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# THE EFFECT OF 3D PRINTING FILAMENT EXTRUSION PROCESS PARAMETERS ON DIMENSIONAL ACCURACY AND STRENGTH USING PLA-BRASS FILAMENTS

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## Abstract

3D printing technology, also known as additive manufacturing, is one of the prototyping systems for creating 3-dimensional models (prototypes). One of the most frequently used techniques is FDM (Fused Deposition Modelling) due to its simple working principle of melting the filament material and then extruding it. However, the price of filament used in 3D printing is still quite expensive, especially filaments with a mixture of metals. This study attempts to fabricate filament made of PLA and brass using a self-made extruder machine. The success criteria are determined by the precision of the filament and its strength. The accuracy of the printed filament was measured using a 0.01 mm micrometre, while strength was measured using the pull-out test. Three parameters were used: barrel temperature, material composition and roller speed, with two levels each. Taguchi L4($2^3$) was used to design the experiments, followed by S/N ratio analysis and ANOVA. The results showed that on the dimensional accuracy, the influential parameters were temperature and roller speed, for the optimal parameter level at a temperature of 95$^o$C, composition 10/30 g, and roller speed 3.02 mm/s. As for the single filament tensile test, the parameters that affect it are temperature and composition. For the optimal parameter level at a temperature of 100$^o$C, the composition is 10/30 g, and the roller speed is 2.70 mm/s.

Keywords: Additive manufacturing, Dimensional accuracy, PLA-brass, Tensile test.

## 1. Introduction

The development of technology is currently very rapidly entering the era of the industrial revolution 4.0, which makes various jobs can be done quickly and efficiently along with the development of human civilization in a modern direction. One of the technologies that support the implementation of Industry 4.0 is rapid prototyping, a technique for creating a product by making a product design using CAD (Computer Aided Design) software, followed by printing the product into a prototype model using a machine with a rapid prototyping system. Rapid prototyping technology is beneficial in reducing the product development cycle time by creating a physical model for direct visual evaluation of a 3D computer model, which is then forwarded to print using a 3D Printer [1].

The technology that uses a rapid prototyping system is 3D printing which is used to create a 3-dimensional model (prototype). In addition, 3D printing can answer the challenges of consumers who want products with high flexibility. Of course, with the development of these technologies in various fields, the methods or techniques also vary. The American Society for Testing and Materials (ISO/ASTM International, 2013), ("Designation: F2792 12a," 2013) has published standards for classifying Additive Manufacturing processes into seven categories. The seven methods in Additive Manufacturing technology are the same: adding materials layer by layer to make a specific product [2].

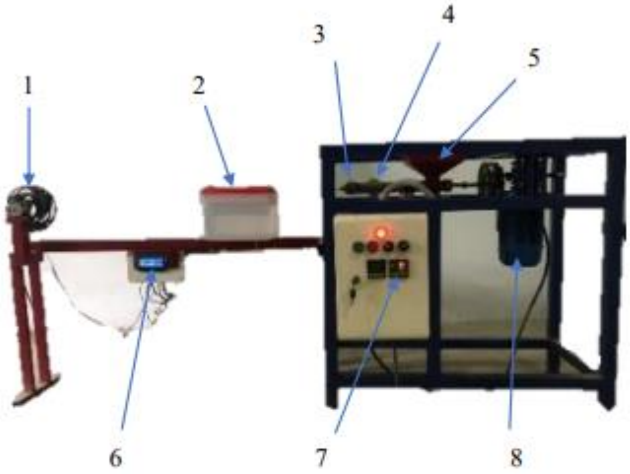
One of the most frequently used techniques in Additive Manufacturing, namely Fused Deposition Modelling, is widely used due to its easy operation, lower costs in the production process, and environmentally friendly properties [3]. The material used in this technique is in the form of a filament. However, the price of the filament is still relatively high even though the availability of filaments is increasing, especially for the price of high-quality filaments. One of them is a filament made from a mixture of PLA - brass, which has a price that is no less high, around $39.90 (573,000 rupiahs) per roll with a weight of 0.5 kg [4].

