MECHANICAL PROPERTIES CHARACTERIZATION OF ABS AND ABS PLUS FUSED DEPOSITION MODELLING PARTS

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1. ABSTRACT

In this work, the mechanical properties of Acrylonitrile butadiene styrene (ABS) and ABS Plus of Fused Deposition Modelling (FDM) parts are studied. ABS and ABS Plus specimens were studied using different building parameters including layer thickness and built orientation. The specimens studied, were tested for tensile and compression strength using the ISO 527 and ASTM D695 standard respectively, for flexion there were tested using the ASTM D790 and ASTM E1820 standards and for impact testing the ASTM D6110 standard was employed. It was found that the difference in the tensile strength between specimens built of the same material with the same layer thickness, but at a different build angle, reached 45% while the layer thickness was a key parameter having a major role in altering the mechanical properties. It was also found that ABS Plus specimens had on average 15% higher mechanical strength than ABS specimens. The fracture surfaces of selected tested specimens were examined under a Scanning Electron Microscope (SEM), to determine the failure mode of the filament strands. It was found that all printed specimens had lower mechanical strength in comparison with the stock materials provided while deposition orientation and layer thickness were key parameters affecting mechanical properties directly.

2. INTRODUCTION

Acrylonitrile-butadiene-styrene (ABS) is a polymer widely used and applied in multiple industries for its unique mechanical and physical properties. These are the fine mechanical response, its chemical resistance and its excellent processing characteristics [1]. Thus, there are several studies [2-7] on the mechanical and physical properties of ABS and its composites for different applications and operating conditions. The mechanical properties of FDM ABS parts have been widely studied in literature mainly focusing on the printing parameters' effects, i.e. layer thickness, deposition temperature and deposition orientation on the mechanical behaviour of specimens and parts [8-16]. The results of these studies vary greatly because of the anisotropic behaviour of FDM filament materials. Several studies have been implemented to experimentally study the mechanical behaviour of ABS by measuring the elastic moduli and strength of FDM ABS [9].

Other studies in literature [16] studied the effects of layer thickness, deposition angle, and infill on maximum bending forces in FDM specimens. The results presented a dominant, statistically significant effect of extrusion speed, a major interaction between deposition angle and infill, as well as a non-linear association of the effects. It has become evident that the contribution of layer thickness to the strength of the FDM built part is major. It also has become evident that the ABS and ABS Plus behave differently with ABS Plus having higher tensile sensitivity at the 0.25mm thickness layer than ABS [17].

ABS composites are also studied [18] to determine their flexural mechanical properties. The qualitative results of this study showed that the built deposition orientation of FDM parts is important to larger mechanical strength of the printed parts and their cost efficiency. These results are of great importance because of the direct link between mechanical properties and cost.

The improvements in impact resistance of FDM parts in various applications, such as biomimetic robotics and coated ABS composites are also studied [19-20]. These studies' results showed that composite designs can outperform constituent materials in impact strength, expanding the next generation of additive manufacturing composite materials with optimal impact-resistant properties to robotic and military applications.

It was also found that the impact strength of FDM ABS specimens is affected by the many discontinuities inside the specimens that behave as notches during impact [21]. This reduces the impact strength of deposition specimens significantly when compared to monolithic samples produced by injection moulding. It was also determined that the impact strength is very sensitive to orientation where parts with orientations of 45° or higher being the most affected.

In this work, the mechanical properties of ABS and ABS Plus materials versus the stock material provided in tensile, compression, flexion and impact tests are summarised and studied. Those tests were implemented according to ASTM standards and specimens were built with various build parameters values related to the layer thickness and the deposition orientation. The purpose of this study was to determine the effect of deposition parameters in ABS and ABS Plus specimens regarding their mechanical properties in direct comparison to stock materials provided by Stratasys Ltd and stock materials from literature. The average difference between the nominal and experimental mechanical strength measured in all case scenarios was about 20% lower for the ABS and about 40% lower for the ABS Plus material.

