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The effect of heating temperature on 3D print filament diameter consistency produced by HDPE and LDPE plastic extrusion machine

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ABSTRACT

3D printing technology is rapidly growing in the industrial world, especially with the Fused Deposition Modeling (FDM) method that uses thermoplastic filament. The manufacture of the filament requires extrusion machines and plastic seeds, with filament diameter as the main indicator of 3D Print quality. This study aims to analyze the effect of heating temperature on the diameter consistency of the 3D print filament produced by plastic extrusion machine for High-Density Polyethylene (HDPE) plastics at temperatures of 160°C, 180°C, 200°C, 220°C, and 240°C and Low-Density Polyethylene (LDPE) at temperatures of 160°C, 170°C, 180°C, 190°C, and 200°C. Each temperature has six filament samples, with the diameter measured every 1 cm for five measurements using a screw micrometre, resulting in 30 data per temperature variation. The data was processed using Statistical Process Control (SPC) and Process Capability methods. Based on data analysis, it can be concluded that each temperature variation produces diameters that are within the control limits, allowing process capability testing. Conditioned process capability resulted in large process variations compared to the established specification range. It indicates imbalance and inconsistency in filament production so filament diameters are often out of specification limits. The conclusion is that temperature variation has a significant effect on the consistency of filament diameter resulting from extrusion machines with HDPE and LDPE plastic seed materials. In addition, the temperature of 220°C for HDPE plastic and 190°C for LDPE plastic produced the best filament.

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1. Introduction

3D printing technology is a fast-rising printing tool based on global demand and will continue to grow in the coming decades. The benefits of 3D printing include free-form processing, feasible and effective production, and time efficiency from concept to manufacturing, compared to conventional or subtractive manufacturing. 3D printing additive manufacturing technology uses thermoplastic filament as raw material with a production process from complex parts to simple ones [1].

Material extrusion-based 3D printing technology is widely used for printing multi-materials and multi-colours in producing various polymer components at a very low cost. Polyethylene is a thermoplastic filament produced as low or high-density PE by adding ethylene polymerization using an organometallic catalyst, which consists of two most common types, High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE)[2].

Filament diameter is the most important indicator of 3D printing quality, as it affects the flow rate during filament extrusion and can lead to 3D printing failures. Failures result from poor surface quality and extruder jams due to irregularity between individual extrusions and excessive overlap [3].

Filament diameter depends on the material properties and extrusion line design is affected by process parameters consisting of extrusion force and temperature. Therefore, it is necessary to vary the temperature due to the rheological properties of the material that affect the diameter of the filament so that it is necessary to adjust the process parameters [4]. Increasing the temperature in the extrusion machine is beneficial for the bonding and degreasing process of the material, as it can improve the bonding quality and the lack of quantity and size of voids in the component [5]. They are based on research in 2016 by Cardona which discusses the effect of filament diameter tolerance on fused filament fabrication (FFF) by measuring the tolerance of Acrylonitrile Butadiene Styrene (ABS) filament which has a nozzle with a diameter of 1.75 mm, with control parameters namely temperature and extrusion rate.

High diameter and low tolerance can be achieved at a low extrusion temperature of 180°C and a low extrusion rate of 10 in/min [3]. Research by Ponsar in 2020 analyzed variations in filament diameter with increasing screw speed, which causes inconsistent diameter and can affect the mechanical resistance of the filament and mass uniformity [6]. The design of a single screw extruder machine with the effect of temperature on extrusion results with LDPE recycled material was carried out experimentally 3 times by Djafar and Fatoni in 2021, with each temperature of 165 °C -170 °C, 185 °C – 190 °C and 205 °C - 210 °C. This research produced filaments with temperatures of 165 °C – 170 °C, 185 °C – 190 °C and 205 °C – 210 °C and revealed the optimal temperature for LDPE material on a single crew extruder machine is 165 °C – 190 °C [7]. Another research related to the analysis of temperature and screw angle on extrusion time of HDPE material using a single screw extrusion machine. The temperature variations used are 160 °C, 170 °C and 180 °C, and the screw angle variations are 0°, 15°, and 25°. This research was analyzed using the ANOVA method and showed that temperature does not affect the extrusion speed because it is not significant, while the screw angle affects the extrusion speed [8].

