**Anisotropic mechanical properties of fused deposition modeled parts fabricated
by using acrylonitrile butadiene styrene (ABS) polymer**

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ABSTRACT:

Anisotropic mechanical properties of parts fabricated using acrylonitrile butadiene styrene (ABS) polymer relative to part built orientation employing fused deposition modeling process is reported. *ABSplus*-P430 polymer was used to investigate the effects of infill orientation on parts mechanical properties under tensile and compression loading. The results revealed that infill orientation strongly affects tensile properties of fabricated ABS samples, namely the values for Young's modulus were found to be ranging from ~1.5 to ~2.1 GPa, ultimate tensile strength from ~12.0 to ~22.0 MPa, yield strength from ~1.0 to ~21.0 MPa and elongation-at-break from ~0.2 to ~4.8 % for different infill orientations. Samples with infill orientation aligned to the vertical (*i.e.* Z-) axis were found to display the highest values relative to all other infill orientations studied. Mechanical properties anisotropy was lower for parts under compressive loading, that is the Young's modulus, ultimate compressive and yield strength were weakly correlated with infill orientation apart from samples those built orientation was aligned at 45° to the vertical Z-axis. The latter samples displayed inferior mechanical properties under all compressive tests. The effects of sample gauge thickness on tensile properties and ABS sample micro- and bulk- hardness with respect to infill orientation are also discussed.

KEYWORDS:

Acrylonitrile butadiene styrene polymer, disordered solids, mechanical properties of solids, mechanical properties anisotropy, fused deposition modeling

MAIN TEXT

1 Introduction

Fused deposition modeling (FDM) is one of the most popular layered manufacturing technology processes used for fabrication of complex-shape parts by means of mechanical extrusion of melted material (*i.e.* a polymer material) through a nozzle. The FDM process uses solid copolymer filaments as a build material, which undergo partial melting within a liquefier at temperatures at or slightly above the polymer melting temperature (*i.e.* 5 - 10°C), followed by mechanical extrusion through a nozzle. The material is extruded atop of previously formed layers over a build platform conforming to a planar, two-dimensional (2D) layer design (*i.e.* across X - Y 2D plane). The extruded layer is allowed to cool naturally as it bonds to a previously extruded layer, and thus a three-dimensional (3D) object is built aligned to the vertical Z -axis with each new layer of built material deposited atop of the previously deposited layer. As a result, a complete 3D FDM object represents a pre-designed agglomeration of vertically stacked and bonded arrays of individually formed 2D extruded layers. Fabrication of complex parts often requires the use of soluble support elements in order to maintain structural and dimensional integrity during the FDM fabrication process.

It is known that the mechanical properties of polymeric FDM parts are significantly affected by the FDM design and processing conditions, frequently displaying anisotropic mechanical properties owing to selection of a particular orientation of an infill layer¹⁻⁵. Findings on this matter were presented earlier by Ahn *et al.*², which highlighted the importance of selecting appropriate FDM build parameters such as an infill bead width, infill orientation (*i.e.* raster angle orientation), layer packing order,

and other parameters to maximise on built parts' tensile strength. Ahn *et al.*² also reported that the FDM parts displayed high discrepancy between compressive and tensile strengths, with compressive strength found to be approximately double of tensile strength. Lee *et al.*⁴ found that the compressive strength of polymeric FDM samples was highly depended on an individual layer-to-layer bond strength, and polymeric samples fabricated under planar (*X-Y*) built orientation were found to display compressive strength of over 20% higher when compared to samples those built orientation was aligned to the vertical *Z*-axis. Tensile strength and Young's modulus of FDM build parts are also affected by the appropriate selection of a fabrication-specific raster angle^{1,3}. The strengths and stiffness of FDM parts can normally be maximised by selecting an infill layer orientation which is aligned to the tension force vector. The FDM samples those infill layer orientation is at an angle to the tension force vector, generally display inferior mechanical properties^{1,3}. In addition to the FDM part build orientation, other parameters such as layer-to-layer adhesion, individual layer strength and, in particular, individual bead strength, play critical roles in mechanical performance of FDM parts as reported in recent works⁶⁻⁹. It is worth mentioning the fact that the strength of an individual polymer bead is primarily defined by the chemical composition and physical properties of a given polymer material that is used in the FDM process^{10,11}.

