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# EFFECT OF CRYOGENIC TREATMENT ON STRENGTH AND WEAR BEHAVIOR OF 3D PRINTED SAMPLES

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## ABSTRACT
This study investigates the effect of Deep Cryogenic Treatment (DCT) on 3D printed standard tensile test (ASTM D638) and wear test (ASTM G99) samples of Polylactic Acid (PLA). The parameters considered in this study are Raster Angles (RA) of 0°, 90°, 0°&90° with constant layer thickness of 0.3mm, a line pattern with 100% infill density. The cryogenic treated (CT) and untreated (RT) 3D printed PLA tensile test samples are tested on Instron Universal Testing Machine and the wear responses of the same thermoplastic are performed on Pin on Disc wear testing machine at a constant load of 20N and disc speed of 700rpm. The test results showed that the CT samples with an RA of 90° exhibited 85% more tensile strength and the samples with RA 0°&90° showed 83% reduction in wear than untreated samples. It is also observed that the magnitude of coefficient of friction and frictional force of CT samples is significantly less as compared to untreated samples.

**Keywords:**
DCT, 3D printing, FDM, PLA, Wear behavior.

## 1. INTRODUCTION
Additive manufacturing, commonly known as 3D printing, has revolutionized the manufacturing industry by enabling the creation of complex geometries and custom components with ease. However, the mechanical properties and wear resistance of 3D printed materials often fall short of those produced by conventional manufacturing methods. Cryogenic treatment, a process involving the exposure of materials to extremely low temperatures, has been explored as a method to enhance the mechanical properties and wear behaviour of these materials [1]. Cryogenic treatment has been shown to alter the microstructure of materials, leading to improvements in properties such as hardness, tensile strength, and wear resistance [2]. Mahdavi & Khosravani (2021) demonstrated that cryogenic treatment could significantly enhance the mechanical properties of additively manufactured polymers [3]. Similarly, Paggi & Zavarise (2019) found that cryogenic treatment improved the mechanical performance of 3D printed composite materials [4].
These findings suggest that cryogenic treatment could be an effective post-processing method to improve the performance of 3D printed components [5]. In recent years, the application of cryogenic treatment has extended to various 3D printed metals and alloys. For example, research by Singh et al. (2020) indicated that cryogenic treatment improved the wear resistance of 3D printed stainless steel parts [6]. Additionally, studies by Kumar et al. (2019) showed that cryogenic treatment enhanced the tensile strength and hardness of 3D printed aluminium alloys, making them more suitable for high-stress applications [7]. Moreover, cryogenic treatment has been reported to reduce residual stresses in 3D printed components, which is a significant advantage for improving the durability and lifespan of these parts [8].
The treatment also contributes to the stabilization of the microstructure, reducing the occurrence of defects such as porosity and micro-cracks, as observed by Zhang & Zhao (2020) [9]. This leads to an overall improvement in the quality and reliability of 3D printed parts, especially in critical applications such as aerospace and biomedical implants [10]. This paper investigates the effects of cryogenic treatment on the strength and wear behaviour of 3D printed

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samples, with a focus on understanding the underlying mechanisms that contribute to the observed improvements. The study aims to provide insights into the potential applications of cryogenic treatment in enhancing the performance of 3D printed components for various industrial applications.

## 2. MATERIALS AND METHODOLOGY

### 2.1 Preparation of Tensile and Wear Test Standard Samples

In this work a commonly available PLA filament of 1.75 mm diameter manufactured by WOL 3D Technologies (Maharashtra, India) is considered as 3D printing material. According to the supplier, its properties are summarized in Table 2 (a). The geometry and dimensions of the tensile test specimens (ASTM D 638 recommended dimensions) and the wear test specimens of 8mm diameter and 30 mm long were printed per ASTM G99 standards are depicted in Fig. 1. The design was prepared in Tinker CAD software. Raster Angles (RA) of 0°, 90°, 0°& 90° were considered in preparation of wear testing specimens. The infill pattern chosen was the solid (line) structure for printing, while the infill density was kept at 100%. The Print temperature and bed temperature was kept fixed at $200^0$ C and $50^0$ C respectively.

