

Mechanical Testing of 3D Printed Parts and Materials

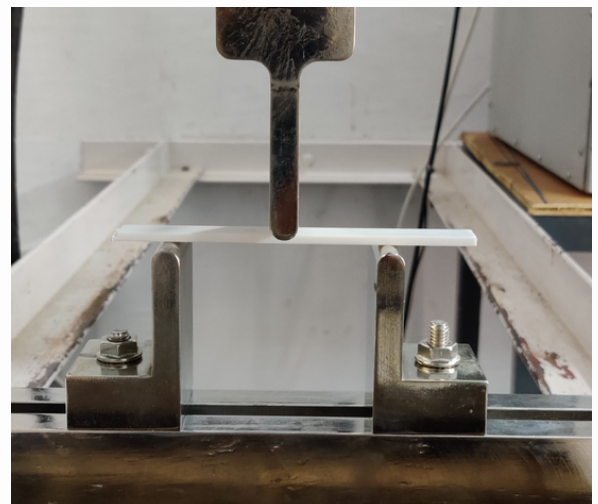
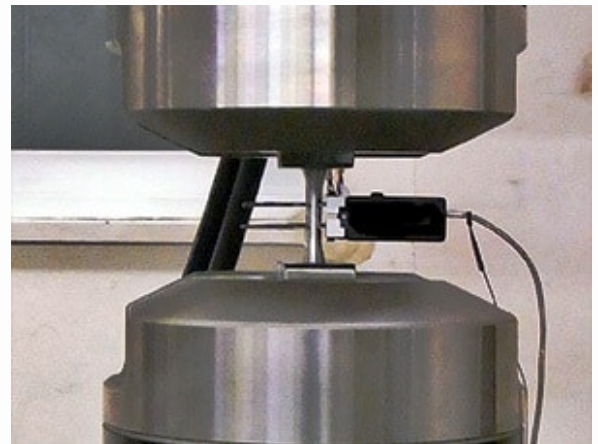
Strength Characterization and Performance Prediction

