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Design and manufacturing of a device made of Additive manufacturing machines for fast and reliable measurement of material stiffness

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Abstract. Additive Manufacturing (AM) technology is constantly expanding to small and large industry over the last 20 years. The vast potential of this technology has been perceived by many companies which invest in research and development for faster and more reliable machines with better capabilities and more quality products. AM expansion in industry has also been helped by a wide variety of materials, such as polymers, whose technology is developing rapidly with better mechanical properties related to stiffness and strength. In this paper we will describe a device which can be fully produced by all AM machines and enables users to measure in a fast and reliable way the stiffness of materials without the need for specialized and expensive methods, large-volume laboratory testing machines, specialized technical personnel and time. The objective is to design a small scaled three-point bending device using design intent through a parametric CAD system and manufacture it using AM technology. The device is designed to calculate the deformation and force applied to specific specimens and the Young's modulus of the material. The proposed device and its process helps users to estimate the mechanical properties of materials and apply that information on production or in a simulation system to optimize the printing quality of products by selecting the right material and adjusting the related printing parameters of the machines with the mechanical properties of the produced parts.

Keywords: Additive Manufacturing Technology, 3d printing, Stiffness, Elastic Modulus, Design intent, Parametric design, Product lifecycle

1 Introduction

Additive Manufacturing (AM) as a technique of 3-D printing technology has revolutionized the way which products are designed and manufactured in industry [1]. The main benefits of AM technology are the construction of complex geometries of both flexible and sustainable products and the ability of making parts with a variety of materials with no need of expensive and specialized machinery [2]. The basic principle of AM processes consists on fabricate parts by adding layers of materials which are placed one above the other [3] with most popular AM techniques being powder

bed fusion, vat photopolymerization, binder jetting and material extrusion [4]. There are also numerous AM desktop machines with many capabilities on building products which differ mainly in the sectors of printable size, surface quality, printing speed and the variety of materials they use during the production process, like metals, polymers, ceramics, concrete and composite materials [5,6]. By selecting the appropriate materials and machine types, users can specify materials properties such as flexibility, hardness, stiffness, and control the quality of final products [1]. The building quality of products, other than materials selection, depends on various machine parameters that needs to be considered during the production process such as build orientation, contour width (CW), raster to raster air gap (RRAG) and others which significantly affect the printing results. Studies, using specialized laboratory machines, have showed that the values of these parameters affect the mechanical properties of the materials, such as Young's modulus and tensile and bending strength [5]. An equally important parameter that affects the mechanical properties of a product during the production process using AM technology is the viscosity of the material that is injected layer by layer mainly with the use of FDM (Fused Deposition Modelling) technology and recent studies proved that different temperatures of the dispensed material change the mechanical behaviour of a product. Another parameter that affects the strength of the produced products is fill density of the materials that determines the amount of the polymer used to print a product. It is confirmed that the tensile strength is influenced by the value of fill density during the production process [6]. Therefore, it is perceived that quality products made of AM technology requires knowledge of material mechanical properties and specific adjustments to the machine's settings such as the values of fill density, viscosity and other parameters which can be changed by the machine software during the production process [5,6]. These parameters are related to the mechanical properties of the material before and after making products using AM technology and it is difficult for users to know the real values of the stiffness of the printed ones [1]. The objective of this paper is to design and manufacture a small scaled three-point bending device using exclusively AM machine and calculate the stiffness of selected AM materials by measuring the force and displacement of suitable selected specimens. The proposed process helps simple users and small-scale industries to know and measure the stiffness of materials and select the appropriate material from a list of available materials according to production needs by knowing and comparing their mechanical properties. The evaluation of Young's modulus was made using small deformation bending theory [7] and the results were compared with similar tests conducted on specialized testing machines.