3. METHODOLOGY

In this study, specimens for different types of mechanical tests built from two different FDM machines, the Dimension Elite and the Dimension BST768, were studied. The Dimension Elite uses ABS Plus material and soluble supports, while the BST768 utilizes ABS material and breakaway supports. ABS Plus is a polymer with improved mechanical properties, compared to the standard ABS material. It has 40% larger nominal tensile strength and 20% larger flexural strength than the standard ABS while absorbing less humidity. The mechanical properties of these two polymers provided by Stratasys Ltd. for the experiments are presented in Table 1 and Table 2.

3.1. Tensile strength

Tensile specimens built as specified in the ASTM D638-02a standard (Fig. 1) were studied. Specimens were built with full infill, with different deposition orientations of, 0°, 45° and 90°. In addition, specimens were built with every layer thickness each machine supports, in each build direction. Seven (7) specimens were tested for each case studied, to comply with the ASTM D638-02a standard, which requires at least five (5) specimens to be tested for each case. The tensile tests were made utilizing a Schenk Trebel Co. tensile test machine according to ASTM D638-02a standard. The tensile test machine chuck was set at a 5 mm/min speed for testing and all specimens were tested at room temperature. This apparatus is practically a hydraulic press which tenses/compresses the specimen fixed within and a strain gauge and other electronic sensors effectively and accurately measure the displacement (deflection) observed in each specimen until it breaks.

	Test Method	**ABS Plus**	**ABS**
Tensile strength, type 1, 51mm/min	ASTM D638	36 MPa	22 MPa
Tensile modulus, type 1, 51mm/min	ASTM D638	2272 MPa	1627 MPa
Tensile elongation, type 1, 51mm/min	ASTM D638	4%	6%
Flexural strength	ASTM D790	52 MPa	41 MPa
Flexural modulus	ASTM D790	2204 MPa	1834 MPa
Izod impact strength, Notched (23°C)	ASTM D256	96 J/m	106,78 J/m

Table 1.
ABS and ABS Plus mechanical properties
(courtesy of Stratasys Ltd.)

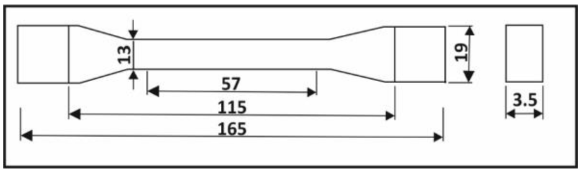

Figure 1.
Tensile test specimen dimensions

3.2. Compressive strength

The same procedure and apparatus was applied to test the compression strength of 3d printed specimens according to ASTM D695 standard.

The specimens built for these experiments have the dimensions presented in Figure 2.

3.3. Flexion (3-point)

Flexion specimens built with dimensions according to ASTM D790 (Fig. 3) were studied. In total, forty (40) specimens, out of which twenty (20) ABS specimens and twenty (20) ABS Plus, were studied, while incorporating different layer thickness and layer orientation combinations. The bending tests were performed using a Schenk Trebel Co. bending test apparatus according to the ASTM E1820 standard for 3-point flexion. The apparatus is a hydraulic press modified for three-point bending experiments. In the specific experimental setup, two rectangular beams with two cylindrical bearings firmly fixed on top them were fixed on the machine work area at an appropriate distance between them. On top of these bearings, the FDM specimens are placed. A cylindrical bearing exerts a force in the centre of the specimen until it breaks.

The fundamental data regarding the flexion procedure was saved real time to a personal computer and used afterwards to calculate the flexion strength of the parts. The experimental results from the machine were processed using equations from literature to determine critical flexural strength parameters, such as the fractural stress, the maximum bending moment, the flexural modulus of rupture, the bending strain, and the elastic flexural modulus.

3.4. Charpy Impact

Impact specimens built according to the ASTM D6110 standard were studied. In total, forty (40) specimens were studied (Fig. 4), twenty (20) with ABS material and twenty (20) with ABS Plus material respectively, with a deposition layer orientation of 45°. Ten (10) specimens of each category were built with the Charpy's notch and the other ten (10) specimens were built without one. The dimensions of the specimens are presented in Figure 4. Specimens were built without the impact notch in order to evaluate the impact and fracture behaviour and compare the overall absorbed energy in specimens with impact notch to specimens without one.

