INTERNATIONAL

Designation: F3489 − 23

Standard Guide for Additive Manufacturing of Polymers — Material Extrusion — Recommendation for Material Handling and Evaluation of Static Mechanical Properties[1]

This standard is issued under the fixed designation F3489; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers existing standards or variations of existing standards that may be applicable to determine specific static mechanical properties of polymeric specimens fabricated with the material extrusion (MEX) additive manufacturing (AM) process. The test methods covered within this document are recommendations supplied coming from the experience previous material qualification programs have provided. Additional test methods may be considered as well depending when evaluating material performance for specific applications. Recommendations for material handling prior to testing and characterization are included as they can greatly affect material properties. It is for the end user to determine if the recommended tests adequately evaluate the material performance for the intended application.

1.2 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D638 Test Method for Tensile Properties of Plastics
D695 Test Method for Compressive Properties of Rigid Plastics
D790 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
D3039 Test Method for Tensile Properties of Polymer Matrix Composite Materials
D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
D5379 Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method
D5766 Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates
D5961 Test Method for Bearing Response of Polymer Matrix Composite Laminates
D6484 Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates
D6641 Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture
D6742 Practice for Filled-Hole Tension and Compression Testing of Polymer Matrix Composite Laminates
D7191 Test Method for Determination of Moisture in Plastics by Relative Humidity Sensor
F2971 Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing

2.2 *ISO/ASTM Standards:*[2]

ISO/ASTM 52900 Additive manufacturing — General principles — Terminology
ISO/ASTM 52921 Standard terminology for additive manufacturing — Coordinate systems and test methodologies

[1] This guide is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.01 on Test Methods.

Current edition approved May 1, 2023. Published June 2023. DOI: 10.1520/F3489-23.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3. Terminology

3.1 *Definitions*—Terminology relating to additive manufacturing (AM) in Terminologies ISO/ASTM 52900 and ISO/ASTM 52921 shall apply.

4. Significance and Use

4.1 As noted in many of the standards in Section 2, there are multiple factors that may influence the reported properties, including material choice, material anisotropy, methods of material storage and preparation, porosity, methods of specimen storage and preparation, orientation and specimen build plate location during fabrication, testing environment, specimen alignment and gripping during testing, testing speed, and testing temperature. These factors should be recorded according to Practice F2971 and the guidelines of the referenced standards. This guide is intended to inform users of best practices for static mechanical testing of additive manufactured polymer specimens fabricated using material extrusion (MEX).

5. Material Handling Considerations

5.1 All material exposure conditions pre- and post-fabrication should be clearly defined and documented to minimize environmental effects on material properties.

5.2 *Inherent Material Properties*—There is a large selection of polymer materials available for MEX fabrication, each material having their own inherent characteristics that can greatly affect both fabrication capability and performance after fabrication. Filament materials are recommended to be stored in a controlled environment to mitigate effects of exposure to temperature, humidity, and UV exposure, among other exposures that may degrade performance of fabricated parts.

5.3 Two material characteristics that can significantly affect tested material properties include a material's moisture absorption and thermal history. Hygroscopic materials are very susceptible to moisture absorption even when located in ambient environments with moderate humidity. For this reason, moisture content of materials under investigation shall be controlled. Nylon is one such material type that readily absorbs moisture from the surrounding air and the rate of absorption is increased in higher humidity environments and even more so when submerged. Other materials such as PLA are much less susceptible to moisture absorption and therefore require less monitoring regarding storage and filament moisture content during fabrication. Secondly, a material's thermal history at both elevated and cold temperatures prior to fabrication can significantly affect fabrication and mechanical performance. A material's glass transition temperature (Tg) is the point at which a material begins to change from a glassy to a rubbery state. It is important to avoid exposing filament materials to temperatures near its inherent Tg to minimize thermal cycling effects on material properties. Some studies have shown that extended exposure to elevated and cold temperatures before fabrication can result in variation or degradation in mechanical performance of fabricated specimens. Moisture absorption and thermal history are not the only conditions that should be controlled but each is known to be a major contributor to material performance variation.