Making filaments must also pay attention to the parameters for setting up the extrusion machine in order to get good filament results. Temperature is the process parameter that has the most influence on diameter consistency [3]. Increasing the temperature in the extrusion machine is beneficial for the bonding and decreasing process of the material, because it can improve the quality of the bond and the lack of quantity and size of the cavity in the component [5]. With that in mind, this study aims to analyze the effect of heating temperatures on the diameter consistency of extruded HDPE and LDPE materials. The melting point temperature for HDPE plastic is 200 ℃ - 280 ℃, while for LDPE plastic is 160 ℃ - 240 ℃. Temperature variations in this study for HDPE plastic materials are 160 ℃, 180 ℃, 200 ℃, 220 ℃, 240 ℃ [8]. While the temperature variation for LDPE plastic material uses temperatures namely 160 ℃, 170 ℃, 180 ℃, 190 ℃, and 200 ℃ [7]. The use of temperature in the plastic extrusion process does not have to match the melting point because a slightly lower temperature can produce a smoother filament surface, a melting point temperature that is too high will cause air bubbles to be trapped in the material resulting in a less smooth filament surface [9]. In the extrusion process, an air-cooling system is recommended to maintain the thermal stability of the process because it can provide slower temperature changes compared to liquid cooling [10]. The extrusion process will be controlled by control variables, namely screw speed and cooling system using a blower [11].

2. Method

There are several stages such as literature study, manufacturing of extruder machines carried out by the research team, preparation of tools and materials, research settings according to variations, extrusion process, measuring filament diameter, and analyzing filament diameter. The tools and materials that need to be prepared for the research can be shown in Fig 1., including extrusion machines and screw micrometres, as well as HDPE and LDPE plastic seeds. Before the extrusion process, a cooling system using a blower and a screw speed parameter of 75 rpm was prepared. The extrusion process begins by starting the extruder machine, and then setting the temperature parameters. Next, plastic seeds are put into the hopper of the machine. Plastic seeds will come out through the machine nozzle in the form of filaments that are ready to be examined or used. The diameter of the filament was measured with a screw micrometre every 1 cm for five times in 6 samples. The measurement results can be processed using the Process Capability and Statistical Process Control methods.

(a) Extruder Machine Design (b) Extruder Machine (c) Skrup Micrometre (d) Plastic Seeds

Fig. 1. Tools and Materials

2.1. Statistical Process Control

The Statistical Process Control method is a collection of quality tools to solve process stability problems and improve capability by reducing variation [11]. Statistical Process Control (SPC) helps ensure the production process is stable and meets standards to produce quality products. Based on the SPC method, there are seven quality control tools to determine whether a production process is under control or vice versa. The seven control tools are check sheets, stratification (grouping), cause and effect diagrams, Pareto diagrams, histograms, scatter diagrams, and control charts [12].

Control charts are graphical tools for evaluating processes in statistical quality control, helping to solve problems and improve quality. In general, control charts have the form of numerical measures and variable data types, so it is necessary to control the average and variability of the process. Controlling the average process can be done with the X-Bar Chart and monitoring process variability using the R Chart or S Chart [13] To make a control map, it is necessary to calculate the control limits for the X-Bar Chart, R Chart, and S Chart as follows.

1. X-bar Control Chart

$$UCL = \bar{X} + A_2 . \bar{R} \tag{1}$$

$$CL = \bar{X} = \frac{\sum \bar{x}}{n} \tag{2}$$

$$LCL = \bar{X} - A_2 . \bar{R} \tag{3}$$

where, $\bar{X}$ is the average of the means of all subgroups, $\bar{X}$ is the mean of each subgroup, n is the number of subgroups, $\bar{R}$ is the mean of the ranges of the subgroups, and A_2 is a constant that depends on the size of the n subgroups.

2. R Control Chart

$$UCL = D_4 . \bar{R} \tag{4}$$

$$CL = \bar{R} \tag{5}$$

$$LCL = D_3 . \bar{R} \tag{6}$$

where, $\bar{R}$ is the average of the subgroup ranges, D_3 and D_4 are constants that depend on the subgroup size n.

3. S Control Chart

$$UCL = D_4 . \bar{R} \tag{7}$$

$$CL = \bar{S} \tag{8}$$

$$LCL = D_3 . \bar{R} \tag{9}$$

where, $\bar{S}$ is the average of the subgroup standard deviations, D_3 and D_4 are constants that depend on the subgroup size *n*.

2.2. Process Capability

Process Capability is a combination of product specifications and Process Parameters. Process Capability is a quality control technique that aims to assess the ability of a production process to produce products according to specifications. Process capability analysis must be carried out on processes within statistical control limits and already statistically controlled. Data with variable quality characteristics can be measured through *Cp* values for precision and *Cpk* for Accuracy [14]. *Cp* is a basic process of process capability by evaluating process performance related to the specified specification limits. *Cp* can measure high precision on condition that the *Cp* value ≥ 1. To calculate the *Cp* value, you can use Equation 10 [15].

$$Cp = \frac{USL - LSL}{6\sigma} \tag{10}$$

Where, *Cp* = Process Capability (process capability ratio), *USL* = Upper Tolerance/Upper Spec, *LSL* = Lower Tolerance/Lower Spec, and σ = standard deviation.