In manufacturing filaments, a filament extruder machine is used with the parameters used, namely temperature, composition, and roller speed. According to research [5], the resulting filament diameter increases with the addition of screw speed and heating temperature and decreases with increasing rolling speed. Characterization of filament dimensions shows that screw speed, rolling speed, and temperature control significantly affect filament output. In [6], the puller filament speed control and temperature control were carried out to produce a filament with a stable diameter. Ramadhan et al. (2022) stated that regulating barrel temperature is essential [7]. Therefore, it requires the right temperature combination because if the temperature is too small, it will cause the plastic seeds in the barrel to melt less, so the extrusion released is unstable.

## 2. Methods

### 2.1. Tools and materials

This study conducted research on manufacturing filaments made of a mixture of PLA and brass. Both materials were bought from the marketplace. The brass powder size of 60 mesh, while PLA is in the form of granules. The extruder machine was self-made and was previously proven to produce PP filament [7]. It has an extruder diameter of 25 mm. The appearance of the extruder machine is presented in Fig. 1. Three parameters, namely barrel temperature, material composition and roller speed, were varied to determine the effect of parameter variations and optimal parameter levels on the dimensional accuracy of the single filament tensile test. The measured outputs were dimensional accuracy and strength of the extruded filaments. The dimensional accuracy was measured using a 0.01 mm accuracy screw micrometre.




Description:
1. Roller
2. Cooling water tank
3. Screw
4. Band heater
5. Hopper
6. Arduino controller
7. Thermocontrol
8. Drive motor

**Fig. 1. Filament extruder machine.**

## 2.2. Response variable

In this study, there are variables used. For the independent variables used are presented in Table 1. The dependent variable is the value of dimensional accuracy and the single filament tensile test (well known as the pull-out test). For dimensional accuracy, the deviation value can be determined by comparison with the standard diameter of the filament and from the actual measurement results using the ISO 2768-1 standard (dekmake.com). As a reference, a deviation tolerance of ± 0.05 mm from the general filament diameter used in FDM (1.75 mm). The dimensions were measured using a screw micrometre with an accuracy of 0.01 mm with 3-point measurements. The single filament tensile test can be determined by observing the graph of the results of the single filament tensile test with a filament length of 4.5 cm according to the ISO 11566 standard (cdn.standards.iteh.ai). The control variables consist of a screw rotation speed of 23.2 rpm, cooling water temperature (26-30 ºC), and room temperature (28-30 ºC).

**Table 1. Independent variables of filament manufacturing research.**

| Control factor | Parameter | Level 1 | Level 2 |
|---|---|---|---|
| A | **Barrel temperature (ºC)** | 95 | 100 |
| B | **Composition of brass/PLA (gram)** | 10 / 20 | 10 / 30 |
| C | **Roller speed (mm/s)** | 2.70 | 3.02 |

### 2.3. Experimental design

The parameters used in the extrusion process are barrel temperature, composition, and roller speed, where each parameter consists of 2 levels. For temperatures of 95°C and 100°C, the composition is 10/20 g and 10/30 g, and the roller speed is 2.70 mm/s and 3.02 mm/s. Both variables and parameters were chosen after doing some initial experiments. The experiment was designed following an orthogonal array matrix $L4(2^3)$ [8]. The experimental design of the study can be seen in Table 2. The extrusion process was carried out according to the design of the matrix, which consisted of 20 replications. The diameter of the extruded filament was measured, and the tensile test was then processed using Taguchi and ANOVA to determine the effect of parameter variations and optimal parameter levels. In addition, fractography analysis was carried out to observe the fracture surface. It is a standard method to determine the cause of product failure [9]; or to classify whether the fracture is brittle or ductile [10].

