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Effect of Build Plate Material and Temperature on Adhesion Performance in Fused Filament Fabrication of HIPS and PP

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Abstract

Adhesion between the printed part and the buildplate was a critical factor governing process stability, dimensional accuracy, and failure prevention in fused filament fabrication (FFF) technology. This study aimed to investigate the effects of build plate material and build plate temperature on interlayer adhesion performance and build-plate adhesion of high-impact polystyrene (HIPS) and polypropylene (PP). The research method used was an experimental approach involving the fabrication of standardized specimens using an FFF-based 3D printer, evaluation of interlayer bonding through tensile testing in accordance with ISO 527-3, and measurement of build-plate adhesion using a specially designed detachment test apparatus integrated with a universal testing machine, complemented by fracture morphology analysis using scanning electron microscopy. The results showed that increasing build plate temperature significantly improved interlayer adhesion strength and fracture surface width in HIPS, particularly at temperatures approaching its glass transition temperature, indicating enhanced molecular diffusion and improved interfacial bonding quality, whereas PP exhibited poor adhesion performance on all tested build plate surfaces due to early warping and interfacial void formation. Optimal and stable build-plate adhesion was achieved only for the HIPS–PEI combination at a build plate temperature of 105 °C, while ultrabed and glass build plates did not demonstrate adequate adhesion performance. These findings confirmed the importance of compatibility between thermal conditions and build plate surface characteristics in FFF processes and highlighted the necessity of material modification or additional surface treatment to improve the printability of PP.

Keywords: *build-plate adhesion; additive manufacturing; interlayer bonding; HIPS, polypropylene.*

Abstrak

Adhesi antara produk cetak dan *buildplate* merupakan faktor krusial yang menentukan stabilitas proses, akurasi dimensi, serta pencegahan kegagalan pada teknologi *fused filament fabrication* (FFF). Penelitian ini bertujuan untuk mengkaji pengaruh jenis material *buildplate* dan temperatur *buildplate* terhadap performa adhesi antar lapisan serta adhesi produk cetak pada material *high-impact polystyrene* (HIPS) dan *polypropylene* (PP). Metode penelitian yang digunakan adalah metode eksperimental melalui pembuatan spesimen terstandar menggunakan printer 3D berbasis FFF, pengujian ikatan antar lapisan melalui uji tarik sesuai standar ISO 527-3, serta pengukuran adhesi *buildplate* menggunakan alat uji pelepasan yang dirancang khusus dan terintegrasi dengan *universal testing machine*, disertai analisis morfologi patahan menggunakan *scanning electron microscopy*. Hasil penelitian menunjukkan bahwa peningkatan temperatur *buildplate* secara signifikan meningkatkan kekuatan adhesi antar lapisan dan lebar permukaan patahan pada material HIPS, terutama pada temperatur mendekati suhu transisi gelas, yang mengindikasikan peningkatan difusi molekul dan kualitas ikatan antarmuka, sedangkan material PP menunjukkan performa adhesi yang rendah pada seluruh jenis *buildplate* akibat terjadinya *warping* dini dan pembentukan *void* antarlapisan. Adhesi *buildplate* yang optimal dan stabil hanya dicapai pada kombinasi HIPS–PEI pada temperatur 105 °C, sementara *buildplate* jenis *ultrabed* dan kaca tidak menunjukkan kinerja adhesi yang memadai. Temuan ini menegaskan pentingnya kesesuaian antara kondisi termal dan karakteristik permukaan *buildplate* dalam proses FFF serta perlunya modifikasi material atau perlakuan permukaan tambahan untuk meningkatkan kemampuan cetak PP.