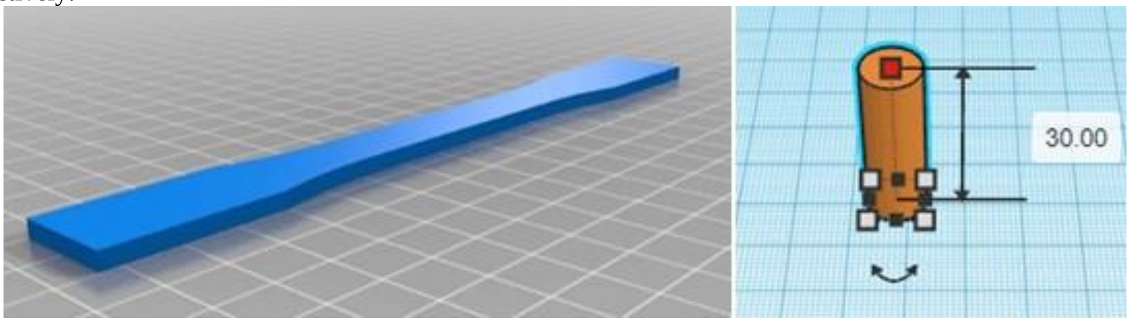


***Fig. 1 Design of tensile test and wear test samples***

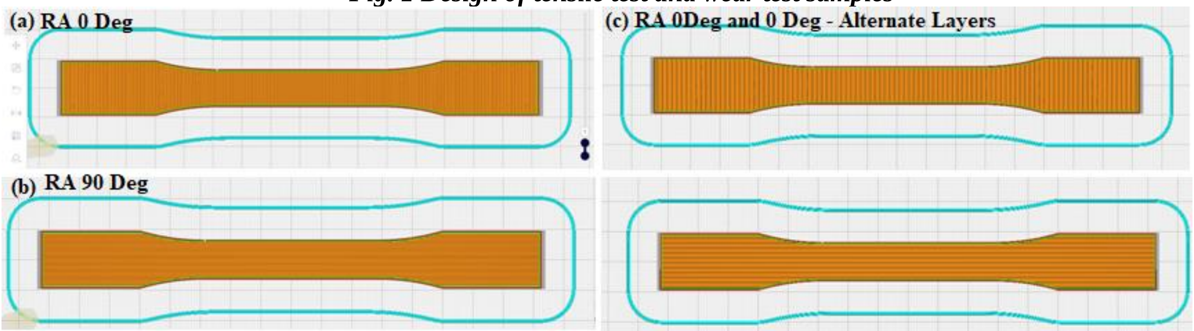


***Fig. 2 Slicing of Tensile test sample with (a) RA $0^0$ (b) RA $90^0$ and (c) RA $0^0$& $90^0$ (Alternate layers)***

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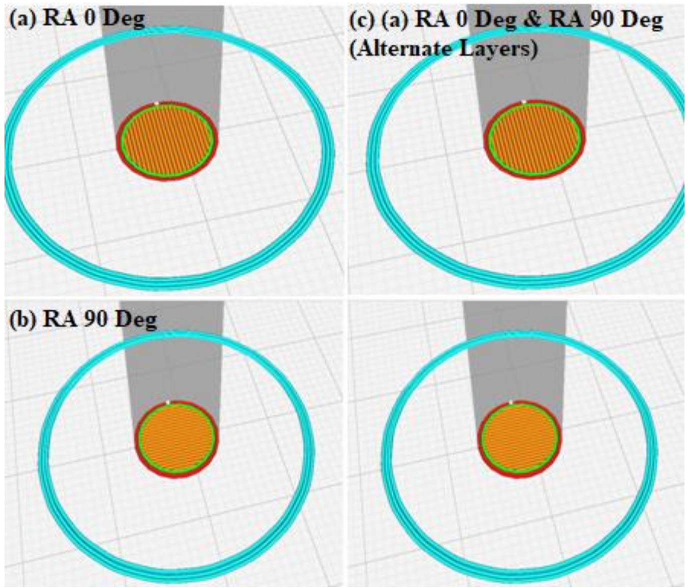


