just hit the market. These inexpensive AM machines have been used in design verification and functional testing of engineering components in addition to being a tool for teaching and communication in the classroom[15]. The cube 3D printers are tiny, affordable machines that can Print Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) materials more rapidly[16]. Such FDM-processed thermoplastic components have found widespread usage in the engineering and medical domains because of their low weight, ease of production of complicated geometry, and affordability. Although thermoplastics are often used in engineering for load-bearing elements in industry[17], their most popular uses are in the biomedical and tissue engineering domains, where they are used in knotless suture anchors and innovative scaffold topologies[18]. Nevertheless, even with PLA's broad use, knowledge of its fatigue behavior is still a vital but little-studied topic. This research conducts a thorough fatigue analysis of PLA material used in 3D printing to close this knowledge gap.

2.0 Materials and Methods

2.1 Sample Preparation

The sample is made of PLA material. This is selected due to its wide applications in Engineering, and biomedical sciences. The mechanical and thermal properties of the PLA material are shown in Table 1.

Table 1. Thermal and mechanical properties of PLA

Thermal and Mechanical Properties	Value
Tensile Strength (MPa)	48
Elongation at break (%)	21.9
Young's Modulus (MPa)	3166
Flexural Strength (MPa)	92.4
Flexural Modulus (MPa)	2823
Flexural Strain at break (%)	4.3
Impact Strength Charpy (kJ/m^2)	20.4
Melting Temperature (^{0}C)	170-180
Glass Transition Temperature (^{0}C)	63

The specimen's dimensions are based on the ASTM D638 standard, as indicated in Figure 1 (a). The sample part was shown in Figure 1 (b) and created using a 3D printer (Make: Creality Ender 3 SE) is shown in Figure 1 (c). The specimen was printed at a layer height of 1mm with 100% infill at a speed of 100mm/s. The 100% infill makes the specimen more strong and durable for this fatigue test.

2.2 Experimental Setup

The rotating beam fatigue machine (make: Ducom Instruments, model: TM-700) is used to study the mechanical behavior of materials subjected to stresses, which continuously rotate about a mean value of zero. The load in the range of 50 to 1000 N can be applied. The machine has a maximum speed of range 5000 rpm. The main objective of this study is to determine bending fatigue strength. The machine is a floor-standing model with an independent controller integrated into the unit. All components for the controller are enclosed within the metallic box positioned over a table near the machine at a convenient height for operation. The operation of the controller is through switches and knobs mounted on the front panels with their respective display units. The principle is for the specimen to be clamped at one end of its length and rotated while it is being subjected to load at the other end. The arrangement consists of a spindle supported on bearings inside a housing mounted on a pedestal, which is rotated by a motor coupled to it at one end, while the specimen for the test is clamped at the other end of the spindle. The specimen is clamped on the spindle with a collet for the true running of it, the rotational speed and the number of cycles are measured