Kata kunci: Adhesi pelat cetak; manufaktur aditif; ikatan antar lapisan; HIPS, polipropilen

1. Introduction

Additive manufacturing has become one of the fastest-evolving technologies and is increasingly adopted by small and medium-sized companies across various industries, including prototyping, souvenirs, 3D figure modeling, and the biomedical field. This technology has greatly accelerated innovation and fostered the growth of a community of additive manufacturing professionals, both locally and globally. Among the different techniques in additive manufacturing, fused filament fabrication (FFF) stands out as the most practical and cost-effective [1–3]. This method works by extruding heated, semi-melted thermoplastic materials to build three-dimensional (3D) objects layer by layer, starting from the bottom and continuing to its topmost layer [4–6]. Despite its potential, FFF technology still faces several limitations. A common issue is the detachment of the printed object from the build plate after printing, which can result in improper product formation. This problem is often caused by material shrinkage during the printing process and insufficient adhesion between layers. Therefore, achieving optimal adhesion both between the initial layer and the build plate, as well as between the successive layers of the object, is crucial. Poor adhesion can reduce print quality or even damage the build plate due to weak bonding, while overly strong adhesion can cause interlayer failures. To mitigate this, intermediate adhesives, such as specialized tapes designed for FDM technology, are often used. It is hypothesized that optimizing build plate temperature settings, along with selecting suitable combinations of filament materials and build plate surfaces, could significantly reduce the risk of product formation failures [7,8].

It is clear that filament and build plate materials each have unique properties, requiring a more in-depth investigation to understand the nature of adhesion between these distinct materials [9]. Previous research has highlighted the critical role of adhesion between the material and the build plate in 3D printing machines. Typically, the 3D printing process is performed at a build plate temperature slightly above the filament material's glass transition temperature to enhance adhesion between the two [8]. Additionally, the effect of varying build plate temperatures and component thickness on acrylonitrile-butadiene-styrene (ABS) parts produced by FFF, while maintaining a fixed nozzle temperature, was observed to influence warpage and shrinkage. Warpage and shrinkage were found to decrease as the build plate temperature increased [10]. Bonding strength between the printed object and the build plate can also be improved by using additional adhesives, and research results have provided a reference table that can be used for future studies [7]. Although many studies have highlighted the importance of the interaction between the printed material and the 3D printer's build plate, the quantification of the interfacial strength between these two materials is still rarely reported in the open literature.

In this study, the interface adhesion between layers in the printed object and the adhesion between the printed material and the build plate of an FFF-based 3D printer was quantitatively examined. Two polymeric materials were printed and evaluated, including high-impact polystyrene (HIPS) and polypropylene (PP). Additionally, three types of build plate materials were investigated: polyetherimide (PEI) sheet, ultrabed with microporous coating, and glass. A novel testing apparatus was developed to measure the interfacial bonding strength between the printed materials and the build plate. The impact of build plate temperature on the interfacial bonding strength was also assessed.

2. Material and Method

2.1. Materials Preparation

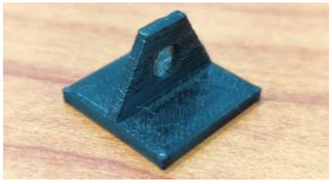
In this study, two types of specimens were prepared to evaluate both the interlayer adhesion within the printed object and its detachment from the 3D printer's build plate. All specimens were fabricated using a 1.75 mm polymeric filament on an Ender-3 S1 Pro FFF-based 3D printer (Shenzhen Creality 3D Technology Co., Ltd., China), with extruder and build plate temperatures set according to the parameters outlined in Table 1.

Table 1 The materials of the printed specimens, their extrusion and build plate temperatures used in the printing process for this research

Filament Materials	Extruder Temperature (°C)	Build-plate Temperture (°C)	Manufacturers
HIPS	220-240	80-120	JMH - China
PP	220-250	50-60	Kreafill - Indonesia

Two material were tested: HIPS and PP, with all specimens printed in accordance with ISO 527-3 standards for interlayer adhesion testing. For the interlayer adhesion test, the specimens were printed with the printing direction oriented perpendicular to the applied load, as shown in Figure 1(a). The specimen used for testing detachment from the build plate is shown in Figure 1(b).

(a)



(b)

Figure 1. (a) The dog-bone shaped specimen for interlayer bonding test and (b) the specimen for the detachment test of the printed polymer from the build-plate of the 3D printer.

