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EFFECT ANALYSIS OF FUSE DEPOSITION MODELING PROCESSES ON MECHANICAL PROPERTIES OF WOOD PLASTIC COMPOSITES

Elias H. Arias-Nava [1], **Delia J. Valles-Rosales***[2], **Juan Miguel Diaz-Mendoza**[3], **Luis Alberto Rodriguez-Picon**[4], **Luis Carlos Mendez-Gonzalez**[5]
[*1,2,3] Department of Industrial Engineering, New Mexico State University, USA.
[4,5] Department of Industrial Engineering and Manufacturing, Autonomous University of Ciudad Juarez, Mexico.

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ABSTRACT

Nowadays, fuse deposition modeling is a growing fabrication technology for developing new products. When using plastics, these processes present various challenges related to fusion distribution, fuse deposition paths, part orientation, and layer thickness among others. The problem is increased however, when fabricating parts using materials that are limited in the literature. The use of different equipment may produce variations in the mechanical properties of a product. This study analyzes the effects of process parameters as well as the use of two different fuse deposition models on mechanical properties of wood-plastic composites. A design of experiments is proposed as a methodology to evaluate the objectives of the study. Results show that makerbot™ is a promising option to improve ultimate tensile strength exposed to different conditions of fabrication. It was observed that the makerbot™ and the printrbot™ had a significant difference in the tensile strength in the wood-plastic composite filled samples. The layer thickness of the samples has a significant impact in the mechanical properties, the tensile strength decreases as the thickness increases

KEYWORDS: 3D printing · additive manufacturing · fuse deposition modeling · mechanical properties · wood plastic composites

I. INTRODUCTION

Wood plastic composites (WPC) are materials that in general are based on a composition of polymers, fiber plant, and coupling agent. The polymer is the matrix of the WPC. The most common polymers used in these kinds of applications are polyethylene (PE), Acrylonitrile Butadiene Styrene (ABS), polypropylene (PP), and poly-lactic acid (PLA) among others. The fiber is the base or reinforcement of the polymer composite. This can be wood, stem rice, juke, nut shell, bamboo, flax and others Ashori [2]. A coupling agent (CA) is a chemical additive used as a bonding mechanism of the fiber and polymer. Variations of the percentage of this CA component is normally used for improving mechanical properties. WPCs have been used in different applications such as in fencing, decking, flooring, construction, and automotive parts among others. In addition, they have excellent physical and mechanical properties; they are as well of low cost, renewable, and easy of manufacturing.

Injection Molding and extrusion processes have been traditionally employed in the process of WPCs products. Currently, additive manufacturing has been explored to be used in the fabrication of parts using WCPs. This represents unique challenges in features such as fuse deposition paths, part orientation, and layer thickness. Manufacturers of FDM machines are currently working on addressing these challenges in various ways which lead to different results impacting most materials specifically their mechanical properties. The precision of each type of machine is definitely a consideration in the selection of a 3-D printing system. Wang et al [9] Bellini and Güçeri, [3]. Few studies have analyzed the use of FDM machines with the purpose of improving mechanical properties in WPCs . Le Duigou et al [5] analyzed the mechanical properties of wood plastic composites using PLA and poly (hydroxyalkanoate) (PHA) combined with wood flour material. The study describes the effects of printing parameters in fuse deposition modeling process (Prusa i3 Rework 3D printer) in the hygroscopic and mechanical properties. The methodology used to manufacture WPC samples consisted of the use of a commercial filament (ColorFab) with a blend of PLA and PHA combined with 10-20% recycled wood fiber content. The process parameters were filling orientation set at 0 and 90 degrees along the X axis and layer thickness set at 100 and 300%. Nozzle temperature, heating plate temperature, and printing speed were parameters identified as having no significant effect in the properties of WPC. Tensile stress, porosity, and swelling rate were the response parameters. Results indicated that layer thickness and orientation have a significant effect in the tensile stress. More specifically, 0 degrees' orientation had a higher tensile stress than the 90 degrees' orientation. A small layer thickness observed a higher tensile stress.