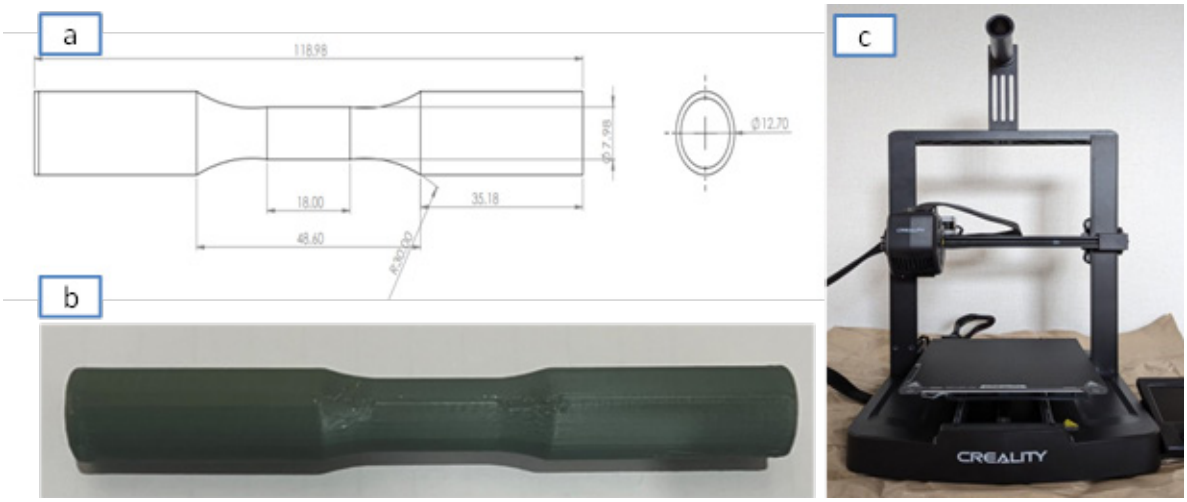


Figure 1. **(a)** Dimension of a specimen, **(b)** 3D printed Specimen, **(c)** 3D printing machine.

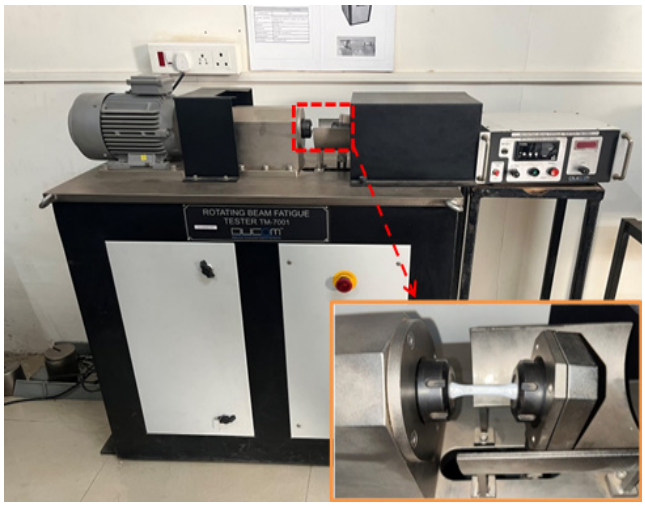


Figure 2. Rotating beam fatigue tester.

by a proximity sensor and are displayed on the module on the controller. The load is applied on the opposite end of the clamped

Specimen by pulling it downward from a known distance from the fracture, the fracture occurs mainly in the middle of the profile on the specimen. The loading end of the specimen is held on a rotating collet within a loading holder, the loading holder is pulled down by a chain connecting it to the loading lever while dead weights are placed on it, and the load applied is measured by a load cell fastened between chains and loading lever. The long loading lever is pivoted towards the end of its length to obtain a mechanical advantage of a 1:5 ratio, this offset in pivot increments the load applied by 5 times, and the load is applied by dead weights suspended from a pan on the longer length of the lever. The loading holder is a loose part seated over the parts catcher, the part catcher is fixed on the base plate positioned below the rotating specimen. While running the test the specimen after shear falls along with the loading holder over the parts catcher, this action in turn results in lowering the loading lever from a horizontal position to press against a limit switch to trip machine rotation.

The controller positioned near the tester is interfaced with a cable to the testing unit, the test specimen clamped on the spindle is rotated by a motor, and the speed of rotation is controlled by a variable frequency drive operated by a potentiometer knob on the front panel of the controller. The speed of rotation is measured by a proximity sensor and displayed on the speed module on the controller front panel. Beside the speed module, the potentiometer knob is positioned, to set speed between 1000 to 5000 rpm. The test duration is set by several cycles on the counter module, the values are input using soft keys provided below the module.

2.3 Fatigue test

It has been observed that Materials collapse under fluctuating strains at a stress magnitude that is less than the ultimate tensile strength of the material. Further, it has been discovered that the amplitude of the stress that causes fatigue failure reduces with the number of stress cycles Fatigue failure is characterized as a time-delayed fracture under cyclic stress. Experiments are performed according to the fluctuating stresses at different stress magnitudes. The fatigue test was performed using the machine Rotating Beam Fatigue Tester shown in Figure 2. The test was done at different fluctuating loads with tension cyclic loading at different RPMs ranging from 500rpm to 2000rpm, Multiple applied loads were used, which are ranging from 500grms to 2kg From the UTS value. The fatigue test was conducted until the specimen broke.

