ANALYSIS OF 3D PRINTED METRIC NUTS MANUFACTURED BY THE MEX METHOD FROM ASA MATERIAL

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Additive technologies represent revolutionary manufacturing technology for many industries, enabling the rapid production of geometrically complex parts or components that replace multi-part assemblies. For those, additive technologies have become an important topic for industry and the military sector. The ability to 3D print parts in foreign operations with minimal manufacturing technology and other components needed to repair damaged equipment and techniques is currently being adopted. This work focuses on the comparison of selected process parameters of the MEX-TRB/P/ASA additive manufacturing method (also known as FFF/FDM) for the production of M10 metric threads and their tensile testing. 3D printed threads were also compared with threads produced by tapping and forming. The results show that the formed threads in 3D printed polymer nuts are completely unsatisfactory and significantly reduce the load carrying capacity of the thread. The highest tensile strength of 3D printed threads was measured when the specimens were oriented at 45°, but with increased material consumption and production time. At the same time, it was found that by appropriate choice of material and process parameters it is possible to achieve a load capacity of more than 14,7 MPa for an M10 polymer nut without further post-processing.

KEYWORDS

additive manufacturing, 3D printing, material extrusion, dismountable joints, tensile strength

1 INTRODUCTION

Additive technology (also known as 3D printing) is currently a rapidly developing manufacturing technology that complements existing manufacturing technologies such as machining, casting, or forming [Godec 2022]. They have found their application through various industries such as aerospace [Dumitrescu 2024], medicine [MacLeod 2020] or mechanical engineering [Nefelov 2017]. The availability and growth of additive technology, especially in the socalled hobby maker sector, has caused a boom in trade and patent names such as FFF (Fused Filament Fabrication) and FDM (Fused Deposition Modeling). According to the technical standard EN ISO/ASTM 52900:2021 [EN ISO/ASTM 52900 2021] the correct name of the additive manufacturing method where the polymer material is extruded through a nozzle is MEX-TRB/P (Material Extrusion - Thermal Reaction Bonding of Polymer) [Fürst 2024]. The MEX method is one of the most versatile additive manufacturing methods available, enabling the production of parts from materials such as polymers, metals [Jasik 2024b], ceramics [Jasik 2024a] or continuous fiber composites [Łakomy 2024]. Applications of such advanced methods of lightweight multi-material structures require mathematical modelling, simulation an testing of the anisotropic mechanical properties [Krzikalla 2022] as well as verification of the dimensional accuracy and surface properties of the 3D printed parts [Kozior 2024].

As with traditional manufacturing methods, the choice of the right material [Dziubek 2022], method [Chudzik 2024], and process parameters such as orientation [MacLeod 2020], layer heights [Rizea 2023] factors that affect the final quality of the part and its mechanical properties are crucial in 3D printing. Several existing works dealing with 3D printing of fasteners and threads mainly address the possibility of using 3D printing and the geometric quality of the printed parts. Examples include the work of Nefelov et al. [Nefelov 2017], who tested the printing of M6, M8, and M14 internal and external threads from ABS using the MEX method, or Mahadevan et al. [Mahadevan 2019], in their work tested the possibility of 3D printing an entire assembly (nut, bolt, washer) of M16 nominal size fasteners from PLA material. The topicality of the issue of 3D printing of threads and threaded connections is also supported by the research of Chudzik et al. [Chudzik 2024], who assessed the quality and geometric accuracy of the M30 metric thread profile of screws produced by MEX, MJT (Material Jetting) and VPP (Vat Photopolymerization) methods or the research of MacLeod et al. [MacLeod 2020], who used the PBF-LB/P (Powder Bed Fusion - Laser Beam Sintering of Polymer) method for printing osteosynthesis screw threads.

Threaded holes can be found not only in fasteners such as nuts but also integrated into the design of the part. That can be achieved by thermal fusion of the threaded insert or by printing the thread directly in the hole. One interesting concept of thread insert integration is addressed in the work of Dumitrescu et al. [Dumitrescu 2024]. As part of their work, they designed and tested locally reinforced saddle structures for the insertion of threaded inserts, thus proposing a more efficient, lighter, and cost-effective panel production. Similar research has been carried out by Furst et al. [Fürst 2024], who embedded threaded sleeves into lightweight structures.

