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RESEARCH ARTICLE

Effect of different amounts of carbon fiber additive ABS on thermal distortion and cooling time

Omer Eyercioglu[1], Engin Tek[*1], Mehmet Aladag[1], Gulaga Tas[2]

[1]Gaziantep University, Engineering Faculty, Mechanical Engineering Department, Gaziantep, Turkey
[2] Hasan Kalyoncu University, Engineering Faculty, Mechanical Engineering Department, Gaziantep, Turkey

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Abstract

This study presents an analysis of the distortions of Acrylonitrile Butadiene Styrene (ABS) composites with different amounts of carbon fiber produced by large-scale additive manufacturing (LSAM). Part failures often occur in extrusion-based large-scale additive manufacturing due to thermal contraction. These are called thermal distortions. Undesirable distortions are caused by differential thermal expansion and contraction and corresponding residual stresses. Residual stress and strain analysis require accurate thermo-mechanical material properties. These can be controlled by changing the number of additives in polymer material. In this study, fiber orientations in ABS reinforced with 10%, 5%, 0% carbon fiber by weight were modeled using a homogenization technique. The distortion amounts of the parts modeled according to these carbon fiber ratios were examined and it was observed that the distortion decreases as the Carbon Fiber (CF) ratio increases and the CF added material cools more slowly than pure ABS.

1. Introduction

Additive manufacturing (AM) is often described as the process of combining materials to make objects from layer-by-layer, 3D model data, as opposed to subtractive manufacturing methodologies such as traditional machining [1]. AM has attained popularity and has captured the imagination of the public as well as researchers in many fields. This technology, which has attracted attention recently, is constantly being redefined, redesigned, and customized for a wide range of applications such as automotive, aerospace, engineering, medicine, biological systems, and food supply chains [2]. By this method, it is possible to produce models with extremely complex geometric shapes. In most commercial three-dimensional printing systems, deposition rates are 0.01-0.085 kg/h, and building volumes are limited to and 0.03-0.3 m3[3]. Thus, it is not suitable for pieces that have large dimensions. Large-Scale Additive Manufacturing (LSAM) describes a system that can be used to print components at high extrusion speeds (up to 50 kg/h) of the order of several meters. This can result in reduced cost and time in manufacturing [4].

In extrusion-based additive manufacturing with thermoplastics, the high-temperature material is laid on a pre-deposited layer whose temperature is lowered, resulting in a large thermal gradient between the layers. Most thermoplastic materials have positive coefficients of thermal expansion, so the material contracts during cooling. Beyond the glass transition temperature (Tg), the material is susceptible to deformation and causes negligible stress during cooling. However, when the temperature drops below Tg, the hardness of the material increases significantly and creates sufficient stress for deformation during shrinkage with cooling [5]. As the newly deposited layer cools below Tg, its further contraction is compensated by the already solidified layers underneath. Therefore, the deposited layer is stressed and exerts differential compression on the underlying layers, causing distortion and residual stresses in the printed part. The accumulation of such thermally induced residual stresses can cause delamination between layers [6, 7].

Many studies have been done about distortion during printing [8, 11]. Love et.al [12] expressed the significance of including short fiber such as carbon fiber (CF) to materials used in large area AM by highlighting three important aspects: production rate, the physical size of the part, and mechanical strength. Kim et.al [6] created a thermomechanical model on big area additive manufacturing to compare the results with experimental study, composition the CF using dehomogenization technique with Acrylonitrile Butadiene Styrene (ABS) weight of 20%. The temperature and the distortion profiles from the experiment were found out in the simulation results. Polyzos et.al [13] studied nylon material with continuous CF. They created a mathematical model and compared the result with the experimental study. The results of the simulations were well in agreement with the experimental study. Also, the carbon fiber decreased the distortions. Ning et.al [10] described composite fabrication by melt mixing ABS pellets and carbon fibers CF up to 15 wt.%. Mechanical characterization proved that tensile strength improved by 75% for the 5 wt.% CF. Increased amounts of fiber content reduced the toughness, yield strength, and ductility. Also, increased carbon fiber decreases the delamination.