The impact strength of the above-mentioned specimens is determined using a hammer pendulum. The most common methods used for impact testing is the Charpy employed in this study and the Izod method. The Charpy's apparatus operating principle is as follows: firstly, the specimen is placed into the Charpy's slot and it is supported at both its ends. Then, the hammer drops from specified and already measured height and impacts the specimen. The specimen then fractures and a portion of kinetic energy is lost upon absorption by the material. However, the hammer continues its path, but to a lesser height than the initial dropping height. The pendulum sweeps the maximum deflection index and immobilizes it at the new lower position over the graduated circular scale of the apparatus. In these experiments, the hammer was released from different angles, from 60° to 20° with a 5° step. The data from the experiments are recorded and with the aid of literature formulas the Impact strength of the specimens and the impact energy are calculated.

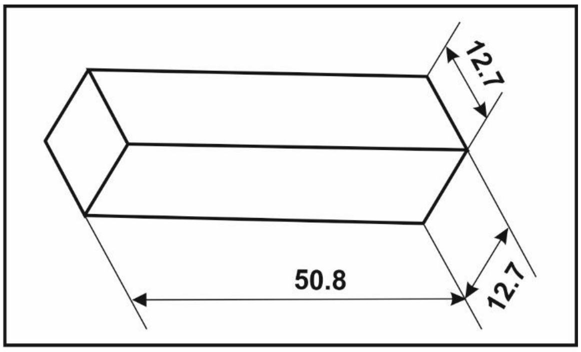

Figure 2.
Flexion test specimen dimensions

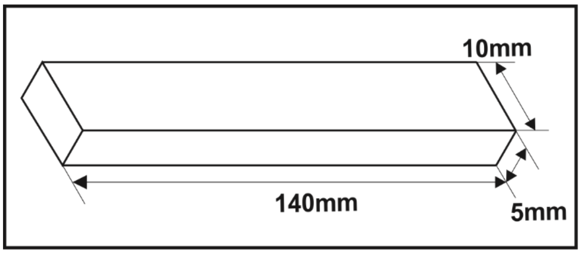

Figure 3.
Flexion test specimen dimensions

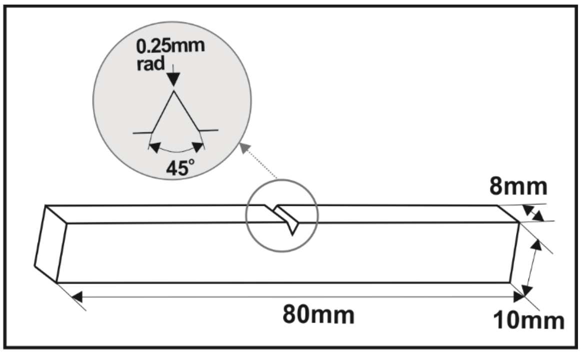

Figure 4.
Charpy impact test notched specimen dimensions

4. RESULTS

4.1. Tensile strength characterization

In the following graphs of Figure 5, the stress results (in MPa) versus the strain of tested specimens in ABS (left) and ABS Plus (right) materials are presented. The SEM images from ABS (Fig. 6A) and ABS Plus (Fig. 6B) specimens, showing the fracture area of selected specimens are presented in Figure 6. In Table 2 the maximum calculated values of ABS and ABS Plus tensile strength parameters are presented.