3.0 Results and Discussion

The fatigue testing of 3D printed specimens has provided valuable insights into the performance of PLA material. Through systematic experimentation, we have collected a comprehensive dataset that sheds light on the fatigue resistance of these specimens under varying conditions. The results indicate that the fatigue life of the specimen is influenced by factors that were included in this experiment such as load magnitude, stress amplitude, and number of cycles. Our findings reveal a clear inversely proportional relationship between load magnitude and number of cycles, emphasizing the importance of meticulous control over stress amplitude and the fatigue life of the material in this fatigue testing procedure.

The tabular data from Table 2 presents the results as the effective load increases from 19.62 N to 68.67 N, there is a proportional increase in stress amplitude, ranging from 41.63 MPa to 145.74 MPa. This direct relationship between load and stress amplitude aligns with fundamental principles of mechanics, wherein an increase in applied force leads to a corresponding rise in stress experienced by the material. Conversely,

Table 2. Readings for fatigue testing on rotating-beam fatigue tester

Sr. no	Effective load (N)	stress amplitude	Fatigue life (cycles)
1	19.62	41.63	2720
2	29.43	62.46	2112
3	39.24	83.28	1670
4	49.05	104.1	1210
5	58.86	124.92	728
6	68.67	145.74	316

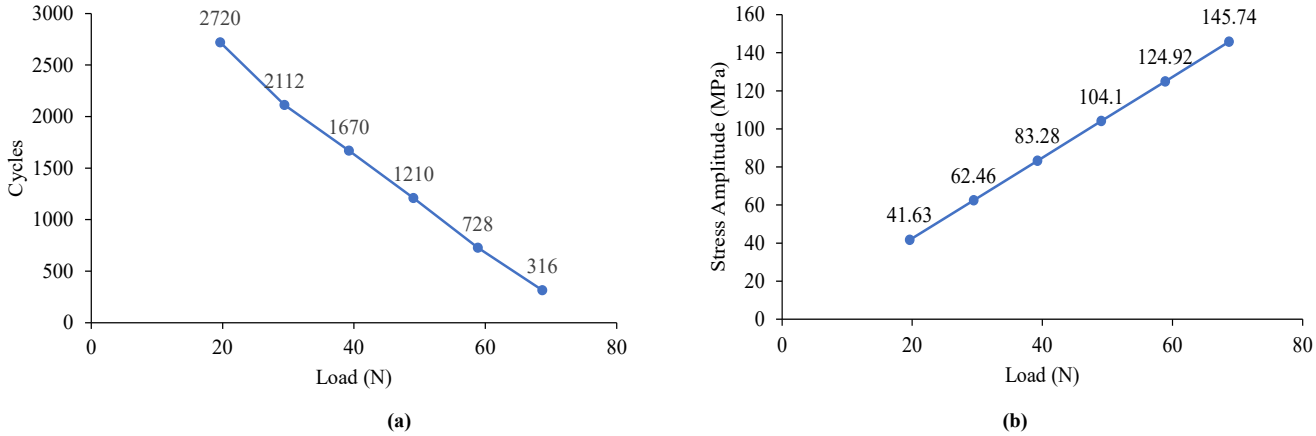


Figure 3. **(a)** S-N curve cycles vs Load **(b)** S-N curve stress amplitude vs load

as the stress amplitude escalates, the fatigue life of the specimens demonstrates a decreasing trend. For instance, at the lowest stress amplitude of 41.63 MPa, the specimen exhibited the highest fatigue life of 2720 cycles.