Meanwhile, three types of buildplates were used for the detachment tests on the FFF-based 3D printer: polyetherimide (PEI) sheets, ultrabed with microporous coating (ULG), and glass. A further step was taken to determine the relationship between surface roughness and the adhesive strength between the build plate and the product by testing the surface roughness of the build plate. The build plate utilized in the research is a readily available item, accessible through both online and offline markets. The different build plates used in this study are shown in Figure 2.

a. PEI Sheet b. ULG c. Glass bed

Figure 2 Surface morphologies of: (a) PEI, (b) ULG and (c) glass build-plates

2.2. Interlayer Adhesion Test

The interlayer adhesion test was performed using a universal testing machine (Zwick/Roell Z020, Germany) at room temperature, with a crosshead speed of 5 mm/min, in accordance with ISO 527-1 and ISO 527-3 standards. An initial load of 0.1 MPa was applied to properly align the specimen on the machine before starting the test. The fracture surfaces of all tested specimens were then examined by using a Zeiss EVO10 electron microscope (Carl Zeiss, Germany) to reveal possible fracture mechanisms in the specimens of each filament material. Figure 3 shows the photograph of the specimen during the interlayer adhesion test.

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Figure 3. Photograph of the specimen during the interlayer adhesion test

2.3. Detachment Test of the Printed Object from the Buildplate of the 3D Printer

The detachment test in this study was conducted to evaluate the effects of different build plate materials and temperatures on the adhesion strength between the printed object and the plate. For this purpose, a novel detachment test setup was developed, as shown schematically in Fig. 3. In this setup, a Zwick/Roell Z020 universal testing machine (Zwick/Roell, Germany) was used in combination with an FFF-based printer (Ender-3 S1 Pro, Shenzhen Creality 3D Technology Co., Ltd., China) to measure the force required to detach the printed object from the build plate after the printing process was completed. The surface morphologies of the polymeric specimens detached from the build plates were also examined using a Zeiss EVO10 electron microscope (Carl Zeiss, Germany). Figure 4 shows the photograph of the specimen during the detachment test.

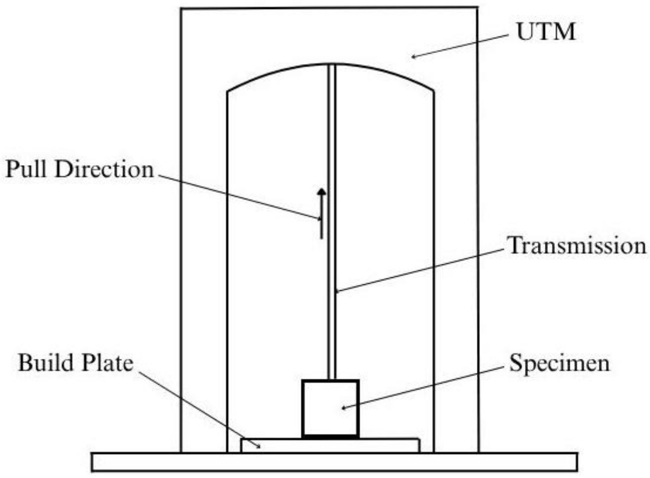

Figure 4. Schematic illustration of the detachment test

Six combinations of specimen and build plate materials were investigated, as outlined in Table 2.

Table 2. Combination table of filament material with build plate type for build plate adhesion testing

Filament – Build-plate Combination
HIPS – PEI Sheet
PP – PEI Sheet
HIPS – Ultrabed lattice glass
PP – Ultrabed lattice glass
HIPS – Glass
PP – Glass

3. Results and Discussion

3.1. Interlayer adhesion tests

Figure 5 presents the results of the interlayer adhesion tests for all specimens examined in this study: HIPS, and PP. The figure shows that increasing the build plate temperature generally improves the interlayer adhesion strength, particularly for HIPS. However, the interlayer adhesion strength of PP showed little to no improvement with increasing build plate temperature. The interlayer adhesion test essentially measured the bonding strength between two adjacent layers within the printed specimen under tensile load. The test was terminated once the specimen fractured.