## 3. Result and Analysis

The filament could be produced using the extruder machine. The sample of the filament is depicted in Fig. 2(a). The distribution of the brass and the PLA matrix was observed using the microscope at the magnification of 50x/ One of which is presented.

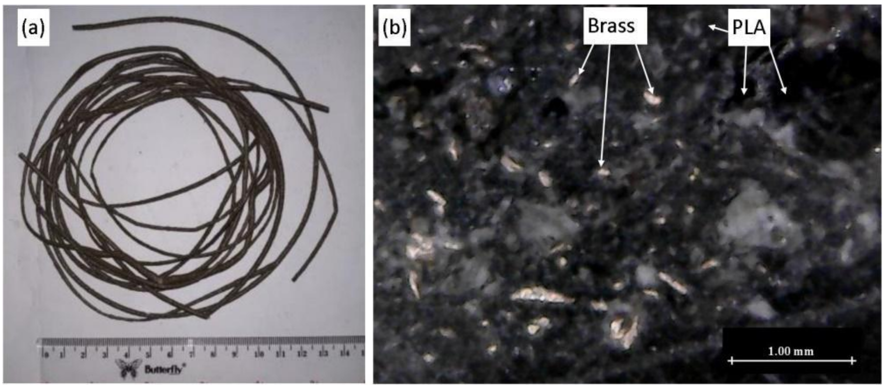



**Fig. 2. A sample of extruded filament (a), and the microstructure of the filament (b).**

### 3.1. Taguchi analysis

Before carrying out the Taguchi analysis of dimensional accuracy, the 4.5 cm long filament was first measured using three measurement points. Then the measurement results were calculated as an average (Table 2, columns 5 & 6). The filaments pull-out tests were carried out using a universal testing machine. Then, the tensile strength results from each variation were averaged (Table 2, columns 9 and 10).

This study's dependent variable is the dimensional accuracy and the tensile test value, where a suitable filament diameter is close to 1.75 mm. Therefore, the type of S/N ratio used is "nominal is best", while for the tensile test itself, the greater the value of the tensile strength, the better. Therefore, the type of S/N ratio used is "large is better" in the Taguchi method.

**Table 2. Data table of dimensional accuracy and tensile test results.**

| | Control factor | | | | Dimensional Accuracy | | | Tensile test | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Temp (ºC)** | **Composition (g)** | **Roller speed (mm/s)** | **Replication** | **Average (mm)** | **Deviation (mm)** | **S/N Ratio (dB)** | **Tensile strength (MPa)** | **Average (MPa)** | **S/N Ratio (dB)** |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| | | | | **I** | 1.76 | 0.01 | | 2.68 | | 9.84 |
| | | | | **II** | 1.80 | 0.05 | | 3.39 | | |
| **1** | **95** | **10/20** | **2.70** | **III** | 1.76 | 0.01 | 38.94 | 2.88 | 3.16 | 9.84 |
| | | | | **IV** | 1.78 | 0.03 | | 3.23 | | |
| | | | | **V** | 1.75 | 0 | | 3.62 | | |
| | | | | **I** | 1.73 | 0.02 | | 3.76 | | |
| | | | | **II** | 1.73 | 0.02 | | 3.55 | | |
| **2** | **95** | **10/30** | **3.02** | **III** | 1.75 | 0 | 45.76 | 3.86 | 3.97 | 11.89 |
| | | | | **IV** | 1.74 | 0.01 | | 4.54 | | |
| | | | | **V** | 1.73 | 0.02 | | 4.15 | | |
| | | | | **I** | 1.71 | 0.04 | | 3.41 | | |
| | | | | **II** | 1.74 | 0.01 | | 3.49 | | |
| **3** | **100** | **10/20** | **3.02** | **III** | 1.73 | 0.02 | 40.73 | 3.02 | 3.48 | 10.70 |
| | | | | **IV** | 1.72 | 0.03 | | 3.37 | | |
| | | | | **V** | 1.70 | 0.05 | | 4.09 | | |
| | | | | **I** | 1.74 | 0.01 | | 4.27 | | |
| | | | | **II** | 1.76 | 0.01 | | 5.22 | | |
| **4** | **100** | **10/30** | **2.70** | **III** | 1.78 | 0.03 | 38.84 | 4.01 | 4.56 | 13.03 |
| | | | | **IV** | 1.74 | 0.01 | | 5.03 | | |
| | | | | **V** | 1.73 | 0.02 | | 4.25 | | |