Acrylonitrile butadiene styrene (ABS) thermoplastic polymer and its derivatives are commonly employed as build materials for FDM studies^{1,2,12-15}. On average, commercial grade ABS polymer blends are suitable for the fabrication of consumer-grade objects containing acrylonitrile 15 – 35 weight per cent (wt.%), butadiene 5 – 30% (wt.%) and styrene 40 – 60% (wt.%)^{5,16}. Stratasys ABS P4xx type blends are among the most common ABS thermoplastics used in direct digital manufacturing

systems, however Lee *et al.*¹⁷ recently established that a newly introduced ABS*plus*-P430/M30^{TM18} polymer blend displays significantly more isotropic mechanical properties and reduced fatigue strength when compared to the superseded ABS-P400TM polymer material¹⁹. Both polymer blends (*i.e.* P430 and P400) contain essentially identical copolymer mixtures of butadiene-styrene-acrylonitrile-methyl methacrylate at 70 – 75 wt.% and styrene/acrylonitrile at 25 – 30 wt.%, however the P430 blend does not appear to contain N,N'-ethylenedi(stearamide) and ethylbenzene compounds. It is reported that the P400 blend contains up to 2 wt.% and just under 0.25 wt.% of N,N'-ethylenedi(stearamide) and ethylbenzene compounds, respectively^{18,19}. While N,N'-ethylenedi(stearamide) is a form/mould release agent, neither the effect from this compound nor physico-chemical contributions from ethylbenzene should be considered as influential in affecting the mechanical properties of P430 ABS blend markedly. The use of ABS P400 polymer mixture is associated with ample technical performance data. However, the application of the ABS*plus*-P430TM polymer blend in the FDM manufacturing processes is gaining popularity and consequently, necessitates confirmatory and parametric research studies as disclosed in the present work.

This paper is aimed at evaluating the mechanical properties of ABS samples fabricated using the ABS*plus*-P430 material under mass-scale FDM production conditions to define and ascertain the degree of anisotropic mechanical properties of the samples under tensile and compressive loading. The investigation will assess the influence of raster angle orientation (*i.e.* part orientation relative to build envelope) on part mechanical strength. In addition, test samples of varying build thickness will be investigated for tensile and compressive strength properties. The effects of sample build thickness on tensile properties and evaluation of hardness measurements using

Vickers and Rockwell hardness measurements with respect to sample built thickness (gauge thickness) and an infill orientation will also be discussed in the present work.

2 Experimental Details

Stratasys ABS^{plus}-P430TM thermoplastic polymer containing butadiene styrene acrylonitrile methyl methacrylate copolymer ~70-75% (wt.%) and styrene acrylonitrile copolymer ~25-30% (wt.%)¹⁸ was used as test filament material (dye free, natural form) at room temperature and 35% relative humidity. Stratasys design series Stratasys FORTUS 250^{mc} 3D system was used to fabricate test samples using 175 μm diameter T14 model tip producing 178 μm layer thickness and T16 SR30 250 μm support tip. Poly(vinyl alcohol) (PVA), a water-soluble synthetic polymer, was used as support material. The support material was not employed during fabrication of horizontal dumbbell-type samples aligned to the X -axis and positioned across the X - Z and X - Y 2D planes (see Fig. 1a) and, the cylindrical samples aligned to the Z - and Y -axes (see Fig. 1b). Fabrication of all other samples employed PVA support. These were the dumbbell-type vertical samples fabricated aligned to the Z -axis and over the X - Z 2D plane and, the cylindrical-type samples fabricated at 45° repose angle to the Z -axis. The support material was removed by soaking as-produced samples in an aqueous 15% NaOH solution at 45°C for 6 hours. All test samples were fabricated at a temperature of 40°C within the build envelope measuring 254(X) $\times$ 254(Y) $\times$ 305(Z) mm with an accuracy of 250 μm . Computer-aided design (CAD) models of samples for tensile and compressive tests were generated in compliance with ASTM D412 Type-A sample types (*i.e.* dumbbell-type) with a gauge length of 50 mm, gauge width of 12 mm, gauge thickness of 3.0 mm and an overall sample length of 120 mm and

