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A New Specimen Geometry for Evaluation of the Mechanical Orthotropic Properties Presented in Parts Printed by FDM

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Abstract: Additive manufacturing (AM) by FDM (Fused Deposition Modeling) has been increasingly adopted due to the low cost of 3D printers as an option capable of producing parts with complex geometries. Since the FDM process is a layer-by-layer manufacturing method, the characterization of the behavior of parts manufactured by this technology, especially with regard to anisotropic mechanical properties, has led to many works relating printing parameters with tensile strength. However, the use of specimens with the conventional flat "dog bone" and cylindrical geometries specified in the ASTM-638 standards do not perfectly suit the special characteristics of parts produced by FDM, since these standards were created for solid and isotropic materials. A new geometry for specimens printed in FDM to study anisotropy transverse to layer deposition is suggested in this work. Problems such as slippage and crushing in the grips of the test machines due to the fragility of the bound between the beds, as well as the appearance of lateral forces that distort the results due to misalignment of the tensile load, twists and curvature of the specimens, normally observed in the Strain measurements by extensometers, are suppressed with the adoption of the new geometry presented in this work.
Keywords: Fused Deposition Modeling, Additive Manufacturing, Mechanical Strength, Tensile Testing, Specimen Geometry

I. INTRODUCTION

Additive Manufacturing (AM) is a technology that promises to revolutionize the object manufacturing industry and has attracted great attention in recent years due to its application in various industries [1]. This technology consists of joining (adding) materials to create objects layer by layer. Stratasys' Fused Deposition Manufacturing (FDM) process is one of the most popular AM technologies today for the prototyping of physical models, having become widespread after the fall of the original patents in the 2000s, and with the advent of low-cost, open-source desktop models based on the RepRap (Replicanting Rapid Prototyper) model [2]. In the FDM process, a partially melted plastic filament is extruded through a fine nozzle (Fig. 1). The movement of the extruder is controlled by software based on a 3D computer model, depositing it layer by layer until the object is formed in three dimensions (Fig. 2). Printing via FDM is generally slow. Thus, it is customary to control the percentage of solid parts filling in order to reduce printing time. With this, an apparently solid object is produced, but hollow, with the interior filled with a checkered or honeycomb structure, for example.

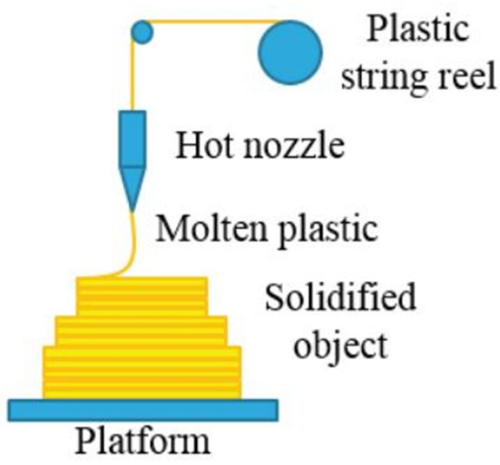

Fig. 1- Schematic model of the FDM process. A molten plastic filament is deposited on a platform layer by layer to form a three-dimensional object. (https://doi.org/10.1109/ICEAA.2017.8065498)

Fig. 2- Example of an object printed on a 3D printer.

Currently, the layer-by-layer 3D printing process uses several types of plastic materials such as ABS – Acrylonitrile-butadiene-styrene, PLA – Polyatic Acid, a biodegradable plastic made from sugar cane, Nylon, rubbers and other non-plastic materials such as foundry waxes, ceramics, concrete, sugar etc.

The mechanical properties of a common structural plastic, such as ABS and PLA, are well known, but their general properties cannot be used for the design of parts using the FDM process mainly due to the mechanical anisotropy created by the deposition formation system in threads and layers of this process which greatly reduces the resistance of the resulting piece, especially in the transversal direction (Z) of deposition of the layers [3][4]. This anisotropy, normally not present in materials created by other technologies, significantly alters the mechanical properties of the final object, mainly related to strain and shear.

Objects manufactured by AM have different mechanical behavior than those manufactured by traditional technologies such as injection and casting. The tensile strength of a PLA printed part, even in the longitudinal (X-Y) printing direction and with 100% infill, is 48% lower than a part manufactured by an injection mold [5].