Both criteria of S/N ratios were calculated using Eq. (1) and (2) [8], respectively.

$$\frac{S}{N}\, the\ ratio\ for\ "nominal\ is\ the\ best" = 10\ log\left[\frac{y^2}{S^2}\right] \quad (1)$$

$$\frac{S}{N}\, ratio\ for\ "large\ is\ better" = -10\ log\ log\ \left(\frac{1}{n}\sum_{i=1}^{n}\ \frac{1}{y^2}\right) \quad (2)$$

where: $n$ = number of replication and $y$ = data from the experiment.

After measuring the dimensional accuracy and tensile test, it was continued by calculating the S/N ratio using the Taguchi method by entering the factor values and responses on the Minitab. The results of the calculation of the dimensional accuracy S/N ratio and tensile test can be seen in Table 3. The next step was calculating each parameter level's average value. Where in Table 3, the enormous difference in dimensional accuracy is roller speed, followed by temperature and composition. Meanwhile, the most significant difference in the tensile test is composition, followed by temperature and roller speed.

**Table 3. The average response of the S/N ratio value at each parameter level.**

| **Control factor** | **Dimensional Accuracy** | | **Difference** | **Tensile test** | | **Difference** |
|---|---|---|---|---|---|---|
| | **Level 1** | **Level 2** | | **Level 1** | **Level 2** | |
| Temperature | 42.35 | 39.79 | 2.56 | 10.86 | 11.87 | 1.00 |
| Composition | 39.84 | 42.30 | 2.47 | 10.27 | 12.46 | 2.19 |
| Roller speed | 38.89 | 43.25 | 4.36 | 11.44 | 11.29 | 0.14 |

From the scatter plot of the S/N ratio, it can be concluded that the optimal factor level for the dimensional accuracy results in Fig. 3 is temperature level 1 (95ºC), composition level 2 (10/30 g), and roller speed level 2 (3.02 mm/s). While for the tensile test value, the optimal factor levels are temperature level 2 (100ºC), composition level 2 (10/30 g), and roller speed level 1 (2.70 mm/s).

