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Parametric Analysis of Building Parameters to MaximizeStrength of Material Using Additive Manufacturing

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Abstract: Fused deposition method (FDM) is of interest in material fabrication and productiondesign. With the introduction of 3-D printing, FDM has become increasingly prevalent as a tool and method due to its high efficiency and convenience in handling various geometries and material structure in production.Thispaper presents a study on the design/build parameters of 3D printing fused deposition to the mechanical properties of material. To gain insight into practical application, Taguchi experimental design methodology for a three-parameter (scan speed, layer height and print), three level (high, medium and low) study was used.The results showed a significant change in the mechanical properties resulting from the selection of various levels of these parameters, indicating that material properties such as strength may be manipulated with various level combination of the building parameters. Optimum levels of building parameters were further identified for achieving maximum mechanical strength of the material.
Keywords: Fused deposition method, 3D printing, Experiment design, Additive manufacturing

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I. INTRODUCTION

Additive manufacturing (AM) is defined as the process of joining materials layer by layer to create objects from 3D model data.As a technology with the ability to create unique objects with characteristics often hard to achieve with conventional methods, AM quickly attracted great interest in engineeringdesign and manufacturing, among industries and academic researchers. Brell et al. [1] presented roadmap for research in the area of additive manufacturing. To help from planning perspective for AM method, Zhang et al. proposed an evaluation framework [2]. Additive manufacturing takes different forms, such as Fused Deposition Modeling, 3D printing, selective laser melting [3]. AM allows parts to be designed with extremely complex geometries and at low cost compared to other manufacturing processes. AM also offers the ability to fabricate different parts using the same machine, making it appealing for low volume product production which would otherwise be prohibitively expensive [4]. However, to expand the scope of end-user applications, one of the major challenges is to increase mechanical properties, such as strength of the material, with increased deposition rate. These challenges limit its engineering applications, especially those under demanding dynamic loading conditions such as machinery parts. As additive manufacturing becomes more prevalent, it is necessary to understand how the mechanical properties of the final products can be controlled [5,6].

In AM, such as the typical Fused Deposition Modeling, fusion of adjacent layers typically dominates the properties of material. Filament and deposition orientation largely determine the anisotropic properties of the material. Many build parameters an affect the material properties of the final product. These parameters include the number of contours within a layer, building orientation, raster angle, air gap, deposition speed, volume rate, temperature, etc.Material property change with AM build parameters, such as build orientation, raster angle and nozzle diameter has been reported.Bellini and Güçeri[7] studied the mechanical characterization of products fabricated using fused deposition modeling.Lee et al. [8] studies the layer thickness, raster angle and air gap to the output performance of the throwing distance from the prototypes. To relate material property of the part by AM method, Lee et al. [9] proposed method measuring the material anisotropic compressive strength for various building parameters.Soodet al. [10] used central composite design and response surface to study effects of layer thickness, orientation, raster angle, raster width and air gap. Further study was done to predict compressive strength of the building material [11]. Bagsik [12] conducted studies of the processing parameters with parts build with thermoplastic ULTEM 9085. Many other studies have been done as well on various materials, such as Domingos's study on morphological and mechanical properties of 3D Bio-extruded poly ;Ziemian's study on the anisotropic mechanical properties of ABS [14]; Park's study on lattice material [15]; Carroll's study on Ti-6Al-4V [16]. Design structures using AM method are studied by researchers. Liang et al.'s investigation on the design and manufacturability of periodic lattice structure using selective laser melting AM method

[17].Gabbrielli conducted study on Foam geometry and porous material [18].Furumotostudies permeability and strength of a porous metal structure built by using AM method [19].