grip-end width of 20 mm for tensile tests. For compressive tests, modified, circular specimens with a diameter of 15 mm and length of 30 mm, comparative to ASTM D7291 standard were used. Statasys Insight™ software package was employed to process proprietary CAD files into stereolithography (STL) compatible output for 3D fabrication. With respect to Insight™ software settings, ‘soluble’ support structure was used for support material and ‘solid-normal’ option giving full-density (100%) prints was used for fabrication of all part interior sections. Dumbbell-type tensile test samples were fabricated under three print orientations as shown in Fig. 1a and cylindrical-type compressive test samples were fabricated as shown in Fig. 1b; a non-specific cylindrical sample fabricated at 45° repose angle to the Z-axis, denoted as ‘reclined test sample’ was also added for compressive tests. In addition, dumbbell-type samples were fabricated with varying gauge thickness. That is, samples with gauge thickness of 2.55 mm, which is reduced by 15% relative to the nominal ‘reference’ sample (i.e. with gauge thickness of 3.0 mm), and samples with gauge thickness of 3.45 mm, which is increased by 15% relative to the nominal sample for supplementary tensile tests. Infill orientation for dumbbell-type samples was aligned to the X-axis for horizontal and flat samples, and to the Z-axis for vertical samples (see Fig. 1a). Infill orientation for cylindrical samples was aligned to the Z-axis for vertical samples and, to the Y-axis for horizontal, and 45° reclined samples (see Fig. 1b). Five samples ($n = 5$) of each built orientation were tested in compliance with ASTM D638 (Tensile testing) and ASTM D695 (Compressive testing) standards, respectively, employing universal testing machine (Instron 3367) equipped with a 30 kN load cell. A standard 50 mm strain gauge extensometer (Instron series 2630) was used for measuring strain; average data values for all test samples are reported. The values for tensile and compressive Young’s moduli were calculated from the slope of

the initial linear portion of the curve. The reported values for tensile and compressive yield strengths were taken at 1.0% plastic strain offset and the values for elongation-at-break (EL.%) were taken at the strain fracture point. The reported values for ultimate tensile strength (UTS) and compressive strength correspond to maximum stress values recorded under tensile and compressive loads, respectively.

Mechanical hardness values were obtained using Vickers (Wolpert Wilson VH1150; Bühler Holding AG) and Rockwell (Wolpert Probat R-TESTOR 2021; Bühler Holding AG) instruments; the instruments were calibrated prior to all measurements taking place in accordance with ASTM D785-08 standard. The Vickers hardness measurements were performed using diamond pyramid indenter at loads of 1.0 kgf and 2.0 kgf and load dwell times of 10, 15 and 20 sec. The Rockwell hardness measurements were conducted using $\frac{1}{2}$ " ball indenter, preliminary load of 10.0 kg, main load of 60.0 kg, giving Rockwell HRR scale for all samples reported.