However, as the stress amplitude rises, the fatigue life progressively diminishes, with the fewest cycles to failure recorded at the highest stress amplitude of 145.74 MPa, with only 316 cycles. Figure 3(a) shows the relationship between cycles and load which states that the fatigue failure of the specimen takes place as an increase in the load and the cycles decrease. Also, Figure 3(b) shows the relationship between the amplitude and load which states that when there is an increase In the load the value of the stress amplitude increases as when the load was 20N the stress amplitude was around 41.63 which is the lowest among all the other readings and when the highest load which is of 70N is applied the stress amplitude of the specimen is the highest among all which is around 145.74. Figure 4 shows S-N curve of the fatigue test.

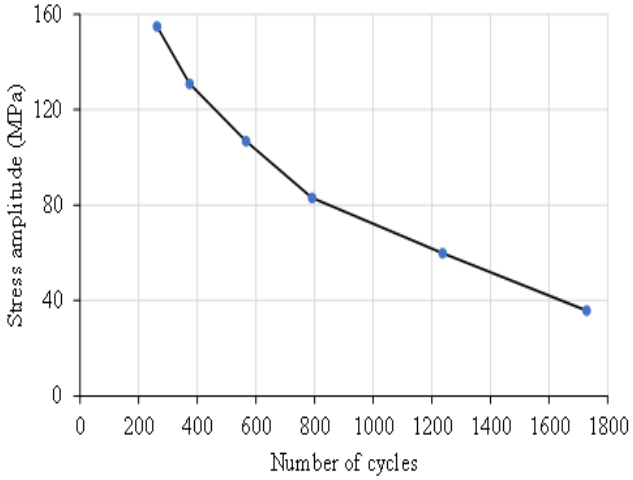


Figure 4. S-N curve of fatigue test.

