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Optimizing the Design for Additive Manufacturing Project in the Manufacturing Processes Lab Course Using the Taguchi Orthogonal Arrays

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Abstract:

As 3D printing technology becomes more extensively used and more users have access to its immense potential, questions regarding which machine parameters affect the performance of the produced object arise. One of the primary projects taught and implemented in the Manufacturing Processes Lab course is the Design for Additive Manufacturing (DfAM). One of the key challenges I had when executing this procedure was determining how to optimize the 3D printing parameters and increase the quality of the manufactured items. In the other course, Design for Manufacturability (DfM), that I am teaching, I was presenting Taguchi Orthogonal Arrays and Quality Loss Functions (QLF) as tools for Design for Quality projects in the DfM course. In the Manufacturing Processes Lab course, I opted to use Taguchi Orthogonal Arrays to investigate the performance of the DfAM project in the Manufacturing processes course. This report seeks to address some of these 3D printing difficulties. The Taguchi Orthogonal Array (L_8 (2^7)) was performed 3D printing systems to assess the effects of 3D printer settings on part quality.

In this evaluation, there are six factors (width, thickness, radius of fillets, temperature of nozzle, layer direction, and layer height) were investigated in this experiment, as well as one interaction between two factors. The width and layer height interaction were investigated. Three trials of eight distinct tensile strength experiments were performed to test the factors. The Taguchi orthogonal array was used to calculate the factors applied to each sample, and each factor was examined. The evaluation revealed that the width and thickness of the pieces were the most significant factors. Except for nozzle temperature, all lower values for the six parameters were shown to have a higher strength-to-weight ratio. The best signal-to-noise ratio was found in Experiment 1. When both parameters (width and layer height) were at Level 1 (lower values), the interaction between them was shown to be the best. Based on desirable qualities, the optimal strength-to-weight ratio was determined to be 35.09 MPa/g.

Keywords:

Additive Manufacturing, Design for Quality, Taguchi Orthogonal Array, Design for Additive Manufacturing, Quality Improvement, Process Optimization

Introduction

Manufacturing has grown substantially in the previous few decades. Today, the possibilities for converting raw materials into useable parts or products (via various manufacturing processes) are practically limitless. Manufacturing research is always focused on inventing and implementing manufacturing processes that are cheaper in cost and waste and have a greater output rate.

Currently, there is rapid and significant variance in product design, as well as intense market competition due to global competition. Design for Additive Manufacturing (DFAM) is one of the key approaches for achieving global manufacturing competition. Additive Manufacturing (AM) is a 3D printing technology that uses fused material to build three-dimensional objects layer by layer. AM is the dominating current and future manufacturing method.[1] Comparing additive manufacturing (AM) procedures to subtractive processes, such as machining and other forms of manufacturing, they are thought to be simpler. This is due to the fact that creating a part using AM is easier than creating the identical item using multiple subtractive manufacturing methods (like casting and then machining). Using additive manufacturing (AM) techniques may produce the same produced parts in less than half the time and at a fraction of the cost of subtractive manufacturing processes, which can need millions of dollars.[2] Furthermore, by producing the part in a single process, subtractive manufacturing does not require multiple skilled workers—rather, it only needs one informed worker.

A variety of factors influence the quality of 3D printed things. The type of material used, the shape of the object, the temperature of the printing tool, the thickness of each layer, the orientation of the layers, and the orientation of the product itself are among these parameters. I chose six factors and one interaction to investigate in order to determine how these factors effect the strength and weight of the printed pieces. To obtain trustworthy results, I repeated eight different types of tests three times. I concentrated on identifying the most essential factors by comparing the values of each factor at various levels.[6]

A tensile test sample shape was used in this study, which is a popular choice for assessing the strength of 3D printed things. I focused on how much power the plastic sample could withstand before breaking. Following the Taguchi Orthogonal Array method, I attempted to enhance the strength of our product by taking many elements into account throughout manufacture. I used an efficient method to achieve accurate and precise findings. Two levels of each factor have been investigated. In this work these factors and their levels have been depicted in Table 1 and a visual representation of used sample in this is shown in Figure 1.

