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3D Printed Internal Structure: Influence on Tensile Strength

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Abstract

This paper discusses the research project and associated laboratory measurements that were assigned to a visiting international undergraduate student of materials engineering for the purpose of providing a research experience. This was the student's first visit to the in the United States of America. Buğra contributed significantly to the literature review and writing of this paper as a team, especially regarding the chemistry of acrylonitrile butadiene styrene (ABS). The professor taught him how to operate a scanning electron microscope. He is now in his third semester of graduate studies at Middle East Technical University in Ankara Turkey conducting research with light emitting diode chips. 3D printed plastic parts are composite structures, having specified porosity and density in different layers within each part. If a 3D printed part has an internal channel it produces a different internal build pattern than the same shaped part without the internal channel. In this research, build orientation and the existence of an internal channel were evaluated for their influence on tensile strength. The presence of an internal channel was found to have no influence on modulus of elasticity but significantly reduced ultimate tensile strength.

Research Experience of the International Student

The international student was expected to be involved in all aspects of the project including 3D printing specimens, operating the scanning electron microscope, environmental conditioning of specimens to ASTM standards, tensile testing and data collection, surface roughness data collection, literature review, statistical analysis, and the technical writing of this paper. The student was required to try all of the above and then expected to seek more depth in his area of choice.

It had been some time since he had taken a course in statistics so he enjoyed reviewing the equations to conduct the student t-test. He enjoyed the chemistry aspect of the literature review and wrote the initial drafts of those paragraphs in this paper. His English was typical for an international student's first visit and he enjoyed the team atmosphere of fine tuning the wording of the sections he wrote initially. He reviewed the entire paper for grammar and punctuation.

His goals were to experience the culture here as well as the academic environment of research. This increased his interest and he applied to a few graduate schools here in the United States of America. His final education decision was to pursue a graduate degree in Materials Engineering at his home university, Middle East Technical University where he is currently conducting research on light emitting diode chips.

Introduction to 3D Printing Plastic

In 2009, there were 29 companies selling additive manufacturing machines, 65 service providers, and more than 5000 users and customers[1]. 3D printing is one of the layering processes available within the field of direct digital manufacturing, also called additive manufacturing. The 3D printing process extrudes downward a tiny thread of molten thermoplastic which solidifies immediately after extrusion. Thread is laid down following a tool-path defined by the computer model until that layer is complete, then the part is lowered one thread diameter and the next layer is built atop the first. Layer by layer, as fine as 0.125 mm (0.005") thick, a composite structure of plastic is created to become any 3D shape that can be modeled on a computer.

The initial purpose of 3D printing was for visual prototypes before mass production, but recently it is being used as a production technique for complex shaped products[2]. Production of complex parts with 3D printing is without any temporary or permanent molds. This significantly reduces cost and lead times, relative to traditional plastic part production techniques such as injection molding. This is especially important for low volume production and products with short life cycles. Using 3D printing for production of finished parts increases the importance of the part's mechanical properties, which is a budding research field in materials engineering due to the composite internal structure.

Several thermoplastic materials can be used in the 3D printing process with acrylonitrile butadiene styrene (ABS) being a common material of choice. Some other materials used in 3D printing are ABS with additives, polycarbonates, PEEK, and ULTEM. For both prototyping and production manufacturing, the 3D printed parts are often coated to either seal and/or smooth the part's surface.

ABS is composed of three monomers to obtain the best properties of all three. The most important mechanical properties of ABS are impact resistance and toughness. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance[3]. The impact resistance can be amplified by increasing the proportions of polybutadiene in relation to styrene and also acrylonitrile, although this causes changes in other properties. Impact resistance does not fall off rapidly at lower temperatures. Stability under load is excellent with limited loads. Thus, changing the proportions of its components ABS can be prepared in different grades[3].

ABS-M30 is a great example for developed ABS's. ABS-M30 is 25-70 percent stronger than standard ABS and is an ideal material for conceptual prototyping, design verification, and direct digital manufacturing. ABS-M30 has greater tensile, impact, and flexural strength than standard ABS. Layer bonding is significantly stronger than that of standard ABS, for a more durable part. Moreover, optimization of the 3D printed build parameters can yield better mechanical properties.

Research Methods

Each of the four experimental groups contained eight replicates for tensile specimens, all were solid density ABS. Table 1 summarizes the experimental groups.

Experimental Group	Build Orientation	Internal Channel
1	Horizontal	None
2	Horizontal	Yes
3	Vertical	None
4	Vertical	Yes

Table 1 - Build Parameters of Each Experimental Group

Layer resolution in the Stratasys Vantage FSM machine was set to 0.51mm (0.020”) with a raster fill pattern (not contoured) and all parts on the build sheet were along the same axis for uniformity.

Tensile specimens with external dimensions specified in ASTM-D638-03 had a rectangular test section of 13mm (0.512”) x 3.2mm(0.126”) and two experimental groups had rectangular internal channel 1mm (0.039”) x 0.5mm(0.020”) centered in the test section, thereby slightly reducing the cross sectional area. Stress values were calculated using the respective cross section area, with or without the internal channel.