Typically, parts manufactured by AM are not 100% solid. Each deposited layer is composed of one or more perimeters and a percent inner fill. The perimeters are responsible for the outer surface of the part while the infill is used to support the upper closing layers of the part and provide lateral compressive strength. In the X-Y directions of deposition, the mechanical tensile strength in a part manufactured by FDM is not very different from the strength of the plastic wire used. In the Z direction, the tensile strength is around 1/3 of the strength relative to the strength in the XY plane [6].

Many authors have been studying the relationship between the printing parameters and the resistance of parts manufactured by FDM. The vast majority of these works study the resistance in the X-Y direction of printing using ABS and PLA [7][8][9][10][11][12]. Others authors [13][14][15][16][17] try to study the resistance in the Z direction but simulating the anisotropy in this direction still using the printed specimen in the XY direction, which does not exactly reflect the deposition conditions layer over layer, necessary to study the resistance between the layers. There are few works where the specimen is printed vertically [18][6][19]. Still, these studies are carried out using ASTM D638 flat “dog-bone” geometry, type I or IV, for tensile tests [20]. Printing these specimens (type I or IV - ASTM D638) in the vertical direction not only requires additional care due to the small area in contact with the printing table, but also introduces non-uniform regions in the plastic deposition due to accelerations and decelerations of the print head (jerk) along edges and rapid changes of direction at vertices due to the rectangular shape of the straight section. These characteristics can vary greatly depending on the firmware of each machine. In addition, an ASTM Type I specimen with gauge region dimensions of 13.0mm x 3.2mm gives us an area of 41.6mm². Considering a printed specimen with at least one perimeter (with 0.3mm layers), the area left over for infill is approximately 32mm², one of the dimensions being reduced to 2.6mm. Considering 2 perimeters, this dimension reduces to a mere 2mm, and leaves us with a padding area of approximately 23mm² (these values can be even smaller for wider layers). Therefore, the evaluation of the contribution of the infill percentage, in the total resistance of the specimen, is compromised by the relatively small area in the gauge region (narrow section) of the specimen (Fig. 3).

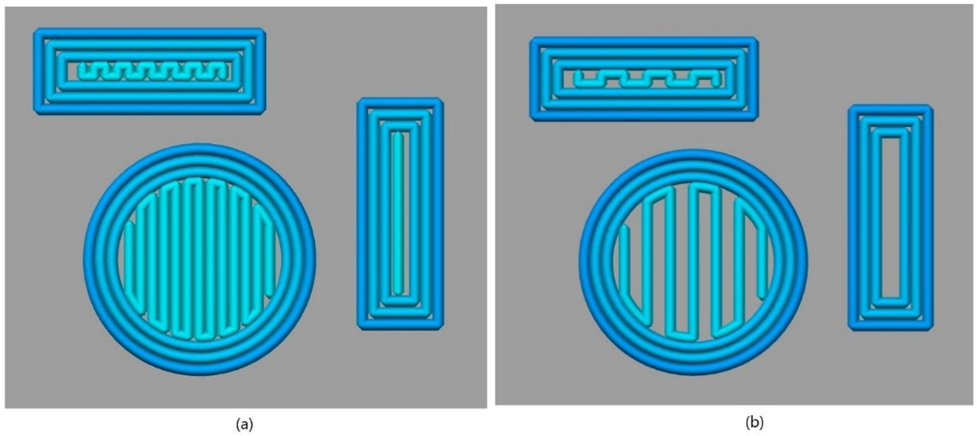

Fig. 3- Comparison of straight sections between the ASTM 638 "dog-bone" type I and a cylindrical specimen. (a) 100% Infill; (b) 50% Infill.