2 Operation and Design intent of the Device

The combination of a parametric CAD system and Fused Deposition Modelling (FDM) technology were the key factors to design and produce, a small sized three-point loading machine that consists of two different parts made of ABS material, referred to as *BTable* (**Fig. 1**), the steady part of the device, and *BSpike* (**Fig. 2**) the moving one. The operation of the device, called "BDevice", was simple. A specimen with dimensions, Length (L) = 60mm, Width (b)= 5mm and height (h) = 1mm, (**Fig. 3**) was designed to fit the geometry of 50 mm BTable support span. BSpike was

placed at the railway of Btable with its lower end touching the upper surface of the specimen. The force was applied by hand with the index finger at the top flat cylindrical surface of BSpike. The applied force was transferred at the end surface of BSpike and therefore at the top surface of the specimen that bends and moves vertically downwards. That force was measured instantaneously using a low scale digital measuring machine which was mounted on BTable base (**Fig. 4**). An appropriate range of scale (0-200 grams) was selected with 0.01grams accuracy, to be close to the range of applied forces that gave greater measuring accuracy. When the specimen bends 1mm distance using finger force the steady applied force was measured each time. At that point the specimen was in equilibrium, meaning that the total effect of external forces on it equals to zero and the indication of the measuring scale shows the value of the applied force.

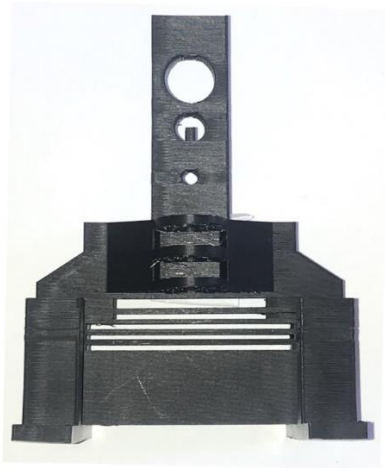


Fig. 1. Steady part of the Device (BTable)

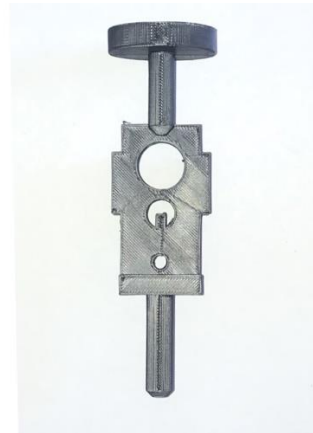


Fig. 2. Moving part of the device (BSpike)

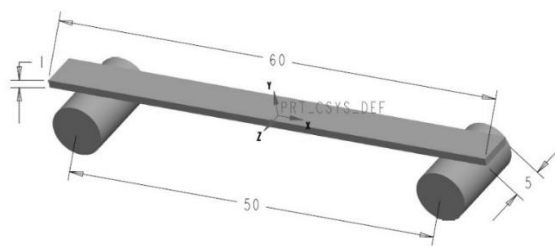


Fig. 3. Specimen dimensions

To measure as accurately as possible, the 1 mm displacement of the specimen during bending the observation of the placement of the cylindrical holes of BSpike was needed in relation to BTable. More specifically, while BSpike moves downwards to Btable and the displacement of the specimen equals to 1mm, the geometry of the cy-

lindrical holes of the two parts become coincident, meaning that they match perfectly (Fig. 4).

Design intent played an important role for the reliability of the device and it was the main factor that makes our device as reliable as possible to control the shifting and endurance of our device and specimens while measuring. One of the most important information that was included in the design intent of the product was the geometrical reference and topology of the cylindrical holes (C1, C2) of the two parts that consists the device and the height (d) of the specimen which had a dependent relationship between parameters such as $C1 = C2 + d$ that was included in the design intent during the design process of the device. The confirmation of the displacement is also carried out using the back pattern of BTable that has been designed with strips spaced apart by one-millimeter distance. During bending of specimen under an applied force a strip of pattern is covered, meaning that the specimen was bent exactly at a millimeter distance, d' (Fig. 5).