Among the building parameters, some of these parameters may play more significant roles than the others in affecting the material properties of the final product. It is evident that the individual parameters with the greatest effect can be obtained based on the current knowledge realized from the many studies done in the AM field. An effort was made to determine if build parameters could be optimized to achieve better mechanical properties of materials under general loading conditions.In the work, an in-depth study of the individual parameters as well as the combination interactions of various building parameters are conducted. To achieve knowledge of optimization of AM build parameters and operational factors to achieve increased mechanical properties, three-parameter and three-level studies have been carried out, and Taguchi experimental design technique was used.A widely used Ultimaker2 3D printer was used to represent the AM method in 3D printing field. This work,provides fundamental knowledge of how and to what extent the various AM build parameters and level factors may affect the mechanical properties of material. These are valuable in design AM 3D printing technologies, in material fabrication using AM 3D printing techniques, and in optimizing AM 3D printing operational configurations.

II. EXPERIMENTAL DESIGN AND PROCEDURES

2.1 Experimental design –

Three parameters were chosen for study: extruder temperature, deposition rate, and layer thickness. Each parameter was tested at three levels. These levels include:1-min, 2-med, and 3-high as shown in **Table 1**. The high and low bounds of each parameter were chosen based on the printer's maximum and minimum settings for that parameter. The intermediate levels were obtained by taking the average of the maximum and minimum values. The temperature is chosen from 200^{o}C–225^{o}C–250^{o}C; the material deposition rate is chosen from 30mm/s–55mm/s–80mm/s; and the material deposition lay thickness is chosen from 0.05mm–0.13mm–0.2mm.

Table 1.ExperimentalParameters

Level	Extruder Temperature [^{o}C]	Deposition Rate [mm/s]	Layer thickness [mm]
1 (low)	200	30	0.05
2 (med)	225	55	0.13
3 (high)	250	80	0.20

To efficiently conduct the study, a proven Taguchi technique was employed to create a total of reduced combination of testing groups without losing the final data significance. Based on this method, a total of nine sample groups (from 27 possible configurations) were created. Each of the nine sample groups is designated by letter (i.e., *trial a*, *trial b*, and so on). In accordance with the Taguchi method, the 3-parameter 3-level experimental design matrix is found and the nine trials (from *trial a* to *trial i*) and their corresponding levels (level 1, 2 and 3) are presented in the following **Table 2**. The numbers 1-3 in the parameter/ level columnof **Table 2** correspond to the values listed in Table 1 for the corresponding parameter.

Table 2.3-Parameter 3-Level Experimental Design Matrix

Trial #	**Parameters**		
	Temperature	Deposition rate	Layer thickness
a	1	1	1
b	1	2	2
c	1	3	3
d	2	1	2
e	2	2	3
f	2	3	1
g	3	1	3
h	3	2	1
i	3	3	2

2.2 Sample design and fabrication –

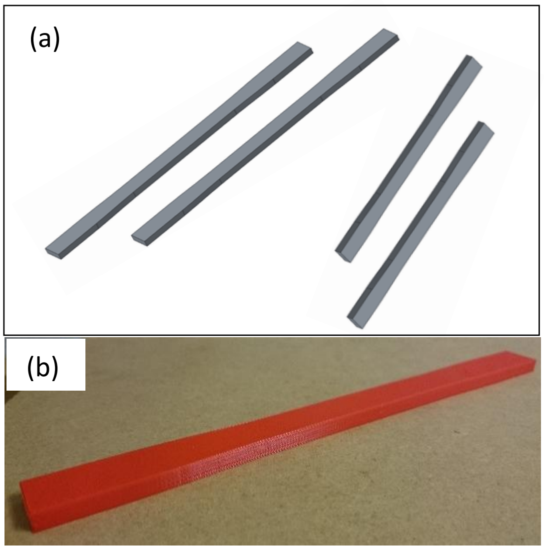


Figure 1. Example of (a) the designed specimens, and (b) a printed testing specimen

PolyLactic Acid (PLA) was chosen as the sample material. PLA was selected as a representative material because 1) biodegradable thermoplastic has no or less environmental impact concerns; 2) it has been used such as used for packaging material, plastic wrap, plastic containers, and biomedical devices such as in orthopedic fixation and sutures; **Figure 2**below shows an example of a microscope-to-digital camera adaptor designed and fabricated using the same PLA material. 3) the strength to weight ratio of PLA is good,but may be further increased such that the engineering application may be widen. If the mechanical strength of the material can be increased with the optimized building parameters, the application of PLA may be expanded to in higher load conditions. Further, this will benefit both the design of new AM technologies, and the design and fabrication of new material with enhanced material strength.