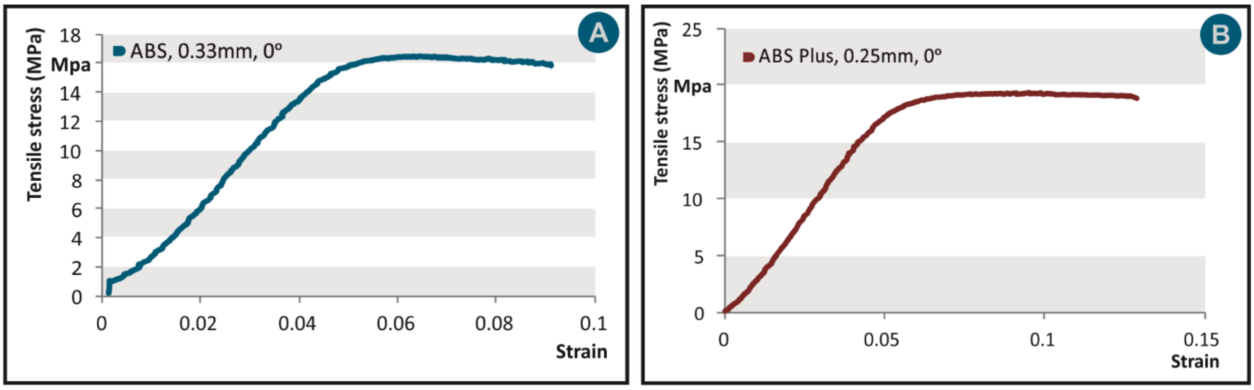

Figure 5.
Tensile stress (MPa) versus strain in ABS (A) and ABS Plus specimens (B) in 0° degrees' deposition orientation

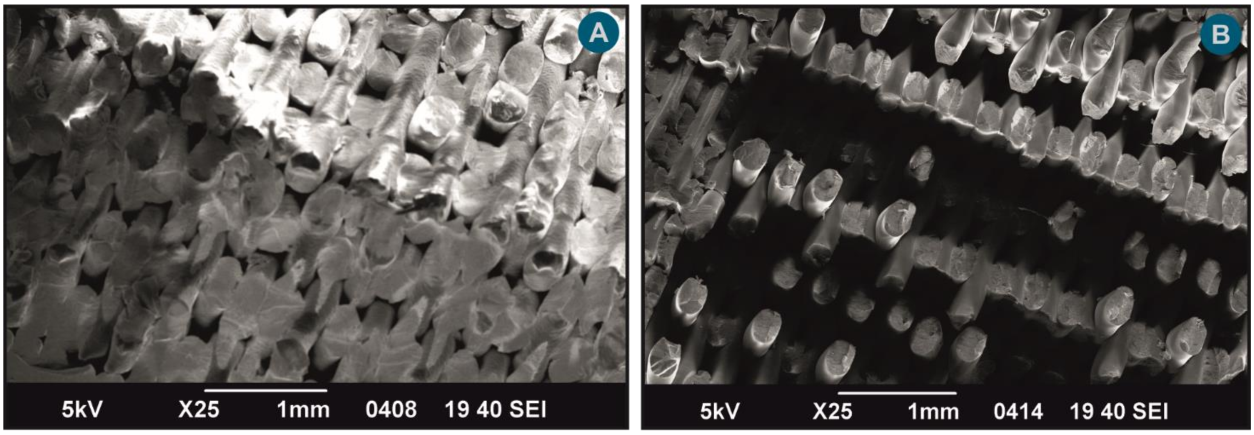

Figure 6.
SEM images of fractured areas of ABS (A) and ABS Plus (B)

Material	ABS Plus		ABS	
Layer thickness (mm)	0.17	0.25	0.25	0.33
Maximum tensile strength (MPa)	19.43	20.68	21.44	18.97
Strain (%)	13.05	6.67	14.93	9.50
Tensile Young Modulus (GPa)	0.39	0.39	0.40	0.34

Table 2.
ABS and ABS Plus specimens' maximum tensile test results

4.2. Compressive strength characterization

Figure 7, presents a typical compressive stress (MPa) versus strain graph of the ABS and ABS Plus materials studied. The maximum compressive test results are presented in Table 3.

The SEM images from ABS (Fig. 8A) and ABS Plus (Fig. 8B) specimens, showing the fracture area of selected specimens for compression, are presented in Figure 8.

