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Modeling Fiber Dispersion During the Plasticizing Process for a Single Screw Extruder

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June 2023

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1. Abstract

Long fiber-reinforced thermoplastics are emerging materials due to their excellent mechanical properties. They are being widely used in industries such as automotive, aerospace and construction. Research and recent developments in this field continue to evolve every day. When processing long fiber-reinforced thermoplastics, the length of the fibers starts decreasing, which affects the mechanical performance of the finished part. For this reason, it is important to understand the mechanics of fiber attrition during the extrusion process, resulting in predicting the strength of long fiber-reinforced thermoplastics composites. This study investigates fiber dispersion during the extrusion process of LFT pellets. The kinetics of fiber damage in conjunction with dispersion are explored. A dispersion model and fiber length is then proposed for single screw extruders to predict fiber dispersion. Screw pull-out experiments were performed to determine fiber dispersion along a single screw extruder.

Table of Contents

2. Introduction

2.1 Fiber-Reinforced Thermoplastic Composites

There are three main types of fiber reinforced thermoplastic composites. Short fiber-reinforced thermoplastics (SFTs), long fiber-reinforced thermoplastics (LFTs), and continuous fiber composites (CFCs).

SFTs materials are often very easy to process because the short length of the fibers allows the material to easily be injection molded. On the other hand, their mechanical properties are worse compared to the other two types of fiber reinforced thermoplastics. This is because of the short length of their fibers, which could lead to the anisotropic effect. When short fibers are added to a thermoplastic matrix, they tend to align themselves in the direction of the flow during the manufacturing process. This effect refers to the variation in mechanical properties of the material in different directions due to the orientation of the fibers. CFC materials have improved mechanical properties but they are more difficult to process in complex geometries. Hence, it could be said that the larger the fibers, the more complex processability the part will have. The manufacturing cost of CFC is also higher, as well as a slow production time. Since SFTs can be injection molded, the cycle time is reduced for this length of fibers. Moreover, the cost to produce these fibers is lower than CFCs, even allowing an increase in the complexity of the part. LFTs properties are located in between SFTs and CFCs. Their main advantage is their processability, since they can be injected molded, compression molded, and extruded at the same time of maintaining high mechanical properties. During these processes, the microstructure properties of SFTs and LFTs are affected. Hence, it is highly important to predict the microstructure of composites from their process parameters. By doing so, we could be able to optimize and improve the end-product properties.

2.2 Uses of Fiber-Reinforced Thermoplastics

These materials are becoming increasingly important in industries such as automotive, construction, and aerospace thanks to their mechanical properties. Some of the uses in those industries are the ones explained in the following section:

In the aviation industry, long fiber composites are very popular and therefore used on a large scale. The main reason for this use is the weight reduction achieved after implementing composite materials. This weight reduction results in fuel savings and a reduction of emissions. The 22% of the weight percent of the biggest commercial airplane in the word, the Airbus A380, consist of fiber composite materials [15].

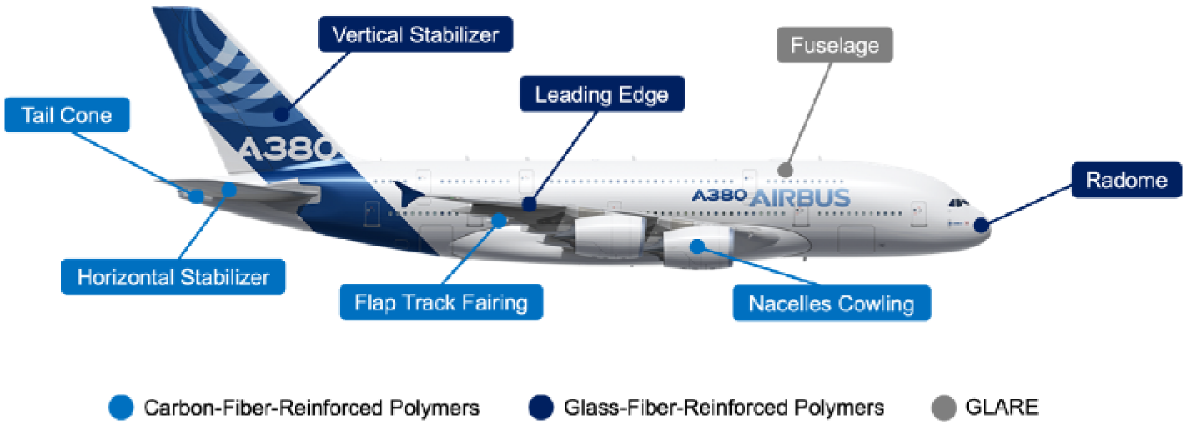
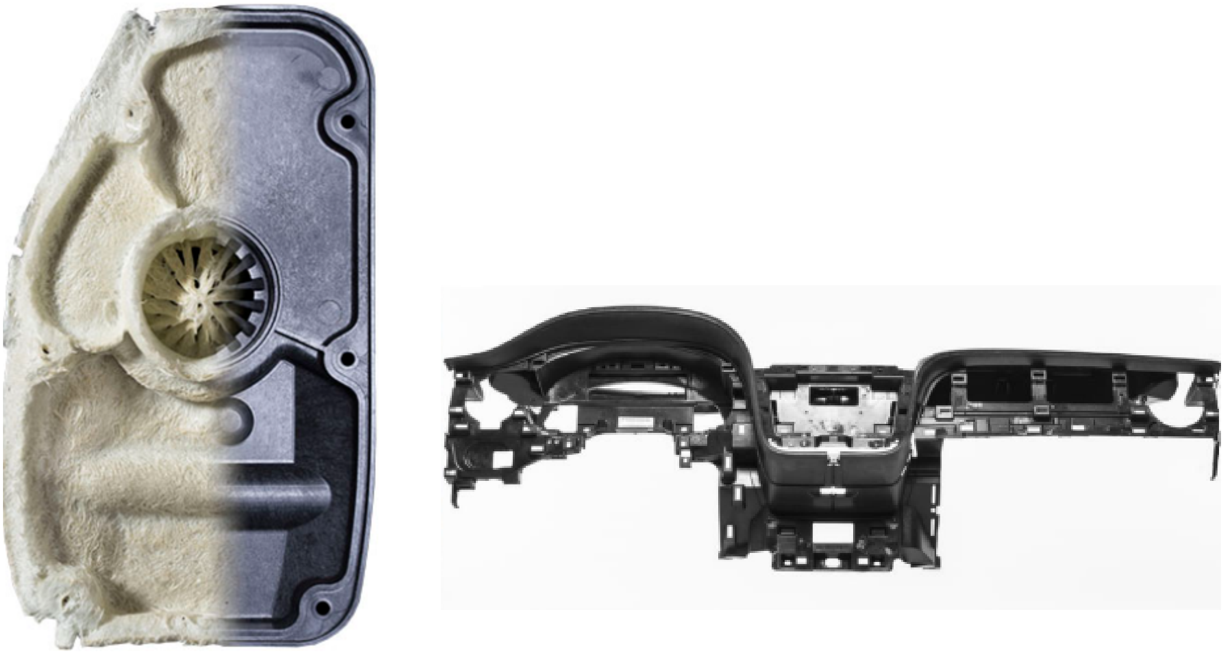


Figure [1] Parts of a plane made by fiber composite materials [15]

Newer models, such as the Airbus A350 consist of around 50% fiber composites. As seen in Figure [1], the most common parts in which fiber reinforced thermoplastics are used in planes are cladding panels, fairings and reinforcements.