The strength of a 3D printed piece in the transversal direction of printing, that is, between the layers, is due not only to the bounds between the perimeters rods that constitute the walls of the piece, but also due to the contribution of the bounds between the rods used in the filling (infill). The more vertical the deposition of the wall, the greater the connection between the layers. The geometry of Type I and IV specimens requires a width in the grip region greater than the gauge width to ensure that the specimen breaks in this last region and that stresses in this region are perfectly transverse and uniform. The transitional curvature of the flat dog-bone ASTM specimen between the gauge region and the grip region implies a lateral displacement between one layer and another, reducing the contact area between the perimeters, resulting in weak zones which can compromise the test of the sample causing the rupture outside the gauge region. This bond can even be easily broken if the specimen is subjected to compression across the layers, which is what usually happens when the specimen is placed in the grips of the tensile testing machine and tightened, especially serrated grips made to prevent slipping. of the specimen. The result of this, added to the reduction of the connection between the layers in the grip/gauge transition area, is the occurrence of areas of weakness that cause the specimen to break outside the gauge area, a result that according to ASTM D638 should be discarded.
The ASTM [21] recommendation for specimens submitted to tensile testing is that they are free from cuts and cracks or any other irregularity that may cause the specimen to rupture prematurely due to a point of localized weakness, producing false results. Typically, Type I and IV specimens for thermoplastics must be molded.

A. The ASTM-D638 Cylindrical Geometry

ASTM D638 also specifies a cylindrical geometry for rigid and solid specimens with widely varying geometric parameters. However, experience shows that both the flat “dog-bone” geometry and the cylindrical geometry specified by ASTM D638 need to be adapted to the reality of the FDM manufacturing process, especially regarding to design. These modifications are necessary due to the imposition of test standards, but mainly due to the geometry of the specimens, which when printed in the layer-by-layer method, present characteristics different from those prepared by the conventional methods of injection, molding, pressing or milling, for which the standards were specified. At the time of this work, ASTM has not yet created a specification for tensile testing on specimens printed on 3D printers by FDM.
Some of the modifications needed in the conventional test samples due to the peculiarities of the FDM 3D printing method are related to:

1) Lateral force imposed by the jaws (grip);
2) Ensuring that the line of action of the applied force coincides with the major axis of the specimen;
3) Displacement between layers at the interface gauge/grip zone;
4) Detachment of layers due to slippage in the grip.

This geometry has advantages over the flat "dog-bone" geometry. It is easier to print vertically as it has a larger contact area with the printing table and prevents the formation of defects caused by deceleration since the circular perimeter is built by small straight segments with the print nozzle moving simultaneously in both X and Y axes. In addition, it has an internal area larger than the flat “dog-bone”, allowing a better evaluation of the contribution of the filling percentage in the total resistance of the specimen, as shown in Fig. 3.

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However, two crucial problems arise in using the cylindrical specimen suggested by the ASTM D638 standard: As with the flat "dog-bone" specimen, the lateral pressure exerted by the grips of the tensile testing machine can destroy the bond between the layers causing slipping of the specimen and making the test result unfeasible. Generally, cylindrical specimen jaws are of the chuck or lathe chuck type with serrated and self-centering jaws. Another possible geometry for cylindrical specimens is the addition of thread in the grip zone, either internally or externally to be fixed by screws or with a lateral cavity to be secured using a split collar. However, due to the characteristics of FDM printing, all these geometries fail to keep the grip zone intact during the tensile test. A less destructive grip would be one to enfold the specimen in the curvature of the transition zone between the gauge zone and the grip zone, but this solution needs a perfect match between the grip and the specimen to avoid non-continuously applied force distribution causing the specimen to twist and bend, creating a net force not aligned with the specimen axis, an unwanted effect normally seen on the extensometer (Fig. 4). This unwanted effect is even more accentuated if there is any roughness or dimensional variation in the deposition of the outer perimeters of the layer.

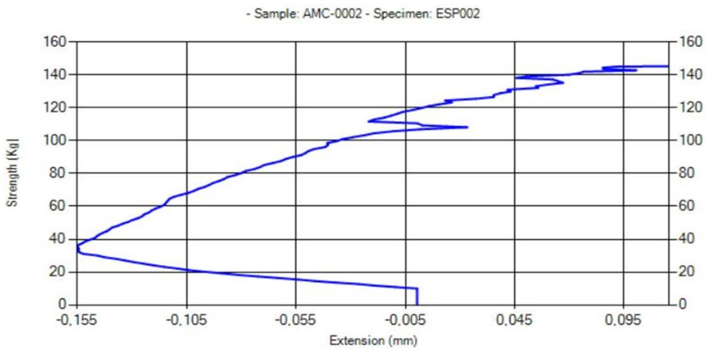

Fig. 4- The anomalous behavior of the extensometer measurements in a conventional cylindrical specimen tensile test due to bending caused by lateral forces and due to slipering of the specimen in the grip's jaws.

