A PARTIAL SOLUTION TO MODELING THE ANISOTROPIC MATERIAL PROPERTIES OF FUSED DEPOSITION MODELING ABS – PART 1 OF 2

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Abstract

Many input parameters are available for the fused deposition modeling (FDM) process and it is known that some of these parameters have significant effects on mechanical properties of FDM parts. The manner in which material is deposited during the FDM process results in anisotropic properties in the final products. In general, this study will utilize an artificial neural network (ANN) to predict 2-D mechanical properties of the resultant prototypes based solely on orientation. Specifically, part 1 of this study presents data that not only verifies the results of previous research but provides confidence that printer output is reasonable and sufficient to train, validate, and test an ANN. Broad correlations are made between printing parameters and mechanical properties and the mechanisms by which these parameters effect properties are discussed. Three input parameters were chosen for this study and methodically varied along a predetermined range while printing prototypes (i.e. tensile specimens). The prototypes' mechanical properties were determined through tensile testing. Results suggest that layer height, printing pattern, and infill density have significant effects on FDM manufactured parts strength, stiffness, and ductility.

Introduction

Fused Deposition Modeling

FDM is a material extrusion additive manufacturing process, typically used to produce prototypes in a variety of applications. The FDM machine, or 3-D printer, is a computer-numerical-controlled (CNC) gantry or delta-arm machine that utilizes slicer and user interface/control software. These software take a 3-D drawing, usually in .STL format, translate it into individual layers, generate the machine code (G-code) used by the printer, and allow users to manipulate input process parameters. The machine 'prints' by extruding a semi-molten filament through a heated nozzle while the printer head or bed moves in a prescribed pattern in the XY-plane, as shown in Fig. 1. As the material is deposited, it cools, solidifies, and bonds with the surrounding material. The machine continues this process layer by layer as the printer head or bed moves incrementally in the Z-direction at a predetermined layer height.

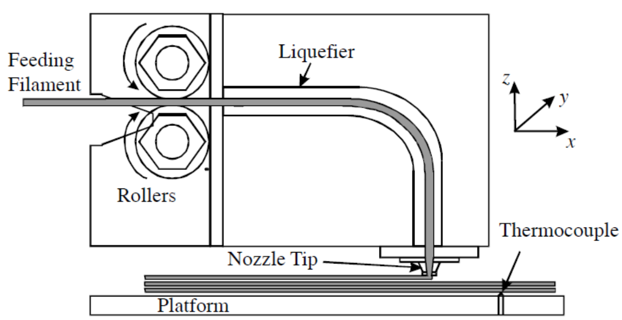

Figure 1. Schematic of typical extrusion head and filament deposition process [1].

Due to FDM's ability to create complex parts quickly and in an inexpensive manner, recent efforts have focused on utilizing the technology in the manufacturing of production-grade, end-use products. However, in order to fully develop FDM into a manufacturing tool a number of improvements are required. The two areas for improvement are quality and integrity. Where quality focuses on accuracy, tolerance, surface finish, and minimum wall thickness [2] and integrity focuses on mechanical properties, solid mechanics, and material modeling. Much research has been performed in these areas and has concentrated its efforts in printer optimization as well as understanding the effects build parameters have on mechanical properties.

The FDM manufacturing process generates parts that are unique and, in terms of mechanical properties, are substandard to their subtractive manufactured (SM) or injection molded (IM) counterparts of the same material. SM and IM components are fundamentally homogeneous and isotropic, while FDM components are not. The FDM manufacturing process, as described previously, produces a composite of partially bonded polymer filament and voids [3]. These imperfect bonds and voids are the characteristics of FDM parts that make them have inferior mechanical properties and make them anisotropic. In this way these characteristics should be considered natural defects. There are many input parameters available for use during the FDM process and it is known that some of these parameters have significant effects on mechanical properties. We reason that these resultant mechanical properties are actually the manifestation of printing parameters either exposing or exacerbating these natural defects.

Thus, the key to understanding how input parameters effect mechanical properties of FDM parts, is understanding by what mechanism (i.e. exposing or exacerbation) a parameter acts. For convenience of discussion herein: a parameter that acts by exposing the natural defects of FDM parts will be referred to as an *extrinsic* parameter, as their effect is dependent upon external conditions (i.e. loads) and these conditions need to be taken into context. While a parameter that acts by exacerbating these natural defects will be denoted as an *intrinsic* parameter, because its effect is independent of external conditions.

Input Process Parameters, Mechanical Properties

Researchers have identified build orientation, raster orientation, printing pattern, layer height, infill density, air gap, and filament cooling rate as having significant effects on mechanical properties of FDM manufactured parts. Abundant data is available on the subject, however, when reviewing these scholarships there is plenty of context to be considered. Many parameters need to be known in order to make proper data comparisons and often times this data is unavailable. Another dimension in this contextual mix-up lies in the shifting vocabulary used across the industry for input parameters – that is, many synonyms exist while standardization does not. In an effort to break through ambivalent terminology, eliminate contextual difficulties, and promote standardization in future works Table 1 is provided. It contains some of these common substitutes along with the nomenclature used herein.

Table 1. Input process parameters synonymous terminology.

	Synonyms	
Layer Height	Layer Thickness	Slice Height
Filament	Raster	Road
Printing Pattern	Infill Pattern	Part Fill Style
Raster Orientation	Build Direction	Raster Angle
Contour Width	Shell Width	Contour Thickness

Layer height refers the thickness of the filament as it is deposited in the Z-direction. It can vary considerably, depending on user settings, and is typically used to optimize printing time verses surface quality. That is, thicker layers means faster prints while thinner layers means higher quality. During a comparative finite element analysis stress study of isotropic FDM material [4] found that as layer height decreased tensile strength generally increased, while elastic modulus increased with increases in layer height. Reference [5] had nearly identical findings in their study on mechanical properties of components fabricated from open-source 3-D printers. While [6] found the opposite – in regards to tensile strength – during their comprehensive study regarding the influences of infill density, layer height, and infill pattern on 3-D printed components – that is, as layer height decreases so does tensile strength. The authors of [6] mention that layer height only seems to influence strength when it becomes low (i.e. 0.1 mm, 0.15mm) and they contribute this trend to lower accuracies of thinner deposits. In addition, [6] found that as layer height increases so does elongation at break. None of the published literature reviewed provided an explanation for layer heights effect on tensile strength.