3 Results and Discussion

3.1 Tensile and Compression testing

A variation of an applied engineering stress vs. strain under tensile and compressive testing load is shown in Figs. 2a and 2b, respectively. Physical appearance of samples prior to and post tensile and compression tests is shown in supplementary Fig. 1S (tensile), and Fig. 2S (compression). Vertically aligned dumbbell samples displayed brittle failure and markedly inferior tensile strength (at less than 50% value) compared to horizontally aligned and/or flat samples, which both displayed ductile failure. This is owing to orientation of infill layer normal to an applied load, which in turn allows

individual layer unravelling under the load. Strain recorded for the vertically aligned tensile samples was extremely low at and below 0.01, which is significantly lower than the strain reported for horizontal and flat samples owing to different failure modes. Ultimate tensile stress for horizontal samples was at 22.5 ± 0.25 MPa. Vertical and horizontal cylindrical samples under compressive load displayed similar stress values, however the vertical sample was found to display progressively higher stress under increasing strain of 0.04 and higher (see Fig. 2b). This tendency is attributed to an individual layer slippage under load projected under the normal angle^{2,4,9}. Non-specific 45° reclined cylindrical samples were found to display reduced stress (*i.e.* approximately 60%) as compared to the vertical and horizontal samples given reduced layer-to-layer bond strength. Notably, delamination of infill layers under compressive load is most evident for these samples (see Fig. 2S) due to large shear stresses associated with samples whose printing orientation is at 45° to the Z-axis. Summary of Young's modulus and tensile strength for dumbbell and cylindrical samples under tensile and compression loading is shown in Fig. 3. In addition, data corresponding to mechanical properties of bulk ABS copolymer material^{20,21} relative to the studied FDM samples is given on the same figure. The results indicate that the Young's modulus is marginally (*i.e.* ~15%) higher for vertical dumbbell-type samples compared to flat and/or horizontal specimens under tensile load. However, tensile strength is essentially equal between the flat and horizontal samples. It was also found that brittle failure of vertical dumbbell-type samples occurred at maximum strength and appeared along matching layer interfaces. The lowest tensile strength recorded for these samples was $\sim 12.0 \pm 3.1$ GPa owing to poor interlayer bond strength. These findings illustrate that the FDM fabrication processes with respect to part orientation within the build envelope should be carefully considered for load-bearing applications.

and, applications where stiffness and strength characteristics are important should avoid and/or minimise part build orientations those infill layer is positioned at normal angle to an applied load. The FDM fabricated parts show an approximately ~30% reduction in tensile strength and just over 50% reduction in UTS under tensile load when compared to bulk ABS copolymer^{1,2,14,22-24}. The cylindrical-type samples fabricated under horizontal and vertical printing orientation were found to be of similar strength and stiffness. However, the cylindrical samples fabricated at 45° repose angle to the Z-axis were found to display reduced mechanical properties compared to the samples printed under horizontal and vertical arrangements with values for compressive strength, yield strength and Young's modulus amounting to ~70% compared to the former. These findings can be effectively explained applying the basics of classical lamination theory^{25,26}. That is, we can broadly consider an individual, one-dimensional (1D) infill bead as a load-bearing element, which makes up a 2D planar structure (a laminate sheet or a ply layer). A ply layer is then assumed to have inherent mechanical properties, as is a vertical three-dimensional stack of laminate sheets or plies. Subsequently, mechanical strains in 2D ply sheet and 3D laminate objects are functionally dependent on the magnitude, direction and frequency of an applied external load relative to a given printing orientation^{6,7,27-29}. Results for yield strength of dumbbell-type samples under tensile load (Fig. 4a) and for elongation-at-break (Fig. 4b) indicate poor elastic deformation characteristics in samples fabricated under the vertical build orientation. These samples showed brittle failure and yield strength of $\sim 1.5 \pm 0.5$ MPa, which is approximately $1/10^{\text{th}}$ of the value recorded for samples fabricated under flat and/or horizontal build orientation. In addition, as evident from Fig. 1S that the vertical specimens break at or near the clamp area owing to the higher degree of tessellation of contour infill volume that