B. A new Geometry.

Therefore, despite having a larger internal area and eliminating some unwanted effects on printing, the cylindrical specimen suggested by ASTM, as well as the variations described above, are not perfectly suitable for a study of tensile strength in the transverse direction of layer deposition. This work suggests a new geometry for samples aimed at studying the relationship between the printing parameters and the anisotropic resistance of parts printed on FDM. To eliminate the problems related to compression on the layers by the grip and resulting forces transverse to the longitudinal axis of the part, a specimen with a geometry that, when being pulled, is only subjected to vertical forces parallel to the longitudinal axis of the specimen is necessary. This geometry was obtained using a collar located in the grip zone, as shown in Fig. 5.

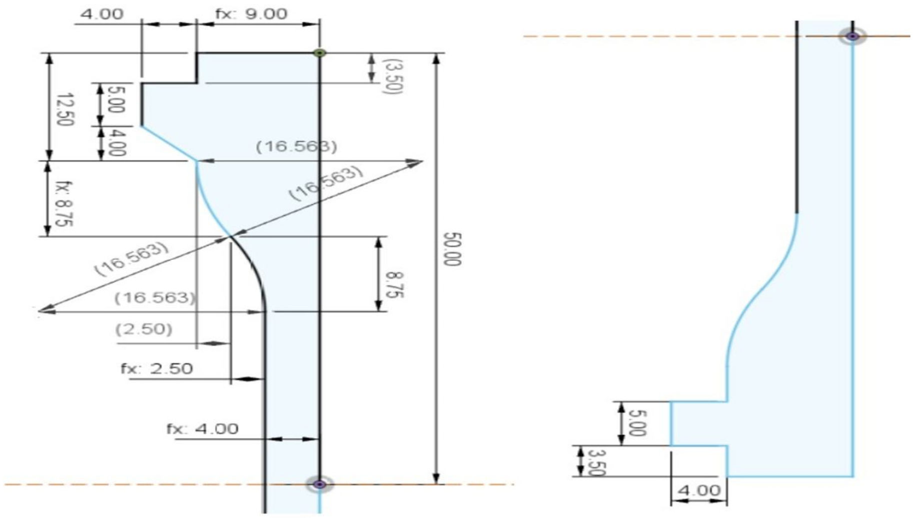

Fig. 5- - Geometry of the upper and lower parts of the suggested sample. Values in mm. O projeto da geometria foi feito no software Autodesk Fusion 360.

The suggested sample has a diameter of 18mm in the grip zone and 8mm in the gauge zone. The transition zone between the grip zone and the gauge zone is made up of two circular curves with continuous derivatives. This ensures a constant offset displacement between each layer of the transition zone in the order of 8% of the default Extrusion Width for a layer of 0.2mm high. The lower face of the upper ring was made inclined to avoid the need for support material during specimen printing, thus avoiding the appearance of roughness when removing it. The ring added in cylindrical geometry is not placed on top of the specimen because the 3.5mm extension above the ring with the same diameter as the grip zone is important to center the specimen in the grip.

The Fig. 6 shows the rendered image of the sample used to generate all specimens used in the tensile tests of this work; a FEM analysis performed in the SOLIDWORKS software and a picture of a specimen printed on the Makerbot Replicator 2 printer. The FEM analysis demonstrates that over longitudinal load, the strain on the specimen is concentrated in the gauge zone, as recommended by the ASTM.