The build plate temperature was found to have a pronounced influence on the adhesion strength between HIPS and the build plate surface. At 100°C, the adhesion strength remained relatively low, which can be attributed to insufficient polymer chain mobility and limited wetting of the molten HIPS on the build plate. As the temperature approaches the glass transition range of HIPS (approximately 95–105 °C), a transition from elastic-dominated behavior to viscoelastic flow occurs, significantly enhancing interfacial contact and molecular diffusion at the interface. This phenomenon elucidates the pronounced increase in adhesion strength observed at 105°C, where optimal wetting and mechanical interlocking are attained. As indicated by earlier research on FDM polymers, analogous non-linear increases in bed adhesion have been documented in the vicinity of the glass transition temperature. These increases have been shown to result from minor temperature increments, which have in turn been observed to engender considerable alterations in adhesion performance, a phenomenon attributed to the amplification of polymer-substrate interactions [11,12].

However, further increasing the build plate temperature to 110°C does not necessarily lead to proportional improvements in adhesion. While elevated temperatures facilitate polymer softening and intimate contact, excessive thermal energy may induce over-softening of the initial layer, resulting in stress relaxation, creep deformation, and diminished structural integrity during mechanical testing. This behavior has been shown to result in higher variability in measured adhesion strength. This finding is supported by the observations of Wang et al. and Seppala & Migler, who reported that excessive bed temperatures can compromise dimensional stability and introduce inconsistencies in adhesion measurements. Furthermore, the significant sensitivity of adhesion strength to build plate temperature underscores the critical role of interfacial wetting angle reduction, residual thermal stress mitigation, and viscoelastic dissipation mechanisms. Collectively, these factors govern the adhesion behavior of HIPS in fused deposition modeling processes. These findings indicate the existence of an optimal temperature window for HIPS bed adhesion, within which interfacial bonding is maximized while mechanical stability is preserved. Given that the buildplate temperature corresponds to the glass transition temperature of HIPS material, the observed variability in measurement results for HIPS material is significant. However, further investigation is necessary to thoroughly assess this phenomenon.

To further investigate the fracture mechanisms, the fractured surfaces of the specimens were examined using an electron microscope, as illustrated in Figure 6.

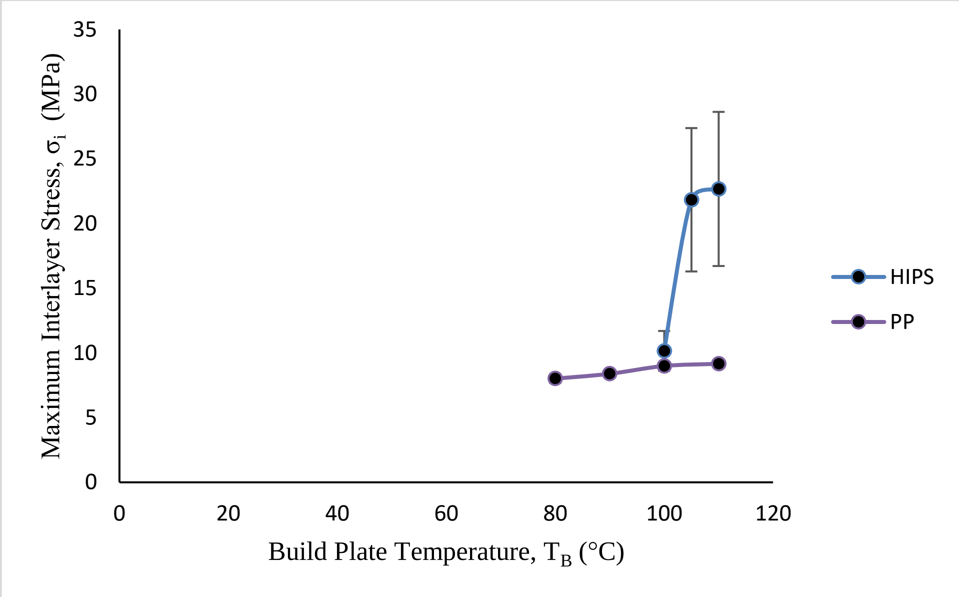

Figure 5. Combined Inter-layer adhesion graph of HIPS and PP

In general, the fractured surfaces of all specimens exhibited characteristics of brittle fracture, as no material elongation in response to the tensile load was observed. This behavior may be attributed to the inherent limitations of FFF-based 3D printing, where the interface between adjacent layers is often a weak region due to differences in cooling rates, leading to poor bonding and residual stress [13,14]. Using the micrographs obtained from electron microscope observations, the fractured surfaces of the specimens were quantified in this study, such as shown in Figure 6. Figure 7 shows the results of width measurements on the fractured specimens.