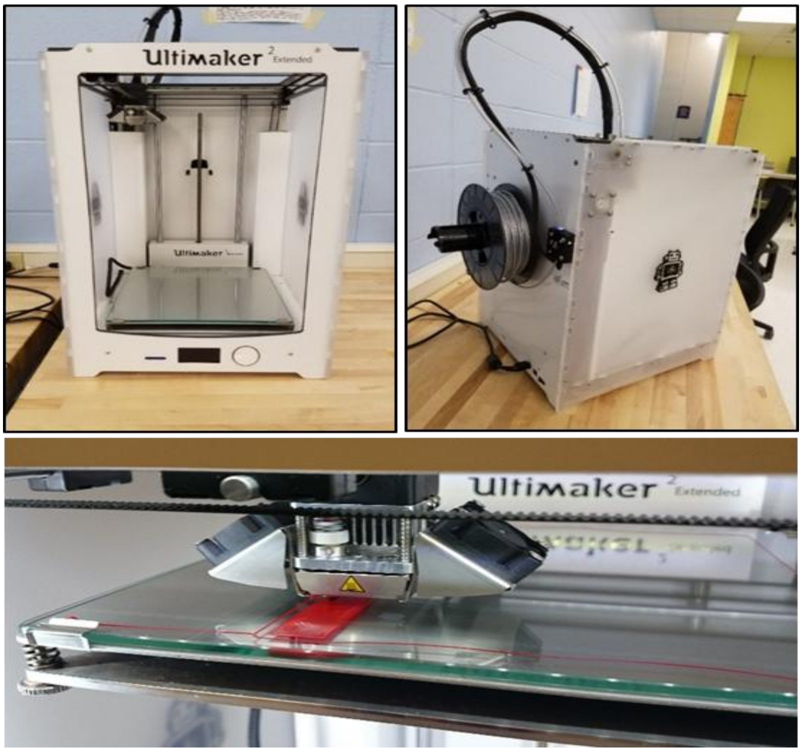
Figure 2. Various micro scope-to-digital camera adaptors made of PLA

The samples for the nine trials were printed using the Ultimaker 2 (as shown in **Figure 3**) based on the experimental design matrix showed in **Table 2**. For example, the sample for *trial a* was printed with a temperature of 200 ^{o}C, a speed of 30 mm/s, and a layer thickness of .05mm.

Three samples were created for each trial to reduce possible error in the testing data. In order help ensure the reliability of the downstream tests, a procedure was developed to control outside variables:

- Each specimen was printed from the same 3-D drafted “dog-bone” shape
- Each specimen was made using the same printing machine (Ultimaker2)
- Each specimen was printed using the same PLA filament material
- All specimens were printed and stored in the same lab location at a constant temperature and humidity

After the printing was complete the following procedure was used to test the tensile strength of each specimen.



2.3 Material testing –

To maintain consistent testing conditions, all testing was done in a lab setting held at a constant temperature and humidity. MTS Material Test System810(as shown in **Figure 4a**), and data acquisition system (as shown in **Figure 4b**) were used for all tensile tests with all configurations consistent.

(a) (b)

Figure 4. a) 810 Material Testing System, and b) data acquisition system

In the test, the width and thickness of the printed specimen were measuredat the center ($3\frac{15}{16}$ inches from either ends). The measured width and thickness were used to calculate the cross-sectional area of the specimen. After the initial measurement, the specimen was placed into MTS testing machine with approximately 1.5 in of the specimen held with each pressure clamp.Tensile test began with specimen experiencing an increase of 0.02 kips per second. The data acquisition software analyzed the load and displacement every 0.25 seconds, and the test continued until specimen fracture. During the test, loading conditions and stress-strain information were recorded by the real-time data acquisition system.