In this study, ABS) material was printed with 0% 5% 10% carbon fiber reinforcement by volume to reduce warping and the

Corresponding Author: Engin Tek
E-mail: engintek@outlook.com

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effects of carbon fiber added ABS were investigated. Test components parts are printed using the LSAM system developed in Gaziantep University Mechanical Engineering, CAD/CAM Laboratory.

2. Materials and methods

2.1 Materials

In the experimental study, an ABS (Acrylonitrile Butadiene Styrene) thermoplastic polymer was used and the properties of the ABS are given in Table 1. Before using, the granules of ABS were dried at 80ºC for four hours. The melted material is deposited at 240ºC on a heated building plate at 80 ºC.

In this study, a layered wall was produced with ABS polymer-based and carbon fiber additive in various amounts, and shape changes of these samples were observed with carbon fiber additive ratio.

2.2 Printing System

A direct extrusion system was designed and manufactured for Large-Scale Additive Manufacturing (LSAM). Then the direct extrusion system was replaced by the spindle of the three-axis CNC unit. The maximum moving capacity of the machine in the X direction is 1800 mm, in the Y direction is 2500 mm, and in the Z, the direction is 400 mm. The extruder has a single screw and is driven by a variable speed motor. Acrylonitrile Butadiene Styrene particles are fed from the granule hooper to the extruder by using an automatic granule feeder system. In order to deposit and melt the Acrylonitrile Butadiene Styrene at a speed consistent with the movement of the axes (build speed) and the desired bead profile, the feed rate of the granules and the speed of the screw can be controlled. To keep the barrel, chamber, and nozzle temperatures within retain required ranges, the extruder has tape heaters and a control unit. In the experimental study, three types of 19-layer layer-wall samples with a thickness of 9 mm, a length of 300 mm, and a height of 85 mm were printed from each material composition.

Table 1. The mechanical properties of ABS.

Properties	Unit	Value
Density	*g/cc*	1.15
Young's Modulus	*GPa*	2.28
Thermal Conductivity	*K (W/mK)*	0.175
Melt Flow	*g/10min*	0.20
Specific Heat	*C (J/KgK)*	2075
Emissivity	ε	0.87
Glass Transition Temp.	T_g *(C)*	105

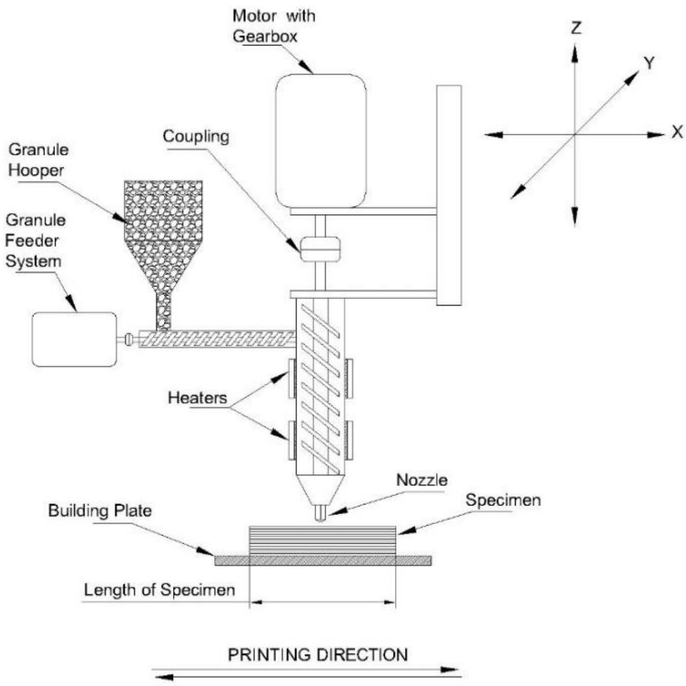

Figure 1. Schematic View of LSAM system.

