The influence of additive manufacturing parameters on the structural and mechanical properties of acrylonitrile butadiene styrene (ABS) parts produced by fused filament fabrication

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Abstract. The key to the operation of additive manufacturing is that the parts are made by adding the material layer by layer. Each layer is a thin cross section of the part derived from the original CAD data. Each layer must have a finite thickness and thus the resulting part will be an approximation of the original data. The thinner each layer, the more the resulting piece will be more like the designed part. All additive manufacturing techniques marketed so far use a layered approach. However, certain drawbacks were reported for this type of manufacturing, all depending on certain process parameters. One of the most important build parameters, in terms of cost and final properties, is the build construction angle. The influence of the build positioning (i.e. angle of the layers) in respect to the building plate, during fused filament fabrication of acrylonitrile butadiene styrene (ABS) parts was studied. The characteristics of interest were: the structural features of the manufactured part and the mechanical properties obtained after tensile, compression, and hardness tests, all as function of the build orientation, while keeping the remaining manufacturing parameters identical. It was observed that the build orientation has a significant influence on the properties.

1. Introduction
Additive manufacturing (AM) technologies have developed rapidly and are now extensively used for the production of final parts in various industries such as aerospace, medicine, electronics, etc. [1]. Various processes were developed in order to obtain parts through the “layer-by-layer” method, from the stereolithography technique (SLA), to selective laser sintering (SLS), and beyond. One of the most widely used techniques, adopted in the present research as well, is filament fused fabrication (FFF) [2]. Acrylonitrile butadiene styrene (ABS) is used on most FFF devices but the range of available materials is very wide, including polyamides, polycarbonate, polystyrene, polylactic acid (PLA), etc. [3]. The research in the field of additive manufacturing is nowadays focused on the optimization of the processes and the involved parameters [4-5]. However, while most articles are related to understanding the process itself, to date, the literature is relatively limited regarding the influence of the print orientation on the properties of the manufactured part. When the build orientation is brought to discussion, some authors focus on the influence upon production time, waste reduction, etc. and not on how the parts’ properties are affected by the printing orientation [6]. However, some reports can be found in the literature, which highlight the influence of the process parameters, including the build orientation, on the mechanical properties of polymer-based 3D printed samples. Casavola et al. report the effect of the raster parameters on the mechanical properties of ABS and PLA 3D printed parts. It
was observed that the specimens showed a reduction of the mechanical characteristics if the raster angle was increased [7]. Ahn et al. [8] determined the effects of air gap, bead width, raster orientation and ABS colour on tensile and compressive strengths. The results showed that air gap and raster orientation have an important effect on the tensile strength. On the other hand, the other parameters have negligible effects. Byberg et al. report the study of the impact of the two process parameters, layer orientation and build direction, on the mechanical properties of the ULTEM 9085 material processed by fused deposition modelling. The authors found that the printing direction that gives the best results is the edge direction. This build direction showed a high level of strength for all the tests performed. In this particular case, the time for printing in this direction is somewhat greater than for flat samples, but less material would be used [9]. Zaldivar et al. investigated the print orientation effects on the macrostructure, the mechanical and thermal properties, and the strain field behaviour of the same ULTEM 9085 material, using Fused Deposition Modelling as the printing technique. In this particular case it was observed that increasing the angle from the build platform results in microstructures that further reduce the volume fraction of extruded fibre material from the primary load direction, resulting in lower strength [10]. The fracture resistance and interlayer adhesion of ABS 3D printed parts was studied by Nahal Aliheidari et al., observing that the samples printed at higher temperatures exhibited fracture resistance close to the fracture resistance of bulk ABS, indicating excellent interlayer bonding, as function of the extrusion temperature [11]. A comprehensive review regarding the influence of build parameters on the mechanical behaviour of polymeric 3D printed parts suggests that the main parameters responsible for adequate characteristics are: raster-to-raster air gap, raster angle, layer thickness, infill density and build orientation [12]. However, the same authors suggest that the intention to generalize results from the literature would be impossible, mostly due to the issue of intra-3D printer variability. This means that one could not implement ideal build parameters obtained on a certain machine/polymer/application combination, onto a different printer. Consequently, our aim was to add to the already available knowledge on the subject of mechanical properties of 3D-printed ABS parts, by studying the influence of the build orientation on the tensile and compressive stress resistance of ABS samples produced on an FFF/FDM machine (CreatBOT DX 3D printer).