Although M10 nuts and inserts are most commonly made from metal, it is also possible to buy M10 nuts made by machining from PA (Polyamide) or also known as Nylon [Prumex s.r.o, n.d.].

2 MATERIALS AND METHODS

Model test specimens were created using Autodesk Fusion 360 CAD software. The models are based on the prescribed dimensions specified in EN ISO 4032:2023 Fasteners - Hexagonal regular nuts (style 1) for M10 × 1.5 nuts with a height of 8 mm. The bearing area of the thread was 130 mm2. One face and the perimeter of the specimen were subsequently adjusted to fit the specimen into the test fixture/machine clamps for tensile strength testing.

ASA (acrylonitrile styrene acrylate) was chosen as the material for the samples. It is a thermoplastic polymer that can be easily printed on commercially available and widely used desktop 3D printers. When compared to materials that do not fall into the high-performance category (i.e., the group of materials requiring printing temperatures above 300 °C and a heated print chamber), it has sufficient mechanical properties, is available, inexpensive, and UV stable, which makes this material a suitable choice for outdoor applications. In addition, the surface can be chemically etched and polished with acetone vapor, which can be advantageous for specific requirements on surface texture and roughness [Prusa Polymers a.s., n.d.].

Local manufacturers of 3D printers, print data preparation software, and 3D printing material with international overlap were chosen for the experiment. The 3D printing configurations (3D printer inside non-heated box) are listed in Table 1.

configuration	
3D printer	Original Prusa MK4
nozzle	Prusa Nozzle brass - 0.4 mm
build plate	Smooth PEI Print Sheet
adhesives	Magigoo
material (1)	**Filament PM ASA**
material (2)	**Prusament ASA**
material (3)	**Spectrum ASA 275**
CAM slicer	PrusaSlicer 2.7.2
material profile	based on the manufacturer
printing parameter	**vaule**
layer height [mm]	**(0.10; 0.15; 0.20)**
perimeters [-]	2
infill/perimeters overlap	15 % (line width)
infil density [%]	100
extrusion multiplier/flow [%]	100
print speed [mm/s]	170
XY, Z support distance [mm]	0.2
build plate temperature [°C]	100
nozzle temperature [°C]	based on recom.

Table 1. 3D Printing configuration and list of process parameters

Conventional tools (taps) were chosen for the production of threads by cutting and forming. The nut models for threading and forming were modified based on the recommended pre-drilled holes. The pre-printed hole for thread forming had a diameter of 9.3 mm. Pre-printed hole for thread cutting had a diameter of 8.5 mm. The threads and the pre-printed samples are shown in Figure 1.

The correct setting of the 3D printing process parameters plays a crucial role not only in achieving successful printing but also in the quality of the product. Unfortunately, technologists are very often put in a situation of compromise between visual quality, surface properties, mechanical properties, and cost-effectiveness of production. The basic printing parameters investigated in this experiment were model orientation during printing and layer height.

Figure 1. M10 cutting tabs (left), M10 forming tap (middle), 3D printed samples (right)

The orientation of 3D printed parts concerning the build plate is most often addressed specifically because of anisotropic properties. The parts are oriented to best withstand their operational stresses. However, the orientation of the part also determines the structure of the functional areas, the printing time, and the need for support structures. An example of this is the nut thread area (see Figure 2), which is formed differently by the different layers at different part orientations. When oriented at a 45 ° angle or vertically at 90 ° degrees, supports are required.

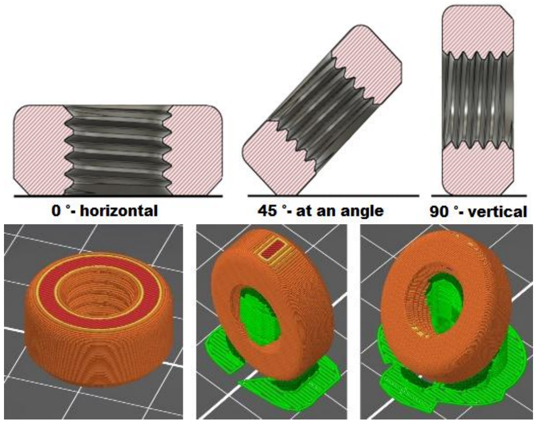

Figure 2. Visualization of the print orientation of the metric threaded nut in the section (top) and the prepared print data with oriented samples (bottom)

The height of the layer significantly affects the printing time, geometric and dimensional accuracy and surface texture of vertically and obliquely oriented surfaces (to the build plate). The higher the layer, the more visible the individual layers and the rougher the surface, see Figure 3.