A New Approach to Product Development & Rapid Prototyping

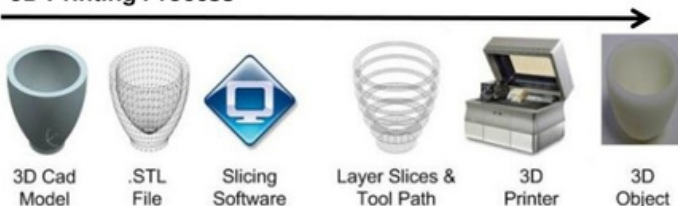
By Kartik Srinivas

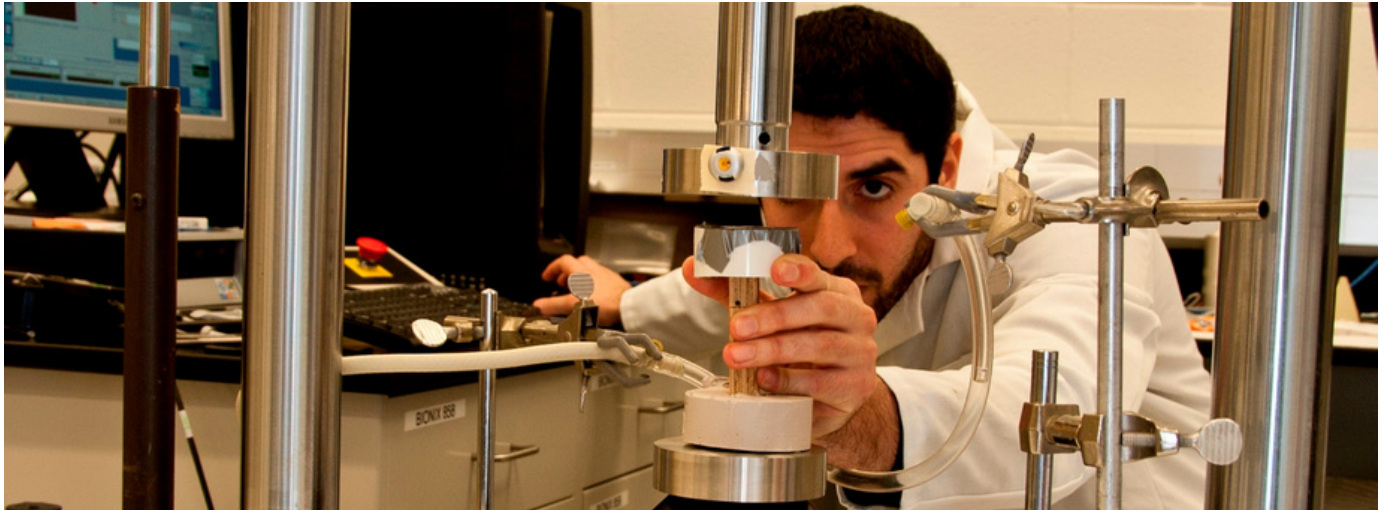
The procedure of manufacturing objects by depositing successive layers upon layers of material, based on 3D digital CAD models, is called Additive Manufacturing (AM) or simply 3D-printing. Fused Deposition Modeling (FDM) technology is one of the most widely used technique in additive manufacturing. A range of other manufacturing materials can be used for 3D printing that include nylon, glass-filled polyamide, epoxy resins, wax, and photopolymers. FDM-based polymer product manufacturing has increased in recent times due to the flexibility it offers in the production of polymer and fibre-based composite parts. FDM-based polymers have the potential to be used in all applications, currently they are primarily used in automotive, aerospace and biomedical applications.

Additive Manufacturing involves a series of processes, from ideation and design development to final product manufacturing using a specialized printer. The different steps depend on the type of manufacturing method and the material type. The primary processes and steps involved are however mostly common and remain the same for different types of manufacturing applications. The steps involved in an AM process are as shown below;



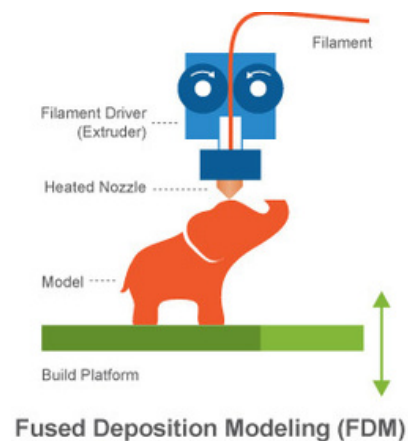
3D Printing Process





Fused Deposition Modeling (FDM)

FDM is the method of choice for manufacturing of 3d printed polymer parts and components due to its simple process, low economic cost and predictable material properties. FDM is already used in the material extrusion manufacturing process for various thermoplastic polymers. Some common thermoplastic filaments used in FDM are acrylonitrile butadiene styrene (ABS), polypropylene (PP), polylactide (PLA), polyamides (PA) like Nylon, polyether-ether-ketone (PEEK) etc. The FDM process consists of the polymer being extruded and deposited in a successive layer by layer method. FDM manufactured polymer parts and components exhibit good mechanical properties, surface finish, and manufacturability. The matrix material used in the FDM process is in the form of a 1.75mm to 2.85 mm filament wound on a spool. The filament is fed into the printer head where it is heated and melted above its glass transition temperature (T_g). The plastic melt is then passed to the nozzle and deposited layer by layer.



FDM of Fibre-Reinforced Polymers

The strength of polymeric materials can be significantly improved through reinforcement by fibres. Fibre-reinforced polymers manufactured using 3d printing technique is gaining traction. Fibre-matrix interaction and porosity are important considerations to be addressed in 3d printing of polymeric composites. FDM is currently the most preferred method for the production of polymeric fiber composites due to its material flexibility, and consistent properties.