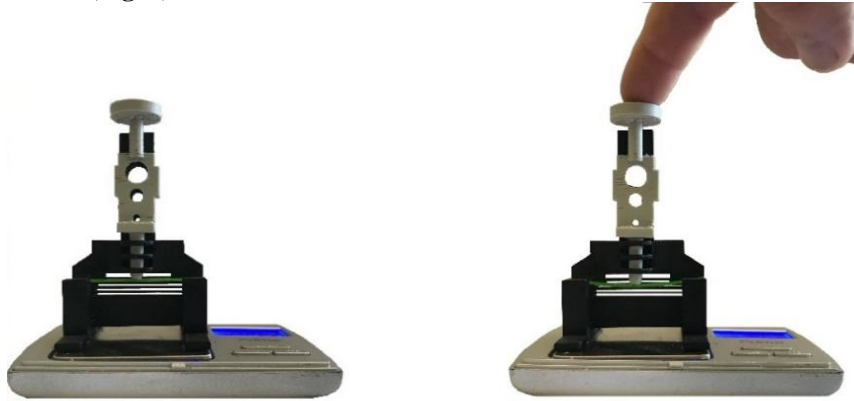


Fig. 4. Optical confirmations of the displacement of the specimen while bending using *geometry strips* and *cylindrical holes* coincidences between parts

3 Preliminary experimental investigation

Three specimens were manufactured from different materials ABS, PLA and PETG using FDM technology. The infill value of the specimens was adjusted through machines parameters and was set to 100% for all specimens with layer building thickness set to 0.25 mm. The dimension of each specimen was, Length (L) = 120mm, Width (b) = 10mm and height (h) = 1.5 mm. The calculation of the Young's modulus for each of the material was made using the three-point bending method on tensile machine SHIMADZU 100KN at the Integrated Industrial Design Lab (INDEL) of the Department of Product and Systems Design Engineering at the University of the Aegean (Fig. 6). The displacement speed of the machine was set to 0.1mm/sec and the calculation of the Young Modulus for each of the specimens was made with the use of

the force-displacement diagrams which gave as the following values: 2088MPa for ABS, 2661MPa for PLA and 1660 MPa for PETG.

Using the same FDM machine and settings, we manufactured three equal dimensioned specimens using the same quality of materials, ABS, PLA and PETG with the following dimensions, Length (L) = 60mm (50mm between support span), Width (b) = 5mm and height (h) = 1mm (Fig. 7) to fit the geometry of BDevice (Fig. 4).

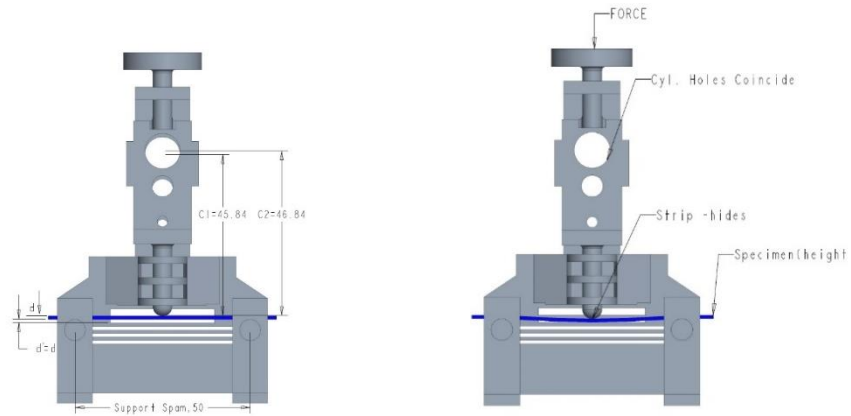


Fig. 5. Design intent of the device



Fig. 6. Three-point bend with Tensile machine SHIMADZU



Fig. 7. Specimens made of FDM technology and ABS, PLA and PETG materials
The calculation of the Young's modulus was done using the equation

$$E = \frac{Fl^3}{4ubh^3}, \quad (1)$$

where E is the Young's modulus, F the bending force, l the distance between supports, u (=1 mm) the deflection, b the width and h the height (thickness) of the specimen.

This formula applies for elastic deformations which can be defined by

$$\sigma_{max} \leq \sigma_e \quad (2)$$

where σ_{max} is the maximum bending stress and σ_e the elasticity limit [7]. We carried out ten measurements for each of the three materials measuring the force for total displacement of 1 mm of the specimen during bending (Fig. 4). We then found the average force of all specimens (Table 1) and applied equation (1) to calculate the Young's modulus of each material. We compare these values with the ones we found using SHIMADZU tensile machine from INDEL (Table 2).