III. RESULTS AND DISCUSSION

3.1 Mechanical strength

Mechanical ultimate tensile strength of the specimens were tested using the method discussed in section 2.3.Corresponding stress and strain data were collected. The stress-stain curves from initial step load to final fracture of the material were created. **Figure5** shows the stress-strain relationship for the nine trials from *trial a* to *i*. To reduce the possible variation in the building process, three specimens were used for each trial group.In the stress-stain curve, the corresponding stress and strain are the average values of the three specimens in each trial. The final fracture point is determined using the fracture failure point of the weakest specimen within each trial. It is observed that the material building factors significantly affected the ultimate strength of the material. The degree of effect of building parameter and level to the ultimate strength of material varies. For the tested specimens, the trial with the highest average ultimate strength(*trial a*: 4.05ksi) is 4 times that of lowest trial (*trial c*: 1.01ksi). This observation indicates the importance of manipulating material properties by using optimized building parameters and the corresponding levels. The results show the brittle aspect of the 3D printed PLA material. However, the ductility of the various trialsare different in average. The building parameters and their level can affect the ductility of the material as well. Assume there exists elastic region and this region can be represented by the short dashed line for the stress-stain curves shown in Figure 5, the modulus of elasticity various between 50ksi to 300 ksi among the samples. The observations confirm that building parameters can significantly affect the properties of the material.

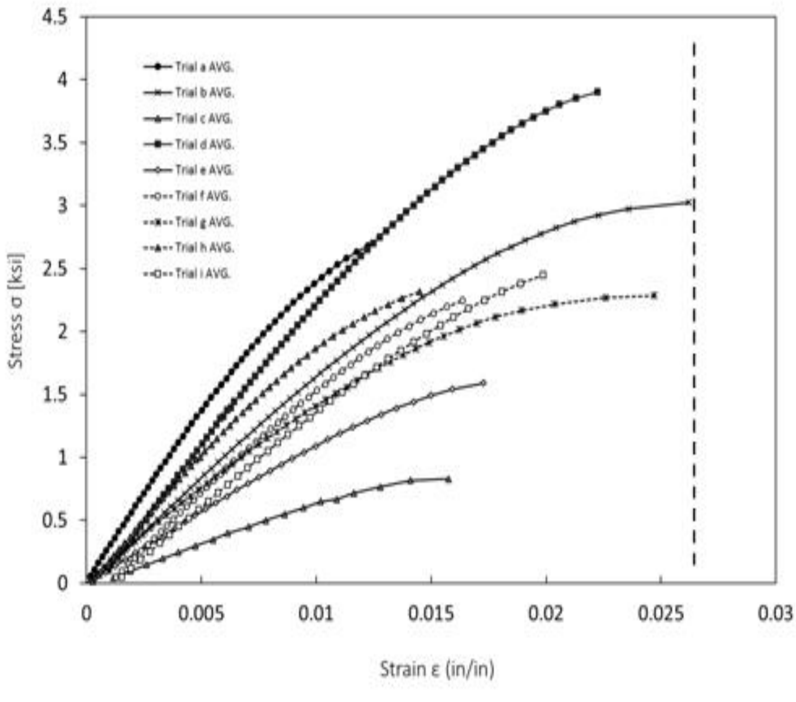


Figure 5. Stress-Strain curve using average data values

For comparison purpose, the stress-strain curve for the strongest specimen of each of the nine trials is presented below as shown in **Figure 6**. Similar observations to **Figure 5** can be made in **Figure 6**. The lowest strength (0.84ksi) is in *trial c* and the highest strength (4.15ksi) occurs in *trial d*. The highest strength is about 4.9 times that of the lowest one. This is comparable to the observations made in the average value presented in **Figure 5**. For the specimen with highest strength, the extended tail shown in *trial d* and *trial b* are believed variations. The fracture point of the material tested may be reasonably estimated to be at the point indicated by the vertical dash line in both **Figure 5** and **6**. For the data shown in both figures, non-linear relationship between stress and strain is generally observed, but the linear elastic part is not obvious seen.