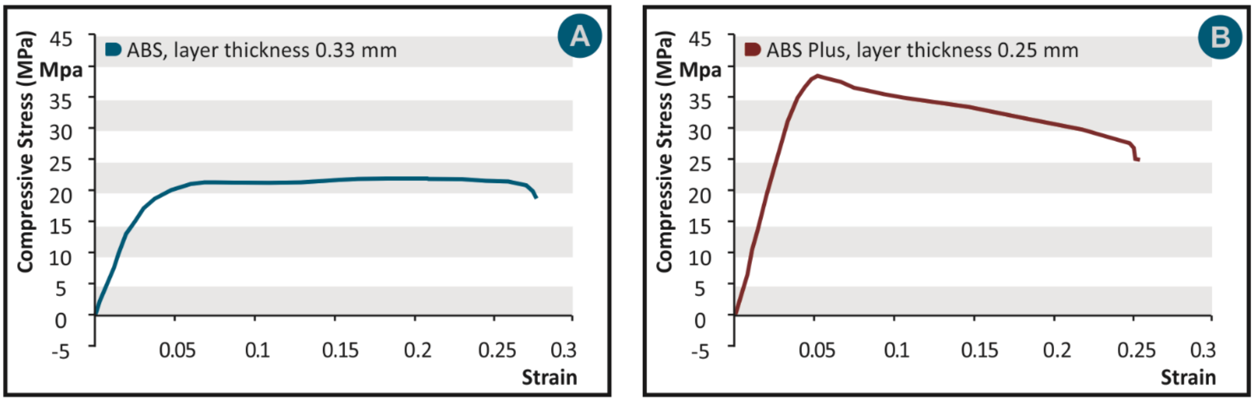

Figure 7.
Compressive stress (MPa) versus strain in ABS (A) and ABS Plus specimens (B)

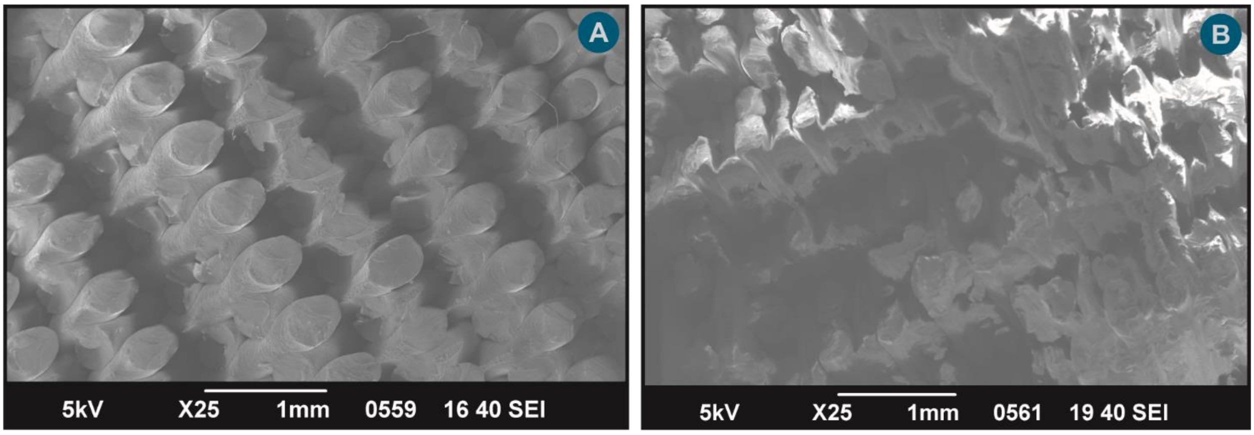

Figure 8.
SEM images of fractured areas of ABS (A) and ABS Plus (B)

Material	**ABS Plus**		**ABS**	
Layer thickness (mm)	0.17	0.25	0.25	0.33
Maximum compressive strength (MPa)	41.85	40.12	22.12	20.03
Strain (%)	0.21	0.28	0.12	0.27
Compressive Young Modulus (GPa)	1.83	1.82	0.96	0.78

Table 3.
ABS and ABS Plus specimens' maximum compressive test results

4.3. Flexural strength characterization

In Tables 4 and 5, the average results of ABS and ABS Plus tested specimens respectively are presented. The tables contain the material used, the deposition orientation selected, the flexural strength (MPa) and the Bending elastic modulus (MPa). In Figure 9 typical graphs of the the flexion stress results versus strain for the tested ABS (Fig. 9A) and ABS Plus (Fig. 9B) specimens are presented. SEM images in Figure 10 illustrate the fracture areas of ABS (Fig. 10A) and ABS Plus (Fig.10B) at 0° degrees' building deposition.