these samples display compared to the flat and horizontal specimens. Meaningful elongation-at-break data could not be obtained for the vertical dumbbell-type specimens under tensile load, whereas the flat and horizontal test samples displayed almost matching values at $\sim 4.8 \pm 0.3\%$ confirming the findings reported earlier^{5,20,21,30}. The vertical cylindrical-type specimens displayed marginally ($\sim 5\%$) higher values for yield strength compared to the horizontal samples (*i.e.* 25.1 MPa vs. 23.9 MPa), whereas the samples fabricated at 45° repose angle to the Z-axis were found of the lowest yield strength at 17.2 MPa (see Fig. 4a). The strength for the latter samples was approximately $2/3$ of the average strength of the vertical and horizontal samples. Notably, the values for yield strength and for elongation-at-break for the FDM parts are approximately $1/2$ and $1/5$, respectively, of bulk the ABS polymer^{2,11,13,20,31}.

3.2 Effects of sample gauge thickness on tensile strength

Tensile strength values were found to be the highest for the flat dumbbell-type tensile samples with reduced ($t -15\%$) gauge thickness as shown in Fig. 5b, whereas the lowest tensile strength was recorded for samples with the increased ($t +15\%$) gauge thickness. The observed difference is approximately 15.0%, as the flat ($t -15\%$) samples showed UTS values of 23.5 MPa compared to the thicker gauge ($t +15\%$) samples with UTS of 20.0 MPa with the standard measurement error of 0.1 MPa. The nominal ‘reference’ samples displayed UTS of 21.7 ± 0.1 MPa, the value that is approximately 7.0% higher than that for the thicker, and lower, than for the thinner specimens, respectively. This observation contradicts the classical macro-scale material behaviour laws, which stipulate that the variation of cross-sectional area of

test sample yields no effect on materials tensile properties under identical test conditions²⁸. In the case of FDM parts the findings presented in Fig. 5b can be explained as follows. As all samples (shown in Fig. 5b) were fabricated under the ‘flat’ build orientation (see Fig. 1a) all infill beads in these specimens are aligned along the longitudinal X -axis direction with all infill layers incrementally built atop of each other, and across the X - Y 2D plane. Specimens such as the thinner gauge ($t - 15\%$), the nominal, and the thicker gauge ($t + 15\%$) samples vary by only two physical criteria namely, the gross number of X - Y 2D ply layers (*i.e.* total number of infill layers in the Z -axis vertical stack), and the contour infill volume that outlines the perimeter of the dumbbell-type samples in the X - Y plane. Generally, it is known that the strength of FDM parts increases as the layer thickness and the total number of layers increases^{9,24}. This is owing to the inter-layer bonding contributing to an enhanced overall strength of a complex structure²⁸. By increasing the number of layers in an FDM object the tensile load is distributed across all bonded surfaces and between the individual ply sheets and, in effect, equalises intrinsic stresses, which are commonly associated with a bulk laminate structure. As seen in Fig. 5b, the stress associated with the thicker gauge specimen ($t + 15\%$) is lower as compared to the nominal gauge and to the thinner gauge ($t - 15\%$) samples. The relative ratio of the contour infill volume to the raster infill volume is higher in the thinner gauge ($t - 15\%$) sample compared to the nominal and the thicker gauge samples, this ratio may contribute the most to the non-characteristic tensile properties of samples shown in Fig. 5b and, may also contribute to the fact that the thicker gauge samples show higher degree of ply de-lamination and ply unravelling within the raster infill volume. The observed differences in the stress/strain characteristics for samples with varied gauge thickness are also in accord with recent findings by Mohamed *et al.*³² that

showed importance of carefully selecting process parameters for FDM parts. The observed inverse dependence of tensile strength relative to the gauge thickness (within a narrow parametric margin) is attributed to the presence of process-induced structural defects such as voids, one-dimensional infill- and bead- breaks and variable bond strength between the laminate sheets. As the gauge thickness increases, the number of ply layers composing an FDM object also increases, resulting in a small increase of structural and topological defects within an FDM object. These defects are responsible for compromised quality and reduced rigidity of the bonded layers and are known to occur owing to high non-uniform temperature gradient between the bottom and the top infill layers during the filling-in process of interior raster planes³².