**Fig. 3 Slicing of Wear test sample with (a) RA $0^0$ (b) RA $90^0$ and (c) RA $0^0$& $90^0$ (Alternate layers)**

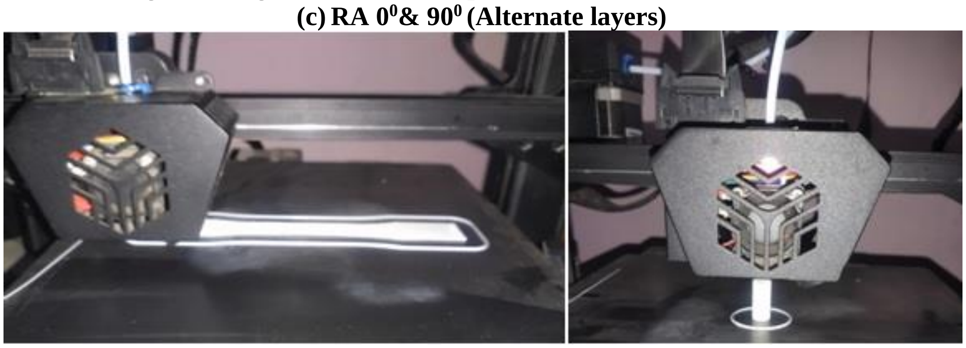

**Fig. 4 3D printing of Tensile and wear testing samples**

FDM fabricated tensile and wear test samples were exposed to controlled DCT in the cryogenic processing chamber. The temperature of 77 K and the specimens were soaked for 2 hours. To protect specimens' sensitive edges, they were wrapped in a thin aluminum foil before placing them in the chamber.

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**Fig. 5 Deep Cryogenic treatment of 3D printed test samples**

### 2.2 Cryogenic Tensile Test of 3D printed samples

There is a scope to report the mechanical properties of thermoplastic materials at cryogenic temperatures to understand the suitability of 3D printed samples at cryogenic environments. Therefore, mechanical characterization at 77 K was conducted to explore the feasibility of using PLA 3D-printed samples in cryogenic applications. Preliminary tensile tests were carried out using a 500 N capacity Instron Universal Testing Machine at GITAM Deemed to be University, Visakhapatnam to assess the strength of deep cryogenically treated (further represented with CT) and untreated (further represented with RT) 3D printed PLA samples. The experimental set up and destructed sample after testing are shown in Fig. 6.

**Fig. 6 Tensile Testing of 3D printed samples**

### 2.3 Cryogenic Wear Test of 3D printed samples

The wear behavior of deep cryogenically treated (CT) and untreated (RT) 3D printed PLA samples are tested using Pin on Disc wear testing machine. The wear tests were conducted 15minutes with a constant applied load of 20N. A track diameter of 100 mm and 700 rpm speed were taken for the study. The wear test results i.e. wear in microns, coefficient of friction and frictional force in Newton's are tabulated to observe the wear behavior of deep cryogenically treated and untreated 3D printed polylactic acid material.

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**Fig. 7 Pin on Disc Wear Test of 3D printed samples**

## 3. RESULTS AND DISCUSSIONS

### 3.1 Tensile Test results

The tensile strength of CT and RT 3D printed PLA samples are presented in Table. 1. The responses of tensile test clearly represent the significance of deep cryogenic treatment on the strength of 3D printed PLA samples. It is observed that the tensile strength of CT samples is improved from 65% to 85% than RT samples. It is also observed that there is a significant effect of raster angle on the tensile strength in both the types of samples i.e. RT and CT samples. The tensile strength of RA [90] samples at RT condition is 38MPa and it is increased to 71MPa i.e. 85% of improvement observed in treated samples than untreated samples. The anisotropic nature of 3D printed samples with RA [90] resulted the more strength in the direction of load applied as compared to other two raster angles. The graphical representation of tensile test responses of CT and RT samples is shown in Fig. 8.

| S. No. | Raster Angle | Tensile Strength (MPa) | |
|---|---|---|---|
| | | RT | CT |
| 1 | RA[0] | 34 | 62 |
| 2 | RA[90] | 38 | 71 |
| 3 | RA[0,90] | 41 | 68 |