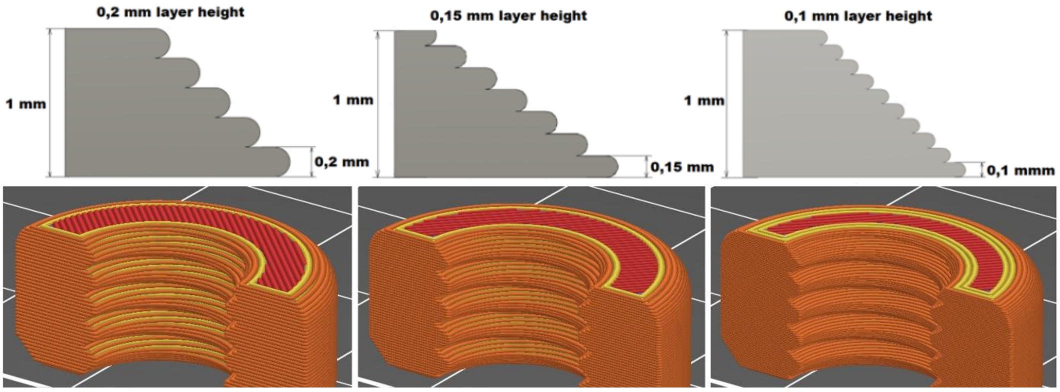

Figure 3. Visualization of different layer heights on a beveled surface (top) and prepared print data with different layer heights (bottom)

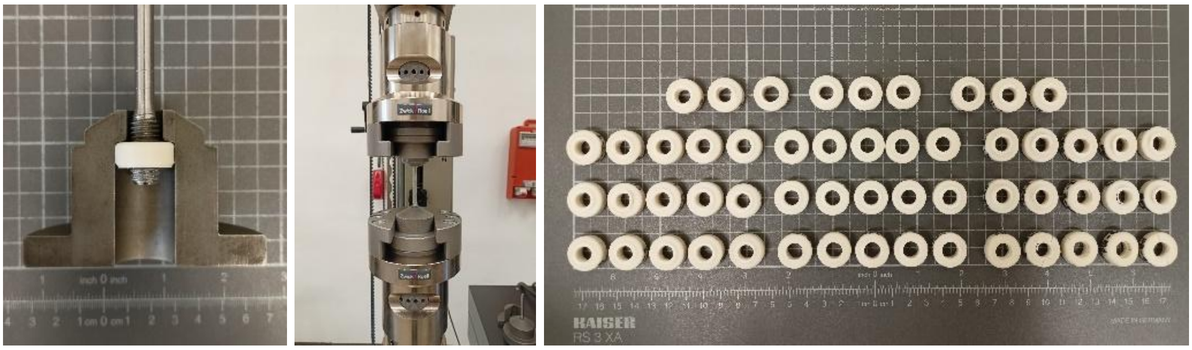

Figure 4. Sample in measuring fixture (left), Zwick Roell Z100 measuring device with sample (middle), selected 3D printed sample sets for experiment (right)

Fasteners such as bolts and nuts are standardly tested for a range of mechanical properties depending on the material grade and type of fastener. The most common mechanical properties test is the tensile and compressive test. In the case of metallic materials, this is according to EN ISO 898-1 and EN ISO 3506-1. For fasteners such as bolts and nuts made of polymeric materials, no standard has been found, and therefore the test parameters are based on the standard for tensile testing EN ISO 527-2. The tensile strength (i.e., the load capacity of the thread until shear) was measured on a Zwick Roell Z100 universal testing machine in this experiment. The displacement was read from the machine crossmember. The method of holding the specimen in the machine clamp and the selected specimen sets are shown in Figure 4.

