ANALYSIS OF THE CAUSE AND EFFECTS OF PART DEFECTS IN ABS SAMPLES MADE USING ADDITIVE MANUFACTURING

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Abstract*:* This study highlights the cause and effects of part defects in ABS-Based samples using an additive manufacturing process. The parameters that were investigated include build orientation, infill pattern, number of contours, airgap, road width and annealing as a post-processing parameter. Samples were made, and their compressive strength was tested. Additionally, the tested samples were investigated using optical microscopy and the classification of their defects was done. This study is unique in investigating the effect of stress relief annealing along with build process parameters. Furthermore, the various defects associated with compressive failure in additively manufactured artefacts were categorized and a cause and effect diagram was derived which would enable designers to predict the areas of failure of a part.

Keywords: *Additive Manufacturing, ABS Material, Compressive Strength, 3D Printing Defects*

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1. Introduction

Additive Manufacturing (AM) is a method of creating parts by fusing, curing or adding material in a layer by layer fashion. It enables the manufacture of complex and freeform parts in a relatively short time when compared to traditional machining methods which would require the use of custom tooling, jigs and fixtures [5]. Invented in the 1980s, Fused Deposition Modelling (FDM) is the name trademarked by Stratasys for a material extrusion-based AM method. Due to the expiration of key patents in 2009 this material extrusion method has become the most common in use today [21]. It has the capability to produce parts which are strong enough for end-use at a lower cost compared to other AM methods, [26]. In AM, there are many process parameters that directly affect the performance of the end product [7]. The current study elaborates that the interactions of these process parameters also have a significant impact on the compressive strength of the part. A similar effect was found in a study by [47] where the interaction of part orientation and road width had the most impact on the surface roughness of the curved portion of a hemisphere. The strength of parts made by material extrusion is usually lower than that of traditionally machined parts [60]. As the machine head moves along its predetermined toolpath, it deposits filament of semi-molten material as layers in a raster pattern. As the head deposits the successive layer, the heat from the head and semi-molten material partially melts the previous raster and as it cools it solidifies and joins the rasters. These areas of the interface are usually the most common points of failure of material extrusion manufactured parts [53].

2. Methodology

Design Expert® was used to develop an experimental plan based on IV-Optimal design approach. This design approach allowed the use of two categorical parameters along with continuous parameters. The build parameters incorporated in this study were road width (RW), layer thickness (LT), number of contours (NC), airgap (AG), annealing (AN) and infill type (IT), additionally, stress relief annealing (AN) was done as a post-processing method. The two categorical parameters used were IT and AN. Table 23 summarizes the parameters along with their levels. The compression specimens with the dimensions 10mm x 10mm x 30mm used in this study were modelled after past research in testing of compression strength of parts made by additive manufacturing [54]. The specimens were then built using a Raise3D N2+ 3D printer and each sample was stored in individual airtight bags to avoid moisture absorption. The samples were then tested on a Tinius Olsen H10KS. The testing followed the procedure used in past research [49][54] that adhered to ISO604-1973 (Plastics-Determination of compressive properties). The testing machine was set to a speed of 2mm/min and a load range of 25kN. The test setup used in the study is shown in Figure 38. The experimental data were subsequently imported into Minitab statistical software for analysis. The defects of the failed samples were then inspected using an optical microscope.

Figure 38: Tinius Olsen H10KS loaded with test sample.

Table 23: Summary of factors and levels

Parameter	**Levels**		
	Level 1	**Level 2**	**Level 3**
LT	**0.1**	**0.2**	**0.3**
RW	**0.3**	**0.35**	**0.4**
AG	**0**	**0.025**	**0.05**
NC	**0**	**3**	**6**
BO	**0**	**90**	**180**
IT	**L**	**HC**	**-**
AN	**No**	**Yes**	**-**

Legend; Continuous Parameter: LT- Layer Thickness; RW-Road Width; AG-Airgap; NC- Number of Contours; BO-Build Orientation; **Categorical Parameter:** IT- Infill Type; AN- Annealing. **Infill Types:** L- Lines, HC- Honeycomb

3. Results and Discussions

Once tested the areas of defects of the samples were then observed using an optical microscope to investigate the regions of occurrence of such defects. The testing results, observations from the microscopy and build parameters are summarized in Table 24. It was observed that defects occurred due to the breaking of the bonds or buckling of the part under load. This observation concurs with previous studies, [54][60].