Saidin et al [7] worked in the process of developing a wood based composite material for 3D printing using a mix of wood flour and ZP102 commercial material. This material is used for building furniture prototypes, art, or architecture mock up. The composition of the new material consisted of three mesh ranges of wood powder: 90m, 120m and 150m sizes and three mix ratios of wood flour 25%, 50% and 75%. A 3D printer from Z corporation Z406, was used to manufacture tensile specimens according to the ASTM D1037 standard and tested in a UTM tensile machine. The results showed that tensile stress increased with the increased of wood content. However, tensile stress decreased as volume percentage increased over 50%. It was also observed that hardness increased as wood content increased. In the aforementioned WPC articles, one discussed the effect of setting parameters in one machine in the mechanical properties of WPC; the other focused on developing a WPC and no changes on printing parameters. However, neither of the studies analyzed the effects of different printers in the mechanical properties. Despite of the progress of the aforementioned studies, there is limited information in determining process repeatability in achieving same properties in different machines. Several work has been done using plastic filaments Bellini and Güçeri [3], Griffiths et al [4], Ahn et al [1], Quintana et al [6], Torrado et al [8], however, there is not enough information in determining process repeatability when manufacturing WPCs and their impact on achieving same mechanical properties. Therefore, this paper presents a study of the effects of the use of two different FDM machines in the manufacturing WPC specimens. The content of the article is organized as follows: section 2 shows a description of the proposed methodology and experimentation, section 3 shows the analysis and results, and section 4 presents the concluding remarks and insights for future research.

II. MATERIALS AND METHODS

Methodology

The methodology to test for repeatability consists of setting up two FDMs and a design of experiments using three parameters to control described as temperature, layer thickness, and the type of machine. Next step in the methodology is described as the manufacturing of wood plastic composite specimens using the ASTM D638-14 Type V standard. The response variable was the ultimate tensile strength (UTS) given in mega-pascal (Mpa) units. Finally, the specimens were tested following the tensile test requirements using a universal testing machine with a constant speed rate of crosshead-movement type.

Material and Equipment

Wood plastic composite material was used to manufacture a total of 40 specimens. This material is a commercial MG Chemicals ® WPC with a filament diameter of 1.75mm consisting of a ratio of 70% of poly lactic acid and 30% of pinewood. The 3D printing machines used were a MakerBot Replicator 2X Experimental 3D Printer ™ and a printrbot simple™. Both 3D printer machines (shown in Figure 1) have same characteristics in terms of print resolution, print speed, extruder, and filament size. Controllable parameters were printing temperature, and layer height. In addition, variables such as printing angle, orientation, printing pattern, material type, field density, printing speed, and filament diameter were kept constant during the experimentation.

Figure 1. Printrbot (left) Makerbot (right)

Experimental Design

Wood The experimental design included three variables, two quantitative (temperature and layer height) and one qualitative variable (3D printing machine). The experiment was a 23 full factorial design with a total of eight runs and five replications. A total of 40 samples were fabricated using the 3D printers and then tested for ultimate tensile strength (Mpa) using a universal testing machine (shown in Figure 2).

Figure 2. Universal testing machine used to measure the ultimate tensile strength

Additionally, table 1 presents the experimental plan and data related to the tensile testing, five replications and 8 runs for a total of 40 samples, re results are presented.

Table 1. Design of experiment and tensile test results (Mpa)

Variables				**Replication**				
Run	(A)	(B)	(C)	1	2	3	4	5
1	205	0.1	m	44.53	55.46	42.85	36.44	42.37
2	215	0.1	m	41.74	51	43.56	44.19	37.34
3	205	0.2	m	39.65	37.03	35.48	39.19	39.67
4	215	0.2	m	41.7	40.11	39.65	34.93	39.24
5	205	0.1	p	31.08	33.57	35.46	36.34	29.84
6	215	0.1	p	47.31	33.85	35.47	35.13	32.47
7	205	0.2	p	31.67	37.56	36.07	33.04	32.8
8	215	0.2	p	35.92	32.7	26.39	35.99	31.58

III. RESULTS AND DISCUSSION

Analysis and Results

Summarizing, 40 poly lactic acid and pinewood composites specimens were fabricated with FDM technology. The samples were printed in two different 3D printers to investigate the influence of the equipment used to fabricate the specimens in the mechanical properties of the material. The set-up conditions of the 3D, specifically the temperature of the printing process and the height (thickness) of each layer on the specimens were analyzed. The analysis of variance (ANOVA) provided information related to the importance and significance of each one of the three factors: Temperature (A), Layer height (B) and Printer (C). The resulted model is statistically significant with a p-value of 0.0004 (shown in table 2).