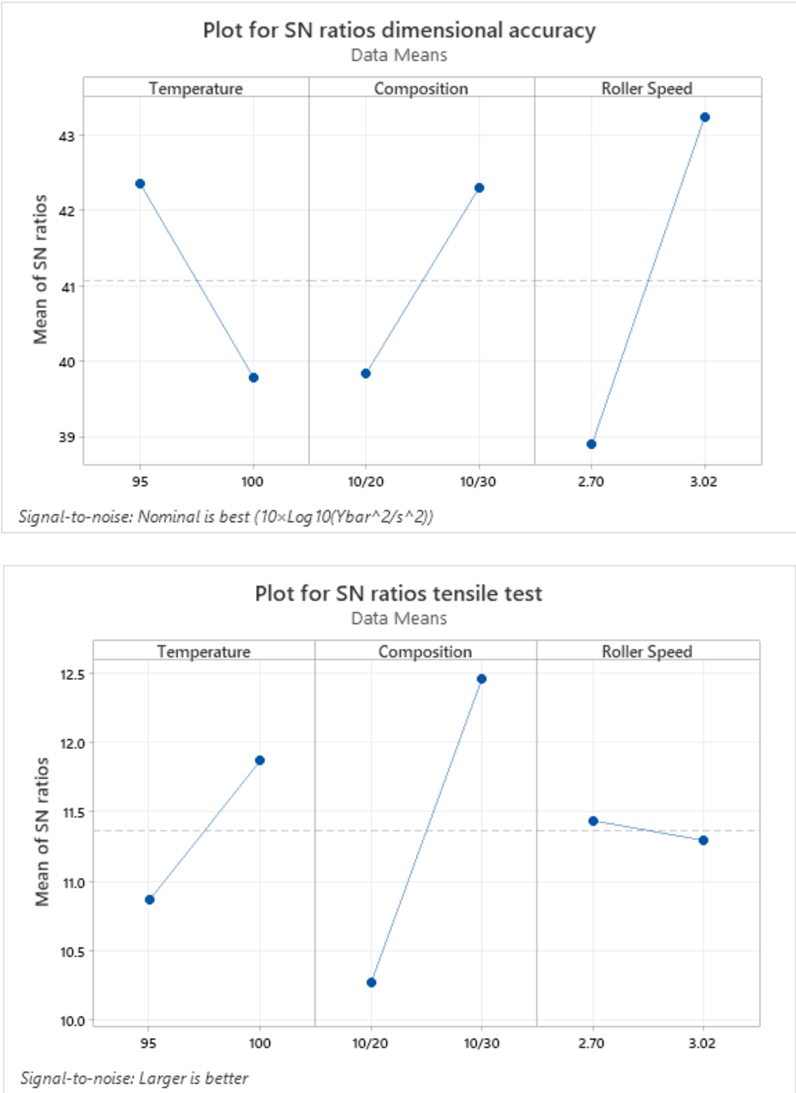



**Fig. 3. The plot of factor level S/N ratio.**

## 3.2. ANOVA

Analysis of variance (ANOVA) is a calculation method that allows quantitatively estimating the contribution of each factor to all response measures. The analytical model used is a two-way analysis of variance. The reason for using two directions is that this study uses three factors and two levels. The two-way analysis of the variance table consists of calculating degrees of freedom, the number of squares, the average number of squares, and the F-ratio. Based on the results of the ANOVA calculation using Microsoft Excel, the parameter that has an effect is a parameter with a value of $F_{-Value} > F_{-Table}$. In this study, the percentage point of the F distribution for the probability used is 0.05 or 5%. The $F_{-Table}$ value used is based on the $DoF_{tot}$ and $DoF_{A}$ calculations, so the value (F0.05;1;16) = 4.49. The results of ANOVA calculations on dimensional accuracy and tensile tests are presented in Tables 4 and 5.

From the ANOVA calculation, the parameters that have a significant effect are temperature, with a contribution of 14.36% and roll speed, with a contribution of 45.36%. As for the tensile test ANOVA calculation, the parameters that have a significant effect are temperature, with a contribution of 11.93% and composition, with a contribution of 52.74%. The percentage error generated in the dimensional accuracy ANOVA and the tensile test has an error percentage value of more than 15% but less than 50%.

An important note in interpreting the experimental analysis: if the percentage contributing to any error (either from unknown or uncontrolled factors) is low, then it is presumed that no essential parameters were neglected from the experiments. The threshold of being low is 15 %. By contrast, if the value is high (50% or more), then it may be because (i) some essential parameters were neglected, (ii) conditions were not precisely controlled, or (iii) there was an excessive error in measurement [11]. In the case of the ANOVA result of the dimensional accuracy and tensile strength, with the error of 40.07% and 34.27%, respectively, it means some factors that may have influenced the thrust force were omitted from the experiments. However, an error of less than 50% is still acceptable.