In the automotive industry, LFTs are used in body panels such as hoods, fenders, roofs, doors, and trunk lids. When it comes to interior componentes, LFTs could be seen in the instrument panels, center console door panels, and dashboard. The fact that LFTs are feasible for very complex geometries, makes them a perfect material for dashboards and interior components in general. Long fiber-reinforced thermoplastics can also be seen in the engine and transmission components. They can be seen in the intake manifolds, engine covers, oil pans, and transmission housing. These materials offer excellent chemical and heat resistance. This makes them useful for high-temperature and harsh environments. For the same reason as in the aviation industry, composite materials are also used in ground vehicles because they reduce the vehicle weight and improve energy efficiency as well as savings in fuel and emissions without compromising their properties such as stiffness and strength.



Figures [2][3] LFTs uses in engine mounts [2] and dashboards [3]

The reduction of body weight is one of the main goals in the top performance automobile industry, sport cars and race cars. A relatively new type of polymer component called carbon fiber is nowadays used in every race car and luxury cars. In Formula 1 cars, 80% of the body weight is made by carbon fiber [11]. This makes the car light. A combination of its reduced weight, a powerful engine, and advanced aerodynamics makes the car able to reach high speed and acceleration.

2.3 Long Fiber-Reinforced Thermoplastics

Fiber-reinforced thermoplastics are advanced composite materials with distinctive properties that could be useful in product's manufacturing. Composite materials are made of glass, carbon, or aramid and are set within the polymer matrix to create high strength and stiffness materials. As explained in Section 2.1, LFTs have some advantages and better performance that distinguish them from SFTs and CFCs. For this reason, they are chosen as substitutes for metals, under-performing plastics and higher cost engineering polymers. LFTs have also gained attention as an eco-friendly alternative to traditional materials due to their superior performance, lightweight, cost-effectiveness, recyclability and low environmental impact.

Some of the main mechanical characteristics of LFTs are the following ones [10]:

- Stiffness: The stiffness is the quality of being firm, hard or unable to bend. There is a direct correlation between stiffness and the length of the fibers. As we can see in Image [4], the longer the fibers, the stronger and more stiffness the material will have.

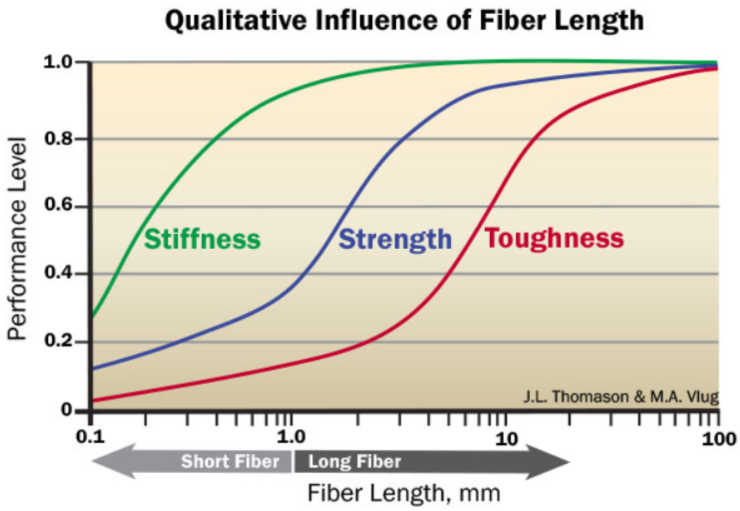


Figure [4] Influence of Fiber Length in Stiffness and Strength [10]

- Strength: As with stiffness, longer length provides long fiber composites with increased strength, which translate into the ability to resist deformation or creep under loads and higher fatigue endurance with minimal compression. The orientation of reinforced fibers within injection molded components significantly influences composite strength. To obtain maximum performance, mold designs should encourage fibers to align perpendicular to the direction of stress forces. It is important to maximize fiber length, however, attrition can occur from shear in the injection molding. Any reductions in median fiber length will reduce performance.
- Toughness or Durability: Long fibers help composites to resist cracking and help as well with crack propagation by creating a robust internal fiber skeleton. Long fiber composites offer durability at low and high temperatures and reduces material fragmentation during failure.
- Light Weighting: Long fiber-reinforced thermoplastics offer a high strength-to-weight ratio, making them suitable if we want to reduce weight. LFTs provide the same level of mechanical performance as common die cast metals such as magnesium or aluminum. In aerospace and automotive industries, light weighting and mass reduction is one of the main goals to achieve because of the reduced emissions and fuel savings. For this reason, long fiber composites are eco-friendly alternatives to heavier materials.
- Design Freedom: Long fiber composites allow production of more complex 3D geometries and shapes, eliminating secondary operations during production and assembly steps, causing labor and time cost-savings.
- Recycling: Melt processable plastics can be easily recyclable without significant loss of their mechanical properties. The production of recycled plastic pellets is often the concluding phase in the recycling process before the material is distributed in the industrial production stage. The recyclability of LFTs plays a crucial role in waste reduction and minimizing the environmental impact typically associated with conventional composite materials.

As already mentioned in the previous section, LFTs are to be classified between SFTs and CFCs regarding the fiber length. The main advantage of LFTs is the high aspect ratio of the fibers they contain, which should also be preserved throughout the manufacturing process to achieve the desired part properties.

Category	Fiber Length [mm]	Aspect Ratio
Short Fiber	0,1 - 1	L/D > 10
Long Fiber	1 – 50	L/D > 1000
Continuous Fiber	> 50	L/D = ∞

Table [1] Comparison between categories of Fibers

Therefore, when we process LFTs, not only a good dispersion of fibers is desirable, also it is crucial that we maintain a high length of the fibers. The mechanical properties of LFT components depend on the transfer of stresses between the matrix and fibers, for this reason, the aspect ratio (L/D) should not drop below the critical value shown in Table [1][17]. If so, the composite's integrity would be affected causing fiber end faces to create stress concentrations [5]. Hence, it is of great interest to always maintain the maximum fiber length possible.