Table 2. Analysis of variance for the DOE results

Source	**Sum of Squares**	**df**	**Mean Square**	**F-Value**	**p-value**
Model	700.07	7	100.01	5.43	*0.0004*
A-A	2.58	1	2.58	0.14	*0.7104*
B-B	121.20	1	121.20	6.58	*0.0152*
C-C	503.31	1	503.31	27.32	*<0.0001*
AB	8.16	1	8.16	0.44	*0.5103*
AC	1.84	1	1.84	0.10	*0.7537*
BC	32.45	1	32.45	1.76	*0.1938*
ABC	30.50	1	30.50	1.65	*0.2074*
Pure Error	589.36	32	18.41		
Cor Total	1289.44	39			

Individually each factor was analyzed concluding that layer height and the printer type were statistically significant with p-values of 0.0152 and 0.0001 respectively. Temperature was not a significant factor meaning that the specimens can be manufactured at their lowest temperature value. The graphical representation of the influence of the factors is presented in figure 3. It can be observed that factors B and C affects significantly the response in (UTS) while factor A does not have a statistically significant effect in the response. In addition, the results of the analysis suggested that there is a slight interaction between factors B and C, however, it is not strong enough to be considered statistically significant.

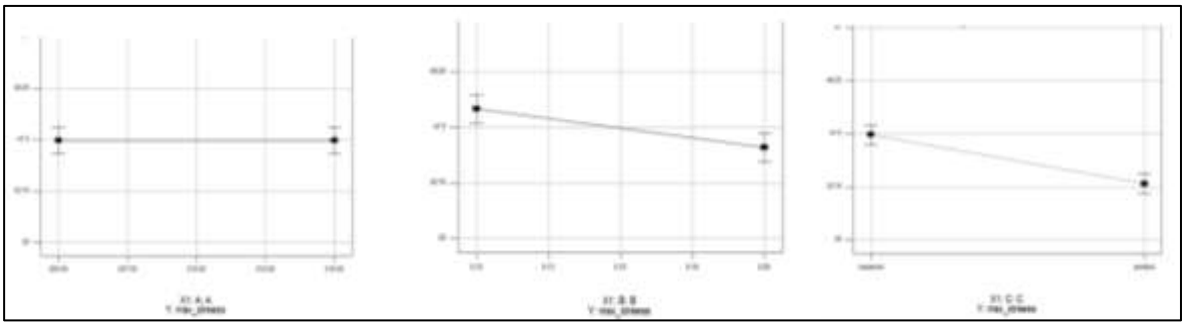

Figure 3. Main effects of individual factors (Temperature (A), layer (B) and 3D printer (C).

A normality test was performed as part of the proposed methodology. Figure 4 shows that the values were normally distributed, even though the normality test results were close to the rejection region (p-value = 0.112).

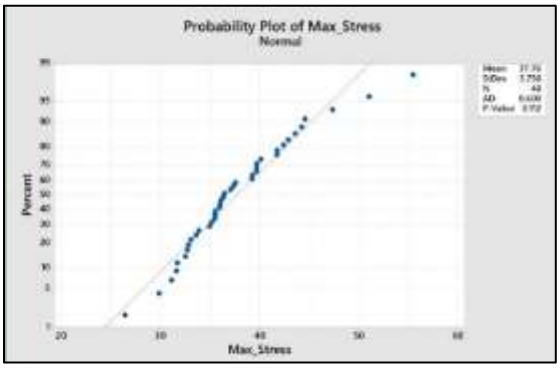

Figure 4. Normality test for residuals

A plot of the residual versus run is presented in the figure 5 to demonstrate the independence of the residual (εi), this test in necessary to avoid biased estimates that may lead to invalid inference in the statistical analysis and in the regression model presented in this paper.

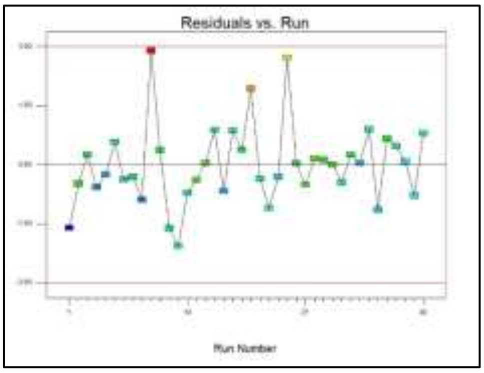

Figure 5. Residuals vs Run

Finally, the resulted R-squared in the experiment was slightly low with a value of 0.540. Potential interpretation is that the commercial WPC filament used in the experimentation does not provide enough technical information about the extrusion process used in the fabrication of the filament as well as other components of the composite employed such as coupling agents and fire retardants. Having this information available will enhance the results of this study.