Infill density refers to the amount of material that lies within the contour of the component. When comparing printing time, cost, and resultant mechanical properties, not surprisingly, [6] discovered that as infill density increases tensile strength and elastic modulus increase drastically and, maybe less intuitively, elongation at break remains fairly constant.

Raster orientation and *printing pattern* are not synonymous although they denote the same function. Printing pattern refers to the prescribed path in which filament is extruded during infill operations. Typically, it is a figure of some sort (i.e. linear, diagonal, hexagon) and remains constant layer by layer. Raster orientation (Fig. 2) also refers to the extruder path during infill deposition but, rather than being a figure, it simply denotes the angle between the axis of the deposited filament and the X-axis of the 3-D printer. Raster orientation may also vary layer by layer, typically layers are stacked normal to one another. Reference [4] printed tensile specimens in [0/90] and [45/-45] raster orientation and found that the [45/-45] specimens had the greatest tensile strength, while the [0/90] specimens had the highest elastic modulus. With regards to acrylonitrile butadiene styrene (ABS) published literature [5] had nearly identical findings. Reference [6] compared linear, diagonal, and hexagonal printing patterns and found, at 100% infill density, that the diagonal pattern yields a higher tensile strength.

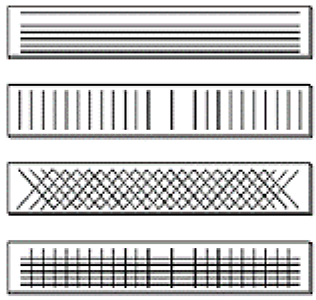

Figure 2. Example of a [0/0], [90/90], [45/-45], and [0/90] raster orientation.

Build orientation is the direction in which a part is built relative to the X, Y, and Z-axis of the 3-D printer. Fig. 3 is provided for clarification, however, it does not do this parameter justice. It only shows how parts can be built in three different directions, which leaves out much complexity – that is, parts can be built in <u>any</u> orientation conceivable in space. The key when considering build orientation with respect to resultant mechanical properties is understanding how a change in build orientation could filament-to-filament bonds to applied loads. Ample research has been done in this area, however, due to contextual ambiguity it will not be discussed herein.

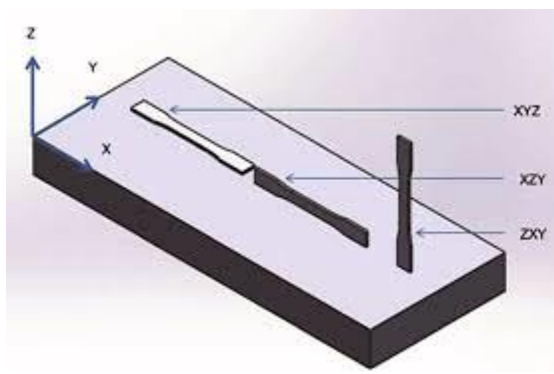

Figure 3. Clarification of build orientation [7].

Air gap is the space between filaments of FDM material. The default setting is zero and can be adjusted to a positive or negative air gap value. A zero air gap means that the filaments just touch, a positive air gap means the filaments do not touch, and a negative air gap means that adjacent filaments partially occupy the same space [8]. During their study of anisotropic material properties of FDM ABS [8] found that a negative air gap (-0.0762mm) resulted in significant increases in tensile strength. Specifically this tensile strength increase was noticed in [0/90], [45/-45], and [90/90] raster orientations, but had only a slight effect on the [0/0] oriented specimens. Reference [7] found similar results in their study. Raster orientations [0/90], [30/-60], and [45/-45] as well as build orientations XYZ, XZY, and ZXY, as shown in Fig. 3, were used. Regardless of the build or raster orientation a negative air gap resulted in the greatest tensile strength. This increase in tensile strength is contributed to the negative air gaps ability to make the ABS structure denser. Similarly, reference [9] found that a positive air gap (0.33mm) resulted in high dispersions of data, due to large voids in the ABS structure.

Filament cooling rate is not an actual input parameter but rather a function of several parameters. References [1,3] suggest that bonding quality between filaments and layers of filaments has tremendous effects on FDM part strength and that this bonding is driven by the thermal energy of the semi-molten material. Their data proposes that better control of filament cooling may have significant effects on bond quality and ultimately the strength of FDM parts. Published literature [1] shows that envelope temperature and variations in convective conditions within the envelope have strong effects on bond quality. While [3] draws similar conclusions for extrusion and envelope temperature but suggest extrusion temperature has a greater impact on bond quality. It seems that filament cooling rate is a function of extrusion temperature, envelope temperature, and extruder/envelope fan speed.

Furthermore, reference [3] modeled bonding between filaments and concluded that the filaments cannot be maintained at high enough temperatures long enough after extrusion for complete bonding to occur during FDM. Subsequently, mechanical properties in the bonding zones are not the same as the ABS filament material, which implies FDM parts are inherently heterogeneous and anisotropic. In other words, as the cooling rate increases – either by large temperature differentials or convection – filament bonding quality decreases and vice versa. Although the results of [3] suggest that extrusion temperature had a greater impact on the neck growth – the means by which bond quality is measured – than envelope temperature does.

The fundamental aspect is not so much that these input parameters impact mechanical properties but understanding the mechanism by which they do. It was shown that filament cooling rate, in some degree, is responsible for the imperfect bonding formed between filaments [3]. Thus it exacerbates this natural defect and is defined as an intrinsic parameter. Whereas build orientation [9] and raster orientation/printing pattern [4-6] don't impact filament bonding per se, but they do influence mechanical properties by exposing these filament bonds to external loads (i.e. tensile, compressive, shear forces) and by this are defined as extrinsic parameters. We speculate that, like filament cooling rate, air gap effects filament bonding. The means and explanation for this speculation are contained later herein. However, the means are direct and independent of exterior conditions, therefore, air gap can be defined as an intrinsic parameter.