**Table 4. ANOVA of control factors on dimensional accuracy.**

| Control factor | DoF | SS | MS | F | P | ($\rho$) |
|---|---|---|---|---|---|---|
| **Temperature** | 1 | 0.00162 | 0.00162 | 5.73451327 | *Significant* | 14,36% |
| **Composition** | 1 | 0.00002 | 0.00002 | 0.07079646 | *Not Significant* | 0.18% |
| **Roller speed** | 1 | 0.00512 | 0.00512 | 18.1238938 | *Significant* | 45.39% |
| ***Error*** | 16 | 0.0045200 | 0.0002825 | | | 40.07% |
| **Total** | 19 | 0.01128 | | | | 100% |

**Table 5. ANOVA of control factors on tensile test.**

| Control factor | DoF | SS | MS | F | P | ($\rho$) |
|---|---|---|---|---|---|---|
| **Temperature** | 1 | 1.0125 | 1.0125 | 5.57099232 | *Significant* | 11.93% |
| **Composition** | 1 | 4.47458 | 4.47458 | 24.6200996 | *Significant* | 52.74% |
| **Roller speed** | 1 | 0.08978 | 0.08978 | 0.49398883 | *Not Significant* | 1.06% |
| ***Error*** | 16 | 2.90792 | 0.18175 | | | 34.27% |
| **Total** | 19 | 8.48478 | | | | 100% |

## 3.3. Parameter effect

The research results obtained from the influence of parameters on the dimensional accuracy and single filament tensile test can be stated as follows.

### 3.3.1. Dimensional Accuracy

**a. Roller speed**

From the data processing results using ANOVA, the roller speed parameter has the most significant contribution percentage, which is 45.39%, with an $F_{-Value}$ of 18.124, because if the roller speed is too low, it can increase the diameter of the filament. Vice versa, if the roller speed is too high, it can decrease the diameter of the filament. The result follows the statement [6], which explains that controlling the puller filament speed and temperature control can produce a filament with a stable diameter. Then a study was conducted [12], which stated that the spooler speed significantly affected the filament diameter.

**b. Temperature**

The data obtained show that the barrel temperature has a significant influence, with a percentage contribution of 14.36% and an $F_{-Value}$ value of 5.735. It may relate to the extrusion of the filament coming out of the nozzle, where if the barrel temperature is too low, the mixture of brass and PLA is less melted and agglomerated so that the extrusion of the extruded material is unstable and affects the uniformity of the filament diameter when rolling. The result is in line with the statement from [13] that viscosity, melt flow characteristics, and melting temperature are very important to help reduce problems in the material extrusion process. Furthermore, Grasso et al. [14] stated that an increase in temperature resulted in a significantly higher strain. Herianto et al. [12] stated that the extrusion temperature significantly affected the diameter of the filament. Therefore, proper temperature regulation in the barrel is so necessary that it requires the right combination to produce stable and consistent filament extrusion.

**c. Composition**

For the composition parameters from the results of ANOVA data processing using Microsoft Excel, the percentage of the minor contribution is 0.18%, with an $F_{-Value}$ of 0.071. It is smaller than the $F_{-Table}$ value. It can be concluded that the composition parameters have no significant effect on the accuracy of the filaments' dimensions.

### 3.3.2. Tensile test

#### a. Composition

From the results of data processing using ANOVA, the composition parameter has the most significant contribution percentage, namely 52.74%, with an $F_{-Value}$ of 24,620, because the higher the matrix composition, the greater the tensile strength. In contrast, the tensile strength is lower if the filler and matrix composition are small. The results are in line with [15], where the tensile strength of pure PLA decreases when a filler is added. Further research was conducted [16], where higher fillers have resulted in lower tensile strength. Therefore, an increase in filler results in a decrease in tensile strength, whereas a higher PLA composition than filler results in higher tensile strength.

#### b. Temperature

From the data obtained, the barrel temperature has a significant influence, with a percentage contribution of 11.93% with an $F_{-Value}$ value of 5.571. It may be because the higher the temperature, the higher the tensile strength of the filament. It follows research [17], where the decrease in tensile strength is directly proportional to the decrease in temperature of the filament extrusion process. Furthermore, research was conducted [18] which stated that temperature dramatically affects the tensile strength in his research. The highest tensile strength was found at a temperature of 260ºC compared to the object tested at 180 ºC and 220 ºC.