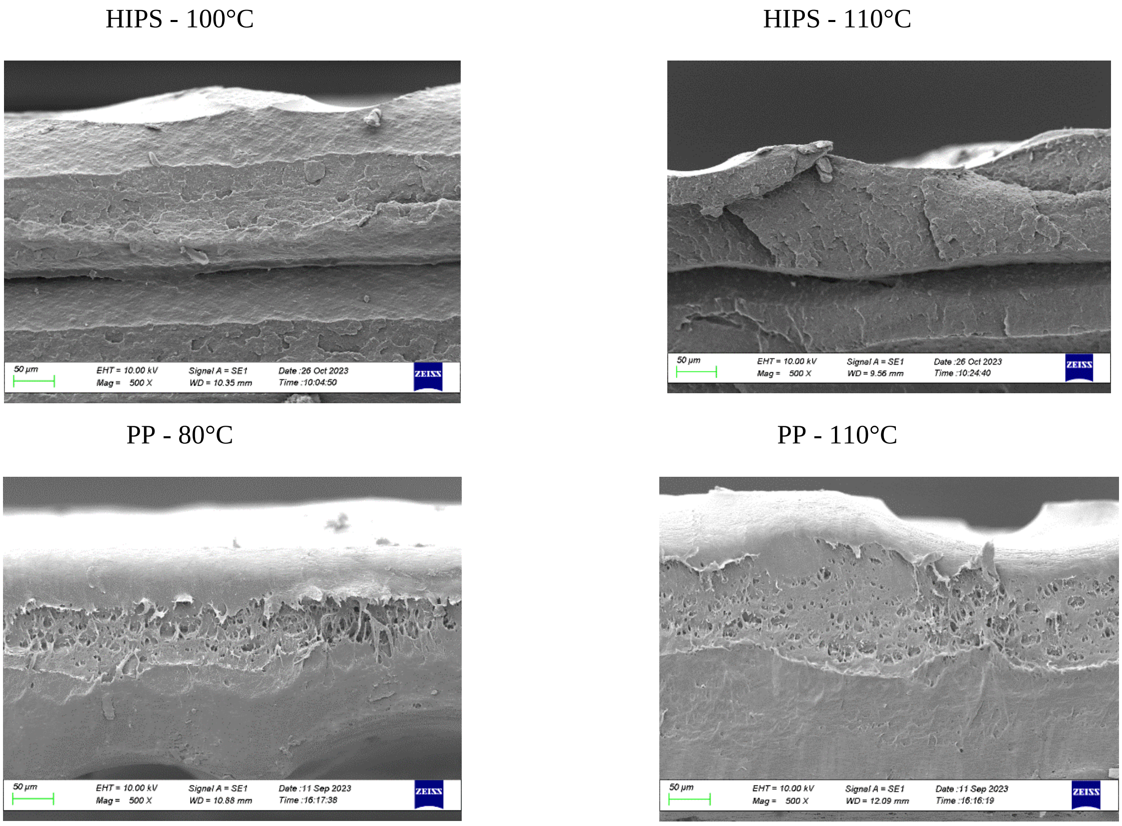

Figure 6. Fracture width from low-high build plate temperature comparison

From the SEM measurements, the data can be compiled into a table of fracture width measurements (Table 3).

Table 3. Fracture width of each specimen material

Filament Materials	Build-plate Temperature (°C)	Average (mm)
HIPS	100	8,19
	110	13,47
PP	80	7,23
	110	11,81

As shown in Figure 7, the average width of the fracture surfaces for HIPS and PP increased noticeably with higher build plate temperatures. This may suggest improved interlayer bonding in both materials.