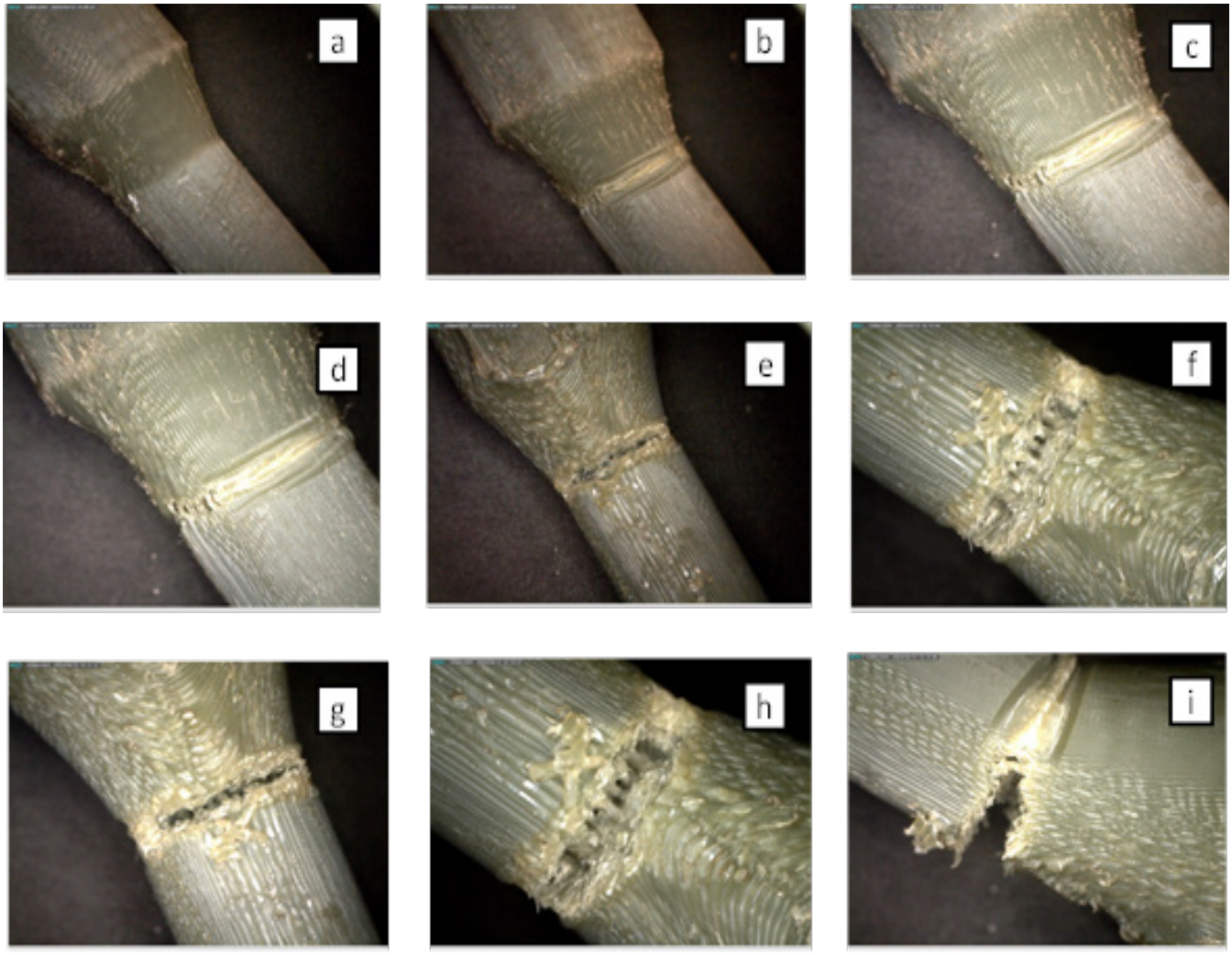


Figure 5. **(a)** Specimen, **(b)** Fractured specimen at 19.62N, **(c)** Fractured specimen at 29.43N, **(d)** Fractured specimen at 39.24N, **(e)** Fractured specimen at 49.05N, **(f)** Fractured specimen at 58.86N, **(g)** Fractured specimen at 68.67N, **(h)** Fractured specimen at 58.86N.

This inverse relationship between stress amplitude and fatigue life underscores the concept of fatigue failure, wherein repeated cyclic loading leads to the gradual weakening and eventual fracture of the material, particularly under higher stress conditions. Therefore, the data highlights the critical role of stress amplitude in determining the fatigue behavior and endurance of materials, with higher stress levels significantly reducing the fatigue life of the specimens.

Figure 5 represents the magnified image of the specimens that failed due to fatigue. This helps to understand the layer deformation of the particular specimen. The specimen at 19.62N started fracturing. It can be seen that the higher the weight applied higher the deformation of the layer, as shown in Figure 5(e). The specimen has a larger deformation of the layers compared to the specimen Figure 5(b) which proves that the higher the weight the higher the deformation takes place.

4.0 Conclusion

According to the findings of this study, fatigue life was determined by several tests conducted using a rotating beam fatigue machine, it can be concluded that the specimen failed when subjected to changing pressures of a magnitude smaller than the material's ultimate

tensile strength. Further, it was determined that the stress amplitude that causes fatigue failure decreases with the number of stress cycles. Fatigue failure occurs when characterized as a time-delayed fracture under cyclic stress. The longer fatigue life of the specimen was observed when low weight was applied. As the weight increased, the number of cycles decreased, resulting in a shorter fatigue life for the specimen.

- PLA cracking under fatigue stress follows three failure modes: (i) rectilinear cracking of filaments, (ii) deboning between neighboring filaments, and (iii) de-bonding between layers that are adjoining.
- Under fatigue loafing, the influence of filament orientation on PLA fatigue behavior may be ignored with minimal loss of accuracy, similar to the static situation. Therefore, from a fatigue design standpoint, PLA may be viewed as a homogeneous and isotropic material.
- Additional research is needed to examine how important AM production factors affect the fatigue strength of notched PLA components. As a result, 3D-printed components may not be suited for Heavy-duty industrial applications. However, in the context of production, 3D-printed components may be produced in low volumes, with customized designs, and for low-strength applications. Furthermore, 3D printing technology has the potential to create a sophisticated product design that would not be possible with traditional molding methods.

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