Table 24: Summary of defects and their potential causes

SAMPLE	DEFECT(S) FOUND	SET BUILD PARAMETERS	FORCE (N)
1	COMPRESSIVE DEFORMATION LEADING TO BUCKLING	BO-90, AG-0.05, LT- 0.1, RW- 0.3, NC- 0, IT- L, HT- 1	2945
2	COMPRESSIVE DEFORMATION LEADING TO BUCKLING	BO-0, AG-0, LT- 0.2, RW- 0.3, NC- 0, IT- L, HT- 0	1458
3	LAYER DELAMINATION	BO-90, AG-0.025, LT- 0.3, RW- 0.3, NC- 0, IT- HC, HT- 1	3002
4	RASTER DELAMINATION	BO-0, AG-0.05, LT- 0.3, RW- 0.35, NC- 0, IT- HC, HT- 0	2055
5	RASTER DELAMINATION	BO-0, AG- 0, LT- 0.1, RW- 0.3, NC- 3, IT- HC, HT- 1	3818
6	DELAMINATION OF CONTOURS FROM INFILL	BO-0, AG-0, LT- 0.3, RW- 0.4, NC- 6, IT- HC, HT- 0	3573
7	LAYER DELAMINATION	BO-0, AG- 0.05, LT- 0.3, RW- 0.3, NC- 6, IT- L, HT- 1	3243
8	COMPRESSIVE DEFORMATION LEADING TO BUCKLING	BO-90, AG- 0, LT- 0.1, RW- 0.35, NC- 6, IT- 0, HT- 1	2953
9	COMPRESSIVE DEFORMATION LEADING TO BUCKLING	BO-0, AG-0.05, LT- 0.1, RW- 0.4, NC- 0, IT- HC, HT- 1	1496
10	LAYER DELAMINATION	BO-90, AG-0.05, LT- 0.2, RW- 0.4, NC- 6, IT- HC, HT- 1	3096
11	LAYER DELAMINATION	BO-0, AG-0.025, LT- 0.1, RW- 0.4, NC- 6, IT- L, HT- 0	1253
12	LAYER DELAMINATION	BO-45, AG-0.025, LT- 0.2, RW- 0.35, NC- 3, IT- L, HT- 0	1406
13	LAYER DELAMINATION	BO-90, AG-0, LT- 0.1, RW- 0.4, NC- 0, IT- HC, HT- 0	2098
14	LAYER DELAMINATION	BO-45, AG-0.05, LT- 0.1, RW- 0.3, NC- 6, IT- HC, HT- 0	3092
15	LAYER DELAMINATION	BO-90, AG-0.05, LT- 0.3, RW- 0.4, NC- 3, IT- L,HT- 0	3292
16	COMPRESSIVE DEFORMATION LEADING TO BUCKLING	BO-45,	2994

		AG-0.025, LT- 0.2, RW- 0.35, NC- 3, IT-HC, HT- 1	
17	Shear along layer	BO-45, AG-0, LT- 0.3, RW- 0.4, NC- 0, IT-L, HT- 1	3532
18	Layer Delamination	BO-90, AG-0, LT- 0.3, RW- 0.3, NC- 6, IT-L, HT- 0	1952

Legend: Continuous Factors: LT- Layer Thickness; RW-Road Width; AG-Airgap; NC- Number of Contours; BO-Build Orientation; **Categorical Factors:** IT- Infill Type; AN-Annealing. **Infill Types:** L- Lines, HC- Honeycomb

Columns in compression usually fail due to buckling [22] and [48]. The maximum theoretical buckling force for an object of the dimensions used was calculated using equation (1).