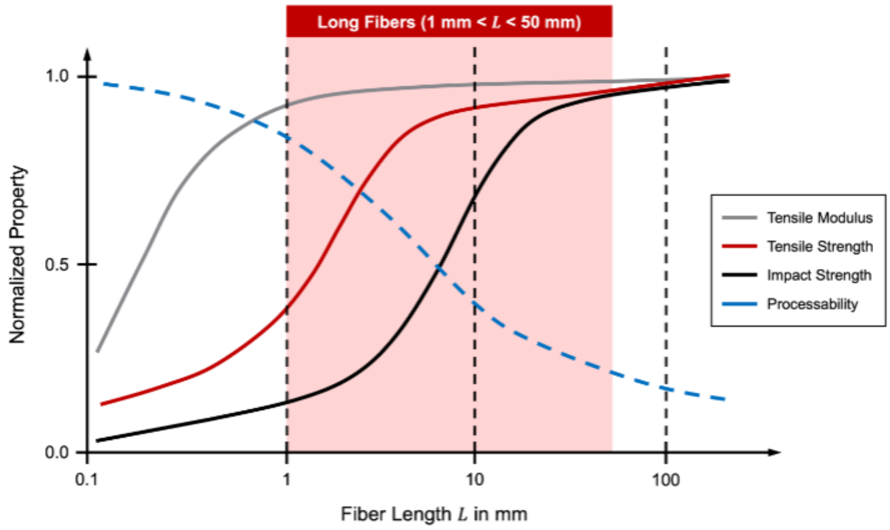


Figure [5] Mechanical Properties depending of the Length [18]

As we can see in Figure [5], short fibers exhibit a much lower tensile strength and impact strength compared to longer fibers. On the other hand, their processability is better because they are easier to handle. The difference in properties between short and long fibers is huge, however, if we compare 50mm fibers with CFCs, we can see that there is not a significant improvement in properties. Thus, the main difference between fibers near the upper limit of long fibers and CFCs is the processability. LFTs can be manufactured using conventional extrusion process, injection molding and compression molding. This is the reason why LFTs are used instead of CFCs. They have a clear advantage in processability with very similar mechanical properties.

2.4 Distributing and Dispersing

Since the main reason for this study is to investigate fiber dispersion, the concept of dispersion is going to be introduced. What is going to make a product better than other quality talking, is the mixing of the material. Mixing is produced in a single-screw extruder, although the mixing effect is smaller than in a twin-screw extruder. To understand the behavior of mixing will lead to an optimization of processing conditions and improvement of part quality. The process of mixing means a good distribution or dispersion of the fibers in the polymer matrix during processing.

If we want a good dispersion, the fibers need to be divided during processing. If they keep agglomerated, their surface area would be inaccessible by the viscous matrix material. Dispersion is a shear-driven effect. This means that dispersion of fibers occurs during the shear stresses applied to the material in the process. The difference between distributed and dispersive mixing is depicted in Figure [6]. In order to achieve the best quality possible, the fibers of the part should be well distributed and dispersed. In the best of cases, a good dispersion and distribution is happening when the fibers are not agglomerated in groups at the same time of being spreaded all over the polymer matrix.

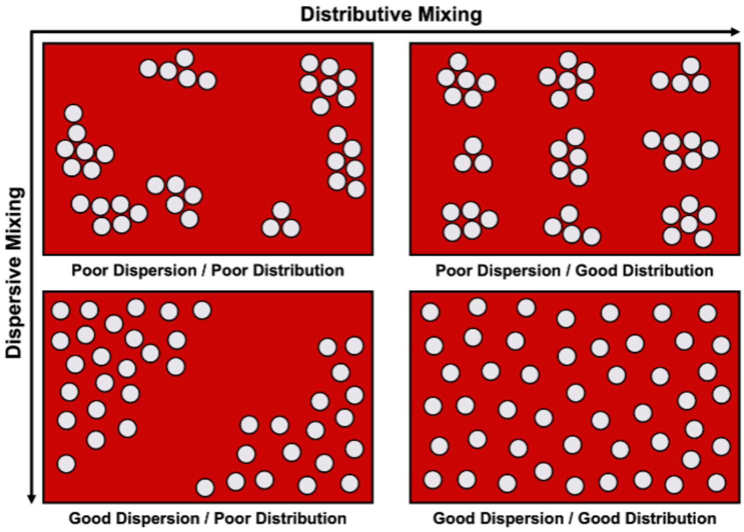


Figure [6] Distributive and Dispersive mixing of fibers [20]

2.5 Extrusion and Single Screw-Extruder

Extruders are one of the most important machineries in the polymer processing industry. In an extruder, the melted material is pushed or forced through a shaping die using a screw. The material is pushed through the extruder die and it acquires the shape of the opening. The final shape could change as the hot polymer melt cools down after going through the die opening. The extruder used in this study is a single-screw extruder. They are usually used to produce molded pipes such as pipes, hooses, profiles, and films. The polymer is fed to the extruder as solid granules called pellets and then melted as it is conveyed by the extruder screw. The single-screw extruder produces at a low cost, it has good reliability, simple design, and a good performance to cost ratio. For these reasons, it is the most used type of extruder in the polymer industry. It is divided in two sections, the drive part, and the process part. The drive part consists of a motor and a gear box and its task is to rotate the extruder screw at a desired speed. This screw speed should be constant if we want to avoid throughput fluctuations. The drive unit must be able to transfer the required torque to the extruder screw. The second part, the proccest part, consists of a feed hopper, from where the system is fed with the pellets, electrical heating, cooling fans, a housing, and the extruder screw, which is located inside a barrel. After the feed hopper, the material is then transferred through the barrel, which has different levels with different heating zones and temperatures. The rotating extruder screw inside the barrel then conveys the material until it reaches the extruder die.

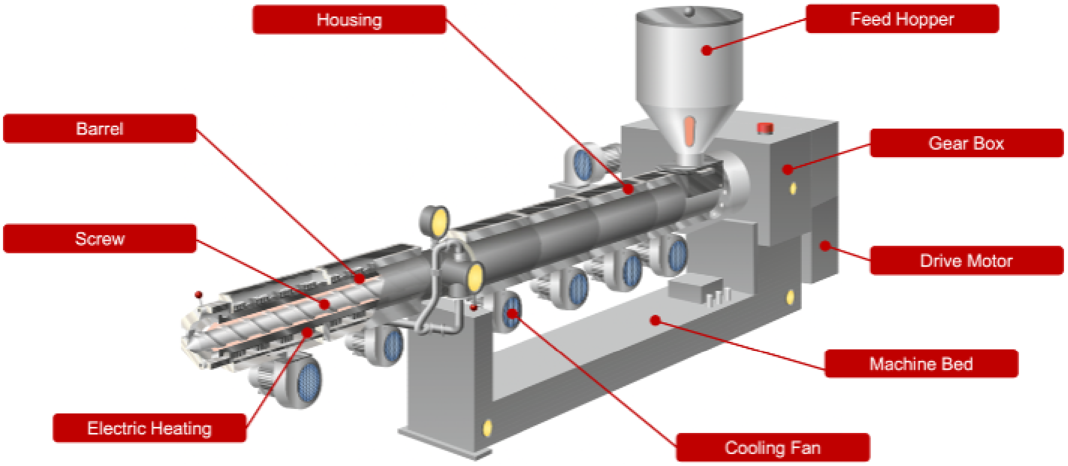


Figure [7] Single-Screw Extruder and its components [24][9]

The screw of a conventional plasticating single-screw extruder is divided into three geometrically different zones. These zones are the feeding zone, compression zone and a metering zone. The pellets flow by gravity from the feed hopper down into the barrel. In the feeding zone the pellets are conveyed to the compression zone. The material is preheated and compacted but we should prevent the pellets from melting in this part of the screw. The pellets are conveyed thanks to the frictional forces exerted by the screw and barrel surfaces on the material. That is because the barrel is stationary while the screw is rotating. As the material moves closer to the compression zone, the pellets keep heating up due to the frictional forces and barrel heating. When the temperature exceeds the melting point of the material, we could say that we are at the end of the solids conveying zone. However, this point does not necessarily coincide with the beginning of the compression section. The different functional zones of the barrel do not coincide with the differences in geometry of the screw. This is because the functional zones depend on the material and processing conditions.