Cpk is an actual capability that aims to show the actual condition of the actual system. *Cpk* can be termed accuracy because it can analyze the closeness between observations and specification limits. Accuracy can be said to be high if the *Cpk* value ≥ 1. To calculate the *Cpk* value, you can use the formula equation 11 [15].

$$\begin{aligned} Maximum\ Cpk\ (CPL) &= \frac{\bar{x} - LSL}{3\sigma} \\ Minimum\ Cpk\ (Cpk) &= \frac{USL - \bar{x}}{3\sigma} \end{aligned} \tag{11}$$

Where, *Cpk* = Process capability index, *USL* = Upper Tolerance/Upper Spec, *LSL* = Lower Tolerance/Lower Spec, and σ = standard deviation.

Table 2 shows the comparison of *Cp* and *Cpk* values along with the estimation of the process that occurs [16].

Table 1. Comparison of *Cp* and *Cpk* with Process Estimation

Capability Index	Estimated conditions that occur
$Cp = Cpk$	The process is right in the middle of the specification boundary
$Cp < 1$	The process is not running properly or the process is not capable
$1 \leq Cp < 1{,}33$	The process is appropriate or good enough (capable)
$Cp \geq 1{,}33$	The process is quite satisfactory
$Cp \geq 1{,}66$	Very satisfying process
$Cpk \neq Cp$	Process Mean is not exactly in the centre of the specification limits

3. Results and Discussion

3.1. Data Collection

This research was conducted in June 2024 at the Basement Building Laboratory, Department of Mechanical Engineering, State Polytechnic of Malang, using a 3D print filament extruder machine. The filament is made from two types of plastic, HDPE and LDPE with temperature variations respectively. HDPE temperatures are 160 ℃, 180 ℃, 200 ℃, 220 ℃, and 240 ℃ while for LDPE plastic types are 160 ℃, 170 ℃, 180 ℃, 190 ℃, and 200 ℃. The screw speed is set at 75 rpm with a cooling system using a blower. Each temperature variation is tested with 6 samples, where each sample is measured in diameter 5 times every 1cm, resulting in 150 data per type of plastic. The data collection process with the extruder machine is shown in Fig. 2a.

(a) 3D print filament manufacturing (b) Filament diameter measurement

Fig. 2. Data capture process

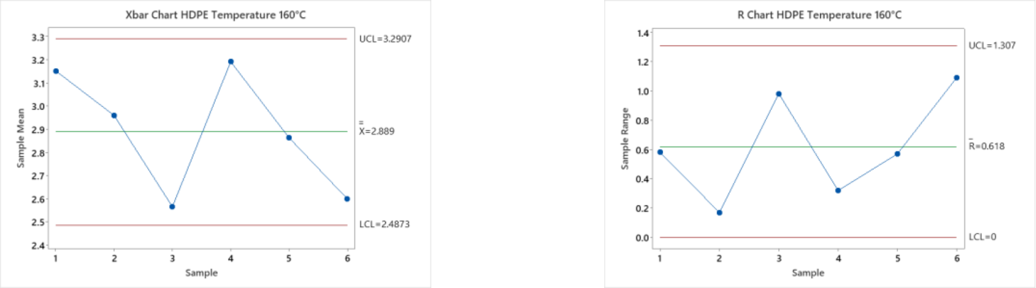
The data collection is in the form of 3D print filaments with varying diameters. The diameter of the filament was measured using a screw micrometre measuring instrument type outside micrometre with a resolution of 0-25 mm with an accuracy of 0.01 mm. The filament measurement process is shown in Fig. 2b.

3.2. Data Processing Result

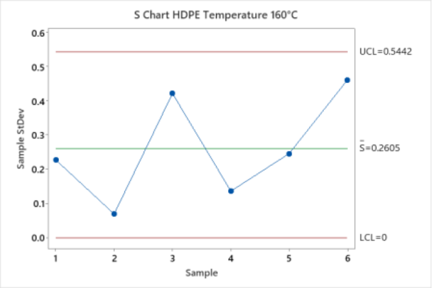
At this stage, the data is processed using Minitab-21 software for data analysis, which includes making control maps and process capability.