$$\boldsymbol{P_{cr} = \frac{\pi^2 EI}{(KL)^2}} \tag{1}$$

Where 'P_{cr}' is the critical buckling load (kN) at which the column would fail, E is the Young's modulus from the material manufacturer of 2.3GPa, 'I' is the moment of inertia 833.33mm^4, L is the length of the member 30mm and K is the effective length factor 0.5. Substituting the results show that the samples have a theoretical critical buckling load of 84.07kN, much greater than what was observed. The theoretical maximum is based on an object of ideal dimensions that is completely solid. The printed samples contain voids which are inherent to the material extrusion process and can lower the actual strength values of the parts [36]. Also inherent to the build process are layer lines that can create areas of stress concentration on the surface of the part. The strength of the bond between the rasters plays a significant role in the overall strength of the part, [40], and the breaking of this bond is known as delamination [60]. Previous studies have shown that under compression ABS specimens can fail by buckling of the structure or one of two forms of delamination. The first form of delamination is a fracture or tearing occurring between layers, while the second is the delamination of rasters of the same layer from each other [60]. A similar study using ABS P400 compressive samples observed two modes of failures of compressive samples due to either buckling of the part or de-bonding of the fibres [54]. From the above two studies, it can be concluded that both failures at the raster interface and de-bonding of fibres can be categorized as the failure mechanisms. However, this study has observed that there are three main modes of part failure which were found at the bond interfaces, these include 1. The failure of bonding between successive layers; 2. Failure at adjacent infill rasters; and 3. Failure at the interface between infill rasters and contour. This differentiation is necessary as the various interface areas are affected independently by the selected process parameters and loading conditions. There were also several parts that failed due to the compression deformation causing the specimen to buckle. In these specimens no visible bond failure was seen however, the specimen colour was changed in areas of high stress, Figure 39(a). It is possible that the various interface areas on the interior of the part may have failed. All other defects involved visible delamination at bond interfaces. The current study found that layer delamination was by far the most common defect that occurred. This may indicate that either, the bonds between successive layers were weaker than the bonds at other interface types or, the loading condition is such that the layer-layer interface undergoes the most stress. A sample of layer delamination defect can be seen in Figure 39(b). Furthermore, Figure 39(c) illustrates an example of raster delamination defect by showing the outer rasters being displaced outward as the compressive force breaks the raster to raster bonding between outer and inner rasters. In addition, infill-contour delamination defect as illustrated in Figure 39(d) is distinct from raster-raster delamination as they are influenced by different process parameters, their intersection angles are also usually much different. Figure **39**(e) illustrates the clean break that occurred in a sample with a build orientation of 45 degrees. This clean break is the result of the compressive force breaking the layer to layer bonding, and along with the angle of the layers, it allowed them to slide relative to each other and induce shear stresses at the layer-layer interface. The force required to break the bonding between the rasters can be linked to a combination of the surface area of the contact as well as the degree to which fusion has taken place at that contact area.

Internal stresses at the various interfaces can be formed by the rapid cooling of the semi-molten material. This can weaken the bond strength of the material at these areas. One method to reduce the internal stresses is annealing. This method was investigated, and it was observed that the annealed samples withstood higher compressive forces before failing when compared with the samples that were not annealed. By looking at the Pareto chart Figure 40, stress relief annealing is seen to have the highest impact on the maximum force that the specimen could withstand. Furthermore, the interaction between road width and layer thickness also has an indication of a significant impact on the strength of the part, this interaction directly affects the bond area of adjacent rasters. Thus, it can be concluded that the stress relief annealing, being the most influential process parameter, the industry may strongly consider it as a post-processing method to enhance the compressive strength of ABS-based 3D printed parts.

Figure **41** summarizes the overall defects observed in this study along with their potential causes. As the illustration points out, most of the defects are caused by poor strength at bond interfaces. This can be attributed to the poor fusion of the rasters or insufficient area of fusion due to the low contact area. The fusion of the rasters can be weakened when cooled quickly and the internal stresses mentioned earlier are induced.