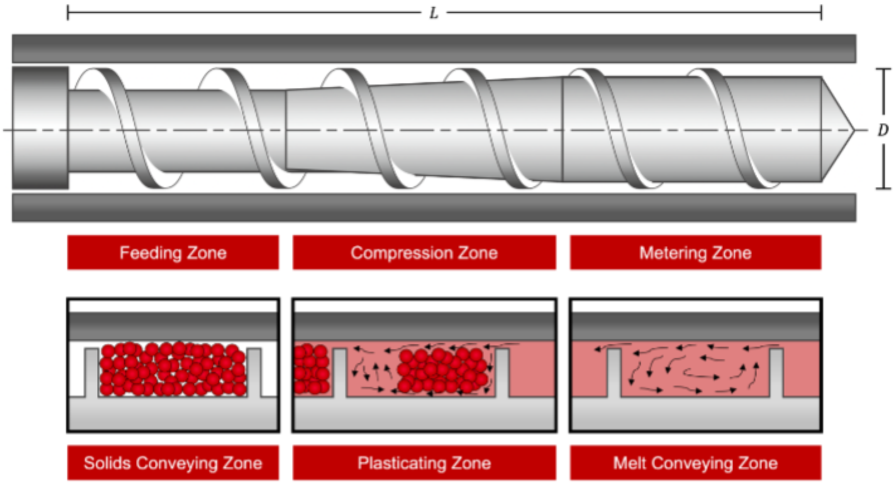


Figure [8] Geometric and Functional zones of a three-section extruder screw [9]

The functional zones of a plasticating extruder can be divided into the solids conveying zone, plasticating or melting zone and melt conveying zone. As the material travels through the barrel, it is continuously melted resulting in a decrease of solid material. The end of the second zone is reached when the solid material is entirely melted. After it, the melt is pumped towards the die in the melt conveying zone. When the material flows through the die, it acquires the geometry of the die channel. After exiting the shaping die, extrudate swelling could occur, producing the melted material to not acquire the exact shape of the die channel.

3. Description and Objective of the Task

3.1 Dispersion-Length Relationship

Other studies showed that fiber breakage can be reduced when the individual fibers are wetter within the polymer matrix during processing. Fibers need to be well dispersed if we want good impregnation of the fibers. Undispersed dry fibers bundles have more friction compared to melt impregnated fibers. This friction can cause an increase in fiber damage. For this reason, it is important to optimize fiber dispersion and reduce fiber damage at the same time to achieve improved part quality and performance. To obtain the best quality possible, the fibers should be equally concentrated in every region. However, this is not as easy as it seems. While fiber dispersion is increased, fiber length also decreases at a similar rate due to the damages occurring during the process. In the following figure, two graphs show a comparison of fiber length and fiber dispersion over the length of the screw.

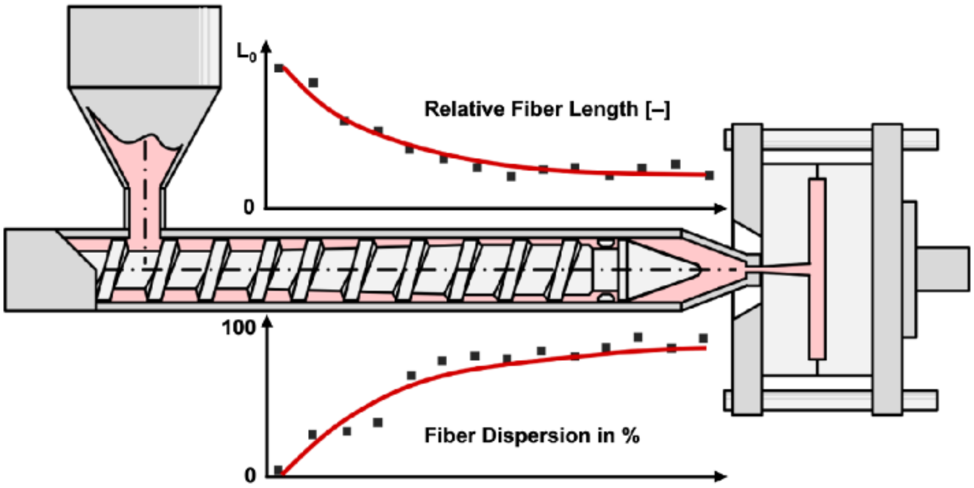


Figure [9] Fiber length and dispersion during plasticization a screw channel [9]

The fact that the region with the highest rate of fiber length degradation seems to coincide with the highest dispersion rate allows to draw the conclusion that fiber dispersion directly influences fiber breakage. The more dispersed we have the fibers, the shorter the fibers length will be due to damage. As explained in Section 2.3, the length of the fibers is crucial to achieve high performance, however, maximizing the length will lead to a poor fiber dispersion. A balance should be found to ensure the fibers to be as long as possible at the same time as guaranteeing a great dispersion of them.

Generally, fiber bundles act like larger and thicker individual fibers which means that their contributions to mechanical properties such as strength and stiffness are considerably lower when compared to a multitude of dispersed fibers. However, a high fiber dispersion alone does not improve the mechanical part properties. Well dispersed fibers improve the quality and stability of the mechanical properties throughout the final part and improve the uniform reproducibility of quality parts, whereas greater fiber length directly improves the mechanical properties. It can be concluded that the ideal result is a part which maintains a high fiber length by minimizing fiber breakage and attrition.

3.2 Types of Pellets

LFT pellets are produced either by pultrusion or a coating process. Pultruded LFT pellets are manufactured by pulling several rovings of fibers through an impregnation die where the rovings are impregnated with the polymer. This technique often spreads the roving with the dies, creating a greater fiber-matrix interface area [6].