Material	**Deposition Orientation (°)**	**Flexural stress (MPa)**	**Bending Elastic Modulus (MPa)**
ABS 0.25mm	0	20.92	532.28
	90	19.27	532.22
ABS 0.33mm	0	20.57	533.46
	90	19.01	465.55

Table 4.
ABS specimens overall average Flexural stress and Bending elastic modulus results

Material	**Deposition Orientation (°)**	**Flexural stress (MPa)**	**Bending Elastic Modulus (MPa)**
ABS Plus 0.17mm	0	39.14	811.62
	90	35.95	903.88
ABS Plus 0.25mm	0	35.68	799.53
	90	35.78	771.74

Table 5.
ABS Plus specimens overall average Bending stress and Bending elastic modulus results

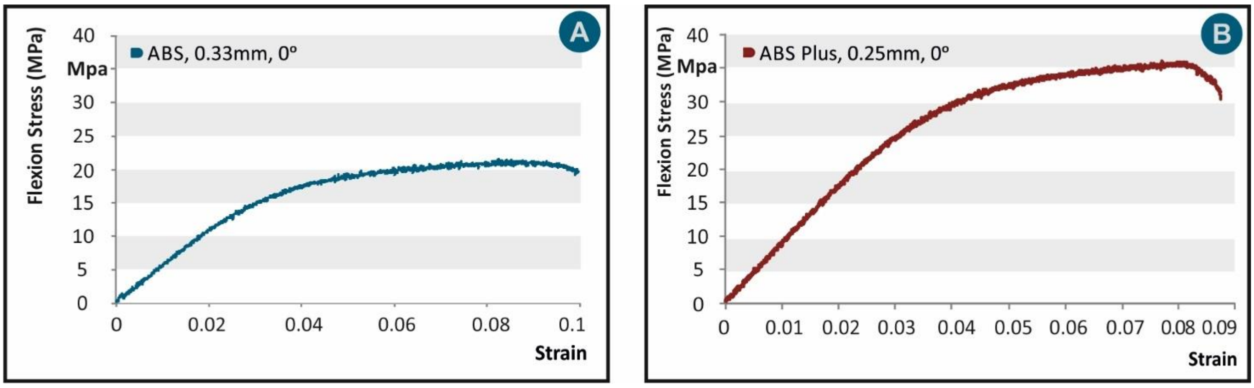

Figure 9
Flexion stress (MPa) versus strain in ABS (A) and ABS Plus specimens (B) in 0° degrees' deposition orientation