**Table. 1. Tensile Test results of DC treated and untreated 3D printed PLA**

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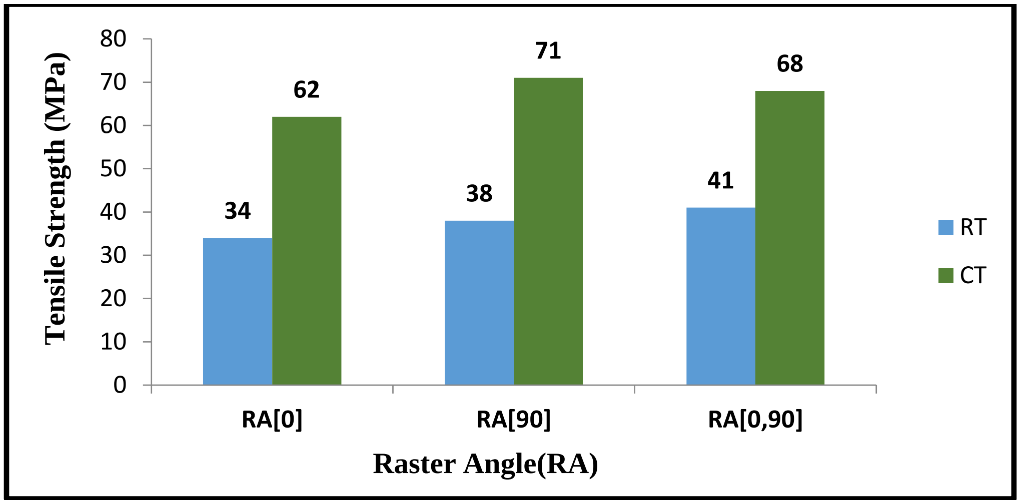


**Fig. 8 Tensile Test Results of 3D printed PLA samples**

### 4.2 Pin on Disc Wear Test results

The wear responses of CT and RT 3D printed PLA samples are presented in Table. 2. The responses of pin on disc wear test clearly represent the significance of deep cryogenic treatment on wear of 3D printed PLA samples. It is observed that there is a significant reduction in wear of CT samples around 70% to 82% than RT samples. It is also observed that there is a significant effect of raster angle on the wear responses in both the types of samples i.e. RT and CT samples. The wear of samples with RA[0,90] samples showed more reduction in wear about 83% than untreated samples. The alternate layers with raster angles ($0^0$ and $90^0$) improved the wear resistance of 3D printed samples and showed notable reduction in wear during the entire period of testing as compared to other two raster angles. The graphical representation of wear test responses of CT and RT samples is shown in Fig. 9 to Fig. 11.

| S. No. | Raster Angle | Wear (microns ) | | COF | | Frictional Force(N) | |
|---|---|---|---|---|---|---|---|
| | | RT | CT | RT | CT | RT | CT |
| 1 | RA[0] | 578 | 169 | 0.91 | 0.73 | 6.3 | 3.6 |
| 2 | RA[90] | 564 | 104 | 0.87 | 0.75 | 7.4 | 2.9 |
| 3 | RA[0,90] | 497 | 88 | 0.49 | 0.25 | 5.9 | 1.7 |

**Table. 2 Wear results of DC treated and untreated 3D printed PLA wear samples**

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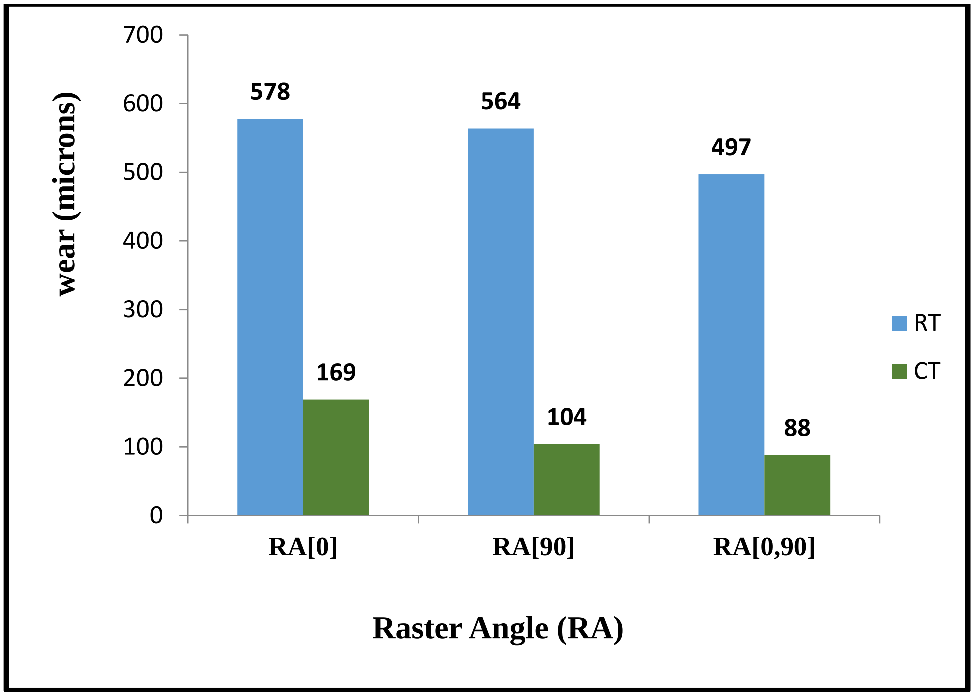