3.3 Hardness measurements

Hardness of all FDM fabricated samples was estimated using Vickers and Rockwell-type hardness measurements. The Vickers hardness measurements, also referred to as micro-hardness measurements, were performed using 1.0 and 2.0 kgf loads for 10, 15 and 20 s load dwell time as noted in Section 2. The Vickers testing regime that employed a load of 2.0 kgf at 15 s dwell time was found to be the most suitable for testing of FDM parts and yielded significantly lower statistical errors compared to measurement protocols that employed 1.0 kgf load and 10 or 20 s load dwell times. Notably, the Vickers measurements did not generate scientifically meaningful data that could allow clear differentiation between all FDM samples studied in our work. The Vickers tests operate with the size and geometry of an indenter's impression mark (*i.e.* an impression mark is used to determine the Vickers hardness value) relative to the size of topological features present on the studied material's surface. Given that

the print resolution of our FDM build samples was set at $\sim 180\text{ }\mu\text{m}$, the empirical read-out parameters associated with the Vickers measurements such as the diagonal tip impression sections d_1 and d_2 , which correspond to an average lengths of diagonals left by an indenter tip, were found measuring approximately $600\text{ }\mu\text{m}$. The latter figure roughly corresponds to four (x 4) bonded infill bead lines. Depending on the position and relative orientation of the Vickers indenter's tip on the FDM part surface, such as whether an indenter tip is a) atop of an individual $180\text{ }\mu\text{m}$ -thick filament layers, b) on the slope of a layer, or c) directly in-between the two adjacent infill bead lines, large variations for d_1 and d_2 variables were recorded. In the case of conducting the Vickers measurements on the FDM parts we found that the surface finish of the build part had major influence on the hardness measurements, as the indentation mark was too small compared to the surface roughness of an FDM object. Furthermore, as the infill surface density remained unchanged across all dumbbell-type and cylindrical-type samples, all FDM build samples were found displaying the Vickers micro-hardness values of $22\text{HV}2.0/15 \pm 6.0$.

The Rockwell hardness measurements were performed on all FDM samples in compliance with ASTM D785-08 standard. All samples were found to display Rockwell hardness values of $\text{HRR } 64.0 \pm 4.5$. The non-specific dumbbell-type tensile samples of varying gauge thickness namely, the samples with the gauge thickness reduced by 15% (*i.e.* denoted as sample ' $t - 15\%$ ' at 2.55 mm) relative to the reference 3.0 mm thick sample, and the samples with the gauge thickness increased by 15% (*i.e.* denoted as sample ' $t + 15\%$ ' at 3.45 mm) relative to the reference sample, displayed the Rockwell hardness values inversely correlated with the gauge thickness (see Fig. 5a). That is, the thinner was the gauge of FDM build test sample - the higher was the recorded Rockwell HRR value. This is owing to distribution of the residual indenter

load from the supporting substrate for thinner gauge specimens, which overall increased the Rockwell HRR values by almost 50% for thinner FDM samples relative to the HRR values reported for the ABS bulk polymer. This phenomenon is commonly observed for micro- and bulk- hardness measurements when performed on thin-film materials or coatings^{33,34}. To mitigate for this effect, the use of test samples with an overall thickness of a least ten-times ($\times 10$) the indenter/tip penetration depth is commonly recommended. The thinner gauge samples ($t -15\%$) samples showed Rockwell hardness HRR of 83.0 ± 3.2 , the nominal 3.0 mm thick ‘reference’ was at HRR 73.0 ± 5.6 , and the thicker gauge ($t +15\%$) samples were found of Rockwell hardness HRR of 68.0 ± 6.3 , in agreement with the hardness values reported in the earlier works for ABS material^{5,12,35}.