A. Control Chart

In analyzing research with process capability, it is necessary to analyze the control map as a tool used in quality management to monitor and control the production or service process. The data in this study is qualitative in filament diameter, so the control map used is the control map of the Chart subgroup variable. The control map in the Chart subgroup variable consists of X-bar, R Chart and S Chart maps. The X-bar control map of HDPE plastic-type at 160 °C can be seen in Fig. 3., which has a UCL of 3.2907, LCL of 2.4873, and an average of 2.889. In the R Chart, the UCL is 1.307, the LCL is 0, and the average range is 0.618. In the S Chart, the UCL is 0.5442, the LCL is 0, and the average standard deviation is 0.2605. Based on the X-bar, R Chart and S Chart of 160 °C temperature for HDPE, it can be concluded that it does not cross the UCL and LCL lines, so it is within the control limits.

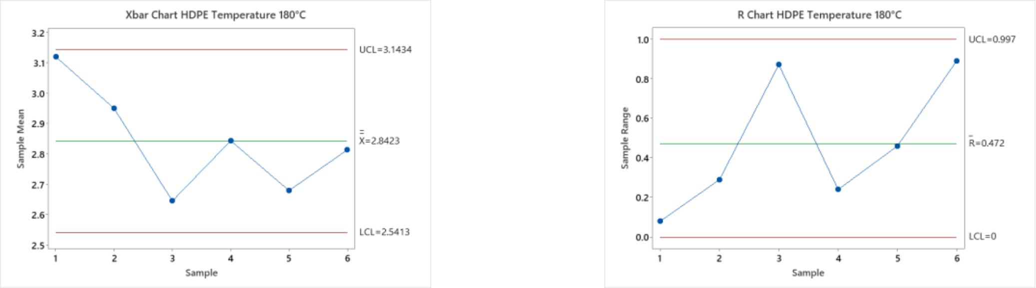


(a) X-Bar (b) R Chart

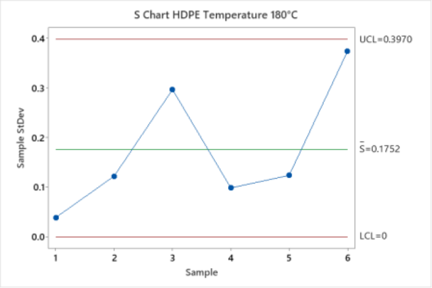


(c) S Chart

Fig. 3. HDPE control map at a temperature of 160 °C



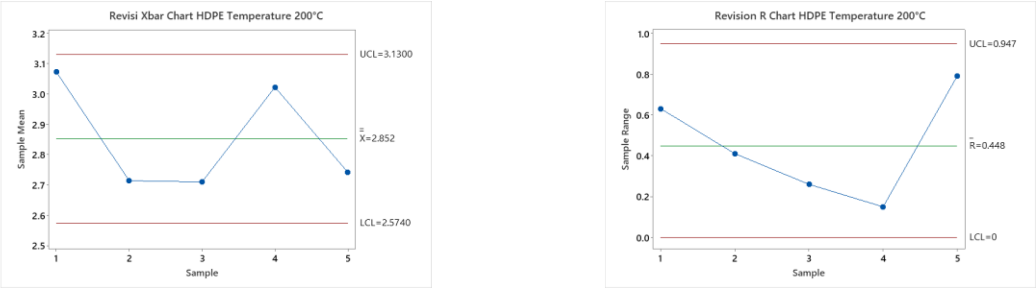
(a) X-Bar (b) R Chart



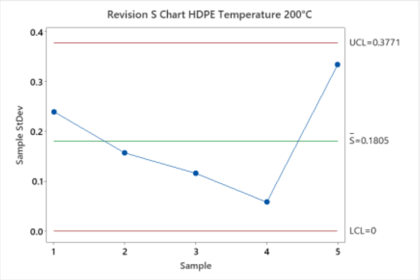
(c) S Chart

Fig. 4. HDPE control map at a temperature of 180 °C

The X-bar control map analysis of HDPE plastic-type at 180 °C is shown in Fig. 4.. It has a UCL of 3.1434, LCL of 2.5413, and an average of 2.8423. The R Chart has a UCL of 0.997, an LCL of 0, and an average range of 0.472. On the S Chart, it has a UCL of 0.3970, an LCL of 0, and an average standard deviation of 0.1752. Based on the X-bar, R Chart, and S Chart of 180 °C temperature for HDPE plastic types, it can be concluded that it is within the control limits because it does not cross the UCL line and LCL line.