Table 1: Factors Tested within the Experiment

Factor	Type	Description	Level 1	Level 2
X1	Quantitative	Width	4mm	6mm
X2	Quantitative	Thickness	3mm	5mm
X3	Quantitative	Radius of Fillets	7.875mm	10.875mm
X4	Quantitative	Temperature of Nozzle	180 C^0	200 C^0
X5	Quantitative	Layer Cross Structure Direction (Lattice Structure)	Parallel to the base	45^0 to the base
X6	Quantitative	Layer Height	0.16mm	0.2mm

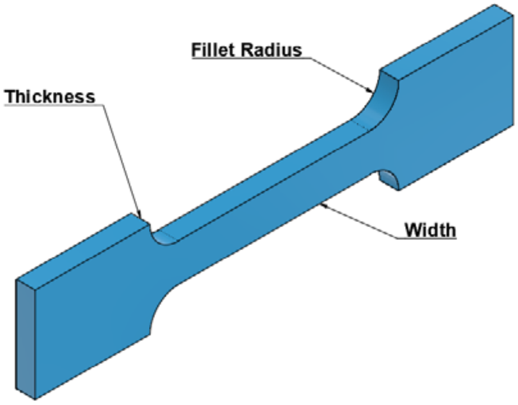

Figure 1:General Shape of the Tensile Test Sample

Figure 2 shown below represents the lattice structure for printing. Two different cross-sectional structures used as two levels of lattice structure, parallel to the base and 45^0 to the base.

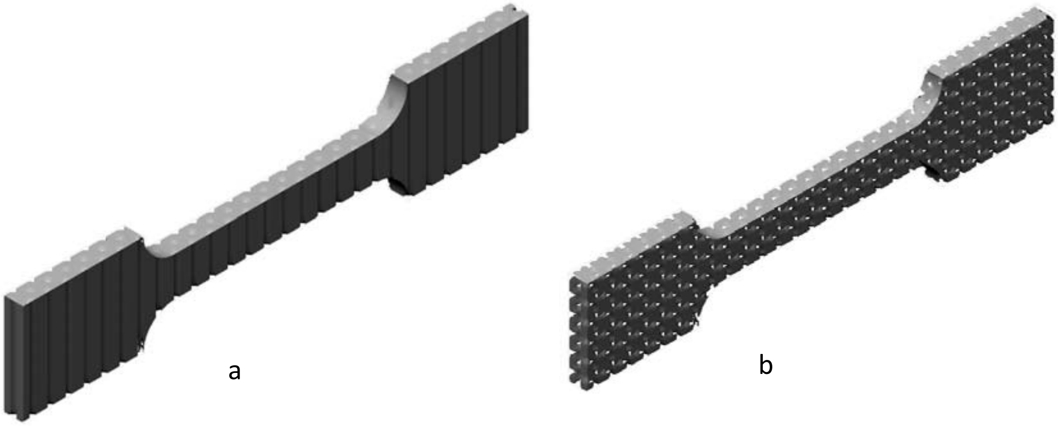

Figure 2: Lattice Structure for the Tensile Test Sample: a) parallel to the base, b) 45^0 to the base

Eight experiments were carried out to examine factors and interactions, each with three iterations, and the mean of the results was chosen. To compute the fracture strength, the fracture force was divided by the cross-sectional area of each specimen, and the strength was divided by the mass of each specimen to calculate the strength to weight ratio. The thickness and width were interpreted thickness and width as the most relevant considerations for this example after studying the response table. The anticipated value is derived using response graphs based on the overall average and each element.

The best factor combination: X1, Level 1, X2, Level 1, X3, Level 1, X4, Level 2, X5, Level 1, X6, Level 1, X1X6, Level 1. That is, employing a smaller width, a thinner layer, a smaller radius, a higher nozzle temperature, a parallel layer direction, a thinner layer height, and a smaller width to layer height interaction. Because a hotter nozzle performs better in increasing material strength, an increased nozzle temperature (X4) was chosen. Because the factor has little effect on the experiment, the temperature was increased from 180 C0 to 200 C0 without a noticeable loss in quality. The signal to noise ratio has been calculated to determine which experiment had the highest tensile strength as effective for the experiment.[4]

Methodology

After tossing around a few ideas, it was agreed that sample-shaped 3D printed plastic components would be investigated to determine which kinds of ABS plastic would provide the best strength-to-weight ratio. Six factors and one interaction between two factors were evaluated in eight studies. For a total of 24 testing pieces, eight experiments were repeated three times. Because the output of these studies would be strength to weight ratios, the mass was estimated using chemistry department scales. The sample was tested using a Shimadzu tensile testing machine. Trapezium, a computer application, was utilized to set up the tensile tests and record the exact force and stroke of the machine at each time step. Each item was tested at a common jaw stroke speed of 3 millimeters per second. Once the pieces were locked inside the Shimadzu's jaws (one at a time), the stroke and force were calibrated, and the test was run. The data was saved using Trapezium, and the ultimate force values were saved in a Microsoft Excel calculation table. Figure 3 shows examples of what the specimens looked like in the machine's jaws. This procedure was carried out for each of the 24 experiment components. Figure 4 depicts all of the parts both before and after testing. [3]