2. Sample preparation and analysis techniques

2.1. Sample preparation

The samples were manufactured on a CreatBOT DX 3D printer, at 290 °C printing temperature and a 200 µm layer thickness. The filament used in the construction of the samples is made of ABS (Sakata 3D supplier), with a diameter of 3 mm, and it was extruded through a nozzle with a diameter of 0.6 mm. Even though the recommended extrusion temperature given by the manufacturer is between 235-256 °C, when the actual printing of the specimens was initiated, several defects occurred during this process (delamination of the layers). Consequently, the temperature was gradually increased to 290 °C, the temperature at which the specimens were obtained at the desired quality. In order to assess the influence of the build construction angle on the properties, the samples were positioned as described in figure 1. One can observe the tensile test samples, positioned on the edge and flat sides, in respect to the building plate, as well as the compression samples (cylindrical blocks), positioned horizontally, vertically and at a 15-degree angle in reference to the building plate. The dimensions of the samples were: i) tensile test samples: total length 94 mm, calibrated length 50 mm, thickness 3 mm, radius between the calibrated section and the fastening sections 4 mm, calibrated width 4 mm, fastening section width 16 mm; ii) cylindrical blocks for compression tests: diameter 10 mm, height 15 mm. Each configuration of the samples was built in five pieces, for statistical relevance of the results after testing.
2.2. Sample analysis
The tensile and compression tests were performed on a WDW-150S universal testing machine, according to ASTM D638 – 14 (tensile), and ASTM D695 – 15 (compression) standards. Sample pieces cut from the tensile test parts and the compression blocks were embedded in resin and polished, in order to analyse the placement and characteristics of the layers, through optical microscopy. The polishing process was performed on a Labo-Pol 5 polishing machine, from Struers, using five granulations, from 800 to 5000 grit. The samples were further analysed on an optical microscope (Nikon Eclipse MA100), with various magnifications. Furthermore, the hardness of the specimens was assessed using a Shore D hardness tester (Sauter). For statistical relevance, the tensile and compression tests were performed five times, while the Shore D hardness measurements were performed ten times on each sample, and the values were averaged. In order to assess the thermal stability of the ABS filament, Differential Scanning Calorimetry (DSC) analysis has been performed in the -100 ÷ +450 °C domain under nitrogen atmosphere, with 10 °C/min cooling/heating rate (DSC-200 F3 Maia/STA 449F3 Jupiter, Netzsch).

3. Results and discussions
The variation in tensile breaking strength and of the Shore D hardness (after the tensile tests), as function of the build orientation can be observed in figure 2. The variation of stress as function of strain can be observed in figure 3. Both the tensile breaking strength and the Shore D hardness exhibit larger values for the flat printed samples, namely 32.6 MPa and 77 HD, while the edge printed samples exhibit slightly poorer characteristics (29.2 MPa and 74 HD). This phenomenon could be related to the internal structure of the samples, which can be observed in figure 4. The flat printed sample is characterized of structural homogeneity, with a significantly lower number of defects, compared to the edge printed sample. The edge printed sample exhibits a great number of pores, caused by the loss of adhesion/fusion between the rows of ABS. The influence of air-gap on the tensile strength was shown to have a detrimental effect [8]. This phenomenon could be related to the build orientation and to the position of each row in relation to the heating sources during printing, namely the printing head and the heated printing plate. Even if the printing head keeps the same temperature for the extrusion, the distance between the heated plate, on which the samples are built, and the upper rows of the sample is increasingly larger for the edge-printed sample, compared to the flat-printed sample. Consequently, the already built rows are cooling much faster, causing a loss of adhesion between the printed material and the incoming material.
Figure 2. The variation of the tensile breaking strength and of the Shore D hardness (after testing), as function of the build orientation.

Figure 3. The variation of stress as function of strain, for the flat and edge printed samples.