“FDM is the method of choice for manufacturing of 3d printed polymer parts and component due to its simple process, low economic cost and predictable material properties.”





Mechanical Testing & Performance Assessment

ASTM and ISO testing methods are used to test the properties of 3d printed polymers. These tests have been originally developed for testing reinforced and unreinforced polymers and subsequently found use and application in 3d printed polymers. Specifications followed for conducting tensile, flexural, impact, and compression tests on FDM based polymers and composites allow for standardized specimens and conditions. Tensile tests can be performed on both the dumbbell shaped and straight bar shaped specimens. For the impact tests, both notched and un-notched specimens can be used. For fatigue and compression tests, samples as per standard recommendations can be used.

The most common mechanical properties such as Modulus of Elasticity, Poisson's ratio, Tensile strength, and Ultimate tensile strain for composites are obtained from tensile testing and these properties are affected by the geometry, size and properties of the reinforcements.

The Modulus of Elasticity and Poisson's ratio are determined by measuring the strains during the elastic deformation part of the test, typically below the strain levels of 0.5%.

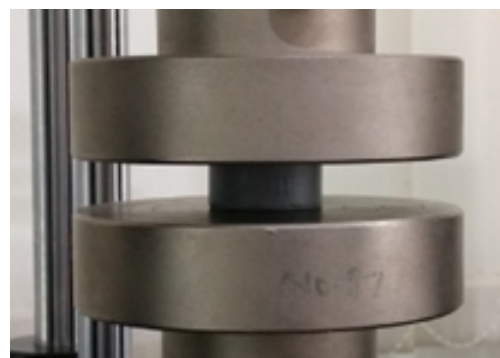
| Sr.No. | Test | Specification / Standard |
|--------|-------------|--------------------------|
| 1. | Tensile | ASTM D638 |
| | | ISO 527-2 |
| | | ASTM D3039 |
| 2. | Flexural | ASTM D790 |
| 3. | Impact | Charpy Impact ASTM D6110 |
| | | Izod Impact ASTM D256 |
| 4. | Compression | ASTM D695 |
| | | ASTM D3410 |
| 5. | Fatigue | ASTM D7791 |
| | | ASTM D3479 |

Due to the layer by layer material deposition technique the directional properties vary in the printed material and it becomes imperative to fully characterize the directional properties.

“

"Due to the layer by layer material deposition technique the directional properties vary in a printed material and it becomes imperative to fully characterize the directional properties."

”





Mechanical Testing & Performance Assessment

Uniaxial Tension Test (Directional) (ASTM D638, ISO 527):

The stress (ζ) in a uniaxial tension test is calculated from;

$$\zeta = \text{Load} / \text{Area of the material sample} \dots\dots\dots(1)$$

The strain(ϵ) is calculated from;

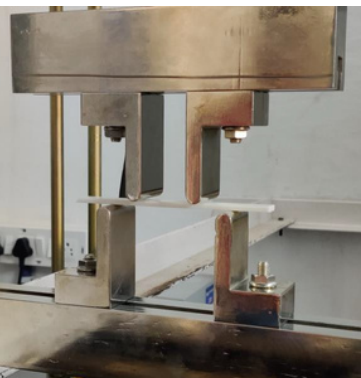
$$\epsilon = \delta l (\text{change in length}) / l_1 (\text{Initial length}) \dots\dots\dots(2)$$

The slope of the initial linear portion of the curve (E) is the Young's modulus and given by;

$$E = (\zeta_2 - \zeta_1) / (\epsilon_2 - \epsilon_1) \dots\dots\dots(3)$$

4 Point Bend Flexure Test (ASTM D6272):

The four-point flexural test provides values for the modulus of elasticity in bending, flexural stress, flexural. This test is very similar to the three-point bending flexural test. The major difference being that with the addition of a fourth nose for load application the portion of the beam between the two loading points is put under maximum stress. In the 3 point bend test only the portion of beam under the loading nose is under stress.