(a)Stress marks from deformation

(b) Layer Delamination

(c)Raster Delamination

(d) Delamination of contour from infill

e) Layers sheared apart

Figure 39: Sample images of defects found in ABS-based specimens

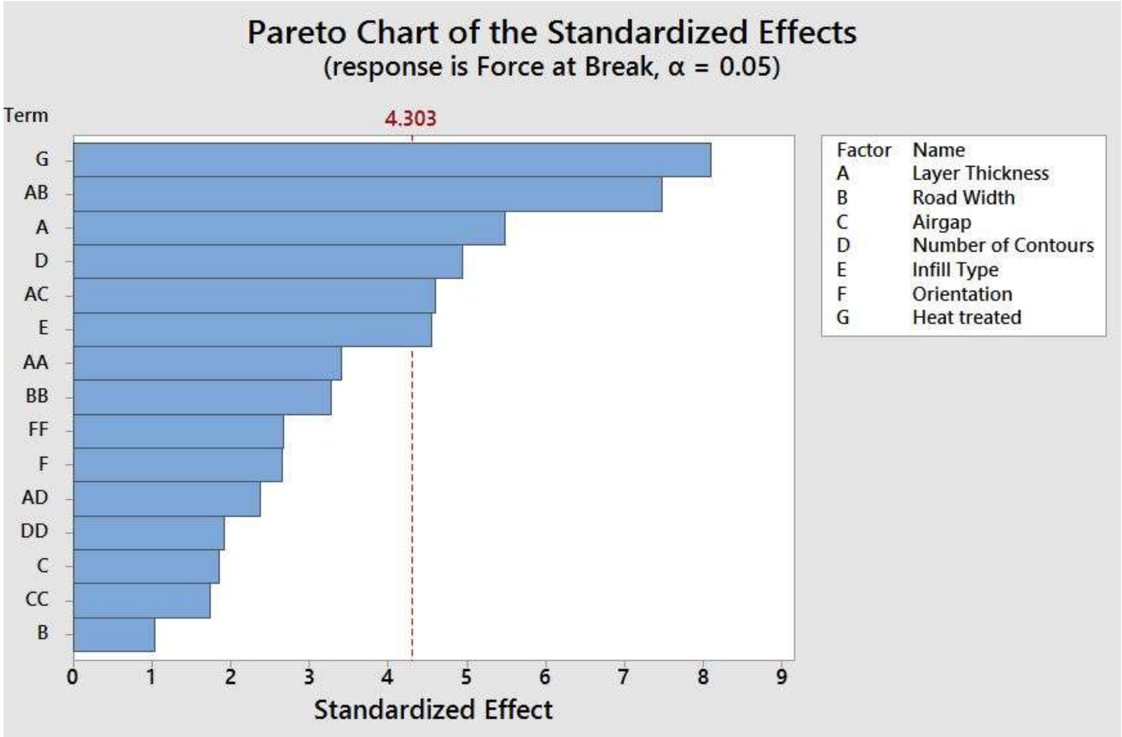

Figure 40: Pareto chart of process parameters and interactions, and their impact on the 3D printed part compressive strength

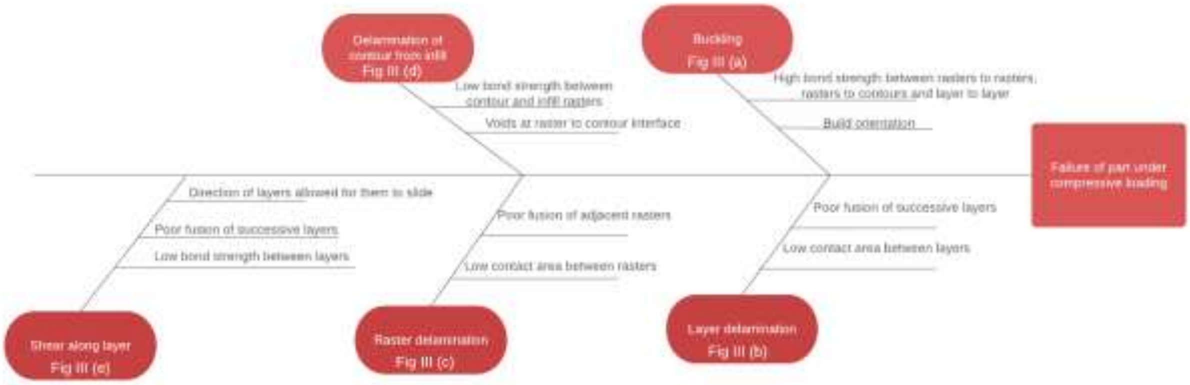

Figure 41: Cause and effect diagram of part failure under compression loading

4. Conclusion and Recommendations

This paper investigated the defects of ABS-based specimens produced through the material extrusion process. The study used a cause and effect technique for analysis of the 3D printed samples. Understanding the type of defect and its cause will allow engineers to more accurately predict the way in which a part would most likely fail earlier in the design process. The study has shown that stress relief annealing is an effective means of increasing the compressive strength of a part through post-processing. As such, a more focused study on the effects of stress relief annealing is encouraged such as its effects on other mechanical properties of the 3D printed samples. Further studies can also be done using new materials available in the market such as ASA, and composite materials such as carbon-fibre filled filament.

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