### c. Roller speed

For the roller speed parameter from the results of ANOVA data processing using Microsoft Excel, the percentage of the minor contribution is 1.06%, with an $F_{\text{-Value}}$ of 0.494. It is smaller than the $F_{\text{-Table}}$ value. Therefore, it can be concluded that the roller speed parameter has no significant effect on the single filament tensile test value. Other researchers recommended that the roller speed should be carefully controlled. However, they did not do statistical analysis, whether this parameter is significant in affecting the strength of the filament [16].

## 4. Fractography

Fractographic testing analyses failure tests related to cracks, metal fracture properties, engineering structures and components. Fractographic testing can obtain information about the type of deformation, failure mode and fracture pattern. Fractography is a science that studies physical metallurgy by observing the fracture surface [9]. Things that appear on the fracture surface can be done by microscopic examination. After knowing the tensile value in this study, an optical analysis of the fracture was performed using a digital microscope to show the mechanical properties of the composite filament of a mixture of PLA-brass powder.

Fractographic testing aimed to determine the filament's ductility or brittleness by observing the filament fractures. The filaments used are filaments that have maximum and minimum values.

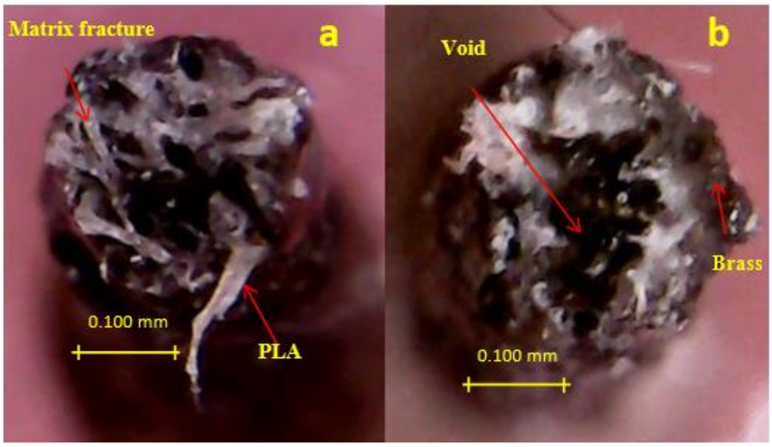



**Fig 4. Fractography tensile test max (a) and min (b).**

From the results of the fracture test, it can be seen in Fig. 4(a). It is a form of filament fracture that produces the highest average tensile strength of 5.22 MPa with a composition of 10/30 g. It can be noticed that there are long white threads and almost no voids in the photo above. It indicates that plastic deformation is higher at the fault location. Greenhalgh [10] stated that the more fractures in the fault, the stronger the material.

Different from Fig. 4(b), the shape of the broken hair after the tensile test has the lowest average value of 2.68 MPa with a composition of 10/20 g. Seen here are several holes or cavities around the surface of the fault. This hole or void is caused by the presence of air and gas remnants trapped in the barrel. Ferreira et al. found that the pores and cavities were caused by gas trapped during the liquefaction of the filament during the extrusion process, which decreased mechanical properties [19].

## 5. Conclusions

It can be concluded that the parameters that have a significant effect are temperature, with a contribution of 14.36%, and roll speed, with a contribution of 45.36%. As for the tensile test ANOVA calculation, the parameters that have a significant effect are temperature, with a contribution of 11.93% and composition, with a contribution of 52.74%. For optimal parameter levels on dimensional accuracy, namely temperature level 1 (95ºC), composition level 2 (10/30 g), and roller speed level 2 (3.02 mm/s). While the optimal factor level tensile test values are temperature level 2 (100ºC), composition level 2 (10/30 g), and roller speed level 1 (2.70 mm/s).

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