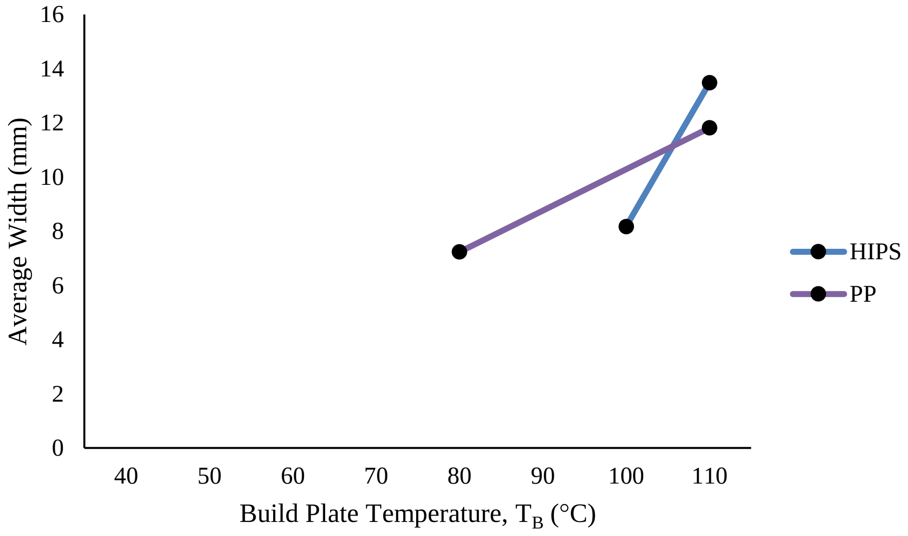

Figure 7. Fracture width of each specimen material

For HIPS, the enhanced bonding between adjacent layers significantly strengthened interlayer adhesion, as illustrated in Figure 5. This improvement could be due to the longer fluid state of the extruded material at elevated build plate temperatures, as the temperature difference between the extruder and the build plate decreases. Consequently, the material from adjacent layers had more opportunity to bond and conform to each other's surfaces. In contrast, while the fracture surface of PP also expanded with increasing build plate temperature, the interlayer adhesion strength did not show a significant improvement, as depicted in Figure 5. This could be attributed to the presence of voids at the interface between contact layers, which may have undermined the bonding despite the larger fracture surface. Similar findings have been reported in previous studies (14).

3.2. Detachment tests

In the second stage of the research, the focus was on testing the adhesion of the build plate with the filament material and build plate material, as outlined in the list of filament-build plate combinations in Table 2.

As previously mentioned, the adhesion test concept applied in the study employed a self-designed instrument design distinct from instruments employed by previous researchers. However, the test method was analogous to the measurement concept utilized in the instrument employed by Plazcek [7].

Table 4 presents an overview of the observations made during the specimen printing process.

Filament Materials	Build plate Temperature	PEI Sheet	ULG (Ultrabed with Microporous Coating)	Glass
HIPS	100	Observed	-	-
	105	Observed	-	-
	110	Observed	-	-
PP	80	-	-	-
	90	-	-	-
	100	-	-	-
	110	-	-	-

The results were obtained through visual observation during the specimen forming process for each combination of filament material and build plate material. Upon initial observation, it can be concluded that specimens of PP material cannot be formed, while specimens of PP material in all types of build plate can only be formed in the first layer to the third layer. The detachment process of the PP specimen begins at the specimen's edge (lifted up) and then progresses to the centre area of the lowest layer of the specimen, repeating this process in a number of planned specimen samples.

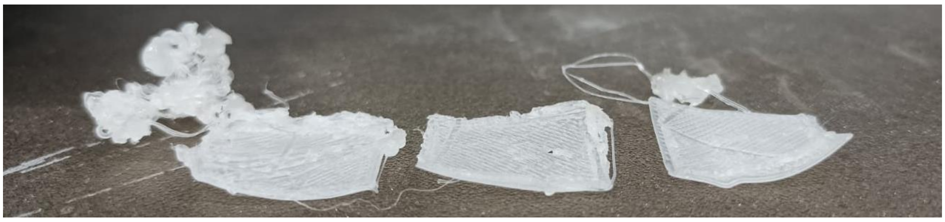

Figure 8. PP specimen forming failure

Table 4 provides insight into the process of forming specimens from HIPS material. It has been observed that HIPS specimens exhibit a tendency to adhere to the PEI Sheet type build plate, with specimens failing to form on the ULG and Glass build plate types. Formation conditions up to the first four layers have been observed to be the optimal for the formation of specimens. However, the remaining layers are found to be loose. In comparison to PP, the deformation observed in HIPS specimens has been found to be relatively smaller. This is evident from a visual comparison.