Figure 4. The internal structure and defects inside the samples, after the tensile tests: a) the sample printed on the flat side; b) the sample printed on the edge side. (Scale length 500 µm)
As far as the compression tests are concerned, a similar variation between samples can be observed, albeit to a lesser degree, especially when discussing about the variation of the Shore D hardness, measured after the compression tests. Minimal differences should be expected in relation to the Shore D hardness values, mostly due to the fact that the material is compressed during the test, and the influence of the voids is minimized, thus leading to an increase in homogeneity of the samples. The variation of the compression strength and that of the Shore D hardness can be observed in figure 5, as function of the build orientation. Other reports suggest that the differences in compressive strength are minimal, regardless of the build orientation or other build parameters [8], thus confirming our findings. The difference between the compression strength for the vertically and horizontally built samples could be explained if one looks at the internal structure of the samples, before the compression tests, shown in figure 6. The dimension of the pores/voids is much smaller inside the vertically built samples, compared to the horizontally built samples. The internal structure of the samples built at a 15-degree angle in relation to the build plate was similar to the samples built vertically, thus it is not shown in this manuscript. Consequently, the compression strength for these two samples is relatively similar (52.75 MPa for the vertically built, versus 51.5 MPa for the 15-degree built sample), especially considering the overlapping measuring error.

![Figure 5](image1.png)

**Figure 5.** The variation of the compression strength and of the Shore D hardness (after testing), as function of the build orientation.

![Figure 6](image2.png)

**Figure 6.** The internal structure of the samples, before compression testing, on the as-built samples: a) vertical sample; b) horizontal sample.

The internal structure of the samples after the compression tests can be observed in figure 7. One can observe that the internal voids disappeared almost entirely, to a higher degree inside the vertically
and 15-degree built samples, and to a lesser degree inside the horizontally built sample. Moreover, one can observe the shifting from the vertical symmetry axis of the lateral void locations, due to the barrelling effect caused by the friction force which acts at the contact surface between the compression plates and the sample, during the compression test. Moreover, the thickness of the individual layers, as expected, is smaller as compared to the thickness prior to the compression tests. The presence of the voids inside the as-printed samples seems to have an influence even on the mass of the final part, as function of the build orientation. The estimated values of the print duration and mass of the final part, calculated for a printing speed of 50 mm/sec are as follows: for the flat-built tensile test samples, 116 minutes with a mass of 31 g, while the edge-built tensile test samples, 113 minutes with a mass of 29 g; the horizontally-built compression samples, 26 minutes, with a mass of 7 g, the 15-degree built samples, 29 minutes with a mass of 7 g, while the vertically-built sample, 30 minutes, with a mass of 7 g. These values are of practical importance when choosing either the mechanical properties needed for a certain application, or the economy in terms of building time or final mass.

**Figure 7.** The internal structure and defects, after compression testing, as function of the build orientation: a) vertical, b) 15 degrees inclination in relation to the build plate, c) horizontal.
The thermogram from figure 8 represents the thermal stability of the ABS filament, when subjected to heating. One can observe a “softening” temperature, related to the endothermic styrene glass transition at ~140 °C, and endothermic acrylonitrile glass transition temperature, between 200-220 °C, while melting occurs at 420-424°C. Since the rubber (butadiene) phase of ABS is susceptible to thermal degradation, crosslink points are formed between the macromolecular chains, which lead to a decreased chain mobility and an increase in the melting temperature is expected for the heat processed (extruded) print. The temperature of interest from this thermogram is the one related to the acrylonitrile glass transition, between 200-220 °C, which is relatively close to the recommended printing temperature, as per the filament manufacturer data sheet. It would seem that the acrylonitrile glass transition occurs in a relatively larger domain than expected, thus potentially leading to the printing defects observed during the initial print runs, and to the need for the filament extrusion temperature increase, from 235-256 °C to 290 °C.

![DSC graph](image)

**Figure 8.** The thermal stability of the ABS filament, obtained from differential scanning calorimetry analysis.

### 4. Conclusions

Acrylonitrile butadiene styrene (ABS) parts were produced by fused filament fabrication, with identical printing parameters, while changing the build orientation in relation to the building plate. Firstly, a significantly larger extrusion temperature was needed, compared to the filament manufacturer data sheet, to be able to obtain structurally sound samples (290 °C, compared to 235-256 °C). Secondly, the mechanical properties were clearly influenced by the build orientation, the tensile test samples built on the flat side showed increased strength compared to the edge-built samples, while the vertically-built compression test samples showed increased strength compared to the 15-degree built and horizontally built samples. Marginal differences were noticed in terms of Shore D hardness variation, mostly related to the internal structure after testing. The appearance of voids is linked to the temperature at the building site, larger distances from the building plate, for identical extrusion temperature, leading to a greater number of voids.

### 5. References

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