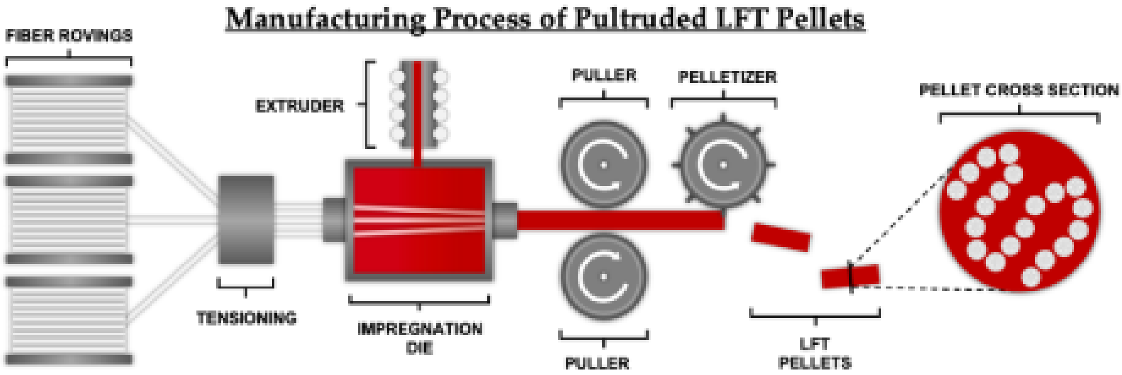


Figure [10] Manufacturing Process of Pultruded LFT Pellets [23][9]

Coated LFT pellets are manufactured by pulling a single roving of fibers through an impregnation die instead of several rovings as in Pultruded LFTs. When pulling a single roving, the pellets produced have longer fiber length in comparison with the ones produced in the pultrusion process. On the other hand, this method leads to fiber bundles, causing the pellets produced to have weaker mechanical characteristics [13].

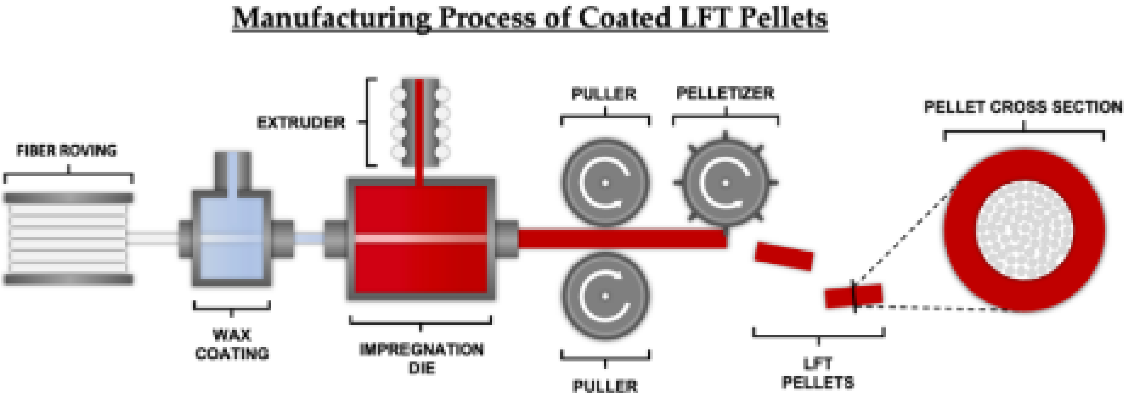


Figure [11] Manufacturing Process of Coated LFT Pellets [9]

3.3 Objectives

During this research, screw pull-out experiments were performed using pultruded and coated pellets to determine fiber dispersion along a single screw extruder. Those experiments were designed to isolate the effects that occur during the plasticizing process and the results were analyzed in order to create a Dispersion Rate - Fiber Length comparison using experimental data.

4. Experimental Setup and Procedure

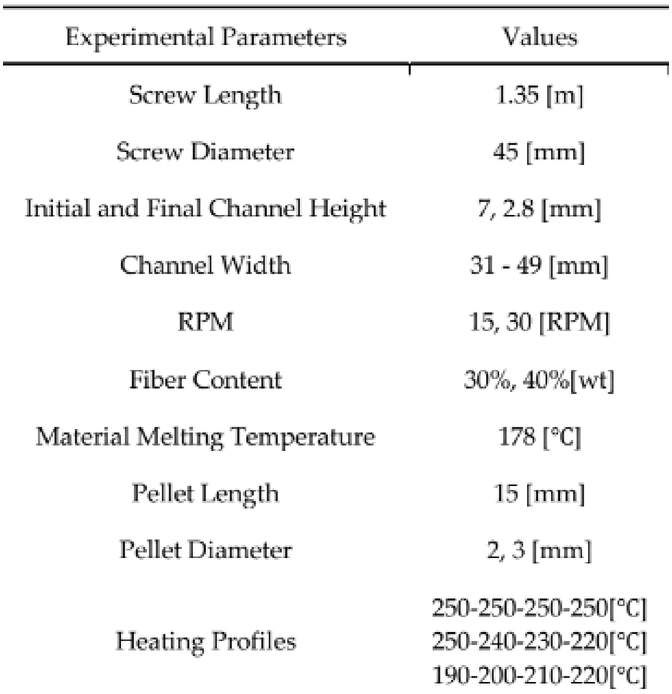
To investigate the dispersion behavior of the material during the extrusion process, we should develop a repeatable experimental procedure involving the extrusion process and the post-processing analysis of the obtained samples. The whole process created is now going to be briefly explained. Then, we will deeply cover each one of the steps followed in this experiment.

To begin with, single-screw pull-out experiments will be performed. Both pultruded and coated pellets to be examined will be processed in the extruder under specific conditions. The solidified pellets will be melted and pushed out of the extruder by force with the screw. When the whole screw is out of the extruder, we will extract samples along the length of the screw, specifically, we will take one sample from each one of the pitches. Thanks to this, we will obtain data points for the characterization of fiber dispersion during the course of the screw. After taking the samples, we will need to trim them because of the helical shape they will have after extracting them from the screw. A band saw will be used, and we will cut from both sides of the sample creating a square geometry that will help further post-processing and make it easier to handle in the following analysis. This post-processing involves flattening the samples without damaging them. To do so, we will place the samples in a convection oven at a constant temperature for a defined time duration or until it is easy to deform them. This temperature should be lower than the melting temperature of the material, if not, the polymer matrix will melt and the sample can not be used for the analysis. When the samples are deformable, we will take them out of the oven and place them between two plane metal plates which are compressed by a bench vise. We will leave the compressed sample in the bench vise until it cools down. The result is a flattened extrusion square sample that represents one pitch of the extruder screw.

In the next step, the individual samples are analyzed by subtracting a sample of fibers from each one of the pitch parts. After this, we will remove a small amount of fiber from the matrix and we will scan images of the dispersed fibers. Those images will then be analyzed with a Matlab code, which calculates the average length of the fibers from that image. Finally, a dispersion-length comparison between coated and pultruded pellets will be created and commented on.