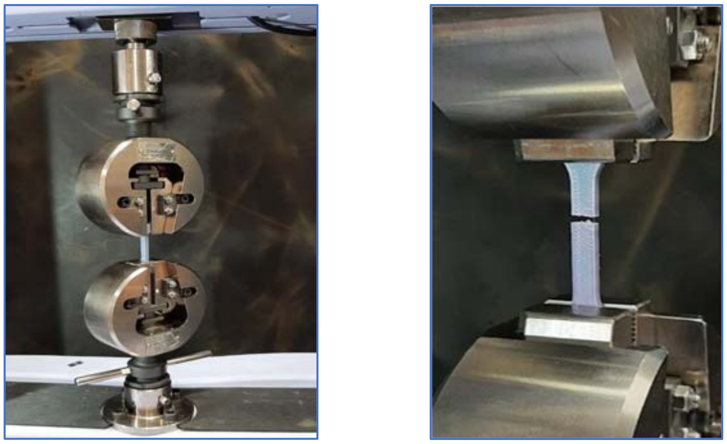

Figure 3: Experimental Setup Before and After Testing

Figure 4: Samples Before and After Testing

The links between the obtained strength to weight ratios and the qualitative factor differences were determined through a series of calculations. Finding the stress was necessary after obtaining the maximum force from the Trapezium program. To determine the final stress values, the force values were divided by the sample shape's cross-sectional area, which is calculated by multiplying the thickness by the width. The strength to weight ratio (mega pascals divided by grams) was then computed by dividing these values by the mass of the sample that was measured.[5] These numbers were utilized to generate and fill an orthogonal array of size $L8(2^7)$. The average strength to weight ratios for each of the eight studies were calculated by averaging the three samples. These values are shown in Table 2 below:

Table 2: Strength to Weight Calculation Table

	Factor							Strength/Weight			
Experiment	**X_1**	**X_2**	**X_3**	**X_4**	**X_5**	**X_6**	**X_1X_6**	**1**	**2**	**3**	**Average**
1	1	1	1	1	1	1	1	37.94	39.08	39.73	38.92
2	1	1	1	2	2	2	2	33.54	38.93	29.75	34.08
3	1	2	2	1	1	2	2	19.17	20.19	19.02	19.46
4	1	2	2	2	2	1	1	21.59	21.50	21.16	21.42
5	2	1	2	1	2	1	2	28.30	28.34	12.47	23.03
6	2	1	2	2	1	2	1	29.00	27.08	28.81	28.30
7	2	2	1	1	2	2	1	12.54	15.22	15.46	14.41
8	2	2	1	2	1	1	2	15.36	16.28	16.45	16.03

After calculating the factor representations within the experiments, the factors were ranked in order of importance as shown in Table 3. First, the average strength to weight ratio of each factor at levels 1 and 2 was determined by averaging the strength to weight ratios of the four experiments conducted at that level. Secondly, the differences between the two levels of each factor were calculated. The larger the difference between the levels, the more significant that factor is in determining the maximum strength to weight ratio for the parts created.

Based on the strength to weight ratio goal, each experiment has a unique signal to noise ratio, the higher the value, the better the outcome. Table 4 shows the equation that was used to determine the signal to noise ratios for each experiment. For every experiment, the standard deviations of the strength to weight ratios were also computed.

Table 4: Signal to Noise Ratios and Standard Deviations

	Strength/Weight					
Experiment	**1**	**2**	**3**	**Average**	**S/N**	**STD**
1	37.94	39.08	39.73	38.92	31.80	0.74
2	33.54	38.93	29.75	34.08	30.49	3.77
3	19.17	20.19	19.02	19.46	25.77	0.52
4	21.59	21.50	21.16	21.42	26.62	0.19
5	28.30	28.34	12.47	23.03	25.26	7.47
6	29.00	27.08	28.81	28.30	29.02	0.86
7	12.54	15.22	15.46	14.41	23.05	1.32
8	15.36	16.28	16.45	16.03	24.09	0.48

The response graphs for each of the six factors and the interaction between factors one through six are displayed in Figure 5. components one and two are the most significant, as the tabulated numbers demonstrate, because their deviation from the mean is greater than that of all the other components. The thinner, slimmer test specimens had a better strength-to-weight ratio because the Level 1 of both components was higher.