**Fig. 9 Wear of 3D printed PLA samples**

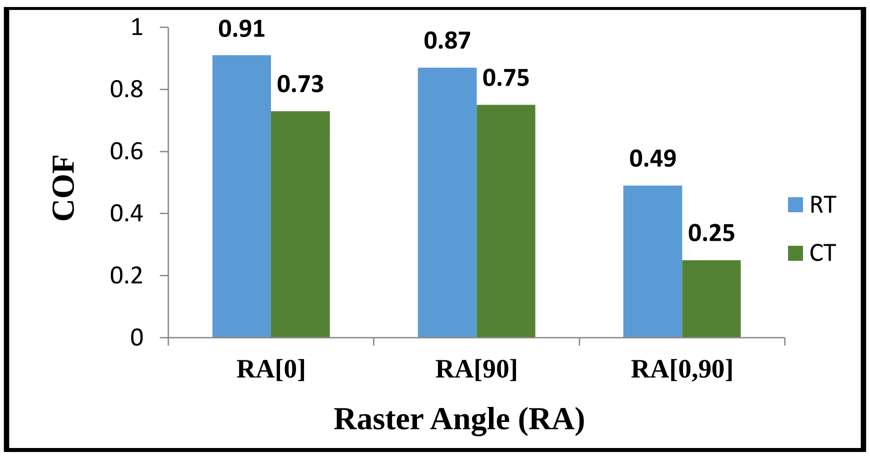


**Fig. 10 Coefficient of Friction on 3D printed PLA samples**

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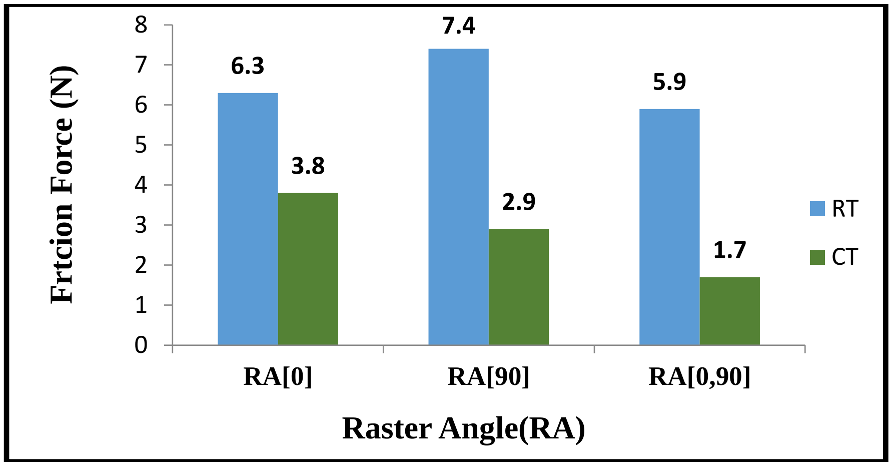


**Fig. 11 Friction Force on 3D printed PLA samples**

## 5. CONCLUSIONS

Based on the findings from the tensile and wear tests of 3D printed PLA samples subjected to Deep Cryogenic Treatment (DCT), the following conclusions can be drawn:

1. Deep Cryogenic Treatment (DCT) significantly enhances the tensile strength of 3D printed PLA samples, with an observed improvement of up to 85% for samples with a raster angle of 90°.
2. The wear resistance of cryogenically treated 3D printed PLA samples is markedly improved, showing a reduction in wear by up to 83% compared to untreated samples.
3. The raster angle plays a crucial role in determining both the tensile strength and wear resistance of the samples, with alternating layers (RA 0°& 90°) offering the best performance in wear reduction.
4. The coefficient of friction and frictional force were significantly reduced in cryogenically treated samples, indicating enhanced tribological properties.
5. The findings demonstrate the potential of using cryogenically treated 3D printed PLA in applications where both mechanical strength and wear resistance are critical, especially in cryogenic environments.

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