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Effect of Extrusion Width and Layer Height on Hardness in Additive Manufacturing with Material Extrusion

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Abstract – Additive manufacturing is a production process in which parts are built layer by layer, saving material and time compared to traditional production methods, and sometimes offering the opportunity to produce parts that cannot be produced with traditional methods. The use of additive manufacturing methods, especially material extrusion, has become very widespread recently. This method produces not only visual prototype parts but also mechanical prototype parts, although some of their mechanical features are limited. The mechanical properties of the produced part are closely dependent on the process parameters, especially the filament material used. From this perspective, the relationship between the mechanical properties of the parts produced by additive manufacturing and the process parameters becomes important. Even if it is desired to be produced as 100% solid, the parts produced with this method have a porous structure due to the nature of the production method, and this porosity affects the mechanical properties. On the other hand, hardness becomes the most important mechanical property, especially where surface contact and friction are involved. In this study, PLA (Polylactic Acid), which is the most used material in additive manufacturing, was preferred as the material in the production of sample parts. The effects of extrusion width and layer height parameters, which affect the porosity of the parts, on hardness were investigated by experimental design. For hardness measurement, a procedure to perform the Rockwell R method was developed on a universal tensile testing device and hardness measurements were carried out. Taguchi method was used in the experimental design, and parameter effects were evaluated with ANOVA.

Keywords – Additive Manufacturing, Layer Height, Extrusion Width, Hardness, Design Of Experiment

I. Introduction

Polymer material extrusion is one of the most popular additive manufacturing methods due to its simplicity, cheapness and the variety of products that can be obtained with the materials used. The rapid transition from design to production and the practicality of prototyping make this method popular[1–3]

Although there are still some limitations and disadvantages compared to traditional methods such as injection and compression molding when compared in terms of mechanical properties, additive manufacturing finds field of use in industries such as medicine, engineering, aeronautics, automotive, architecture, etc. Mechanical properties are important in the production of structural prototype parts. Basically, the filament material is determined depending on the intended use of the prototype part to be produced. However, parameters such as infill density, infill pattern, nozzle temperature, layer height, raster angle and printing speed have the main influence on mechanical properties [4–6].

Although there are a lot of studies on mechanical properties under various loading conditions such as tensile [4,6–10], bending [11–15], compression

[6,12,16–18], studies about surface properties are limited [19–22].

In this study, it was investigated how the hardness values of the parts produced using additive manufacturing method by material extrusion are affected by the parameters of layer height and extrusion width, which cause the porosity of the part cross-section. For this purpose, Taguchi method experimental design and Analysis of variance (ANOVA) was used to investigate how these parameters affect the hardness values measured in Rockwell R scale.

II. MATERIALS AND METHOD

This experimental study used PLA (Polylactic acid), the most commonly used filament material in additive manufacturing. The samples were produced using 3D3 brand white colored tough PLA filament with a diameter of 1.75 mm and a tolerance of ±0.05 mm, with dimensions of 30X30X5mm.

Creality Ender 3 Pro 3D printer was used for sample production. The samples having 100% infill densities were produced with a rectangular filling pattern using a 0.8mm diameter nozzle. The nozzle and table temperatures were kept constant at 220 Co and 60 Co, respectively.

Parts produced by additive manufacturing have a naturally porous structure. This porosity observed in the cross-section of the part is given schematically in Figure 1. The geometric effects of layer height and extrusion width parameters on the pores are also shown in the same figure. These pores affect the macro hardness of the part and these parameters determine the hardness. In this study, the effect of these two parameters on the hardness of the part was investigated. As the minimum and maximum values of the process parameters, 25% to 75% of the nozzle diameter was determined for the layer height, and 60% to 150% of the nozzle diameter was determined for the extrusion width. Figure 2 depicts the pores' appearance when the determined parameters are applied.

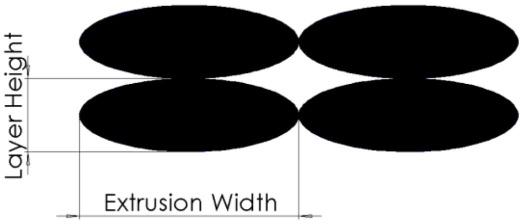
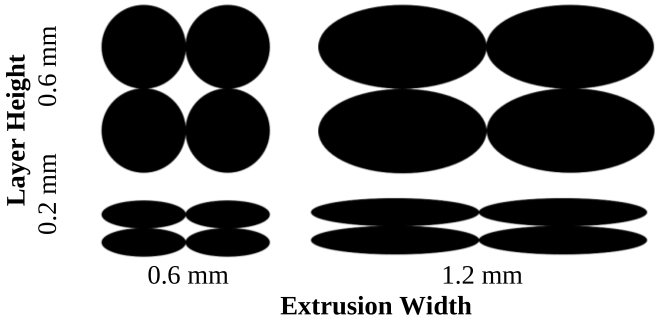


Figure 1. Pores formed in the cross-section of an additively manufactured part



**Note: Dimensions are scaled.*

Figure 2. Variation of pores depending on layer height and extrusion width parameters

Taguchi method and ANOVA (analysis of variables) were used for experimental design and data analysis. For this purpose, the L9 orthogonal array with 3 levels and 2 parameters was chosen (Table 1). All calculations were performed with Excel.