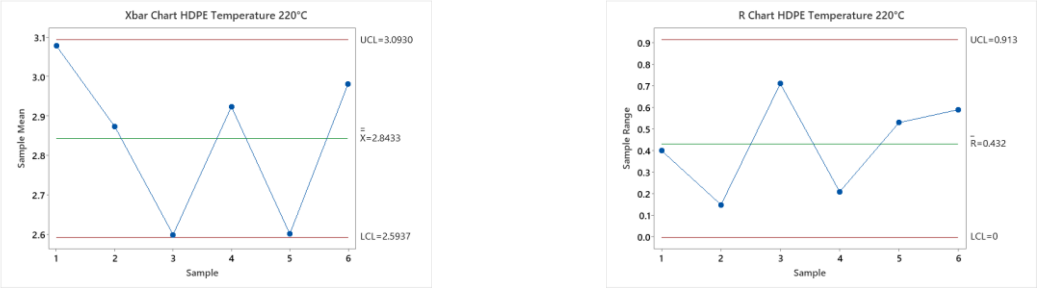
(a) X-Bar (b) R Chart



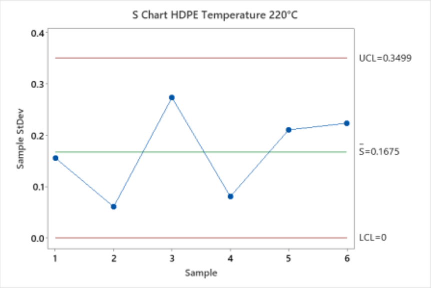
(c) S Chart

Fig. 5. Revised control map of HDPE at a temperature of 200 °C

Based on the X-bar control map for the 200 °C type in Fig. 5, the HDPE plastic type is out of control because there is Out of Control data in the 6th sample that passes the UCL, so it is necessary to revise by deleting Out of Control data [17], so that the number of samples becomes 5 from the previous 6 sample data[18].



(a) X-Bar (b) R Chart

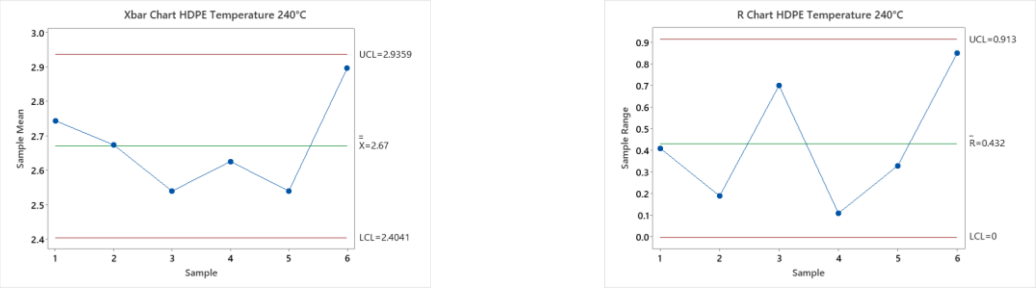


(c) S Chart

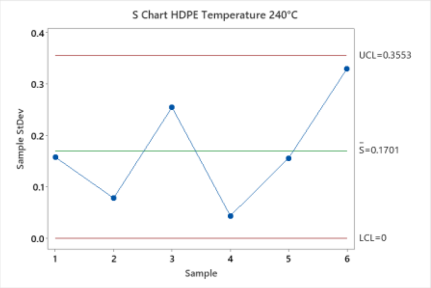
Fig. 6. HDPE control map at a temperature of 220 °C

In Fig. 5, the results of the revised X-bar control map, obtained a UCL of 3.1300, an LCL of 2.5740, and an average of 2.852. The revised R Chart control map results, obtained a UCL of 0.947, LCL of 0 and an average range of 0.448. The results of the revised S Chart control map, obtained UCL of 0.3771, LCL of 0 and average standard deviation of 0. From the revised X-bar, R Chart and S Chart control maps at 200 °C for HDPE, it can be concluded that the data does not cross the UCL line and LCL line so it is within the control limits.

The X-bar control map analysis of HDPE plastic type at 220 °C as shown in Fig. 6, has a UCL of 3.0930, LCL of 2.5937 and an average of 2.8433. In the R Chart, it has a UCL of 0.913, an LCL of 0, and an average range of 0.432. In the S Chart, it has a UCL of 0.3499, an LCL of 0, and an average standard deviation of 0.1675. Based on the X-bar, R Chart and S Chart of 220 °C temperature for HDPE, it can be concluded that it is within the control limits because it does not cross the UCL line and LCL line.