4.1 Extrusion Setup and Pull-out Experiments

In this section, it will be explained how the extruder is prepared for the test, which parameters are used during the process and how the pull-out experiments are performed. The single-screw extruder's brand used for this research is Extrudex Kunststoffmaschinen. The properties of the extruder are shown in the following table:



Experimental Parameters	Values
Screw Length	1.35 [m]
Screw Diameter	45 [mm]
Initial and Final Channel Height	7, 2.8 [mm]
Channel Width	31 - 49 [mm]
RPM	15, 30 [RPM]
Fiber Content	30%, 40%[wt]
Material Melting Temperature	178 [°C]
Pellet Length	15 [mm]
Pellet Diameter	2, 3 [mm]
Heating Profiles	250-250-250-250[°C] 250-240-230-220[°C] 190-200-210-220[°C]

Table [2] Screw Pull-out experimental parameters

The extruder consists of a feed hopper, a water-cooled feed section, four barrel heating zones and a heated extruder die. The parameters of the process and temperatures for each one of the heating zones can be set in the extruder control panel. A clearer picture of these parts can be seen in the following figure:

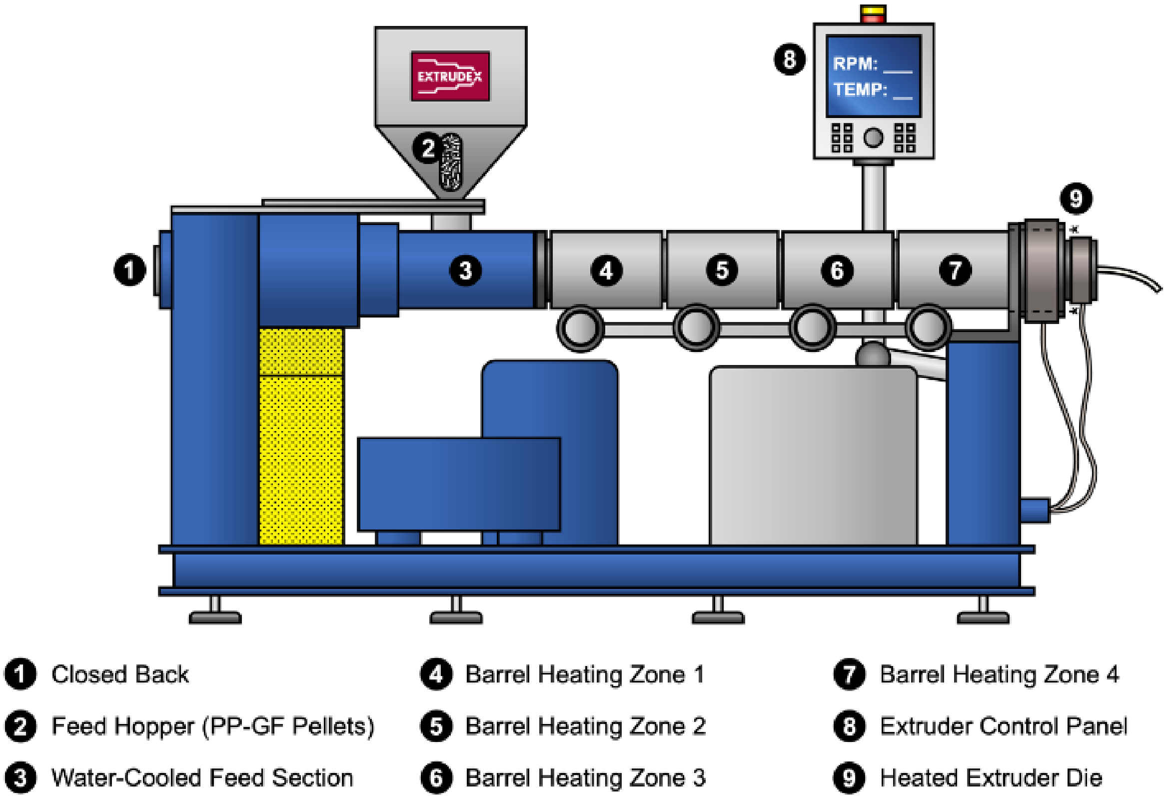


Figure [12] Single-Screw Extruder used and its parts [22]

To set up and prepare the extruder for the experiment, the material that we want to examine will be placed on the feed hopper. We heat up the barrel zones and die to the desired temperature profile. It is important to see that the cooling section is placed before the heating zones. As briefly explained before, the pellets should not melt in this part of the process. If they did, the material will not receive the proper heat distribution and uniform melting in the next parts of the extruder, which can affect the homogeneity and quality of the final extruded product. Another effect of premature melting is the looseness of the pellets' shape, leading to a difficulty to feed constantly. In the final part, this could result in inconsistent flow rates and disruptions in the extrusion process.

After feeding the system, the screw speed should be set and the extruder will be running for approximately 10 minutes after reaching a constant throughput. Then, we set the speed to 0 rpm and turn off the drive system. It is important to not turn off the extruder drive before it reaches 0 rpm. When the screw is stopped, we set the barrel heating zones to room temperature for a fast cooling of the material. The extruder die should be removed in hot condition. We will see that the die will have some remains of melted material, which have to be cleaned. When the heating zones reach the room temperature, it could be affirmed that the preparations for the screw pull-out experiment can begin.

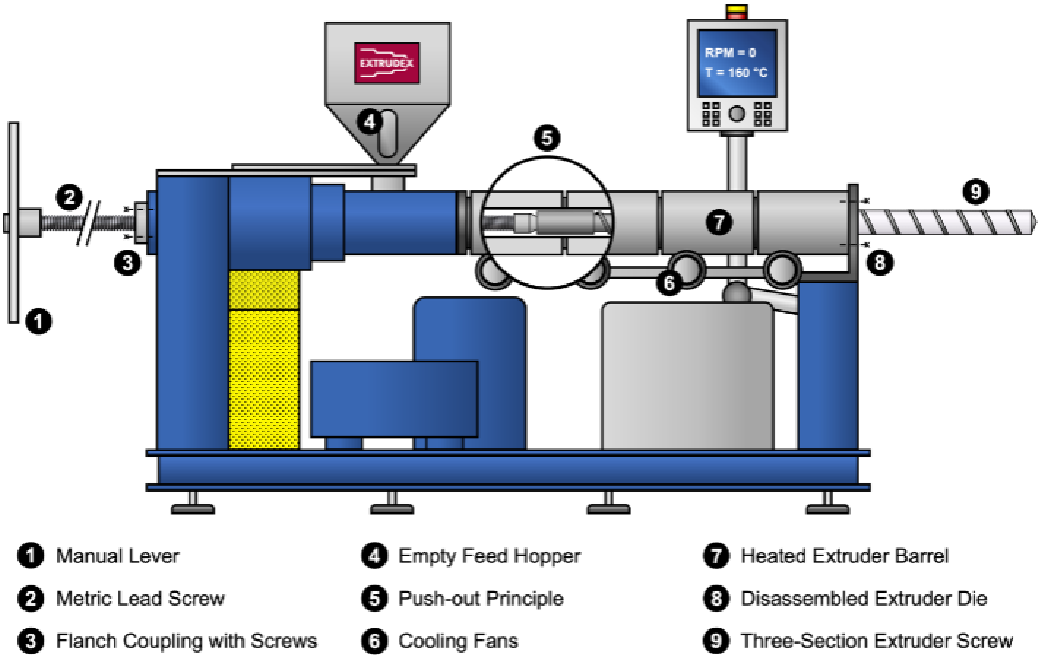


Figure [13] Single-Screw Extruder Pull-out Experiment [22]

Before starting the preparations for the pull-out experiment, first, the feed hopper has to be emptied using a vacuum machine to remove all the pellets that are left in the feed section. All the remaining pellets should be removed to avoid further supply of pellets during the pull-out which would make it more difficult to push the screw. The next step is to open the back of the extruder and attach the screw extractor. This is 2 meters M24 precision screw with a travel distance of 5mm per turn. Due to the length of the screw, we will need a wooden support, which has the same shape as the metric lead screw. If not, the weight of the screw extractor could make itself bend. If the lead screw bends, it could not be used to extract the screw because it could not travel forward after turning. Moreover, a rotating cone is attached to the tip of the lead screw, which comes with axial and radial bearings inside.