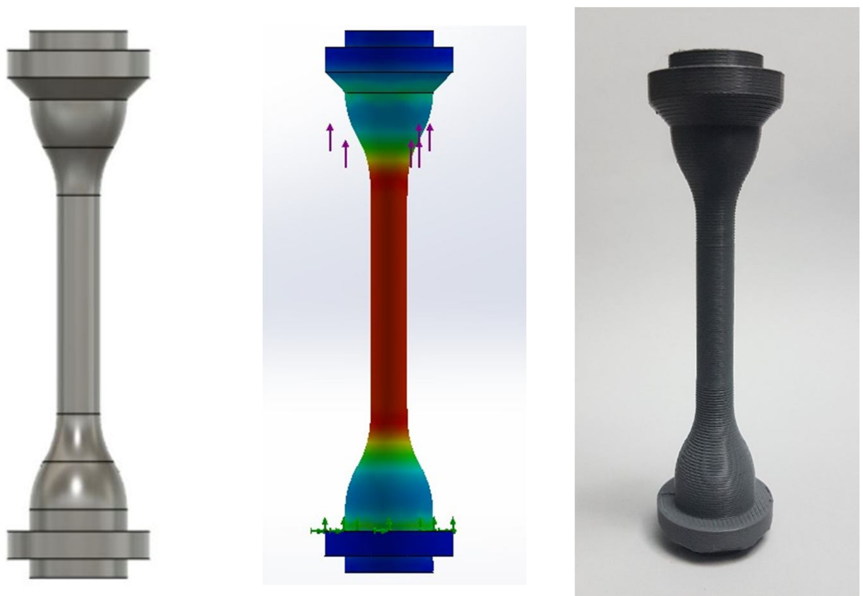

Fig. 6- A Rendered image of the suggested cylindrical geometry; a force-on-sample (FEM) analysis and a specimen printed on PLA on the Makerbot Replicator 2 desktop 3D printer.

Two specific grips for this sample were designed. A split cylinder shaped to embrace the grip zone and distribute the loads only on the faces of the ring. These grips are shown in Fig. 7 and Fig. 8. At the top of the grip, an M12 bolt with a steel circular nut connects the grip to the machine's drive and test system. Fig. 9 shows the entire specimen/grip set placed in the tensile testing machine and ready for testing.

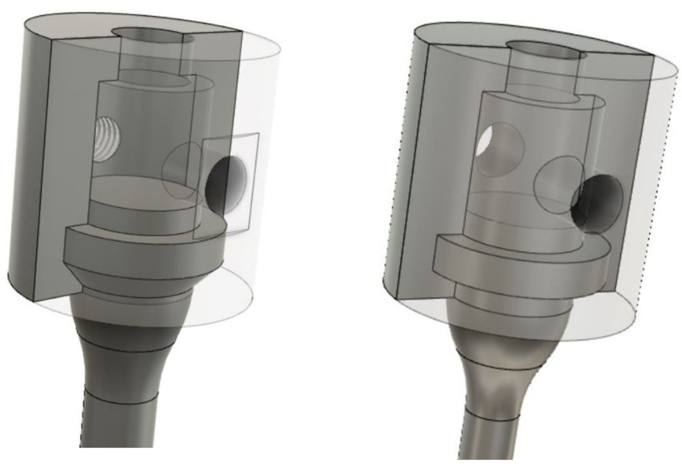

Fig. 7- Rendering of designed grips to the new sample geometry.

Fig. 8- Grips specially designed for the new sample geometry.

II. METHODOLOGY AND EXPERIMENTAL SETUP

The suggested geometry was modeled using Autodek Fusion 360 software and exported as an STL file. The STL file was sliced by the Simplify3D software using the parameters shown in TABLE I, exported as an x3g file and printed on a Makerbot Replicator 2 printer with a nozzle diameter of 0.4mm (Fig. 9). The material used to manufacture the specimens was 1.75mm diameter PLA filament. Five identical specimens with 1 perimeter and 100% infill were prepared. Tensile tests were performed on a Tensile Testing Machine [22] with a capacity of 10kN and a constant speed of 2mm/min (Fig. 10). All tests were performed within 24 hours of specimen fabrication.

TABLE I - Slicing and Printing Parameters to the Tested Samples.

Parameters	Values
Layer height (mm)	0.3
Default printing speed (mm/min)	4800
Extrusion Width (mm)	0.48
Extruder temperature (°C)	220
Number of shells	1
Infill density (%)	100
Raster angle (°)	-45/45
Nozzle diameter (mm)	0.4
Part printing orientation	vertical
Material	PLA
Feed filamento diameter (mm)	1.75
Generte support material	yes
Machine Type	Makerbot Replicator 2

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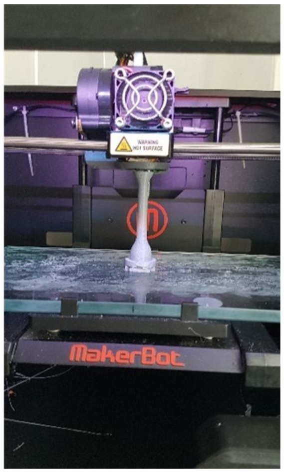

Fig. 9- Specimen being printed in the Makerbot Replicator 2 3D printer.