2.3 Printing of the Samples and Distortion Measurement

The samples were divided into four groups according to their carbon fiber additives; it is printed from 0%, 5%, and 10% carbon fiber blended ABS material by weight. The carbon fiber was 7 µm in diameter and 1±0.3 mm in length.

The samples were printed directly on the extrusion printing system, were 19 layers, and were printed along axes with a constant speed feed in the form of a flat wall. In addition, the ambient temperature and printing conditions were kept constant during printing. The parameters of printing are listed in Table 2.

In order to measure the amount of distortion on the wall, a 2D scanning method was used. Scanned data were exported to AutoCAD and, scaled in the real ratio using the auxiliary scales. Then, along the horizontal length of the wall, 21 measurements were taken (See Figure 2).

Table 2. Parameters of Printing

Feature	Unit	Value
Printing Temperature	°C	240
Deposition rate	kg/hr.	0.2
Feed rate	mm/min	240

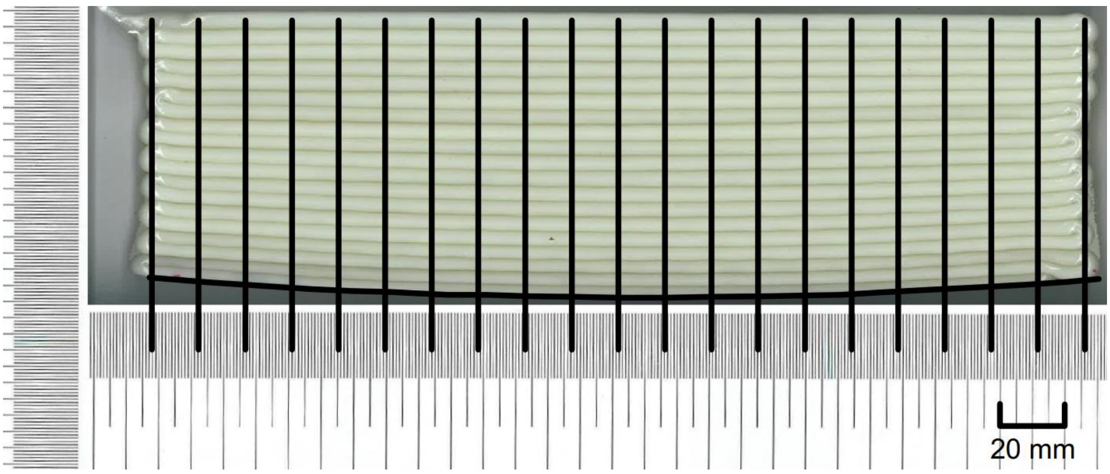

Figure 2. Measurement of the part distortion by using AutoCAD.

3. Results and discussion

A single line wall was produced with ABS material containing different carbon fiber content. Thermal images of each sample were recorded throughout the production to examine the thermal variables during production. Both samples and their thermal images were given in Figure 3.

The temperature and cooling time graph showing the thermal change is given in Figure 4. This figure showed how long it took to produce the first layer and how much its temperature had dropped during this time. When the cooling curves of the first layer are examined, it is seen that ABS cools more slowly than ABS with CF additives. However, after 65 seconds, it is seen that it quickly drops below T_g. This situation occurs later in CF added ABS. In other words, the cooling time is slower after 65 seconds in CF ABS. In the sample where the CF ratio is 5%, the heating value is lower than ABS, but it is clearly seen that the cooling rate is low. In the sample where the CF ratio is 10%, the heating value is approximately between pure ABS and 5% CF ABS curves. However, after the 30th second, it is observed that it proceeds at a lower temperature compared to other materials.