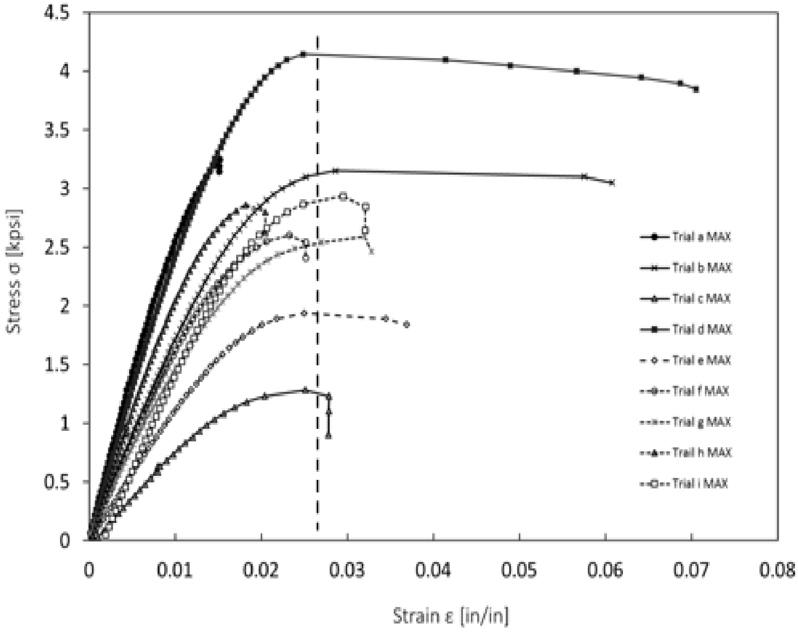


Figure 6. Stress-Strain curve of the strongest specimen in each trial

3.2Material facture failure

Fracture failure images were taken as well. **Figure 7** showsthe fracture location and surface of the strongest specimen from each of the trials. It can be seen that the location and shape of the fracture varied significantly from one sample to another. It is reasonable to believe that the building parameters and their corresponding levels contributed to the fracture phenomena since each of the samples were handled the same during the tensile tests. However, how and to what extent a building factor affects the fracture location and shape cannot be concluded in general.

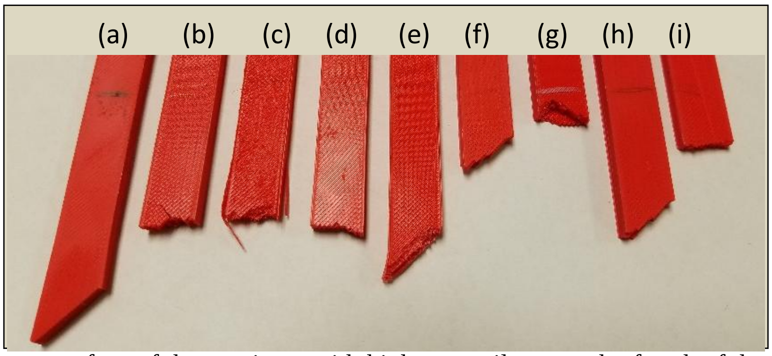


Figure 1. Fracture surface of the specimen with highest tensile strength of each of the trials a-i

As shown in the figure, the fracture cross sections varied from one sample to another after inspection of the samples, but no apparent correlation between the cross sectional area of the fracture and the strength of the specimenthat was calculated. The fracture patterns observed seemed random, some followed an angle at which the filament was laid and some broke straight across the specimen perpendicular to the direction of the force. Although the location and shape of the fracturevaried in an unpredictable manner, the magnitude of the standard deviation from one trial to the next was small in comparison to the differences in the average strengths of the trials. No obvious necking occurred for all the tested specimens. Theseshowed the properties of brittle material. Also, it suggested somehow that it was not the final cross sectional area of the fracture that dictated the difference in the strength of the specimens, but rather the difference in their building parameter combination.