It was shown that air gap is also known to effect ABS structure density [7-8], which we contribute to void size alteration. In addition, layer height was shown to influence mechanical properties [4-6], which again we contribute to void size alteration. Both these parameters exacerbate this natural defect and by this are defined as intrinsic parameters.

Objectives

We argue that until perfect bonds can be formed between filaments and voids can be illuminated, FDM manufactured parts will never be isotropic, regardless of the plane considered. This is why the generation of an accurate material model for the current FDM process is of utmost importance. That is, the ability to model an anisotropic product, from a process, greatly increases the assurance in that process, and further enables its progression into production of end-use goods.

Methods

The Rostock MAX^{TM} V2 Desktop 3-D Printer kit was utilized for this study. This hobby-level 3-D printer has a resolution of 0.1 mm in the X/Y-directions and 0.0125 mm in the Z-direction which is at least commensurate to commercial-grade printers. In addition, an after-market E3-D-v6 Hotend was used to increase our printing temperature range. MatterSlice, an open-source G-code generating software was exploited. This software allowed specific constraints to be designated on a layer by layer basis, which in turn allowed us to have ultimate control of build parameters. The hobby-level 3-D printer was utilized in lieu of a commercial-grade printer for this reason, as commercial-printer software typically allow little to no parameter control. This approach is consistent with the findings of [5] which demonstrated that the mechanical properties of components fabricated by well-tuned, open-source, 3-D printers are comparable to parts printed on commercial 3-D printing systems, in terms of tensile strength and elastic modulus.

The 3-D printer was located in an unconditioned environment (i.e. a garage) and an envelope was not utilized. The term 'unconditioned' suggests that the environment was susceptible to naturally occurring changes in ambient temperature and humidity as well as exposure to variable convective conditions. This is consistent with practices used in [5] however, it has been recognized that envelope temperature and convective conditions influence FDM part mechanical properties [1,3] and shall be considered in future works.

Layer height, infill density, and printing pattern where the specific input process parameters chosen for this study. Four layer heights – 0.15mm, 0.2mm, 0.25mm, and 0.3mm – were selected. Typical commercial-printers allow layer height to be set at certain values in the range of 0.25mm to 0.35mm. The selected heights covered this range and allowed lower levels of the possible span to be explored. Infill density can range from 0-100%. Six infill densities were chosen (i.e. 25%, 45%, 60%, 70%, 80%, 90%, and 100%) which covered a large portion of the infill density span with emphasis at the upper half. Concentric and diagonal patterns were chosen for this study. The specified layer heights and infill densities were then dispersed across their range on the concentric and diagonal patterns until every combination of the selected input parameters was represented. It is important to note that the number of shells varied by specimen, however, it remained constant with respect to the layer height used. That is: 0.2mm, 0.25mm, and 0.3mm layer heights all consisted of five shells – two on top and three on bottom – which resulted in 1.0mm, 1.25mm, and 1.5mm respectively of the specimens being solid regardless of the selected infill density. The wall thickness became too thin at just five shells for the 0.15 mm layer height, instead eight shells were used – four on top and four on bottom – which results in 1.2mm of the specimen being solid.

ABS material, a thermoplastic polymer, was employed for this study. It is highly popular throughout the FDM and RepRap communities and plenty of research has been performed utilizing ABS material.

An MTS frame, load cell, and extensometer were used during tensile testing. Tensile tests were performed in accordance with applicable ASTM standards [10-11] at a crosshead rate of 2.0 mm/min. Reference [11] was also used, in conjunction with Eq. (1)-(3), to calculate tensile strength, σ_{uts}, elongation at break, $\%El$, and modulus of elasticity, E. Where F is tensile force, A is cross-sectional area, ε is strain, δl is change in gage length at break, and l_o is original gage length.

$$\sigma = {}^{F}/_{A} \tag{1}$$

$$\varepsilon = {}^{\sigma}/_{E} \tag{2}$$

$$\%El = \left({}^{\delta l}/_{l_o}\right) \cdot 100 \tag{3}$$

Due to unavailability of test equipment, a 1in extensometer was used in lieu of a 2in, which is required by reference [11]. This may have increased the number of specimens that broke outside of gage length, like shown in Fig. 4, but, because tensile specimens exhibited little to no necking, the data were included in this study. Reference [5] utilized a 2in extensometer and still had many specimens break outside the gage length. However, since these specimens displayed a distinct maximum stress before failure, conclusions were made regarding modulus of elasticity and strength and the data were included in the study. By this same notion – that is, since a distinct stress and strain are displayed at failure – elongation at break could be determined and its data are included in this study.

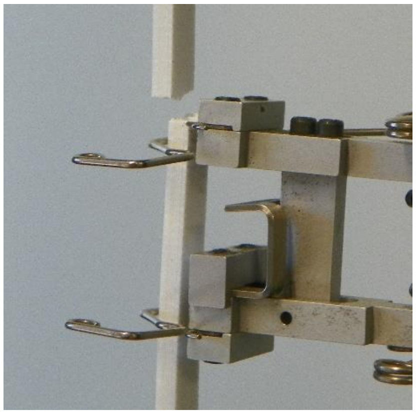

Figure 4. Tensile specimen breaking outside of 1in extensometer gage length.

In a time and cost savings effort some samples did not meet the minimum recommended specimen count. Reference [11] mentions that at least five specimens for each sample be tested, while our specimen quantity per sample ranged from three to six. Although our specimen count was low, our data were able to match that of previous studies, which suggests our data are reliable.

Results

Infill Density

Our data suggest that, in concentric specimens, as infill density increases there is a definite rise in tensile strength and modulus of elasticity (Fig. 5, Fig. 6), while elongation at break remains generally constant (Fig. 7) throughout the infill density domain. These results are consistent with those of reference [6].