The visual quality assessment of threaded surfaces and defects was performed on an Olympus DSX 100 opto-digital microscope with a magnification of 24 ×. Thus, a total of 15 sets of five specimens were produced, measured, and evaluated.

3 RESULTS

The measurement results of 3D printed M10 metric matrices are divided into print orientation, layer heights, and comparison of thread manufacturing methods. The initial phase of all tensile strength measurements was accompanied by a 0.6 - 0.8 mm long stretch region with minimal stress increase. This phenomenon may be the result of defining clearances in the jigs, threaded connections, slight rotation of the specimen, threaded surface indentation, and seating. The clearance that arises between the threaded surfaces printed by the MEX method is also referred to in the work of Chudzik et al. [Chudzik 2024] and the work of Rizea et al. [Rizea 2023]. However, this hypothesis needs to be further verified in this case.

The samples for measuring the effect of print orientation were made of Prusament ASA with a layer height of 0.15 mm. Orienting the nuts from a horizontal position (0 °) to an angle of 45 ° resulted in a 20 % increase in material consumption and an 82 % increase in printing time. For vertically printed nuts (90 °), there was a 5 % increase in material consumption and a 100 % increase in printing time. The highest ultimate strength (37.9 ± 0.8 MPa) was achieved for nuts printed at 45 ° (see Figure 5).

The microscope images (Figure 6) clearly show that the horizontally printed thread has by far the best geometry compared to threads printed vertically or at an angle, where the use of supports led to a deterioration of the thread surface quality. Such deformations and material build-ups can lead to a deterioration in thread throughput. After the test, specimens printed vertically and at 45° show not only tearing of the threaded surfaces but also cracking of the entire nut in the layers as printed. It is therefore evident that the stress is distributed throughout the layers across the sample.

Samples for investigating the effect of print layer heights were made from Prusament ASA material oriented horizontally (0 °). The microscope image (see Figure 6) shows that the geometry and structure of the thread surface improve with lower layer height. A thread profile printed with a layer height of 0.2 mm is made up of 7 layers, with a layer height of 0.15 mm, the profile is made up of 10 layers, and with a layer height of 0.1 mm, the profile is made up of 18 layers. The images of the threads after the tensile test show a complete tearing of the thread printed with a layer height of 0.2 mm, while the other samples lost strength while retaining the thread in the nut.

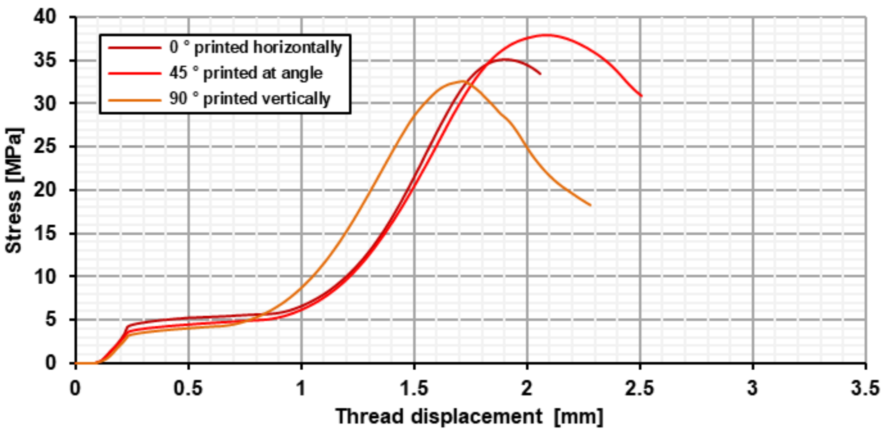

Figure 5. Graphical comparison of variable print orientation (Prusament ASA)