5.4 *Filament Material Conditioning*—Environment control should be in place for both pre- and post-fabrication states (filament and fabricated specimens), as material performance for both fabrication and testing mechanical performance can be altered if environmental exposure occurs in either state. Testing of polymer filament for moisture content before fabrication is recommended to follow Test Method D7191. Recommended acceptable values may be defined per material manufacturer recommendations. If material moisture content exceeds the recommended passing limit, material drying should be required at a predetermined temperature and duration to reduce the material moisture content to a passing level. Temperature, duration, and process for drying is specific to the material being used and it is commonly recommended to use a temperature at least 14 °C (25 °F) below the material's Tg unless otherwise stated by the manufacturer. Moisture testing should occur after the drying procedure to verify that the material drying sufficiently reduced the material moisture content before fabrication.

5.5 *Specimen Material Conditioning*—Post-fabrication specimen conditioning also plays a significant role in physical and mechanical performance. Investigations of material performance as a result of various specimen conditioning effects is a typical area of interest for end users depending on the expected application for the materials. Some standard specimen and testing conditions that are of interest in most cases include, but are not limited to, room temperature dry (RTD), cold temperature dry (CTD), elevated temperature dry (ETD), and elevated temperature wet (ETW). To achieve a dry or wet (saturated) material state or both before mechanical testing it is recommended to use Test Method D5229/D5229M to validate when a material has stabilized its moisture content via periodic weight measurements. Test temperatures are specific to the material under investigation and should be determined by the end user based on end-use application.

5.6 *Specimen Handling*—If available, follow specimen handling conditions provided within each available ASTM test standard. In the absence of specified material handling conditions, appropriate methods can be used to minimize effects of ambient environment on conditioned specimens. One potential way to accomplish this is to store specimens properly in between conditioning and testing. For wet conditioned specimens, a small moist fabric towel should be placed in a sealed bag with the specimens after the specimen has reached saturation from conditioning. The moist towel should not introduce excess moisture within the bag during specimen storage prior to testing. The goal of this is to keep the specimen at a saturated steady state prior to testing. Similarly, dried specimens should be placed in a sealed bag with a desiccant pack to maintain a dried specimen state. It is recommended that specimens in a sealed bag be tested within two weeks from the end of conditioning or within 8 h if specimens are not stored in the sealed bag environment.

6. Fabrication Considerations

6.1 *Fabrication Orientation Overview*—It is an inherent property within the MEX process that the same geometry specimen fabricated in different orientations will experience slightly different dimensional results for features. For example, the radius of a Test Method D638 Type I specimen can be easily produced for a flat (XY) orientation, but that same radius when fabricated in the upright (XZ) orientation will be built using individual layers resulting in a stair step. Mechanical performance will vary between the different specimen orientations and the resultant strength will be a characteristic of contour strength, raster (infill) strength, layer line adhesion, or a combination of all. User considerations should include evaluation of problematic fabrication orientations, specifically the ZX (vertical) orientation, which primarily evaluates layer line adhesion. This orientation may require additional support structures/materials or design modifications in order to fabricate successfully. An additional consideration for specimen orientation on the build plate includes the rotation of specimen placement in the Z-Axis. Adjustment of this rotation will affect the internal toolpath placement within the specimen geometry and therefore can affect mechanical properties. Minimization of artifacts within the specimen gauge section is important for proper testing and mechanical performance. Fig. 1 is a representation of multiple build orientations for the same specimen.

6.2 *Pre-Processing Overview*—Because of the anisotropic behavior observed for MEX in polymeric fabrications, additional information should be included in process specification reports. These reports should include, but are not limited to, definitions of the orientation tested, number of contours, layer height, raster angles, and nozzle diameter with potential for full disclosure of geometric toolpath output from the slicing software. All pre-processing parameters may affect the resultant fabricated material performance. For instance, increasing the number of contours for a tension specimen where the load path is in-plane to the contour direction has shown to increase tensile strength in some instances. Process specifications for material fabrication should also include machine type, machine configuration, and operation environment definitions to identify specific manufacturing methods accurately.