Table 1. Experimental design

Experiment no	Layer height (mm)	Extrusion width (mm)
1	0.2	0.6
2	0.2	0.9
3	0.2	1.2
4	0.4	0.6
5	0.4	0.9
6	0.4	1.2
7	0.6	0.6
8	0.6	0.9
9	0.6	1.2

Rockwell R scale (HRR) was used for hardness tests[23]. The procedure of the hardness measurement method was programmed in UTEST-7014 universal tensile-compression test machine and hardness tests were performed. The algorithm of the program created for hardness tests is given in Figure 3.

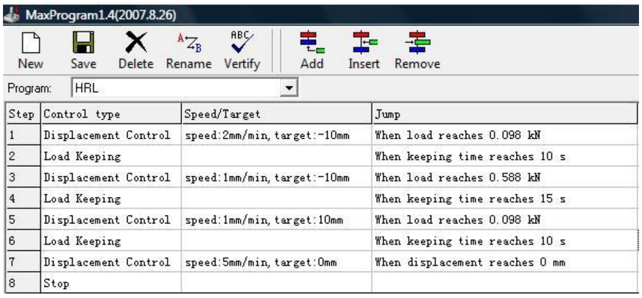


Figure 3. Algorithm of the program created for Rockwell R measurement

The value of indentation at step 2 of the algorithm, i.e. under the first minor loading (10 kg) and the value of indentation at step 6, i.e. under the second minor loading (10 kg) after the major loading (60 kg) were recorded and HRR values were calculated using Equation 1. The image of the sample during the hardness test is given in Figure 4. An example indentation depth versus time during hardness test is also given in Figure 5.

$$\mathrm{HRR} = 130 - \mathrm{e} \qquad (1)$$

Where, HR = the Rockwell hardness number, and e = the depth of impression after removal of the major load, in units of 0.002 mm.

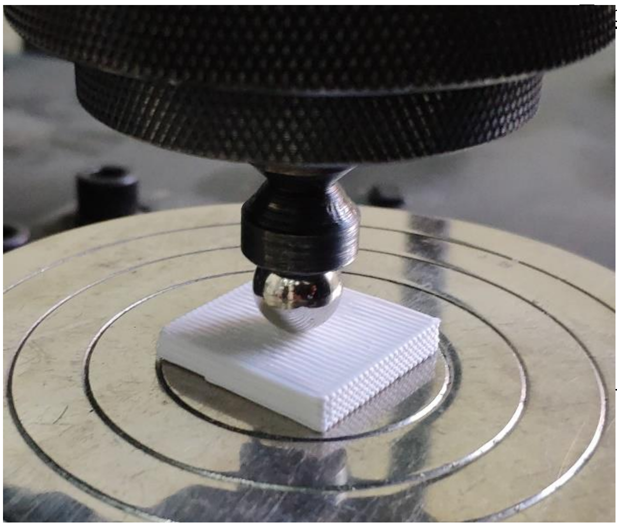


Figure 4. The sample during the hardness test

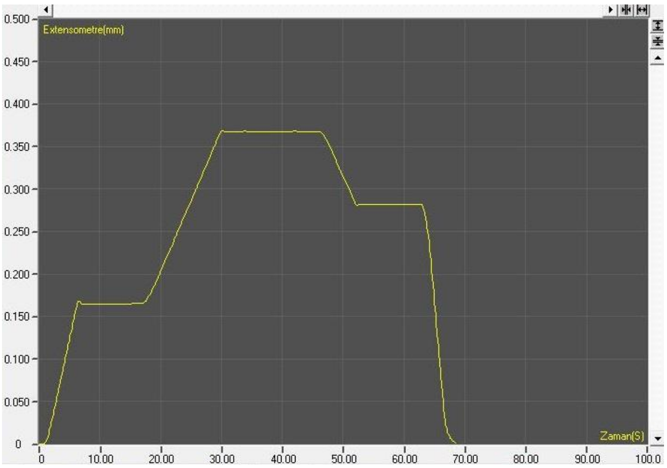


Figure 5. Indentation depth versus time during hardness test

III. RESULT AND DISCUSSION

Hardness measurements obtained as a result of the experiments, standard deviations and S/N ratio values of these data are given in Table 2. The small standard deviation values prove the consistency of the experiments. In the calculation of SN ratios, the larger is better formula was used given in Equation 2.