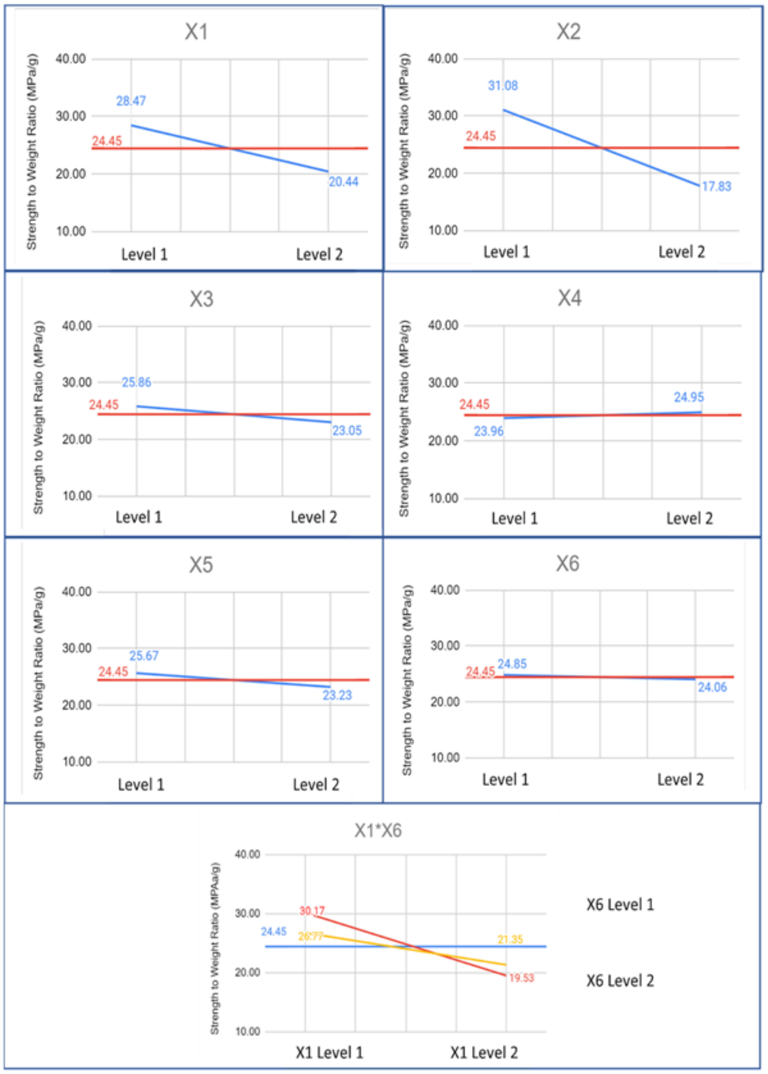

Figure 5: Charts of each Factor Level Results Relative to the Average

Results Discussion

The strength to weight ratios computed from the results of these studies were in line with expectations. Given that ABS plastic has an ultimate tensile strength of 40 MPa according to MatWeb, the strength readings between 16 and 43 MPa were unquestionably within an acceptable range. The thickness and width of the part are the two most crucial parameters for strength to weight ratios, according to experimental results. The orientation of the layer cross structure, the fillet radius, and the relationship between the nozzle temperature and breadth were all considered to be of medium importance. Finally, it was determined that the layer height and nozzle temperature had little bearing on the outcome.

Determining the potential error that happened throughout the experiment is crucial. Most ultimate forces were found to be similar by comparing the force measurements between each specimen in each experiment. The third specimen from experiment 5 was the only value that caught attention. This specimen could withstand a force that was less than half that of the other two specimens. Due to its small malformation, this sample can be eliminated from the final calculations. As seen in Figure 6, this item had a broken notch from one sample head before testing. The results were recalculated without taking this specimen into account, and the only change made was moving the layer height (X_6) up to the third position (considered of medium relevance).

Figure 6. Chipped Test Specimen

Out of all the eight experiments, experiment one's signal to noise ratio was hardly the highest. The second experiment was higher than the others, yet it was still closer together. The breadth, thickness, and radius of the fillets (factors X_1, X_2, and X_3) were the characteristics that these two trials had in common, indicating that they are the three most crucial elements to enable the best strength to weight ratios.

Conclusions

The strength-to-weight ratio was found to be higher for all six parameters, with the exception of nozzle temperature, where the results were lower. The following are included in this: a thinner and slimmer portion; a smaller fillet radius; a higher nozzle temperature; a parallel layer direction; a smaller layer height; and a less interaction between the width and layer height.

There was very little variation in the experiments because every trial was successfully finished. The strength-to-weight ratio of 35.09 MPa/g was demonstrated by the optimal part. Experiment 5 was the lone outlier trial because one of the parts was chipped. This had no bearing on the experiment's overall outcomes because the crucial variables held true whether or not this value was included. The trials demonstrated how important it is to take every aspect into account while 3D printing. This will boost the good qualities of the products, lower the cost, and produce high-quality parts.

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