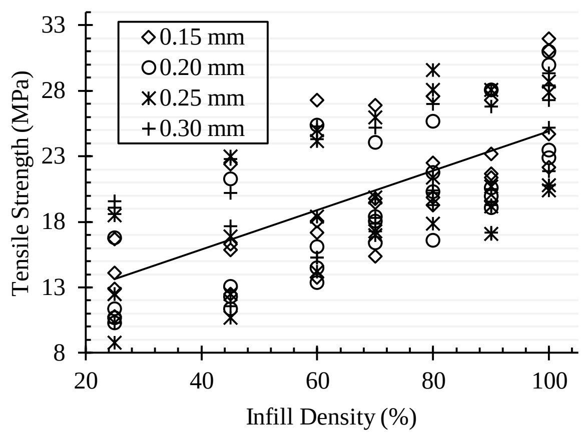

Figure 5. Concentric samples comparison between tensile strength and infill density.

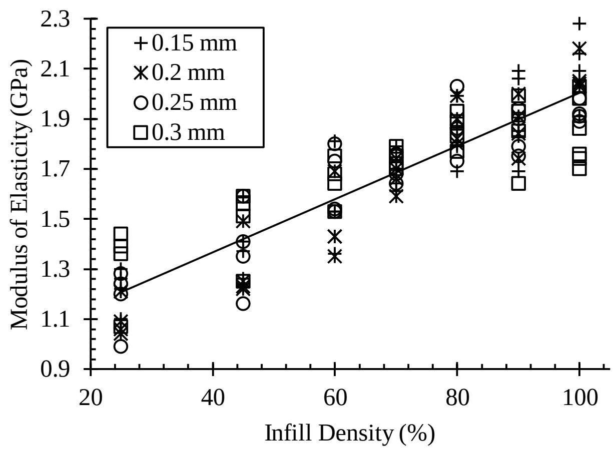

Figure 6. Concentric samples comparison between modulus of elasticity and infill density.

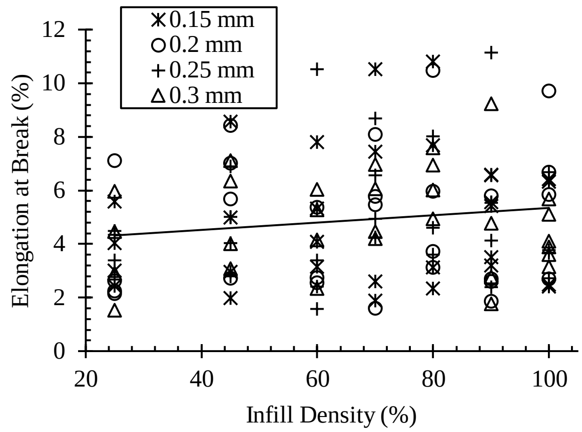

Figure 7. Concentric samples comparison between elongation at break and infill density.

The resultant tensile properties of diagonal specimens differ from that of the concentric ones. In the diagonal specimens as infill density increased tensile strength remained fairly constant (Fig. 8), modulus of elasticity – similar to that of the concentric specimens – had a distinct rise (Fig. 9), while ductility (Fig. 10) actually decreased.

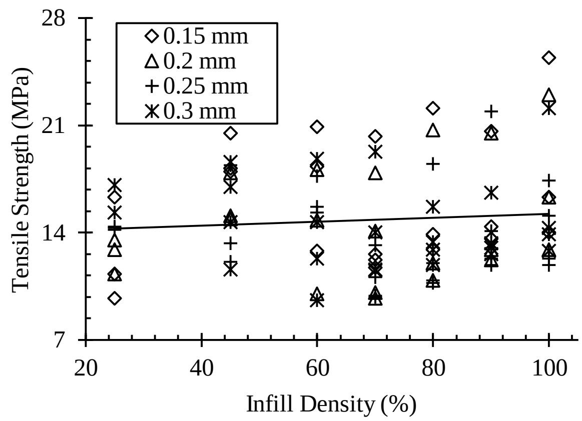

Figure 8. Diagonal samples comparison between tensile strength and infill density.

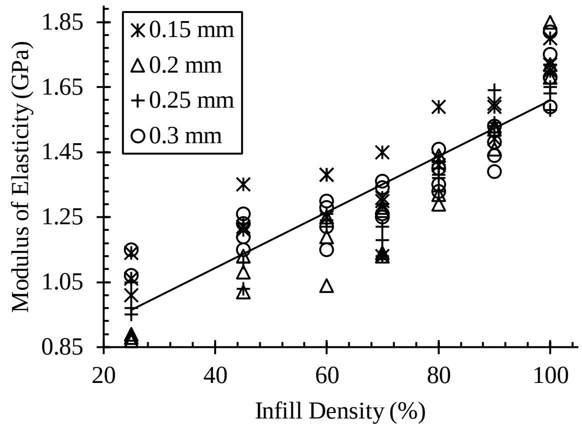

Figure 9. Diagonal samples comparison between modulus of elasticity and infill density.

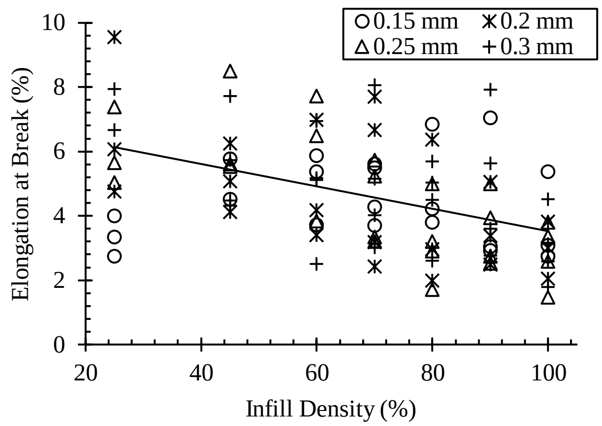

Figure 10. Diagonal samples comparison between elongation at break and infill density.

With respect to the concentric specimens, it is intuitive that as infill density increases so does tensile strength and stiffness, but, when reviewing Eq. (1)-(2), it is not so intuitive. That is, as infill density increases, only the voids within the component are filled leaving the dimensions and resultant cross-sectional area unchanged. However, it can be said that, the efficacy of the cross-sectional area increases as infill density increase, allowing strength and stiffness to increase.