(a) X-Bar (b) R Chart

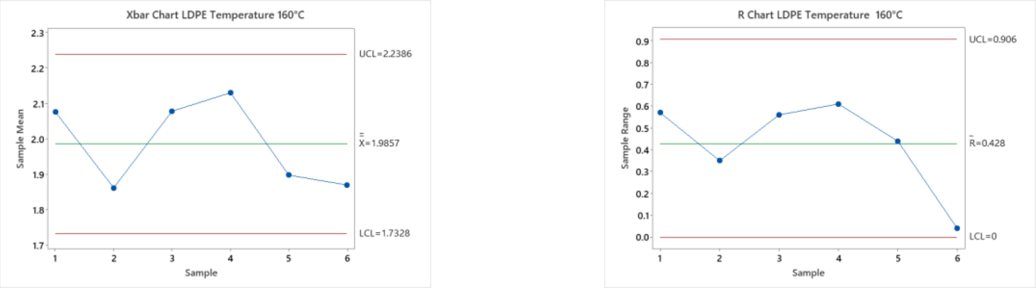


(c) S Chart

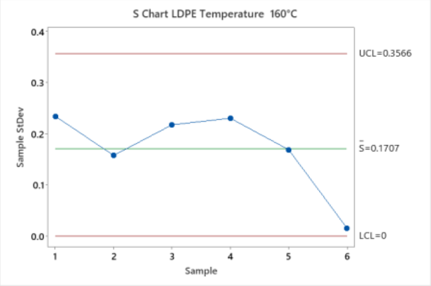
Fig. 7. HDPE control map at a temperature of 240 °C

The X-bar control map analysis of HDPE at 240 °C as can be seen in Fig. 7, has a UCL of 2.9359, LCL of 2.4041, and an average of 2.67. In the R Chart, it has a UCL of 0.913, an LCL of 0, and an average range of 0.432. In the S Chart, it has a UCL of 0.3553, an LCL of 0, and an average standard deviation of 0.1701. Based on the X-bar, R Chart and S Chart of 240 °C temperature for HDPE, it can be concluded that it is within the control limits because it does not cross the UCL line and LCL line.

The X-bar control map analysis of LDPE at 160 °C can be seen in Fig. 8, which has a UCL of 2.2386, an LCL of 1.7328, and an average of 1.9857. In the R chart, it has a UCL of 0.906, an LCL of 0, and an average range of 0.428. In the S chart, it has a UCL of 0.3566, an LCL of 0, and an average standard deviation of 0.1707. Based on the X-bar, R Chart and S Chart of 160 °C temperature for LDPE, it can be concluded that it is within the control limits because it does not cross the UCL line and LCL line.