Table 1. Average force applied per specimen (in N).

| Test Nr. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Avg. |
|-------------------------|------|------|------|------|------|------|------|------|------|------|--------------|
| F_{abs} | 0.35 | 0.34 | 0.38 | 0.39 | 0.37 | 0.33 | 0.4 | 0.32 | 0.31 | 0.37 | 0.359 |
| F_{pla} | 0.41 | 0.47 | 0.42 | 0.47 | 0.46 | 0.47 | 0.42 | 0.43 | 0.47 | 0.44 | 0.446 |
| F_{petg} | 0.28 | 0.26 | 0.22 | 0.26 | 0.28 | 0.23 | 0.28 | 0.26 | 0.27 | 0.21 | 0.255 |

Table 2. Deviation of Young's modulus values (MPa) between two different machines.

| | ABS | PLA | PETG |
|------------------|------|------|------|
| BDevice | 2244 | 2788 | 1594 |
| INDEL | 2088 | 2661 | 1660 |
| Deviation | 8% | 5% | 4% |

The results of the measuring elastic moduli of all specimens of the devices we used did not exceed 8% deviation, which means that BDevice reached the results of a more

reliable and accurate machine like the tensile machine SHIMADZU during those tests. We also noticed that all tests carried out with BDevice were accomplished in a much shorter time than the laboratory testing machines. It is also worth noting that the specimens used in the tensile machine were almost twice the size the ones used for BDevice and we need to spend more material during manufacturing process, so they can be within the limits of the machine's specification.

4 Experimental investigation according ASTM D790

The measurement reliability of the device was an important issue during this study and for that reason we choose to redesign BDevice and specimen's geometry according to ASTM D790 which defines strictly design standards during measurements [8]. Thus applying all the limitations and standards of that method we took new measurements of the materials Young's modulus and compare them with the ones from the previous geometry used at the preliminary experimental investigation. These standards were introduced in the form of parameters and constraints through design intent to the geometry of each part of the device and specimen. According to these standards both loading nose of BSpike and supports of Btable were designed to have cylindrical surfaces to avoid excessive indentation or failure due to stress concentration. According to the standards, for the specimens less than 3.2 mm thickness, the radius of the support should be up to 1.6 times the specimen thickness and the radius of the loading nose to be no more than 4 times the specimen thickness (**Fig. 8**). The specimens should have rectangular cross section and must rest on the midway between the supports during loading. The specimens we used had 1mm thickness, which is less than 1.6mm, and according to D790 standards for that thickness each specimen's length should be long enough on each end at least 10 percent of the support span but no less than 6.4 mm. Also, each specimen must be 50.8 mm long and 12.6 mm wide (**Fig. 9**) and the number of specimens need to be tested must be no less than five for each sample in the case of isotropic materials tested flatwise on a 25.4mm support span.