3.3AM building parameter and level analysis

It is observed that AM building parameters affect the strength of material significantly. This section attempts to analysesthe significance of each building parameter to the strength of material, and to identify the optimal building parameter combination to achieve better strength of the chosen material. It was stated previously that Taguchi methodology was utilized to efficiently complete the experiment without sacrificing the value of information gained from the results. Taguchi methodology highlights three signal-to-noise ratioapproaches for data analysis, namely "the larger is better", "nominal is best", and "smaller is better". "The larger is better" analysis method searches for a parameter combination most likely to result in a larger response. In order to find the parameter combination that results in the highest tensile strength "the larger is better"signal-to-noise ratio (S/N) was chosen in this study. The equation for "the larger is better" calculation is shown below in Equation (1),

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{x_i^2}\right) \quad (1)$$

where x is the sample response (here it's the strength of the material) and n is the sample number.

Table 3 Below is the experimental data (collected during the sample testing) that were used to complete the parametric analysis of the test.In the table, the maximum strength (in ksi) of each of the three samples in each trial is recorded. The average response (strength of the material) of each trial is taken and shown in the table. The signal-to-noise ratio of each trial is further calculated based using Equation (1), and the standard deviation is also recorded. For the tested trials,the trial with the highest average ultimate strength (*trial a*: 4.05ksi) is 4 times that of lowest trial (*trial c*: 1.01ksi) as aforementioned (section 3.1). This indicates the significant effect of building parameters to the strength of material. It is noticed that the standard deviation of each trial group is relatively small with 0.317 to be the highest and 0.067 to be the smallest. This shows that the material strength is comparable and predictable if the building parameters in AM are specified for their levels.

Table 3.Material tensile strength under designed building conditions

Trial	Parameters			Max Response (ksi)			Average Response (ksi)	SN_L	SD
	A (Temperature)	B (Deposition rate)	C (Thickness)	Sample 1	Sample 2	Sample 3			
a	1	1	1	2.669	3.183	3.246	3.033	9.534	0.317
b	1	2	2	3.022	3.050	3.151	3.074	9.751	0.067
c	1	3	3	0.840	0.923	1.282	1.015	-0.278	0.235
d	2	1	2	3.984	4.029	4.147	4.053	12.153	0.084
e	2	2	3	1.940	1.594	1.632	1.722	4.622	0.190
f	2	3	1	2.592	2.259	2.603	2.485	7.849	0.195
g	3	1	3	2.270	2.591	2.502	2.454	7.758	0.166
h	3	2	1	2.863	2.352	2.844	2.686	8.473	0.289
i	3	3	2	2.934	2.483	2.461	2.626	8.302	0.267

Parametric analysis of the building parameters (building temperature, deposition rate and layer thickness), and their corresponding levels (1-low, 2-med, and 3-high) were further studied.

The contribution of each parameter to the specimen response was further evaluated through use of Taguchi parametric methodology.Each parameter (Temperature, Deposition Rate, and Layer thickness) was evaluated separately in order to draw conclusions as to how changing the parameter level effected the strength and signal to noise ratio of the printed specimen. Evaluation was completed by averaging the average response responses(Average Strength) andSN_L for specific level of each building parameter of those trials printed at the same level under the specified parameter. For example, to evaluate the effect of low temperature printing on the strength of printed parts, the average strength response of *trials a*, *b* and, *c*were averaged. This method was used for each parameter and done for each building level. **Table 4** shows the average response (strength of material) and signal-to-noise level obtained for each building parameter at its' specific respective level. With this data, the significance of each building parameter and its specific level can be analyzed. This makes the identification of a combination of optimal building parameter levels possible in order to achieve maximum strength of material.