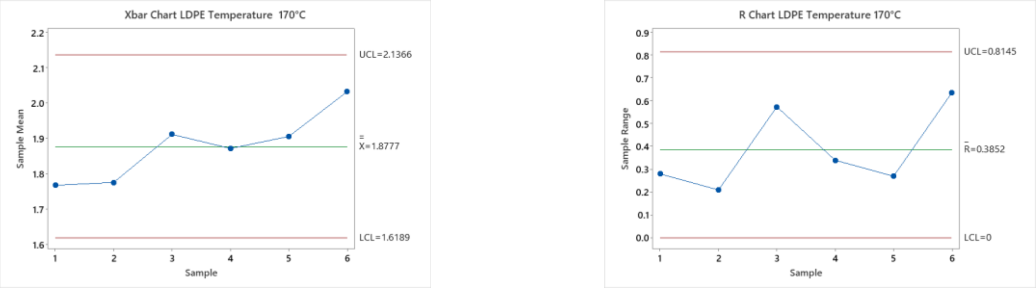


(a) X-Bar (b) R Chart

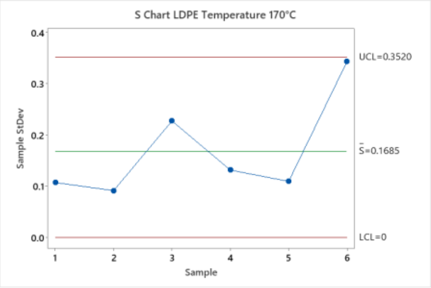


(c) S Chart

Fig. 8. LDPE control map at a temperature of 160 °C



(a) X-Bar (b) R Chart

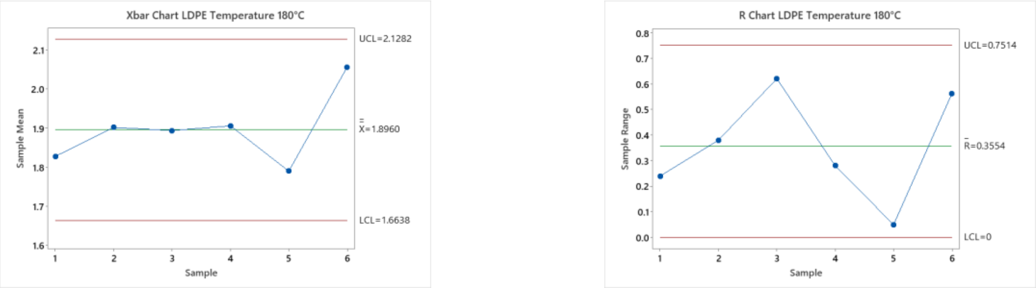


(c) S Chart

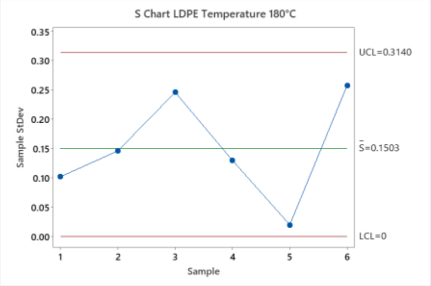
Fig. 9. LDPE control map at a temperature of 170 °C

The X-bar control map analysis of LDPE at 170 °C can be seen in Fig. 9, which has a UCL of 2.1366, an LCL of 1.6189, and an average of 1.8777. In the R chart, it has a UCL of 0.8145, an LCL of 0, and an average range of 0.3852. In the S chart, it has a UCL of 0.3520, an LCL of 0, and an average standard deviation of 0.1685. Based on the X-bar, R Chart and S Chart of 170 °C for LDPE, it can be concluded that it is within the control limits because it does not cross the UCL line and LCL line.

The X-bar control map analysis of LDPE at 180 °C can be seen in Fig. 10, which has a UCL of 2.1282, an LCL of 1.6638, and an average of 1.8960. In the R chart, it has a UCL of 0.7514, an LCL of 0, and an average range of 0.3554. In the S chart, it has a UCL of 0.3140, an LCL of 0, and an average standard deviation of 0.1503. Based on the X-bar, R Chart and S Chart of 180 °C for LDPE, it can be concluded that it is within the control limits because it does not cross the UCL line and LCL line.



(a) X-Bar (b) R Chart

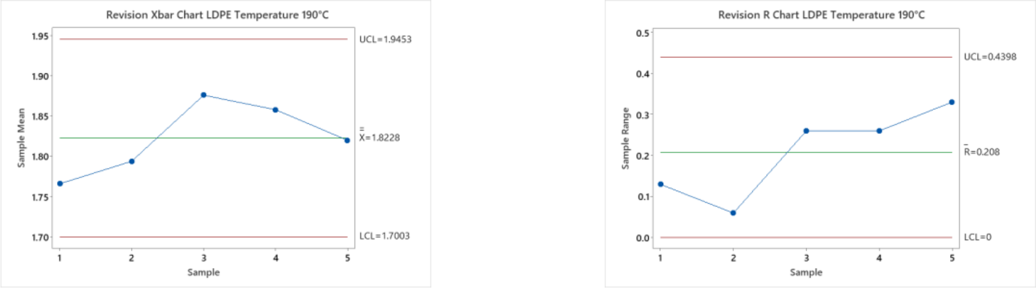


(c) S Chart

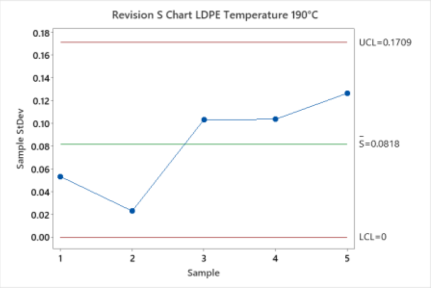
Fig. 10. LDPE control map at a temperature of 180 °C

Based on the control map analysis at 190 °C for LDPE plastic type, it is within the control limits on the X-Bar and R Chart control maps. However, in the S Chart, there is out-of-control data on the 6th sample which crosses the UCL limit. So, it is necessary to revise the control map by deleting the out-of-control data. The process of revising the X-bar control map at 190 °C for LDPE is done by deleting out-of-control data to get a revised X-bar control map, R Chart and S Chart shown in Fig. 11. The revised X-bar control obtained UCL of 1.9453, LCL of 1.7003 and an average of 1.8228. The revised R Chart obtained a UCL of 0.4398, LCL of 0 and an average range of 0.0208. The revised S Chart obtained a UCL of 0.1709, LCL of 0 and an average standard deviation of 0.0818. From the results of the revised X-bar, R Chart and S Chart control maps at 190 °C for LDPE, it can be concluded that the data does not cross the UCL line and LCL line so that it is within the control limits.