4. Summary

The results of this work revealed that the mechanical properties of dumbbell-type and cylindrical-type ABS test samples fabricated using the FDM method under tensile and compressive loading are strongly affected by the FDM part build orientation within the build envelope. The dumbbell-type test samples were found to display values for Young’s modulus ranging from ~ 1.5 to ~ 2.1 GPa, ultimate tensile strength ranging from ~ 12.0 to ~ 22.0 MPa, yield strength from ~ 1.0 to ~ 21.0 MPa and elongation-at-break ranging from ~ 0.2 to $\sim 4.8\%$. The ABS test specimens with print orientation aligned to the vertical Z-axis and with infill orientation aligned at normal angle to an applied (*i.e.* tensile) load showed the highest discrepancy in tensile strength results. Compression properties of cylindrical-type FDM samples were found varying to a lesser degree compared to the dumbbell-type tensile specimens. The cylindrical-type

ABS samples under compression displayed almost identical values for the Young's modulus, ultimate compressive and yield strength. An exception was the non-specific cylindrical-type sample fabricated at 45° repose angle to the vertical Z -axis, the 'reclined test sample', that was found to be of the highest degree of mechanical properties isotropy and consistently displaying inferior properties under all compressive tests when compared to the cylindrical-type specimens those built orientation was aligned to the Y - or the Z - directional axes (see Fig. 1b). Poor mechanical properties of this test sample are attributed to infill layer and ply orientations aligned at 45° relative to an applied load, which is associated with the highest strains in the FDM laminate structure. The mechanical tensile and compressive strength of FDM samples (both the dumbbell-type and cylindrical-type test samples) fabricated using the *ABSplus*-P430 material were found to be approximately at 50% or lower the reported values for bulk ABS copolymer material owing to laminate and layered composition of FDM objects. In addition, we found that variation of sample gauge thickness in the dumbbell-type samples was inversely related to the tensile strength in these samples. However, the gauge thickness was also found to be directly proportional to mechanical strain in the flat dumbbell-type samples with built orientation aligned to the X -axis and across the X - Y 2D plane. This observation was attributed to specific fabrication characteristics during the FDM process and the presence of sizable contour infill volume in the latter samples; further research efforts may be warranted to quantitatively and qualitatively elucidate the observed phenomena. In addition, we found that infill orientation has no feasible effect on bulk mechanical hardness of ABS parts when Vickers or Rockwell hardness measurements are employed. For testing of ABS FDM samples the results from Rockwell bulk-hardness measurements were found to be highly uniform and

reproducible compared to the results obtained from the Vickers micro-hardness measurements. The Rockwell bulk-hardness measurements results were affected by variation of the test sample thickness when the HRR test scale was employed.

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FIGURE CAPTIONS

Figure 1. Sample built orientation for tensile (a) and compressive (b) tests.

Figure 2. Stress vs. strain curves for the dumbbell-type samples under tensile load (a) and the cylindrical-type samples under compressive load (b).

Figure 3. Young's modulus (a) and tensile strength (b) data for the dumbbell-type and the cylindrical-type samples under tensile and compressive load. *ABS bulk sample characteristics are adapted from Refs. ^{20,21}.

Figure 4. Yield strength (a) and elongation-at-break (b) data for the dumbbell-type and the cylindrical-type samples under tensile and compressive load; the elongation-at-break data for the cylindrical-type samples under compressive load is not available. *ABS bulk sample characteristics are adapted from Refs. ^{20,21}.

Figure 5. The variation of the Rockwell HRR hardness (a) and tensile strength (b) for the dumbbell-type tensile samples of different gauge thickness.

Figure 1S. Samples before and after tensile testing.

Figure 2S. Samples before and after compression testing.

FIGURES

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

SUPPLEMENTARY FIGURES

Figure 1S.

Figure 2S.