Fig. 10- A Specimen placed in the tensile testing machine.

III. RESULTS AND DISCUSSION

The TABLE II shows the results for the 5 stress tests performed on the printed specimens. Values for ultimate strength, ultimate stress, elongation, and strain are shown. The mean and standard deviation values are also shown. The graph in Fig. 11 shows the evolution of Stress X Strain during the entire test of each specimen, superimposed, showing an excellent repeatability of the values in the tests.

TABLE II - Tensile Test Results for the Five Printed Samples

Specimen	Ultimate Strength (kN)	Ultimate Stress (MPa)	Elongation (mm)	Strain (%)
ESP0001	0,80	16,00	0,20	0,88
ESP0002	0,81	16,13	0,19	0,85
ESP0003	0,76	15,13	0,17	0,74
ESP0004	0,76	15,18	0,18	0,81
ESP0005	0,81	16,14	0,19	0,85
Mean	0,79	15,72	0,18	0,83
SD	0,03	0,52	0,01	0,05

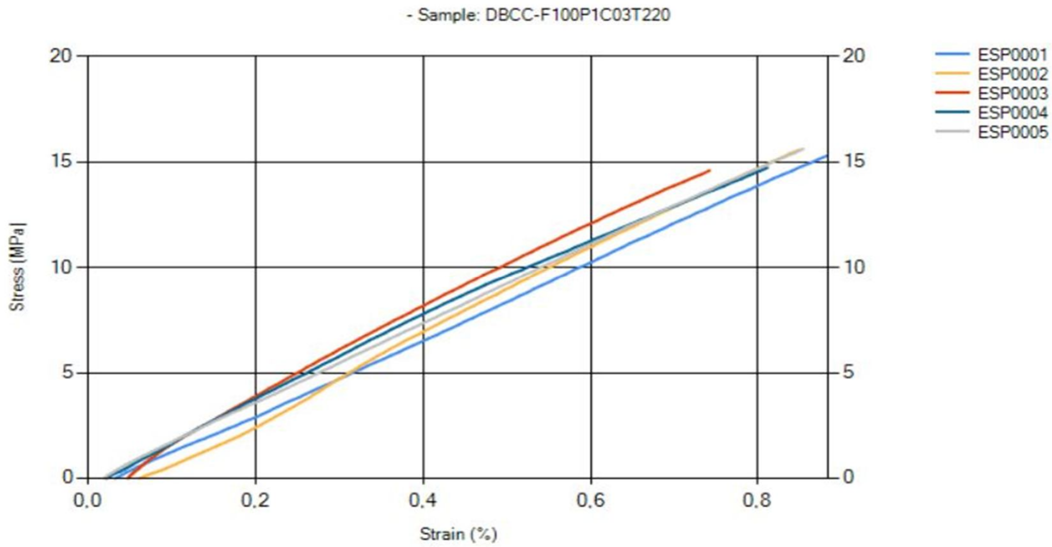

Fig. 11 - Stress x Strain curves of 5 identical specimens made with the new cylindrical geometry printed with PLA.

IV. CONCLUSIONS

A new geometry for ultimate tensile strength tests due to transverse anisotropy presented by parts printed on 3D printers was presented. Tests carried out on specimens printed in PLA with the new geometry shown excellent results regarding the elimination of slipping of the specimens in the grip, demonstrated in the linearity of the Stress vs. Strain curves, while eliminating the lateral stresses suffered by the specimens, due to the weak bond strength in the transverse direction of the layers, when being squeezed by the jaws of the grips. As it has a larger contact area with the printing table than the flat dog-bone ASTM 638, this new geometry is easier to print in vertical direction and not to much time consuming. Because it has a straight circular section, it is not subject to the formation of defects caused by the sudden change of direction of the print head. In addition, the larger area of the gauge zone should allow a better comparison in tests involving different percentages of infill.

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