6.3 *Process Controls Overview*—Fabrication, post-processing, and conditioning methods for process-sensitive materials shall be defined and held constant for a proper characterization of a material dataset. Process considerations such as annealing post-fabrication or material conditioning before fabrication should be clearly identified within the manufacturer's process specification to identify any variations observed in mechanical performance as a result of process modifications. Additional data that shall be clearly defined and documented include build designs and job travelers that identify the specimen geometry and the number and locations of specimens being fabricated for each build along with part spacing and orientation within a fabrication. Specimen material properties can be highly affected by variables including fabrication speeds and temperatures including, but not limited to, extruder travel velocity and acceleration within the build volume and nozzle, bed, and chamber heating set temperatures.

6.4 *Quality Inspections*—Even with all processing controls documented and held constant, variation between fabricated specimens is probable. With this in mind, evaluation of build quality using various inspection techniques will allow the user to identify potential causes in variation of mechanical performance. Inspection methods include, but are not limited to, external optical microscopy, nondestructive inspection (NDI) techniques such as X-ray computed tomography (CT), and destructive inspection methods including analysis by cross-sectional photomicrograph. Identification of specimen characteristics and defects provides data to better inform variations that may be seen in material mechanical performance after mechanical testing.

7. Measuring Mechanical Properties

7.1 See Table 1 for a summary of recommended test methods.

7.2 The relativeness of the chosen test standard is dependent on the composition and end use. For example, a continuous

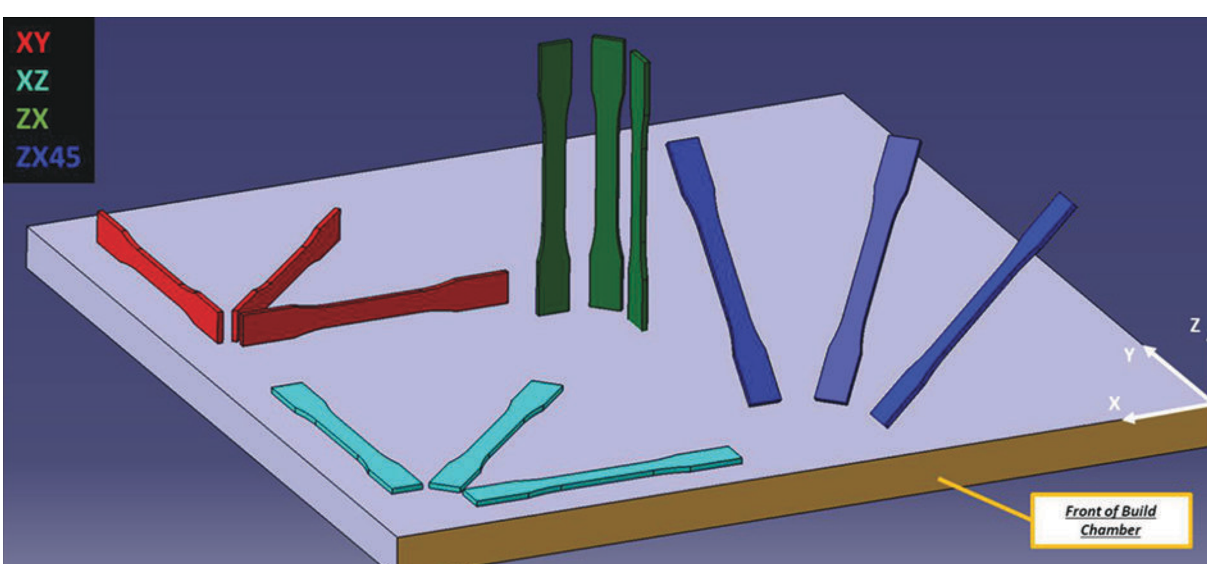

FIG. 1 Varying Fabrication Orientations for the MEX Methodology

TABLE 1 Summary of Test Methods

Test Method	Use	Relevant Standards
Tension	Modulus of elasticity, Poisson's ratio, percent elongation, yield and tensile strengths	D638 and D3039
Tension—design guidance	Tensile strength	D5766 and D6742
Compression	Modulus of elasticity, compressive offset yield strength	D695 and D6641
Compression—design guidance	Compressive strength, open hole and filled hole	D6484 and D6742
Bearing	Bearing stiffness, offset bearing strength, ultimate bearing strength	D5961
Flex	Modulus of elasticity, flexural strength of reinforce and unreinforced plastic	D790
Shear	Shear modulus of elasticity, offset shear strength, ultimate strength for V-notched polymer matrix composite specimen	D5379

fiber MEX specimen would be more comparable to most composites using Test Method D3039 versus Test Method D638. There are similar ISO standards to generate relative and somewhat comparable results that can be used at the discretion of the user. Results from ISO standards compared to ASTM standards will vary and should be used to draw more direct comparisons between previous or expected results. As with any test standard, load, displacement or strain rate will impact the test results and should be aligned with the comparison or end result.