Table 4. Taguchi Parametric Evaluation

Level	Parameter Effects					
	A (Temperature)		B (Deposition rate)		C (Layer thickness)	
	Avg. Stress (ksi)	SN_L	Avg. Stress (ksi)	SN_L	Avg. Stress (ksi)	SN_L
1-Low	2.374	6.336	3.180	9.815	2.735	7.486
2-Med	2.753	8.208	2.494	7.615	3.251	8.453
3-High	2.589	8.178	2.042	5.291	1.731	6.783

The effects of building parameters and their respective levels are charted for better analysis and gain insights the relationship of these parameters and the levels to the strength of material. Figure 8below shows both the results for "thelarger is better" analysis and the parametric analysis of the average stress from each trial.Figure 8(a) shows the average response (average strength) of material to low, medium and high levels for building parameter temperature;Figure 8(b) shows the average response of material to low, medium and high levels for deposition rate; and Figure 8(c) shows the average response of material to low, medium and high levels for layer thickness.

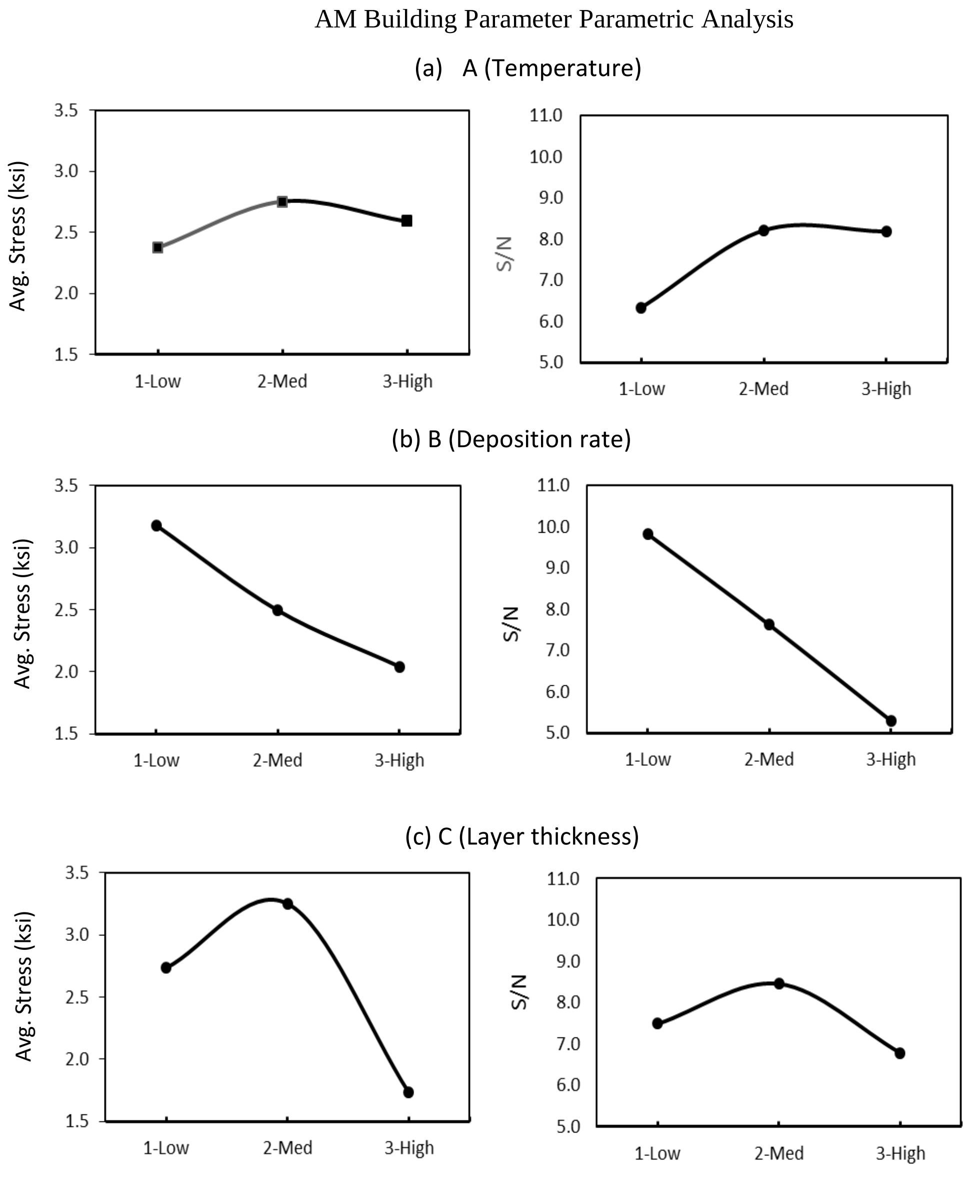


Figure 2. Parametric analysis of building parameter(a) Temperature, (b) Deposition rate, and (c) Layer thickness to the strength of material

For temperature effect, it can be clearly observed (in **Figure 8(a)**) that medium temperature leads to a highest strength (2.753ksi) with a highest signal-to-noise ratio. Both low and high temperatures resulted in reduction in material strength.Inferences were made that the lowest temperature level did not allow for consistent bonding between extruded filament layers. This would lead to the layers being unable to work together to withstand tensile force. Decreased strength from the highest temperature level is possibly due to a change in the mechanical properties of the filament at excessive temperatures.For deposition rate effect, it can be observed (in **Figure 8(b)**) that lower deposition rate leads to a highest strength (3.180 ksi) with a significantly higher signal-to-noise ratio. The increase in deposition rate resulted in decreased strength of the material. This could be related to the failure of the machine nozzle head to be efficiently moved to match the extrusion speed. Trials printed with higher speeds had more drastic inconsistencies across the specimen; some sections were more porous than others. Each of the samples printed at higher speeds failed in an area with visibly higher porosity (space between layers). For the effect of layer thickness, it can be observed (in **Figure 8(c)**) that medium layer thickness leads to a highest strength (3.251ksi) with a higher signal-to-noise ratio.The increase or decrease in layer thickness resulted in decrease in strength of the material.This was credited to two factors that must balance: (1) density of filament