The degree of deformation observed between specimens cannot be compared due to the variability in specimen failure. Specimens that fail in a particular layer may exhibit a different degree of deformation compared to those that survive to a greater depth within the build. Therefore, the results of measurements taken on specimens that have failed at different points within the same layer cannot be directly compared with those from specimens that have survived to a greater depth.

Figure 9. HIPS specimen forming failure

One of the principal objectives of this research is to reduce the amount of waste generated during the production process of 3D printers. The results of this research indicate that HIPS and PP are not the most suitable materials for FFF technology. However, it is possible to form these materials using FFF technology

The data presented in Table 4 served as the foundation for the subsequent experiment, which involved the measurement of adhesion through the utilisation of a bespoke instrument integrated into the UTM.

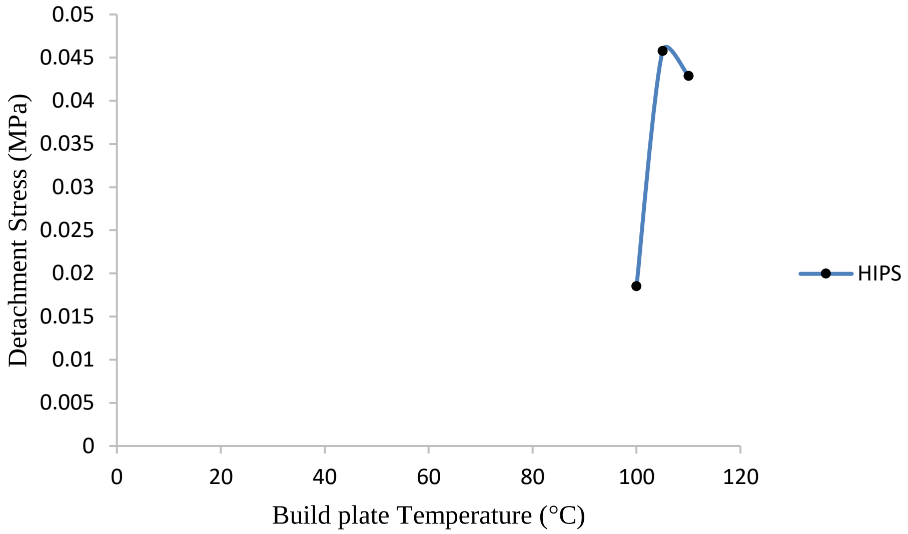

Figure 10 Chart of adhesion profile of HIPS material to PEI sheet build plate

The results of the tensile test, which indicate the adhesion between the specimens of each material and the PEI sheet-type build plate, are presented in Figure 10. The highest stress of the HIPS material is indicated in the graph when the build plate is set at 105°C.

Specimens made of PP filament exhibited poor formation, as illustrated in Figure 8 and in accordance with the observation data in Table 4. In the PEI Sheet type build plate, the PP was particularly warped at the edge of the specimen. The formation of the lowest layer can be accomplished with satisfactory results. However, the bending process begins to occur in the formation of the next layer, which results in the detachment of the specimen from the build plate when the specimen has only reached 2 to 3 layers.

The results of the adhesion measurement between the specimens from both materials (HIPS and PP) and the build plate of ULG also glass material exhibited disparate outcomes. The photo is presented in Figure 8 and Figure 9. According to Table 4, no specimens could be formed on this type of ULG build plate with similar causative symptoms, namely the occurrence of warping at the edge of the specimen when the printing process has only reached the first 2-3 layer [17]

In order to ascertain whether each specimen material can be employed in accordance with the specified parameters, it is necessary to measure the dimensions of the specimen following the adhesion test. The dimensions are measured in the direction of the pull force applied during the adhesion test. In this instance, the height of the specimen is of interest.

The results of the specimen adhesion test were measured 48 hours after release in the adhesion test for each filament material and each type of buldplate material. This was done to ensure that the specimen measurement process was carried out in a stable specimen condition in terms of dimensions and temperature.