“Mechanical testing of 3d printed polymeric composites involves the determination of mechanical parameters such as strength, stiffness, elongation, fatigue life etc., to facilitate its use in the design of structures..”



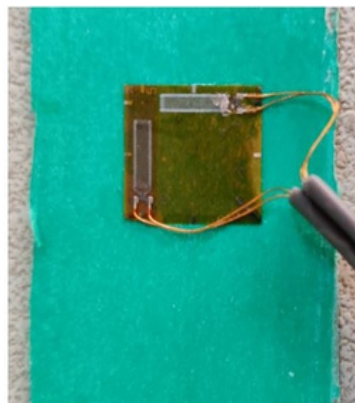


Mechanical Testing & Performance Assessment

This arrangement helps when testing high stiffness materials like ceramics infused polymers, where the number and severity of flaws under maximum stress is directly related to the flexural strength and crack initiation in the material. Compared to the three-point bending flexural test, there are no shear forces in the four-point bending flexural test in the area between the two loading pins.

Poisson's Ratio Test as per ASTM D3039:

Poisson's ratio is one of the most important parameter used for structure design where all dimensional changes resulting from application of force need to be taken into account, specially for 3d printed materials. For this test method, Poisson's ratio is obtained from strains resulting from uniaxial stress only. ASTM D3039 is primarily used to evaluate the Poisson's ratio. Testing is performed by applying a tensile force to a specimen and measuring various properties of the specimen under stress.



Two strain gauges are bonded to the specimen at 0 and 90 degrees to measure the lateral and linear strains. The ratio of the lateral and linear strain provides us with the Poisson's ratio.

Flatwise Compression Test as per ASTM D695:

The compressive properties of 3d printed materials are important when the product performs under compressive loading conditions. The testing is carried out in the direction normal to the plane of facings as the core would be placed in a structural sandwich construction.

“

"Poisson's ratio is one of the most important parameter used for structure design where all dimensional changes resulting from application of force need to be taken into account."

”



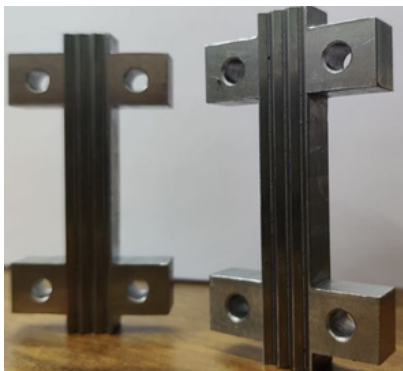


Mechanical Testing & Performance Assessment

The test procedures pertain to compression call for test conditions where the deformation is applied under quasi-static conditions negating the mass and inertia effects.

Modified Compression Test as per Boeing BSS 7260:

Modified ASTM D695 and Boeing BSS 7260 is the testing specification that determines compressive strength and stiffness of polymer matrix composite materials using a loading compression test fixture. This test procedure introduces the compressive force into the specimen through end loading.



Axial Fatigue Test as per ASTM D7791 & D3479:

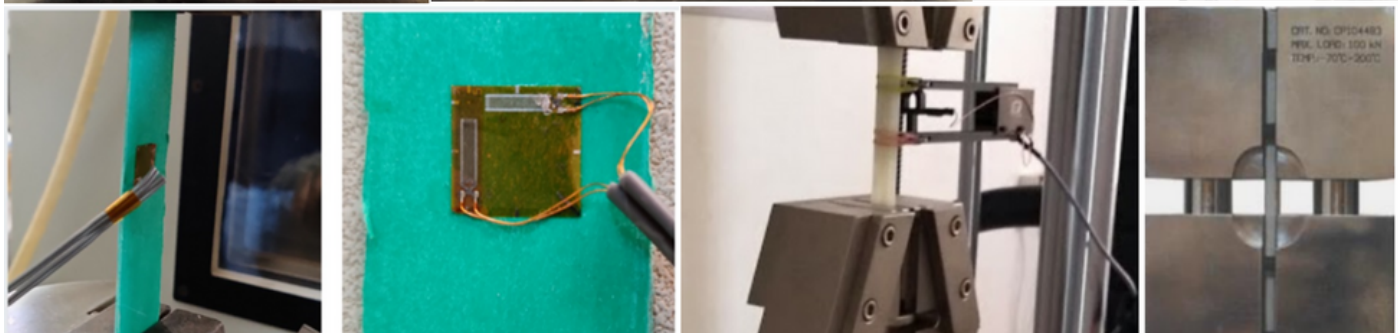
ASTM D7791 describes the determination of dynamic fatigue properties of plastics in uniaxial loading conditions. Rigid or semi-rigid plastic samples are loaded in tension (Procedure A) and rigid plastic samples are loaded in compression (Procedure B) to determine the effect of processing, surface condition, stress, and such, on the fatigue resistance of plastic and reinforced composite materials subjected to uniaxial stress for a large number of cycles. The results are suitable for study of high load carrying capability of candidate materials. ASTM recommends a test frequency of 5 hz or lower. The tests can be carried out under load or displacement control. The test method allows generation of a stress or strain as a function of cycles, with the fatigue limit characterized by failure of the specimen or reaching $10E7$ cycles. The maximum and minimum stress or strain levels are defined through an R ratio..



“

"Mechanical testing of 3d printed polymeric composites involves the determination of mechanical parameters such as strength, stiffness, elongation, fatigue life etc., to facilitate their use in the design of structures, parts and components.."

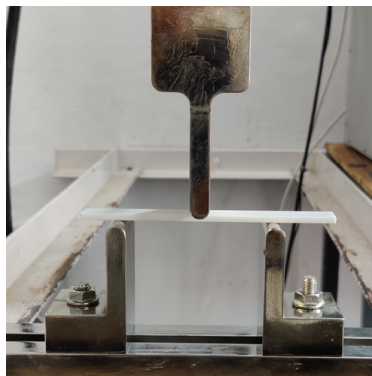
”



Mechanical Testing & Performance Assessment

3 Point Bend Flexure Test (ASTM D790):

Three point bending testing is done to understand the bending stress, flexural stress and strain of composite and thermoplastic 3d printed materials. The specimen is loaded in a horizontal position, and in such a way that the compressive stress occurs in the upper portion and the tensile stress occurs in the lower portion of the cross section. This is done by having round bars or curved surfaces supporting the specimen from underneath. Round bars or supports with suitable radius are provided so as to have a single point or line of contact with the specimen. The load is applied by the rounded nose on the top surface of the specimen. If the specimen is symmetrical about its cross section the maximum tensile and compressive stresses will be equal. This test fixture and geometry provides loading conditions so that specimen fails in tension or compression.



For most composite materials, the compressive strength is lower than the tensile and the specimen will fail at the compression surface. This compressive failure is associated with the local buckling (micro buckling) of individual fibres.

Summary:

A variety of standardized mechanical tests on unreinforced and reinforced 3d printed materials including tension, compression, flexural, and fatigue have been discussed.

Summary:

Mechanical properties of 3d printed polymers, fiber-reinforced polymeric composites immensely depend on the nature of the polymer filament, fiber, and the layer by layer interfacial bonding. Advanced engineering design and analysis applications like Finite Element Analysis use this mechanical test data to characterize the materials. These material properties can be used to develop material models for use in FEA software like Ansys, Abaqus, LS-Dyna, MSC-Marc etc.

References:

- 1) Coutney, T.H., Mechanical Behaviour of materials, Waveland, 1996.
- 2) Dowling, N.E., Mechanical Behaviour of materials, engineering methods for deformation, fracture and fatigue, Pearson, 2016.
- 3) Ian McEnteggart, Composites Testing: Challenges & Solutions.
- 4) V. Shanmugam et al., The mechanical testing and performance analysis of polymer-fibre composites prepared through the additive manufacturing, PT, 21