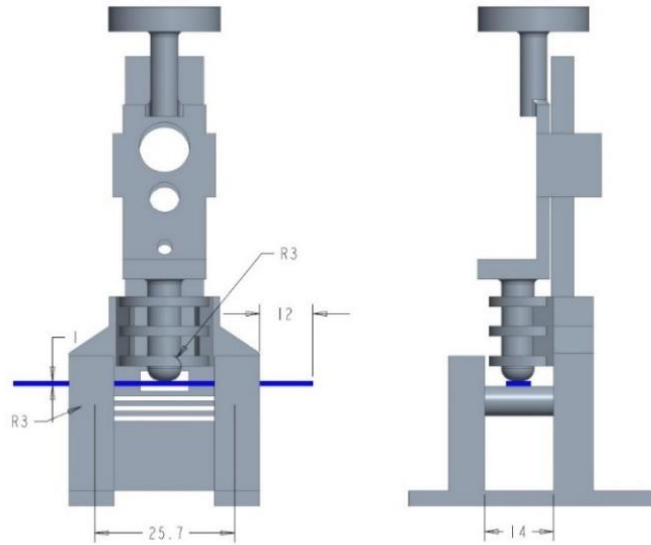


Fig. 8. BDevice geometry according to test method D790

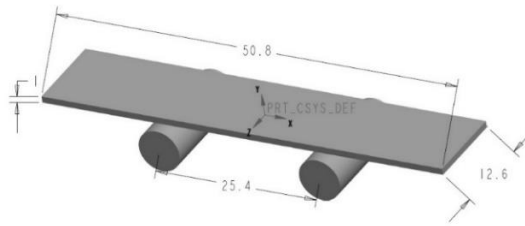


Fig. 9. Specimens geometry according to test method D790

Test method D790 also determines that the stiffness of the testing machine shall be such that the total elastic deformation of the systems does not exceed 1% of the total deflection of specimen during test. To confirm this standard, we needed to use mechanical analysis on a CAD software and to simulate BDevice loading machine as accurate as possible. To this end, apart from the exact geometry, the model included contact between the specimen and supports. We simulate three different BDevices with ABS, PLA and PETG material and we conducted the analyses using Creo Simulate platform (**Fig.10**) to find and compare the results of the total elastic deformation of the testing machine with the deflection of each specimen that was, in all cases, under 1% (**Table 3**).

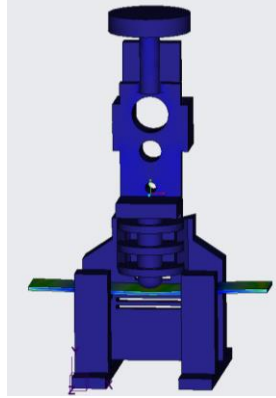


Fig. 10. Mechanical analysis of BDevice during bending using Creo Simulate software

Table 3. Total deformation of Bdevice according to Specimen Deformation during bending in a simulation mode.

| Material | ABS | PLA | PETG |
|----------------------------------|------------|------------|-------------|
| Young's modulus (MPa) | 2088 | 2661 | 1660 |
| Specimen deformation (mm) | 1mm | 1mm | 1mm |
| Total deformation (mm) | 1.0053 | 1.006 | 1.0053 |
| % | 0.53% | 0.6% | 0.51% |

Using FDM machine, we manufactured a new Bdevice and specimens (**Fig. 11**) and measured the Young's modulus of all three materials. The elasticity moduli calculated using equation (1) were: $E_{abs} = 2045$ MPa, $E_{pla} = 2445$ MPa and $E_{petg} = 1703$ MPa (**Table 4**). The new results, as it can be seen comparing with the values of Table 2 are much closer to the values obtained using the traditional testing equipment. Specifically, the deviation range from 4-8% was reduced to 2-8%.



Fig. 11. BDevice Geometry using standards

Table 4. Deviation of Young's modulus values (MPa) between two different machines.

| | ABS | PLA | PETG |
|--------------------|------------|------------|-------------|
| BDevice | 2244 | 2788 | 1594 |
| New BDevice | 2045 | 2445 | 1703 |
| Deviation | 9 % | 9% | 7% |

5 Conclusions

AM technology with its main capability and advantage in making complex geometries of both flexible and sustainable products helped us to manufacture a device (BDevice) with a specific geometry which includes all the necessary mechanical information such as design limits and standards that were inserted and controlled through parameters and constraints using Design Intent and a parametric CAD system. We showed that the measurements of Young's moduli of three different materials using BDevice had a small deviation considering the measurements taken from specialized and expensive laboratory testing machines that also needed to use large scaled and more expensive specimens. The reliability of the device was also proved by adjusting its geometry and specimens in an easy and fast way changing design intent under standards that method D790 requires. Bdevice can be manufactured using any AM machine by a simple user or a small company which then can measure and compare the stiffness between the materials and thus know at any time which material is best suited for each construction. Knowing the material required for the manufacturing of a product, enable us to control and manage its lifecycle in all manufacturing phases. Using BDevice we can also estimate the real values of the Young's modulus of each polymer that differs before and after manufacturing process using AM machines. The measured modulus of each polymer can also be used after printing a model using AM ma-

chine to simulate, optimize and predict the mechanical behaviour of a single part or an assembly through FEA software. Using BDevice and the right adjustments to AM machines printing parameters we can also control the stiffness of any polymer material we use.

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