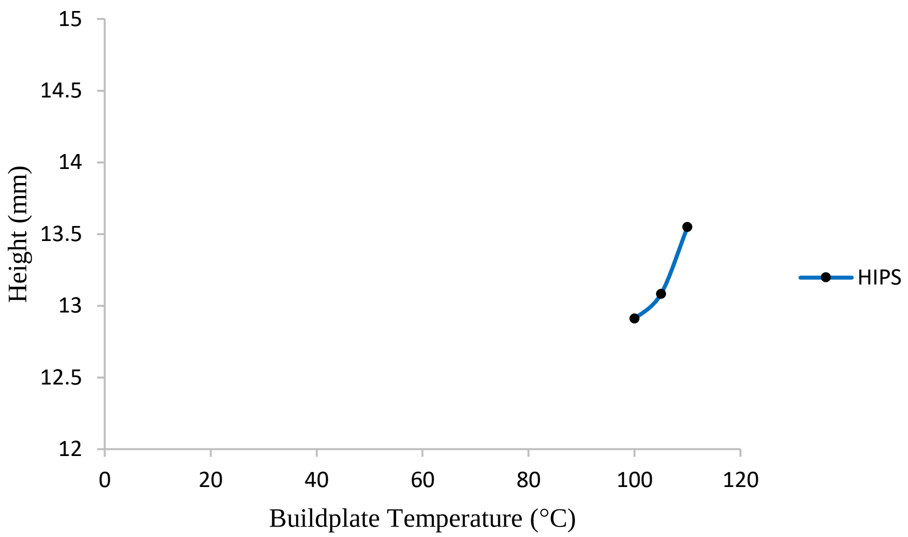

Figure 11. Deformation of Specimen's height on PEI Sheet Build plate

The results of measuring the specimen height of HIPS material against the PEI Sheet build plate are shown in Figure 11. The HIPS filament material adheres well to the PEI Sheet build-plate material. The increase in build-plate temperature applied to the system, resulted in higher adhesion [8].

A topic of interest was the use of HIPS and PP materials, both of which are commonplace in the plastics industry, employed in a variety of sectors [18]. However, both materials require specific processing techniques in order to be utilised in FFF. A great deal of research has been conducted on these two materials, including studies on the utilisation of recycled plastic derived from HIPS and PP, with the objective of identifying potential benefits [19]. Nevertheless, there is a paucity of attention devoted to the implementation of countermeasures and preventive measures designed to reduce the frequency of product forming failures, with particular emphasis on instances in which the base component of the product construction does not achieve the desired form. This is closely related to the adhesion between the product and the build plate.

The images displayed in Figure 8 and 9 provide evidence of failures that occurred during the adhesion measurement experiments with the various combinations presented in Tables 2 and 4. It is crucial to identify the underlying cause of the bending condition observed in the specimens made from HIPS and PP materials. Some previous research studies have indicated that the density factor may be a contributing factor to the occurrence of bending in 3D printing results for HIPS and PP materials [20].

4. Conclusion

The research carried out so far has focused on the adhesion between 3D printed products and two types of materials namely HIPS and PP filament and three type of build-plate namely PEI sheet, ULG and glass build plate materials. Initial tests were carried out to obtain data on how temperature changes affect the adhesion between the layers. Two results were obtained in the initial phase of testing, namely the adhesion strength between extrudates in a single layer and the size of the fracture width in the post-tensile test. From the experimental results, for all the filament materials tested, the adhesion strength between layers (extrudates) showed higher values when the build plate temperature was also set at a high temperature. The results of measuring the post fracture width of HIPS and PP adhesion tests at high build plate temperatures are greater in value compared to the results of measuring the fracture width of specimens formed at low build plate temperatures. In the second phase of testing, data was obtained in the form of visual observation of specimen formation and adhesive strength test data between specimens from four types of filament materials and three types of build plates with results showing that in comparison to ULG and glass build plate types, PEI sheet has been demonstrated to be a superior option when used with filaments comprising HIPS. However, in a series of experiments, PP filaments have been found to exhibit no adhesion to any build plate, including PEI sheet. Likewise, HIPS can only be 3d printed on PEI Sheet material.

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