Optimization: FDM

The results regarding the tensile strength showed significant results between the two 3D printers. Ultimate tensile strength (UTS) was significantly higher on samples fabricated with the makerbot™ printer. The results showed a 20.33 percent higher ultimate tensile strength. The point prediction indicates the highest value that in this case each printer can achieve. In this experiment, the makerbot™ maximum point reached 44.33 Mpa, on the other hand the printrbot™ reached 36.84 Mpa as the maximum tensile point. In addition, when using the makerbot™ during the optimization of factors affecting UTS, the results presented in figure 6 show a smoother graph transition rate when changes in temperature.

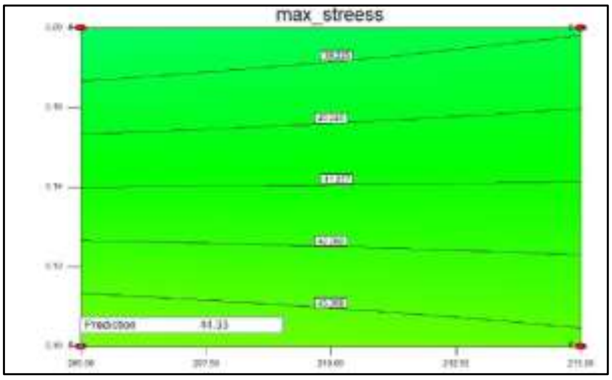

Figure 6. Point prediction: Makerbot™

On the other hand, figure 7 shows a large variation on the graph transition rate of the printrbot™ when changes in temperature are presented.

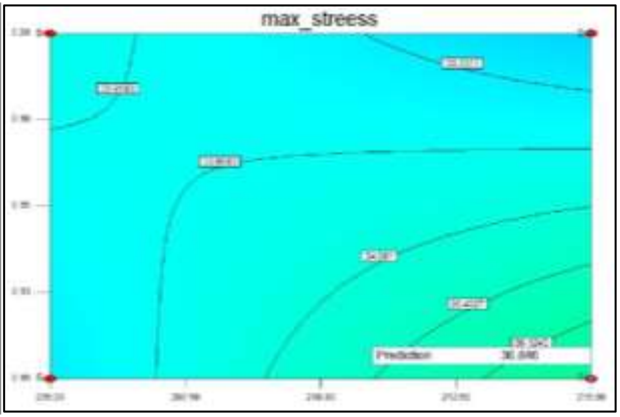

Figure 6. Point prediction: printrbot™

In conclusion, the study shows that the use of the makerbot™ maximizes the tensile stress compared to the printrbot™. In addition, the model that provides the best results when using the maketbot™is the one that uses a combination of factors temperature set up at 205 degrees and layer height set up at 0.10 mm. In this study no statistically significant interaction of factors was found when using maketbot™ nor printrbot™

For maketbot™

Y_i= 35.85 + 0.0508A – 34.815B (1)

For printrbot ™

Y_i= 28.755 + 0.0508A – 34.815B (2)

IV. CONCLUSION

The overall goal of this research was the technical comparison of the FDM machines makerbot™ and printrbot™

through the use of design of experiment to arrange the sample fabrication and ANOVA to evaluate the results. ASTM standards were considered to validate the experimentation as well as five replications per run. The specimens' appearance was compared with other filaments from previous studies suggested that the internal adhesion between PLA and pine wood was good. Ultimate tensile strength was selected as indicator of the response to analyze the behavior of the specimens under different conditions of fabrication. It was observed that the makerbot™ and the printrbot™ had a significant difference in the tensile strength in the WPC filled samples. The layer thickness of the samples has a significant impact in the mechanical properties, the tensile strength decreases as the thickness increases. Moreover, there is a significant correlation between each of the parameters analyzed (temperature and layer thickness) and the effect on the mechanical properties. Future research would involve the use of composites where information on the composition will be available. In addition, layer pattern and layer printing orientation will be observed as well as a variation of proportions wood, plastic, and coupling agents among other components.

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