Figure [14] M24 precision screw extractor supported by wooden stand

As seen in Figure [14], the lever is rotated by two people by force. This rotation is then translated into torque for the screw. This rotation of the screw is what makes it go through the flange and push the screw out of the extruder. In Figure [13] we can see that “Number 5” represents the lead screw pushing the screw inside the extruder while it moves forward thanks to the rotation just explained. Sometimes when doing the pull-out experiment, the torque forces produced by the lead screw were so powerful that the screws from the flange broke by a brittle fracture. To avoid this, we should not tighten the screws on the flange too much. To make it easier for the lead screw to push the screw through the barrel, we will reheat the barrel heating zones before we start to rotate the lever. This will cause the barrel to expand, which is what makes it easier to move the screw through the barrel. The temperature chosen is 157ºC. Temperatures above 178°C should be avoided to prevent further melting of the solidified material. We will set this temperature in the extruder control panel (Number 8, Figure [12]). The control panel will look like this:


```
097. Temp. difference zone 1        Zone 01
EXTRUDER 1                                   19:26:12  Mo 20.02.2023
  0.0 RPM
  0.0 Nm
ON   Zone 01    123.5°C   157°C   feeding bush:
ON   Zone 02    135.7°C   157°C   24.0 °C
ON   Zone 03    137.1°C   157°C
ON   Zone 04    139.0°C   157°C
ON   Flange     121.9°C   157°C
OFF  Tool 01     21.1°C    23°C
                                  val.: 20
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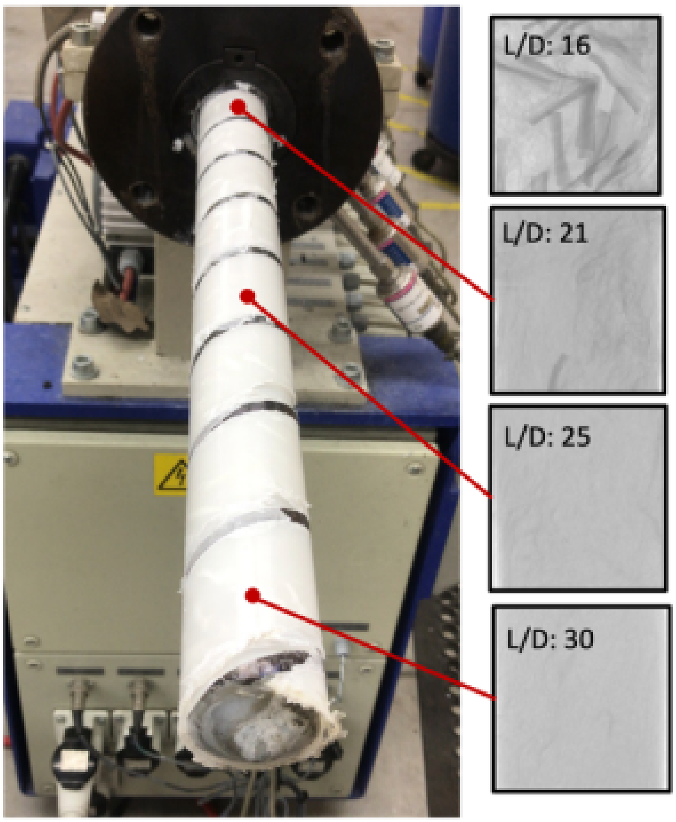
Figure [15] Control Panel with set Temperature

As shown in Figure [15], the temperature is set to 157ºC on the right. The values on the left represent the current temperature, and it will increase for a long time until it reaches the set temperature. Before we start the pull-out experiment, we will wait until this current temperature is 157ºC.

When the experiment is ready to be executed, we will start rotating the lever to push out the extruder screw. Usually, the first 2-3 rotations are difficult, requiring a very high torque that turns into a sufficiently high axial force to overcome the adhesion that has built up. When this adhesion has been overcome, less torque is required. When doing the experiments, this first difficult part was performed by two people and lever extensions were placed to apply more torque with less force. After those 2-3 rotations, the experiment can continue with one person. When the whole screw is pushed out of the extruder, we will label the samples of each pitch of the screw, starting with “1” from the screw tip. The position of the screw is measured in terms of the Aspect Ratio, where an L/D of 0 represents the position at the hopper and an L/D of 30 represents the position at the die of the screw.



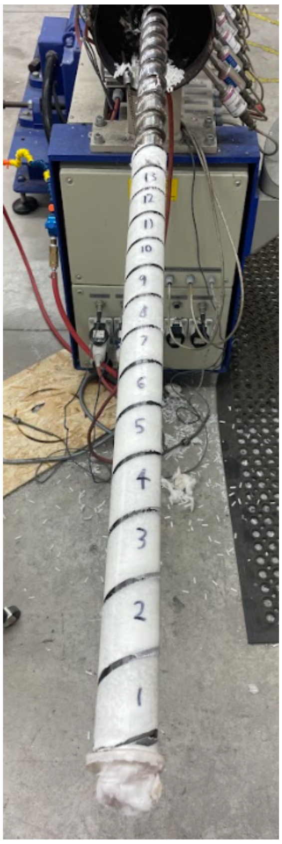


Figure [16] Aspect Ratio depending on the position in the screw [25]

Figure [17] Labeling the Samples of each one of the Pitches

In Figure [16], we can see that the Aspect Ratio depends on where the pitch is located in the extruder screw. The further the pitch is located from the feeding zone, the larger the Aspect Ratio will be. Furthermore, we can see that the pitches close to the die, the ones with lower Aspect Ratio, have not been melted properly, since it is visible that the material is not well dispersed and some pellets can also be seen. As stated in Table [1], the Aspect Ratio of LFTs vary between 10 and 1000. Due to the lower limit of 10 and the poor dispersion of the last pitches, we will use as valid samples for this study the first 13-15 pitches. In Figure [17], we can see the extruder screw after the pull-out experiment. The samples are labeled starting with Pitch 1 from the screw tip. It is also seen in this last Figure that during the experiments, the pitches from the bottom of the screw do not have any material. This is linked with the melting ratio of the material. As said before, the dispersion is poorer at the bottom of the screw. If we continue going backwards we will see that we will find pitches in which the material is not even melted. We can observe this while doing the experiment. At some point when pushing the screw, the solidified pellets start to fall from the tie to the floor.

The next step is to extract the pitch samples from the extruder screw. To do so, we will use brass spatulas to cut the material with the help of a torch. We will heat the spatula with the torch for around 15-20 seconds. When the spatula starts becoming red because of the heat, we will place it on the material, causing it to melt and therefore to cut. The cuts should be on both sides of the "label number", resulting in a helical cut of the sample that represents each one of the pitches of the screw. We will have after the cuts around 13-15 samples of the first 13-15 pitches of the screw starting from the tip with their respective number on it. Those samples are ready to go through the next step of the study, which is the Flattening of the Samples.

To finish the pull-out experiment, the screw extruder should be cleaned and purged before starting a new process. For purging, it will not be necessary to attach the extruder die. There are several reasons why this is highly important [12].

- Material Residue: residues could be left by the previous material used in the pull-out experiment. These residues could be particles, fragments, or contaminants. Purging helps to remove this residue to ensure a clean starting point for the next process.
- Different Materials: The object of this study is to compare the dispersion between pultruded and coated pellets. Purging is essential to avoid cross-contamination between both types of materials.
- Process Consistency: Cleaning the extruder screw will help to maintain consistent process parameters and material properties, so the extruder can achieve accurate temperature control, uniform material flow, and reliable processing conditions.