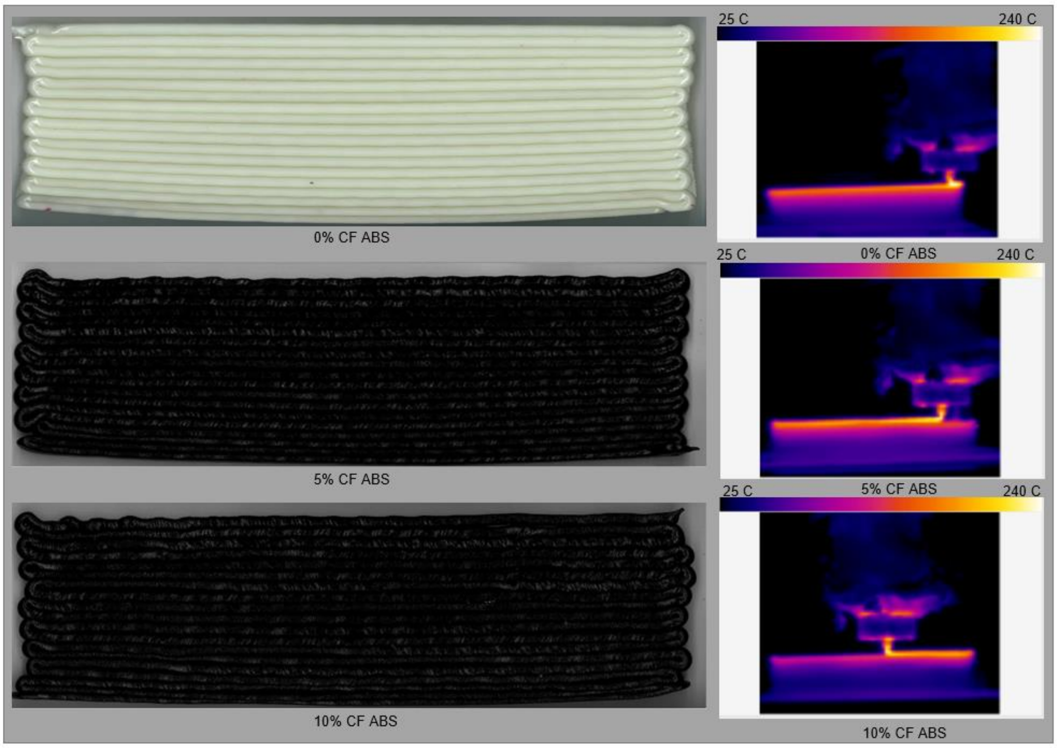

Figure 3. Printed samples and their thermal images

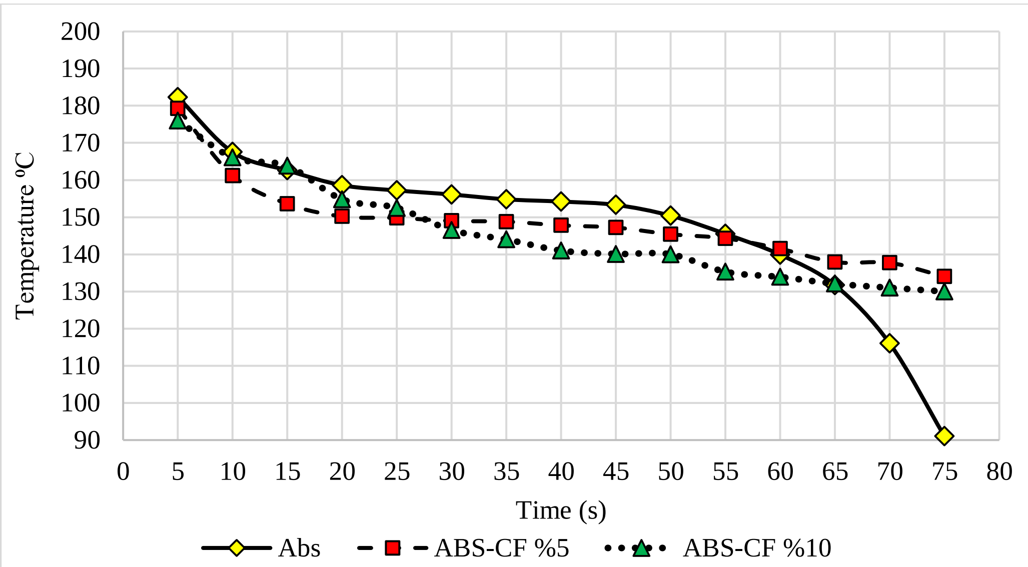

Figure 4. Temperature-Cooling time of the first layer for each sample.