7.3 *Tension*—The recommended procedures outlined in Test Methods D638 and D5766 [open hole tension (OHT)], Practice D6742 [filled hole tension (FHT)], and Test Method D3039 explain guidelines for tension testing to determine numerous material properties including, but not limited to, modulus of elasticity, Poisson's ratio, percent elongation, yield strength, and ultimate tensile strength. Each test method is intended to produce specific material properties, as is defined within their ASTM test standard documentation. For instance, Test Method D638 may be used to determine Poisson's ratio, modulus of elasticity, yield strength, and ultimate strength, while Test Method D5766 is used to generate ultimate and offset strength properties for materials with design features specific to open hole geometries. The largest extensometer that can be used for each specimen size per the ASTM International standards is recommended to be used for each test method because of its ability to capture deformation over a larger representative area.

7.4 *Test Method D638 Recommendations*—Given that Test Method D638 is intended to evaluate polymer materials, this should be the default test standard when evaluating tensile performance of polymer materials fabricated via MEX. If a specific machine and methodology cannot accurately produce sufficient Test Method D638 specimen quality, geometries from other test standards that have more simplistic designs, such as Test Method D3039, may be used. In Test Method D638, several different specimen geometries are provided with varying dimensions that change cross sectional geometry from a larger gripping portion of the specimen down to a narrower cross-sectional gauge section. For MEX additive manufacturing (AM) methods, a concave transition from grip to gauge section across the width is preferred. The Type I specimen is the preferred geometry and should be used if the thickness requirements of the Type I geometry can be met. Specimens should conform to the thickness requirements of the designated test standard unless an alternate thickness is expressly specified. Specimen thickness should be the primary factor for selection of Test Method D638 specimen geometries based on Test Method D638 requirements or selection of an alternate specimen geometry within the standard may be made if improper failure types are observed. When evaluating the thickness of specimens, a micrometer should be used to measure the thickness of the specimen at multiple locations along the length of the gauge section. Avoid measuring around the edges of the specimens because of a rounded corner effect caused by the toolpaths in the material extrusion process resulting in a change in cross-sectional calculation. It is recommended that specimens be fabricated to drawing specifications provided within the standard rather than machining specimens to final dimensions from oversized fabrications or fabricated panels. Specimen machining can induce defects and alter contour bead dimensions so that beads are not consistent throughout the specimen cross section. Therefore, machining of specimens post-fabrication should be avoided unless deemed absolutely necessary. If machining is deemed necessary to meet test standard requirements or ensure proper specimen alignment within the test fixtures, then post-processing trials should be conducted to validate machining methods that will not meaningfully alter the material performance. To avoid specimen failures in the grip section, test fixture grips with a roughened thermal spray coating should be used whenever possible with the grip pressure adjusted based on an estimated failure load. Test speeds are outlined in Test Method D638 recommending potential test speeds with the goal to achieve specimen failure within a specified test duration range.

7.5 *Tension Test Method Comparisons*—The recommended tensile testing procedures outlined in Test Methods D638, Test Method D3039, Test Method D5766 (OHT), and Practice D6742 (FHT) detail testing methodologies and conditioning given specified geometries. Test Method D3039 is utilized to provide tensile properties of polymer matrix composite materials and Test Method D638 is utilized for the tensile properties of plastics. A benefit of Test Method D3039 compared to Test Method D638 is the ease of fabrication for MEX methods given that Test Method D3039 uses a simple rectangular geometry. Both OHT and FHT test methods require a similar rectangular geometry to that of Test Method D3039 before hole machining. The OHT test method uses a centrally located unfilled hole, while the FHT is the same tension test with a close tolerance fastener or pin filling the centrally located hole. OHT and FHT are intended to provide design guidance mechanical performance while Test Method D638 and Test