When considering infill density the data indicate a significant difference between the concentric and diagonal patterns. This variance is contributed solely to pattern geometry. For instance, unlike the concentric specimens in the diagonal specimens as infill density increases voids are being filled but due to the way in which material is deposited (i.e. pattern) there is very little load bearing structure. That is, until 100% infill density is reached the only load bearing material that exists is the contour layers. Furthermore, when 100% infill density is reached the inferior filament-to-filament bonds are exposed to the applied tensile stresses unlike in the concentric specimens where these bonds are parallel to the stresses and thus are unaffected or *isolated*.

Now, when considering elongation at break we reason it is appropriate to discuss stress concentration. As stated previously, in the concentric specimens elongation at break remains fairly constant as infill density increases. This is due to an interchange between the amount of load bearing material deposited parallel to tensile stresses and the increased load bearing materials way of forming stress concentrators within the ABS structure. As infill density increases the amount of material available to absorb energy increases thus elongation at break increases, however, as the ABS structure becomes denser spaces between filaments essentially disappear, sometimes leaving long, narrow cavities with very sharp radius of curvatures, ρ. These sharp radii cause stress amplification, σ_{max}, in void zones which lead to premature failure as shown in Eq. (4), and thus decrease elongation at break. This interchange leaves elongation at break essentially constant over the domain of infill density.

$$\sigma_{max} = 2 \cdot \sigma \left(\frac{a}{\rho}\right)^{1/2} \tag{4}$$

The same reasoning can be used to explain why elongation at break decreases as infill density increases in the diagonal specimens. Except, as explained previously, in the diagonal specimens tensile strength is basically constant as infill density increases, therefore no interchange occurs and the resultant elongation at break is essentially a function of the stress concentrators that develop as infill density increases. Again, these stress concentrations cause premature failure consequently reducing elongation at break.

Layer Height

The data generally suggest that in the concentric specimens, changes in layer height has little to no effect on tensile strength, as shown in Fig. 11. However, when the data are viewed a little differently some interesting results are revealed (Fig. 12). That is, at greater infill densities tensile strength tends to decrease as layer height increases and at lower infill densities tensile strength tends to increase with increases in layer height. In the concentric specimens the transition from increasing to decreasing tensile strength with increased layer height occurs between 60% and 70% infill density. These results are consistent with references [4-5].

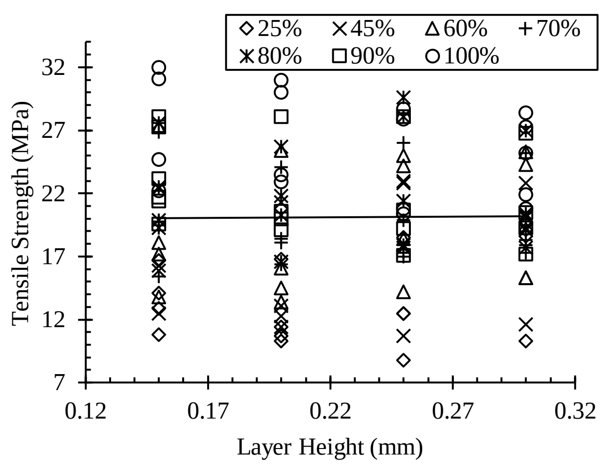

Figure 11. Concentric samples comparison between tensile strength and layer height.

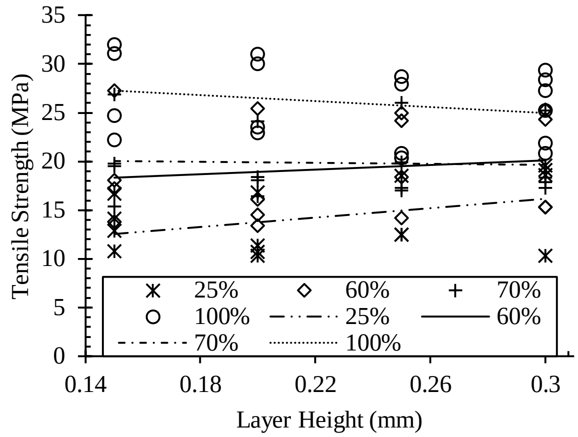

Figure 12. Concentric samples comparison between tensile strength and layer height, with respect to infill density.

Similar trends were observed in the diagonal specimens with respect to tensile strength verse layer height. Although there seems to be a general decrease in tensile strength as layer height increases (Fig. 13). This is contributed to the early transition from increasing to decreasing tensile strength with increased layer height which occurs between 25% and 45% infill density (Fig. 14). Thus all infill densities, with the exception of 25%, have a negative correlation between strength and layer height resulting in the general decrease in diagonal specimens tensile strength as previously described.

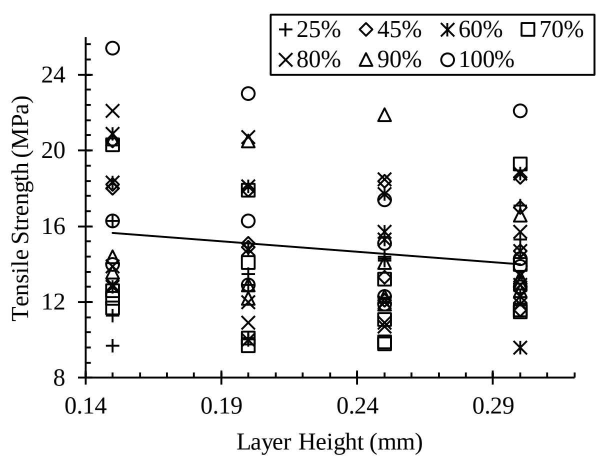

Figure 13. Diagonal samples comparison between tensile strength and layer height.