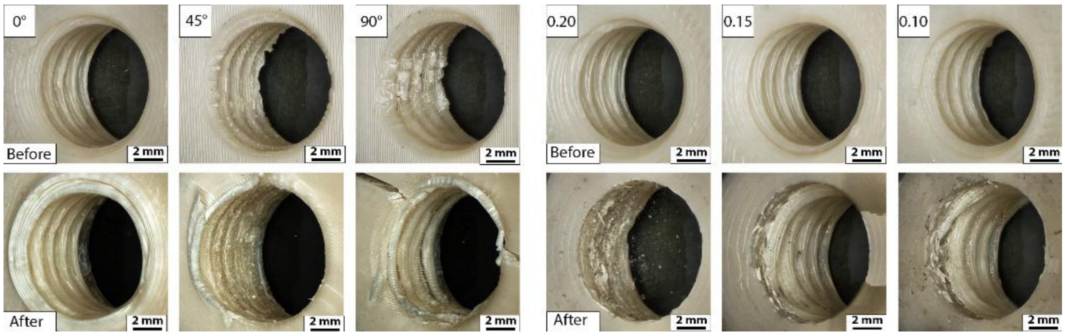

Figure 6. Macroscopic images of threads printed in different orientations (left), and various layer heights (right), material Prusament, 24 ×

With decreasing layer height during printing, a theoretically higher tensile strength is achieved. However, this trend is negligible when evaluating the measurement uncertainties (see Figure 7). The increase in strength may be due to the greater filling of the thread profile when more layers resist the load. However, the choice of layer height will be mostly determined by the requirements of the whole model and the nominal thread diameter. When printing large complex parts containing threaded holes, for example, to assemble an assembly, printing with low layer heights would take too long. From a manufacturing concept, therefore, a compromise must be sought between thread quality and the difficulty of producing complete parts.

The specimens used to investigate the effect of material manufacturer and thread manufacturing method were printed horizontally (0 °) at a layer height of 0.15 mm. In the case of Filament PM ASA, there was a 49 % decrease in the load capacity of the formed threads. In the case of Prusament ASA, the decrease was 33 %, and in the case of Spectrum ASA, there was a 20 % decrease in strength. Cut threads and 3D printed threads achieved similar thread load capacity results within the measurement uncertainties. The records of the tensile test (Figure 8, Table 2) show that the major influence on the load capacity of the thread is based on the properties of the selected material. The results confirm the well-known trend that the filament manufacturing process and the added additives have a significant effect on the mechanical properties of the printed products. The graph shows that the highest 3D printed thread load capacity was measured for the samples made from Prusament ASA, namely 35.1 ± 1.8 MPa. In contrast, samples made from Filament PM ASA achieved 15.1 % lower load capacity, and samples made from Spectrum ASA achieved 33.9 % lower load capacity.

The decrease in load carrying capacity for specimens with formed threads may be a combination of the reduced cold formability of the ASA polymer material (where the material is damaged when deformed into the shape of the thread profile) and the orientation of the thread profile relative to the stacked layers of material during printing. Attempting to form threads can disrupt the cohesion of entire layers across the sample. This is evidenced by microscopic images in which the thread surface is slightly torn. Fürst et al. [Fürst 2024] encountered a similar trend in their work, where they used metallic threaded inserts that propagated the crack through horizontally printed inserts.

material/thread	σ_T printed [MPa]	σ_T cut [MPa]	σ_T formed [MPa]
Filament PM	29.8 ± 1.5	27.4 ± 0.8	15.2 ± 1.7
Prusament	35.1 ± 1.8	37.3 ± 1.1	23.4 ± 2.1
Spectrum	23.2 ± 1.2	23.2 ± 0.8	18.5 ± 1.9

Table 2. Comparison of the tensile strength depending on the thread manufacturing method

The disruption of the integrity of the cut and formed thread specimens is also indicated by the initial phase of thread loading during the tensile test, where the post-produced threads achieve thread seating at significantly lower values. The exception appears to be the Spectrum ASA material, which is more ductile and therefore the integrity of the specimen is not as significantly compromised during thread formation.

Macroscopic examination of 3D printed threads across material manufacturers shows no significant differences in surface quality and printed layer composition.