Two of the specimens in group 4 experienced stress concentration problems of breaking at the jaw or separate fractures on either side of the internal vacuum channel. These tensile data were excluded from the results of that particular experimental group. This reduced sample size for those experimental groups. This required the use of a pooled variance in the student’s T-test analysis.

Tensile tests were measured with an Instron model 4444 conducted in an environment controlled room at 74°F and 56% relative humidity after specimens had conditioned there for 48 hours. Tensile tests were conducted at a rate of 5 mm/min (0.2in/min) and data was collected at 20 points per second. Data was recorded for modulus of elasticity, ultimate tensile stress (UTS), and strain.

As a point of interest, surface roughness was measured with a Mitutoyo model SJ-201 on the largest surface of the tensile specimens. The three surface types of a 3D printed part are the under side, vertical wall, and top side. The 3D print begins the part with a layer of support material, then builds on top of that. The underside of the part is the first layer of ABS on top of the support material. Four specimens were selected at random. Roughness was measured on the underside, vertical, and top surfaces. Three replications of each measurement were made on each surface. In all, 36 roughness measurements were made, 12 underside, 12 vertical, and 12 top.

Results

The results of the surface roughness measurements are given in Table 2.

Material and Surface	Mean (Ra)	Std. Dev.
ABS Underside	20.44	1.18
ABS Vertical	18.60	0.19
ABS Top	22.04	1.27

Table 2 -Surface Roughness Measurements of ABS Parts

The results of the tensile test measurements are given in Table 3. This data includes the modulus of elasticity or tensile modulus, the ultimate tensile stress (UTS), and the tensile strain. Standard deviation of each data group is given based on the resulting sample size.

Experimental Group	**Description of Group**	**Resulting Sample Size**	**Tensile Modulus E (MPa)**	**E Standard Deviation**	**Tensile Stress @UTS (MPa)**	**Sress@UTS Std. Dev.**	**Tensile Strain**	**Tensile Strain Std. Deviation**
1	**Horizontal, No Channel**	**8**	**409.27**	**13.0**	**16.54**	**0.27**	**6.00**	**0.43**
2	**Horizontal, With Channel**	**8**	**418.71**	**17.7**	**16.12**	**0.25**	**6.10**	**0.15**
3	**Vertical, No Channel**	**8**	**463.23**	**25.2**	**19.55**	**0.25**	**5.10**	**0.50**
4	**Vertical, With Channel**	**6**	**456.92**	**15.6**	**18.08**	**0.34**	**5.33**	**0.86**

Table 3 - Experiment Results for Each Experimental Group

Analytical Methods

Statistical hypothesis testing using the student's t-test was used to compare experimental group means to each other. In every case the null hypothesis was that the two experimental means were equal and the alternative hypothesis was that they were not equal (a two tailed t-test). A 5% probability of a type 1 error (α=0.05) was used yielding a 95% level of confidence for results.

Technical Outcomes

Statistical evidence was found to conclude the following at the 95% confidence level:
The presence of an internal channel did not influence the modulus of elasticity or tensile strain. However, the presence of an internal channel did significantly influence ultimate tensile stress (UTS).

Vertical build orientation gave greater tensile strength the than horizontal orientation. This might be explained by the fact that in the vertically built parts, a larger percentage of fibers were oriented parallel to the tensile axis, whereas most fibers were 45 degrees to the tensile axis in the horizontally built parts. It is important to note that these fiber directions were simply the software defaults but are configurable. These results imply that slightly greater tensile strength in a specified direction is configurable in the 3D printing process, but that it could also cause a reduction in tensile strength in other directions. These anisotropic material properties are expected in 3D printed parts as is documented in the literature [4 & 5].

Ultimate tensile strength of specimens without an internal channel was higher than those with internal channels. It was obvious that the internal channel caused stress concentrations and lowered the tensile strength. This was observed occasionally in some of the trial runs and two of the specimens in this experiment. In these cases, the specimen sheared in a plane parallel to the tensile axis, exactly along the internal channel.

The presence of an internal channel and the build orientation may have an interactive effect on ultimate tensile properties, a designed experiment would be needed to explore this further. Surface roughness was measured on the bottom, side, and top of the 3D printed parts. These surfaces had different roughness values as expected. Applying a surface sealant would be expected to reduce the surface roughness.

In summary of the technical content, the presence of an internal channel within a 3D printed part was shown to influence ultimate tensile strength while not influencing modulus of elasticity.

Conclusions

This research experience was intended to give the international student an introduction to many aspects of research; operating lab equipment, statistics, and technical writing. The student seemed to enjoy all of the research environment as well as the cultural experience here in Wisconsin. He seemed to most enjoy reviewing the statistical methods of the student t-test and in particular, the pooled variance from differing sample sizes. Writing of the paper was conducted in a team environment expressly for the purpose of the student learning by editing and re-editing. This opportunity to do technical writing in a language other than his native language seemed to be an aspect that he appreciated as it improved his written English.

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