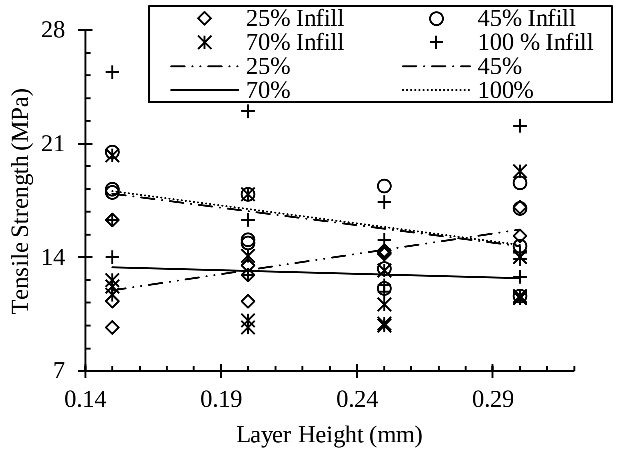

Figure 14. Diagonal samples comparison between tensile strength and layer height, with respect to infill density.

We suggest that the negative correlation between layer height and tensile strength in the greater infill density specimens is due to shrinking of the inherent voids of the FDM structure. That is, as layer height decreases the natural voids between filaments become smaller, in turn the ABS structure becomes denser and tensile strength consequently increases. This process is modeled in Fig. 15.

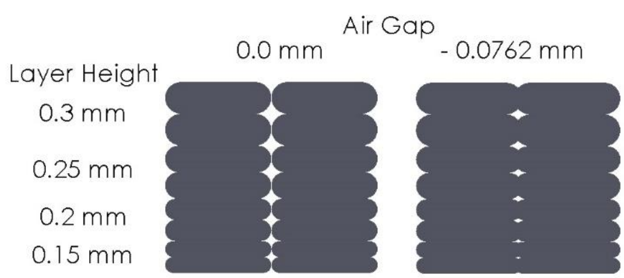

Figure 15. An idealized model of FDM filament cross-section showing layer height and air gap effects on part density ([0/0], 1.0 mm filament width).

One might suspect that, although overall void size is reduced, because layer height decreases there are more voids present within the same cross-section thus tensile strength should actually decrease. We also considered this and tested this notion by determining the percent area occupied by voids on a fixed surface area with varying layer heights. The results are shown in Fig. 16 and yield, for this idealized model, that void surface area increases nearly linearly with increases in layer height. These results underlie our speculation that layer height is an intrinsic parameter and it effects tensile strength by reducing void size between filaments.

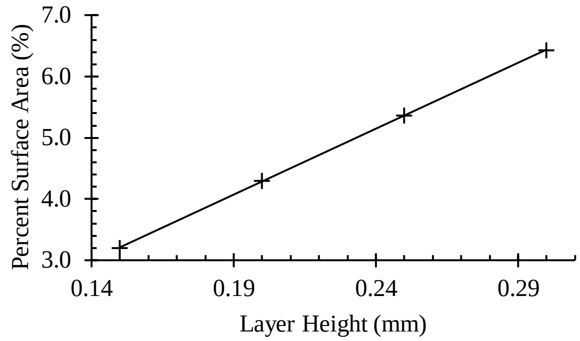

Figure 16. An idealized comparison between void percent surface area and layer height (1.5mm x 2.0mm area utilized for comparison).

Similar to layer heights effect on tensile strength, the data generally suggest that layer height has little effect on modulus of elasticity for both concentric and diagonal specimens (Fig. 17, Fig. 19). But again, when the data are viewed with respect to infill density a transition between increasing and decreasing stiffness is revealed (Fig. 18, Fig. 20). These transitions are similar to those identified in tensile strength – that is, at higher infill densities there is a negative correlation between layer height and modulus of elasticity, while at lower infill densities a positive correlation exists - although the transitions occur at different infill densities.

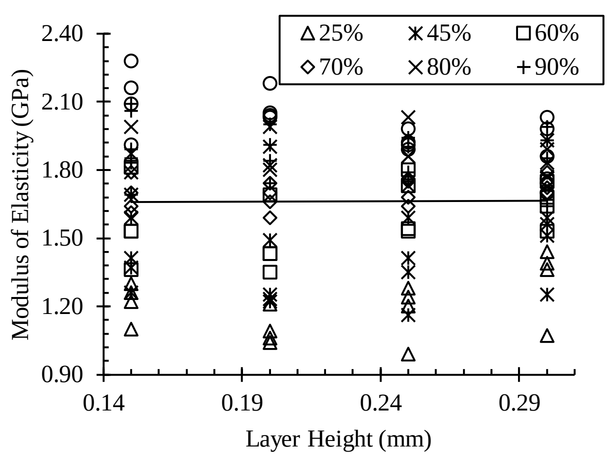

Figure 17. Concentric samples comparison between modulus of elasticity and layer height.

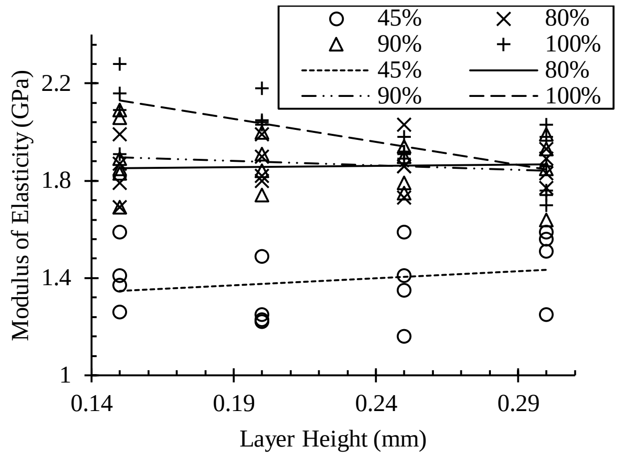

Figure 18. Concentric samples comparison between modulus of elasticity and layer height, with respect to infill density.