Table 2. HRR values with standard deviation and S/N ratios

Experiment no	Hardness (HRR)	Standard Deviation	S/N Ratio
1	98.25	2.47	39.85
2	94.75	3.18	39.53
3	96.00	0.71	39.65
4	96.25	0.35	39.67
5	94.75	1.77	39.53
6	93.75	1.06	39.44
7	95.50	2.83	39.60
8	94.25	0.35	39.49
9	90.00	1.41	39.08

$$\mathrm{S/N} = -10\log\left(\frac{1}{n}\sum_{1}^{n} 1/yi^2\right) \qquad (2)$$

Response tables for mean and S/N ratios of hardness values are given in Table 3 and 4. The main effects plot for means and S/N ratios using the results given in Table 3 and 4 can also be seen in Figure 6 and 7. Main effect plots show how each factor affects the response characteristic. The main effects of the means exhibit a perfect correlation with the S/N ratios. Increasing layer height and extrusion width decreased hardness almost linearly. This finding can be attributed to the shape of the pores shown in Figure 2. These pores play an effective role in determining the amount of support between the layers. In contrast to the results of this investigation, Kumar claim that increasing layer height raises hardness. But it is noted that layer height has less impact on hardness value than other considered parameters [22,24]. The reason for this difference can be considered that the effect of layer height on hardness in studies where the infill density is not 100% is related to interlayer bonding and not to the effect of pore structure.

Table 3. Response table for means

Means	Layer height	Extrusion width
1	96.33	96.67
2	94.92	94.58
3	93.25	93.25
Delta	3.08	3.42
Rank	2	1

Table 4. Response table for S/N ratios

S/N ratios	Layer height	Extrusion width
1	**39.67**	**39.70**
2	39.55	39.52
3	39.39	39.39
Delta	0.28	0.32
Rank	2	1

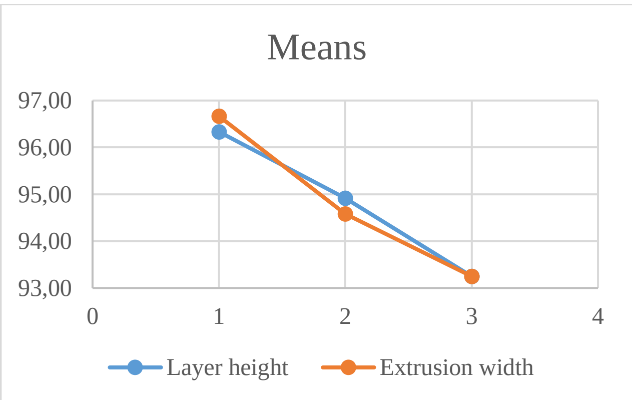


Figure 6. Main effects plot for means

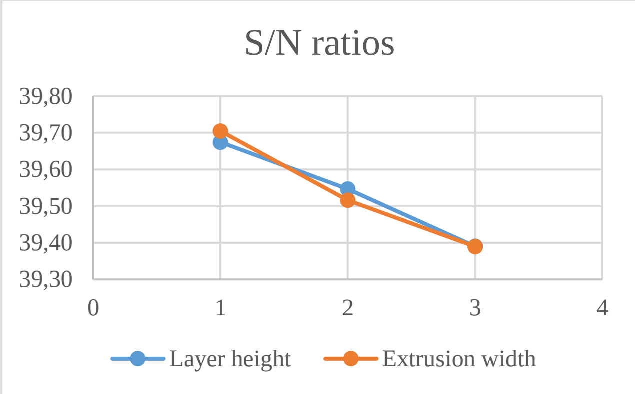


Figure 7. Main effects plot for S/N ratios

The statistical method most frequently used to analyze experimental findings and calculate the percentage contribution of each parameter is Analysis of variance (ANOVA) [22,25]. ANOVA was performed to determine the contribution of the parameters on hardness measurement values. ANOVA table is given in Table 5. According to the table, 79.46% of the total effect on hardness can be explained by layer height and extrusion width. The most effective parameter was found to be the extrusion width with a contribution of 44.07% and the contribution of the layer value was 35.40%.

Table 5. Analysis of variance for means (ANOVA)

Source	DF	SS	MS	F	Contribution
Layer Height	2	14.292	7.146	3.45	35.40%
Extrusion Width	2	17.792	8.896	4.29	44.07%
Residual Error	4	8.292	2.073		20.54%
Total	8	40.375			

IV. CONCLUSIONS

In this research, the effect of layer hardness and extrusion width parameters, which are the most important parameters determining the pore shape and size, on the hardness of additively produced PLA samples were investigated using Taguchi method and ANOVA. The main conclusions can be summarized as follows:

- Hardness values decreased almost linearly with increasing layer height and extrusion width.

- 79.46% of the total effect on hardness can be explained by layer height and extrusion width.
- The most effective parameter was found to be the extrusion width with a contribution of 44.07% and the contribution of the layer value was 35.40%.

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