layers and (2) individual layer strength. Greater layer height yields greater cross sectional area of each layer, and thus a greater ability to withstand force. Furthermore, the decreased strength from the smallest layer height was considered to be due to early local failure of a filament layer which led to complete specimen failure. For those trials printed with the largest layer height, failure was accredited to an insufficient density of layers, or in other words not enough filament fibers resisting the tension per specimen cross sectional area.It is evident from the analysis above that the combination of medium temperature, low speed, and medium layer height yield the highest tensile strength for a printed part.From these analyses, better material properties can be achieved using AM methods at optimal building parameter levels. This result agrees with the results from the initial tensile testing that was done for this experiment. Trial d had the same parametric combination (temperature 225^{o}C, deposition rate 30mm/s, layer thickness 0.13mm) suggested by the data and also had the largest average tensile strength of all the trials (4.053 ksi).

IV. CONCLUSION

The study presented the effects of building parameters to the strength of material using AM method. Experiments were designed to investigate whether or not one could significantly change the strength of a AM printed part by selecting its building parameter levels in the set-up stage of the print. The parameters tested were layer height, print speed, and extruder temperature. Each of the three parameters were tested at three levels using Taguchi test methodology. The results from the testing data showed significant differences in the tensile strength and elasticity of the trials. Fracture geometry also varied from sample to sample but it was concluded that this did not affect the merit of the experiment. It was shown through the Taguchi test methodology that the strongest part (with high test tensile strength) would come from a combination of medium temperature, lower speed and medium layer height. From this analysis, better material properties can be achieved using AM methodsatoptimal building parameter levels. This conclusion was paralleled by the results from the tensile tests. Furthermore, the data also suggest additional applications for AM printing parameter manipulation. Further research could result in prints being made to have specific material properties that fit its application (to break under specifies load, or deform to a specified degree). The insights gained are valuable for new material development as well as for designing and developing new AM technologies for achieving preferable material mechanical properties.

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