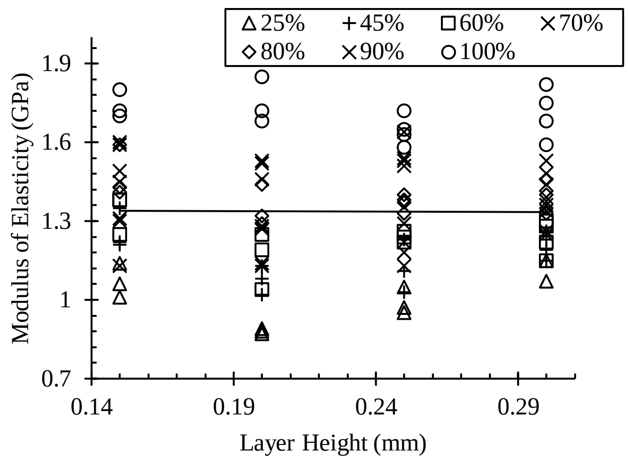

Figure 19. Diagonal samples comparison between modulus of elasticity and layer height.

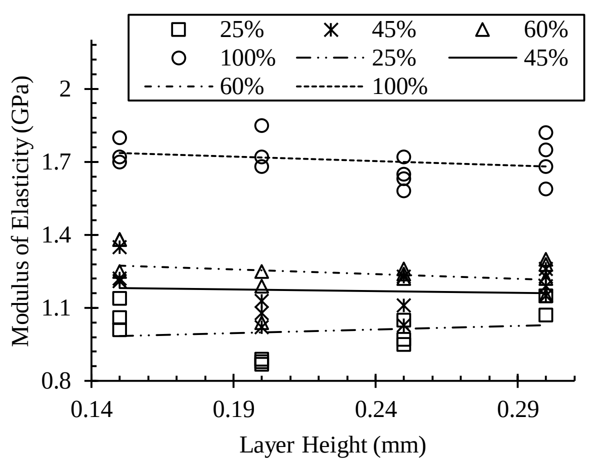

Figure 20. Diagonal samples comparison between modulus of elasticity and layer height, with respect to infill density.

The negative to positive correlation transition for concentric specimen occurs between 80% and 90% infill density, which is 10-30% greater than that seen in the tensile strength figures. Likewise, the transition for diagonal specimen occurs between 45% and 60% infill density, which is as much as 35% greater than previously observed. It is also noticed that the effect layer height has on stiffness in diagonal specimens is nearly trivial. Again, this points out the significant effect imperfect filament-to-filament bonds have on FDM part mechanical properties.

In general our data show that layer height has little to no effect on ductility in both the concentric and diagonal specimens (Fig. 21, Fig. 22). In fact, when looking at comparisons between elongation at break and layer height with respect to infill density, at nearly all infill densities ductility remains constant throughout the layer height domain, with the exception of those shown in Fig. 23. At 100% infill density, both concentric and diagonal specimens show a decrease in ductility as layer height increases. While at 25% infill density the diagonal specimens show significant gains in ductility as layer height increases.

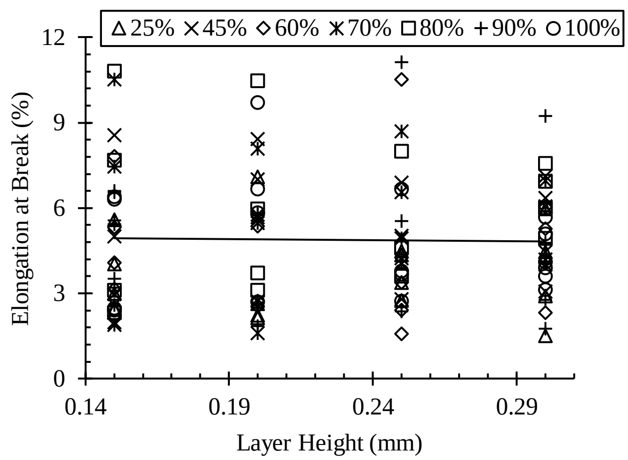

Figure 21. Concentric samples comparison between elongation at break and layer height.

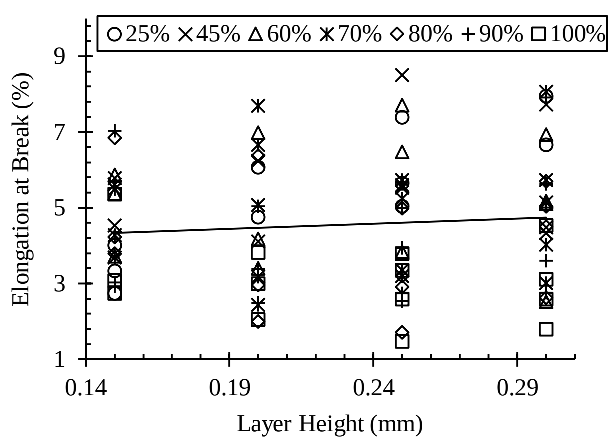

Figure 22. Diagonal samples comparison between elongation at break and layer height.

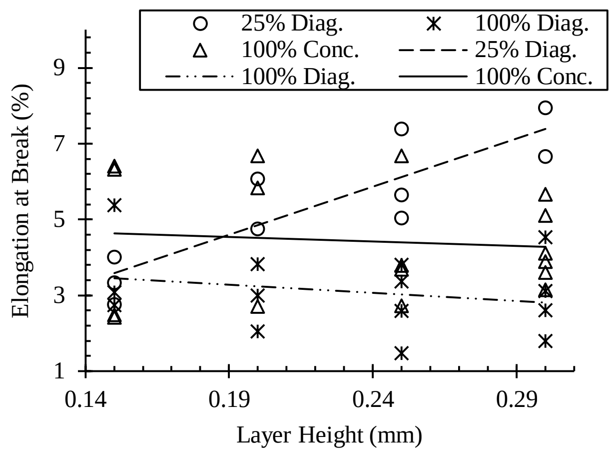

Figure 23. Conspicuous comparisons between elongation at break and layer height.

It is important to note that concentric specimens, when compared to diagonal specimens with respect to layer height and infill density always have greater strength, stiffness, and ductility. These results are consistent with those of reference [6]. This is contributed solely to the fact that in the concentric specimen filament-to-filament bonds are isolated from tensile stresses, whereas in the diagonal specimen they are not. However, if a tensile load were applied at any other angle – not parallel to the concentric filament – these results might very well be completely different. It is because of this that we classify raster orientation/printing pattern as an extrinsic parameter.