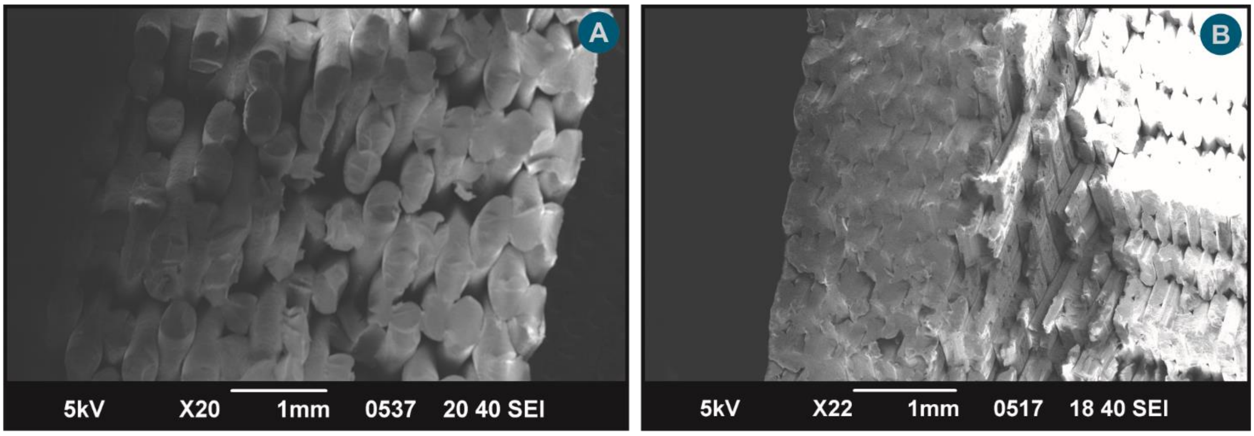

Figure 10.
SEM images of fractured areas of ABS (A) and ABS Plus (B) at 0° degrees' deposition build

Results	**ABS with notch**	**ABS without notch**	**ABS Plus with notch**	**ABS Plus without notch**
	Gc (kJ/m^2)	**Gc (kJ/m^2)**	**Gc (kJ/m^2)**	**Gc (kJ/m^2)**
Average	18.66	21.58	20.04	23.16
Max. deviation	35.5%	30.8%	33.5%	30.3%

Table 6.
ABS and ABS Plus specimens overall average critical fracture strength results and max. deviations

4.4. Impact strength characterization

Regarding impact strength, specimens' results are presented in the Table 6. In Table 6 the average critical fracture strength Gc (kJ/m^2) for ABS and ABS Plus specimens with and without impact notch is summarized including the maximum deviation between specimens.

5. DISCUSSION

In this work the tensile, compressive, flexural and impact strength of FDM ABS and ABS Plus specimens was studied. In the tensile tests, ABS specimens with 0.25mm layer thickness build at a 45° degrees' angle had the maximum stress closest to the stock material values, while ABS also had the largest difference from nominal material stress values specifically in the case of the 0.25mm layer thickness build at 90° degrees. ABS Plus showed a more stable behaviour, with similar deviation from the nominal material maximum stress for all cases studied. The average difference between the nominal and experimental tensile strength measured was about 15% for the ABS and about 42% for the ABS Plus case, with the 3d printed specimens showing lower tensile strength as expected. The ABS Plus parts had on average 9% higher strength than ABS, with the maximum tensile strength measured being about 20% higher than ABS [24].

Regarding compressive strength characterization, as it was expected, the ABS Plus specimens broke under higher loads than the ABS specimens. The results indicated a difference in the compressive strength between specimens build with the same material and layer thickness of about 29% for the ABS material and 9% for the ABS Plus respectively. In parallel, the deviation for the compressive Young modulus was 8% for ABS and 12% for the ABS Plus material [23].

From the flexural results presented in this work, it is evident that ABS Plus specimens developed higher flexural modulus and higher flexural strength than ABS specimens. That is consistent with specifications and literature [18]. Comparing the specimens to stock materials provided by Stratasys Ltd., ABS printed specimens, had flexural strength 42.3% (41 MPa versus 23.65 MPa) lower than stock values while the flexural modulus of the specimens had 70% lower values (1.83 GPa versus 0.55 GPa) irrespective of printing orientation and layer thickness. For ABS Plus specimens respectively, the flexural strength of the specimens is 20.4% lower than stock (52 MPa against 41.38 MPa) whilst the flexural modulus is by 57.28% lower (2.2 GPa versus 0.94 GPa).

From impact test measurements presented in this work, it is evident that the absorbed impact energy was smaller in specimens with an impact notch than without one. That difference in absorbed energy was 16.5% and is attributable to stress concentration and reduced release area that causes the material to crack with lower energy absorption. Studying the effects of impact between ABS and ABS Plus specimens regardless of the impact notch, it is shown that ABS Plus specimens require 20% less energy to fail than ABS specimens. These results are in agreement with literature [21-22].

6. ACKNOWLEDGEMENTS

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