The X-bar control map analysis of LDPE plastic type at 200 °C shown in Fig 12, has a UCL of 2.1806, LCL of 1.7619 and an average of 1.9713. In the R Chart, it has a UCL of 0.7311, an LCL of 0, and an average range of 0.3457. On the S Chart, it has a UCL of 0.2995, an LCL of 0, and an average standard deviation of 0.1434. Based on the X-bar, R Chart and S Chart of 180 °C temperature for LDPE, it can be concluded that it is within the control limits because it does not cross the UCL line and LCL line.

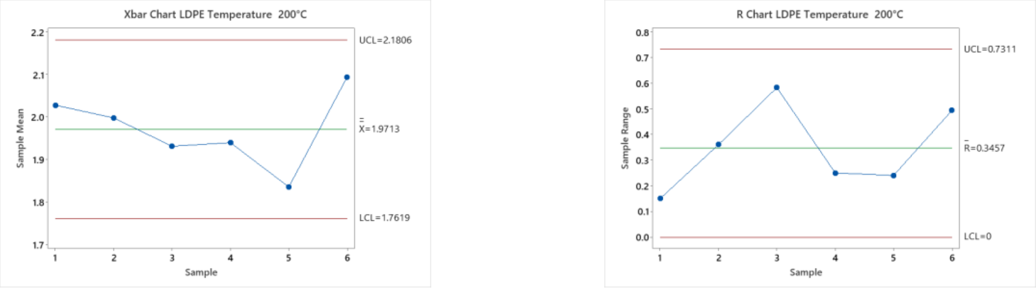


(a) X-Bar (b) R Chart

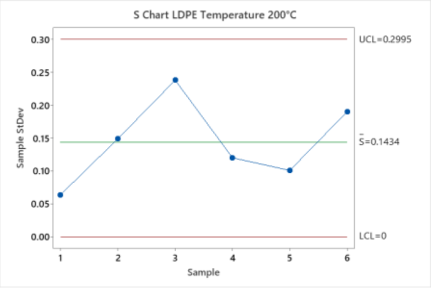


(c) S Chart

Fig. 11. Revised control map of LDPE at a temperature of 190 °C



(a) X-Bar (b) R Chart



(c) S Chart

Fig. 12. LDPE control map at a temperature of 200 °C

B. Process Capability

Process capability is the ability to evaluate the extent to which a manufacturing process can meet set specifications, measuring how well the process can produce products according to specifications. Capability evaluation is important to ensure consistency in the quality of extruded filament diameter. The two main measures in this evaluation are the Capability Index (*Cp*) and Capability Ratio (*Cpk*). *Cp* measures the width of the process distribution compared to the width of the specification, while *Cpk* measures how well the process produces the product to the target specification. A good process capability analysis indicates production quality within specification limits. This research conducted a process capability analysis on each variation of heating temperature. Table 2 and Table 3 recap the results of the process capability analysis for each heating temperature on HDPE and LDPE, respectively.

Table 2. HDPE Process Capability Calculation Results

Temperature	LSL	USL	*Cp*	*Cpk*
160°C	1.12	3.39	0.71	0.56
180°C	2.28	3.19	0.61	0.52
200°C	2.43	3.32	0.72	0.68
220°C	2.18	3.32	1.02	0.85
240°C	2.25	3.31	0.89	0.71

Both Table 2 and Table 3 show that the *Cp* value is below 1.00. This indicates that the potential process capability is low, which means the process variation is still quite large compared to the specified specification range. In addition, the low *Cpk* value below 1.00 indicates an imbalance in the process, with some of the production output falling outside the specification limits, indicating an inconsistency in the diameter of the filaments produced. Thus, the variation in heating temperature in the HDPE and LDPE plastic production process cannot be categorized as statistically capable of meeting the provisions of the specifications that have been set. So it is necessary to make improvements to reduce process variations and improve the consistency of production results.

Table 3. LDPE Process Capability Calculation Results

Temperature	LSL	USL	*Cp*	*Cpk*
160°C	1.69	2.46	0.68	0.52
170°C	1.66	2.41	0.65	0.38
180°C	1.70	2.35	0.63	0.38
190°C	1.64	2.04	0.73	0.67
200°C	1.73	2.31	0.62	0.52

4. Conclusion

Based on the data processing analysis, it is found that the temperature affects the diameter of filaments of HDPE and LDPE where the best filaments were produced at 220 °C and 190 °C for HDPE and LDPE, respectively. However for both HDPE and LDPE, the *Cp* and *Cpk* values are less than 1.00 which indicates incapability and that the process variation is quite large compared to the range of specifications set, as well as showing imbalance and inconsistency in filament diameter.

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