Air Gap

Although air gap was not considered as a variable input parameter within this study, a crucial insight regarding air gap and its effects on FDM mechanical properties was discovered during this undertaking. It was previously stated that a negative air gap – where adjacent filament partially occupy the same space – makes FDM parts denser and stronger [7-8]. This idea is shown in Fig. 15 and is similar to that of layer height as previously discussed. That is, as air gap decreases void size also decreases. Reference [8] showed this during tensile tests of specimens with [0/0] raster orientations. The gains in tensile strength where just slight, yet comparable to the gains we observed when analyzing layer height. Thus, it is fair to conclude that air gap effects tensile strength by altering void size, much in the same way that layer height does.

Moreover, bearing in mind what a negative air gap implies and considering that bonding between filaments is caused by local re-melting of previously solidified material and diffusion [1], we speculate that a negative air gap actually increases the quality of bonds. This is evident when [8] observed a negative air gap producing significant increases in tensile strength in specimens with [0/90], [45/-45], and [90/90] raster orientations, while tensile strength in [0/0] oriented specimens were only slightly effected. This means that significant gains in tensile strength were only observed in specimens whose orientation exposed filament-to-filament bonds to tensile stresses ([0/90], [45/-45], [90/90]). In the [0/0] raster orientation these bonds were isolated from stresses and only slight gains were observed – which are contributed to reductions in void size as previously discussed. Therefore, air gap is an intrinsic parameter that affects strength by both altering void size and varying bond quality.

Conclusion

This study performed an in depth analysis of the effect infill density, layer height, and printing pattern have on the mechanical properties of FDM manufactured parts. The mechanisms by which these input parameters – as well as raster orientation, air gap, build orientation, and filament cooling rate – effect mechanical properties were discussed. New vocabulary was introduced to classify these parameters in an attempt to provide clarity with regard to the way in which these parameters influence ABS structure. Speculations were made relating to the mechanisms by which mechanical properties are influenced by these input parameters. And finally, this study provided confidence that printer output is reasonable and sufficient to train, validate, and test an ANN.

It was discovered that rises in infill density had dramatic effects on resultant mechanical properties, increasing infill density: (a) significantly increased concentric specimen's tensile strength while having little effect on the strength of diagonal specimens, (b) caused modulus of elasticity to increase considerably in both concentric and diagonal specimens, and (c) had little effect on concentric specimen's ductility while actually decreasing the ductility of the diagonal specimens. The practical point being that in a concentric specimen – or one in which filament axis are aligned with tensile forces – infill density can be raised to significantly increase specimen strength and stiffness while leaving its ductility unchanged. These effects occur through gains in area efficacy.

It was revealed that in specimens of higher infill density increases in layer height led to decreases in tensile strength and stiffness and vice versa for specimens of lower infill density. The ductility of specimens were uninfluenced by changes in layer height. This effect is due to a decreasing layer heights ability to make the ABS structure denser by limiting void size between filaments. The useful fact being that by decreasing layer height, stronger and stiffer parts can be generated in the FDM process.

It has been shown that the concentric specimens, in light of the details of this experiment, is a superior printing pattern when it comes to strength, stiffness, and ductility. Keeping in context that the concentric specimens in this experiment aligned filament axis with tensile stresses and that any other load orientation would have very well revealed different results. However, we can conclude that: (a) a diagonal printing pattern is not conducive to bearing loads, (b) filament axis should be aligned as much as possible with tensile stresses in load bearing FDM parts, and (c) a rectilinear printing pattern is currently the nearest one can come to achieving two-dimensional isotropy.

The FDM manufacturing process generates parts with two natural defects – voids between filaments and imperfect bonds. Build orientation, raster orientation/printing pattern, layer height, air gap, and filament cooling rate effect mechanical properties by exposing or exacerbating these natural defects. Build orientation and raster orientation/printing pattern have been classified as extrinsic parameters because they indirectly effect mechanical properties by either exposing or isolating imperfect bonds to/from external loads. While layer height, air gap, and filament cooling rate have been classified as intrinsic parameters because they have direct effects on mechanical properties by either exacerbating or improving these natural defects. Furthermore, we suggest that changes in air gap not only have the ability to effect mechanical properties by enlarging or reducing void size, but more importantly, by improving or exacerbating filament-to-filament bonds.

Experimental Critique

Although we are confident that our experimental technique yielded reliable results, hindsight illustrates the importance of reducing temperature differentials, stabilizing conductive conditions, maximizing sample specimen count, and reducing stress concentrations thru proper test specimen designation. Future works shall utilize a printing enclosure/envelope, the printer shall be placed in a controlled environment, and ventilation within the environment shall be directed away from the printer. Specimen count per sample shall increase from 3-6 to greater than 20. Operating experience shows great success in premature failure reduction due to reduced stress concentration utilizing an ASTM D638 Type I [4-5] or an ASTM D3039 (229mm x 25.4mm x 3.3mm) [8] test specimen. Future works shall utilize one of these test specimen configurations in lieu of the ASTM D638 Type II that was used herein.

Future Work

Part 2 of this study will focus on utilizing an ANN to develop a partial solution to modeling the anisotropic behavior of FDM manufactured parts in two-dimensions. Specimens at 100% infill density, 0.15mm layer height, and -0.0762mm air gap will be printed using a rectilinear pattern with variable raster orientations. The following raster orientations will be used: [0/90], [15,-75], [30/-60], and [45/-45]. Test specimen tensile properties will be determined through tensile testing, then the tensile property data for the [0/90], [30/-60], and [45/-45] orientations will be used to train the ANN. The raster orientation will be used as ANN input and tensile properties will be used as output. Then the tensile data for the [15/-75] orientation will be predicted by the ANN during the validation and testing phase. Once this is complete the ANN can be used to accurately predict tensile properties in the XY-plane independent of load presence, population, and/or configuration. Reference [12] incorporated an ANN material model within a finite element analysis software to provide rheological behavior prediction that was more accurate than conventional models. Thus, a solution to modeling the two-dimensional anisotropic behavior of FDM manufactured parts is well within reach by this method.

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