The reason for the asymmetrical distortion; after the first layer is laid, the second layer is superimposed on the first layer. In this case, the cooling is less than where the first layer starts. In addition, each new layer increases the temperature of the previous layer. The author has done a previous study on this on pure ABS. The graphic in the related study is given in Figure 6 and referred to [14].

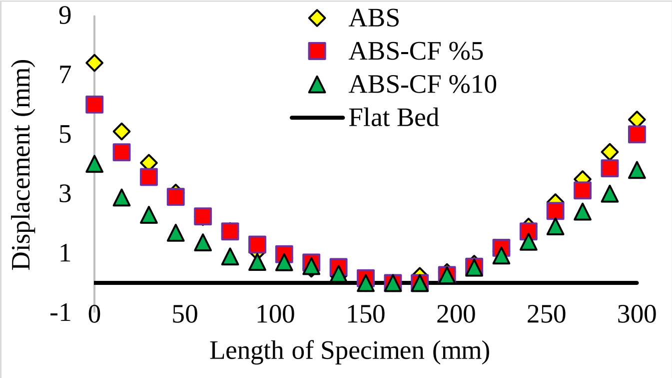

Figure 5. Amount of distortion of each sample

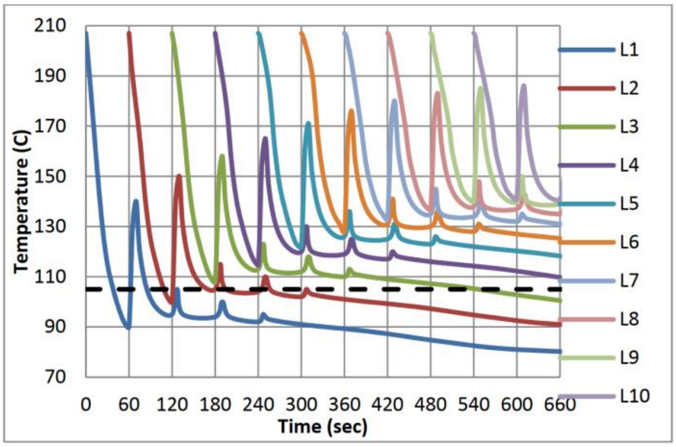

Figure 6. The time evolution of the temperature of the extruded deposit 1-10 layers at the midsection [14].

4. Conclusions

In this study, a single wall was produced with carbon fiber reinforced ABS material in different ratios, and the effect of the CF ratio on distortion was investigated. Moreover, in order to see the effect of CF ratio on cooling, temperature values were obtained by thermal imaging method and, it is examined and evaluated. The outputs obtained are as follows;

- The cooling time in carbon fiber reinforced ABS material is considerably longer than in pure ABS. This plays an important role in the warping of the material.
- The maximum distortion was observed in the sample produced with pure ABS material (see Figure 5). The reason for this is when the cooling graph (see Figure 4) is examined. ABS material falls below Tg=105 °C in a short time. Therefore, the distortion occurs more in unit time.
- Asymmetrical distortions have occurred. Since the volume of the material deposited in the first place where the extruder nozzle starts production (at nozzle 0 mm) is less, rapid cooling occurs and therefore more distortions occur compared to the other place (at nozzle 300 mm) (See Figure 5).
- In addition, the effect of heat on thermal distortion is as great as the effect of carbon fiber. Because in order to shape ABS without breaking your polymer chain, it is necessary to keep the temperature above the Tg value. For this, the ambient temperature must be above 105 °C.

Experimental studies are continuing in order to obtain the parameters that meet the necessary conditions for the production of ABS or CF added ABS material on a large scale in a large-scale additive manufacturing system, geometrically closest to the net.

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Author contributions

Omer Eyercioglu: Supervision, review & editing.
Engin Tek: Preparing samples, Testing, Writing - original draft
Mehmet Aladag: Analysis, Writing - original draft
Gulaga Tas: Investigation, Writing - original draft

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