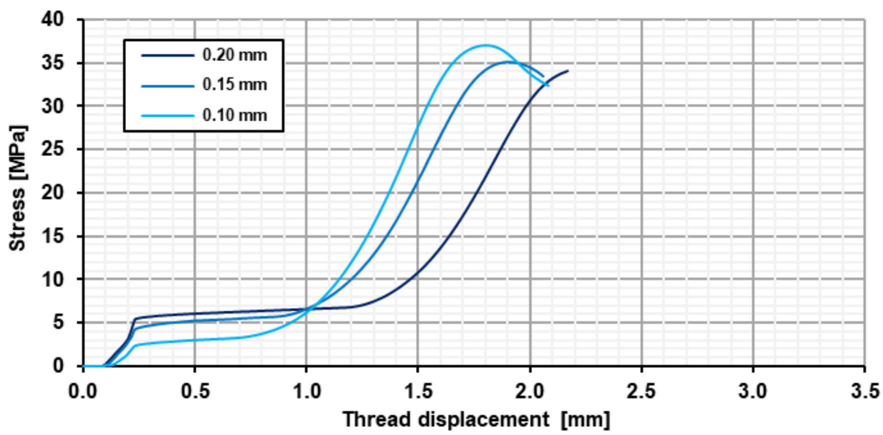

Figure 7. Graphical comparison of various layer heights (Prusament ASA)

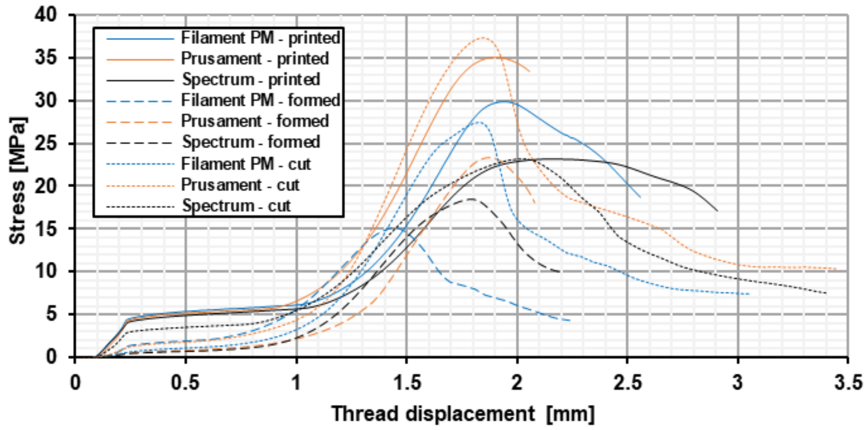

Figure 8. Macroscopic images of threads printed in different orientations (left), and various layer heights (right), material Prusament, 24 ×

4 CONCLUSIONS

In this work, the tensile load capacity of metric threads of 3D printed M10 nuts was investigated using the MEX-TRB/P method. Not only ASA materials from different manufacturers were compared, but also selected printing parameters such as specimen orientation during printing, variable layer heights during printing, and methods of thread fabrication like 3D printing, cutting, and forming. 65 samples were evaluated in the experiment. The results of the research can be summarized as follows:

The orientation of the part when printed at an angle of 45 ° to the printing substrate achieved the highest load carrying capacity. In contrast, horizontally printed samples result in consistent thread quality across the entire sample and are the easiest to print.

The highest strength was measured for the samples printed with the smallest layer height (0.1 mm). Taking into account the measurement uncertainty, the thread load capacity results do not show a significant increase or trend. By choosing small layer heights, the best approximation of the thread profile and lower surface roughness was achieved, but at the cost of a multiple increase in printing time. When evaluating the results of thread manufacturing methods, differences in thread surface quality and geometry are evident. The tensile load capacity of the threads for 3D printed threads and cut threads is very similar within the measurement uncertainties, and their values depend mainly on the choice of material. A significant effect of the material manufacturer was confirmed. In contrast, threads produced by forming achieve a significant drop in load capacity.

In terms of saving the number of operations, it could be reasoned that thread cutting makes sense, especially for parts that are large and require printing with a higher layer height or parts with smaller nominal thread diameters, where 3D printed threads would achieve low surface quality and thread profile fill.

Further research on 3D printed threaded joints should include other materials such as PA, PC, printing methods such as PBF-LB/P or VPP-UVL/P and methods of testing mechanical properties. Comparison of 3D printed threads with melting threaded inserts would also be very beneficial. It would be valuable to compare these results with surface texture and geometric analysis.

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