- Prevent Blockages: Residues left in the extruder can accumulate over time and potentially lead to blockages or clogs in the system. Those blockages will make it more difficult to push the extruder screw.
- Adhesion: Cleaning the screw will reduce adhesion of the material to the screw and barrel

To purge the extruder, we will heat up the barrel to 280ºC with the control panel. This high temperature will not melt the residues, it will completely burn off the residual material. The remaining material, which will mostly be burnt, should be removed from the screw with the help of brass brushes. When the screw is completely clean, it will be sprayed with silicone mold release and wiped with a napkin. The screw is then placed back to the inside of the extruder. The back of the extruder is closed again and the barrel heated up with the control panel. The feed hopper will be filled with purging compound and HDPE (High Density Polyethylene). This last compound is cheaper than the purging compound, but it is still a good alternative for the purging process. The extruder will be run at several speeds between 5 and 30 rpm and then cooled down to room temperature. After this, we will reproduce the pull-out experiment using the lever. This time, the torque force required is significantly reduced in comparison with the studied materials. This experiment will be performed at a lower temperature, specifically at 100ºC because the cleaning material has a lower melting temperature. When the extruder screw is pushed out of the extruder, the HDPE will be removed and the screw cleaned again with the brass brush and the spray. The HDPE extracted will have the shape shown in Figure [18] and can be discarded. The cleaned screw can be back in the extruder, concluding the pull-out experiment and later cleaning.

Figure [18] HDPE extracted from the Screw after Purging Process

4.2 Flattening of the Samples

At this point of the study, each sample of the screw pitches is labeled and has to be scanned with a micro CT scanner to evaluate its dispersion. To facilitate the scan, the samples should be flat and with a square geometry. After the previous step, the samples will have helical shape, making them not suitable yet for the study. The parts are cutted with a band saw, removing some material from each one of the sides of the sample. The result part will be a still bended sample with the label in the middle of it.

Figure [19] Helical Shape of the Sample

Figure [20] Shape of the Sample after cut with Band Saw

Figure [19] shows the original shape of the samples after extracting them from the screw. We can see a black line, which was drawn with a marker to know where to cut with the heated spatula. The label is not seen in the images because it is written in the other face of the part. It is also visible that the surfaces next to the cuts are melted due to the heat of the spatula. Figure [20] shows the sample after cutting the borders with the band saw. It is important to cut most of the bent material to facilitate post-processing but remaining a certain piece of sample to ensure that most of the area can still be scanned properly. The cut sample shown in the second image is the perfect example of what has been explained above. It could still be seen the bent surface of the original helical shape, however, the part does not look as closed as in Figure [19].

When the samples are cut, they should be wrapped with industrial aluminum foil before heated in the oven. The reason why they are wrapped is to maintain the high temperature as long as possible after taking them out of the oven and flattening them. The more time the hot temperature is kept, the more time the parts will be available to deform. The samples are placed in an oven at a temperature of 165ºC until they achieve a good deformability level. The time to achieve this deformability depends on the sample because each one of the parts have different thickness. The thicker the sample, the more time will be required to achieve the deformability state. To avoid this problem, all the samples were placed in the oven for around 20-30 minutes, ensuring that at the moment of taking them out, all the parts are ready to be deformed.

Figure [20] Samples inside the oven

To check if the parts are ready to be deformed, they were bent by hand with the help of thermal protection gloves. If they could be bent, then the samples are placed between two plane metal plates which are compressed by a bench vise. The plates used to compress the parts are made of metal to help the sample cool down as quickly as possible thanks to heat dissipation. Furthermore, at the time of tightening the vise, it is important to stop as soon as the sample appears to be flat in order to prevent further compression of the sample. This compression could cause the sample to expand, making that sample not valid for this study.

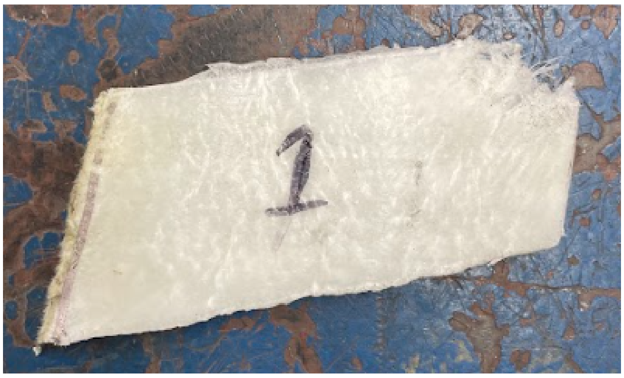


Figure [21] Plane metal plates in a bench vise

Figure [22] Flattened Sample

In Figure [21], it is shown the flattening device used in this study. The deformable samples are placed between the two metal panels. The vise is tighteen until the sample is flat and then cooled down for around 1 minute. When the part is at room temperature, the material used to wrap is removed, resulting in a flat piece of the screw pitch. This final state of the sample is illustrated in Figure [22].

4.3 Analysis of Dispersion using X-ray Scanning

The first part of the analysis will be the study of dispersion in each one of the samples obtained in the previous steps. To do so, a micro-CT scanner was used. The use of the scanner ensures the correct analysis of the parts, with an automated and non-destructive procedure. It is important that the procedure used is non-destructive because the samples are then studied again in the fiber length analysis. The samples are placed in a rotating plate in front of the X-ray Tube. At the moment of the scan, a “picture” of the sample is taken and the result is shown in a 2D detector. The picture taken consists of an image of the sample in a gray scale. Thanks to these pictures, the dispersion of the part’s fibers can be studied and analyzed. This procedure is shown in Figure [23].

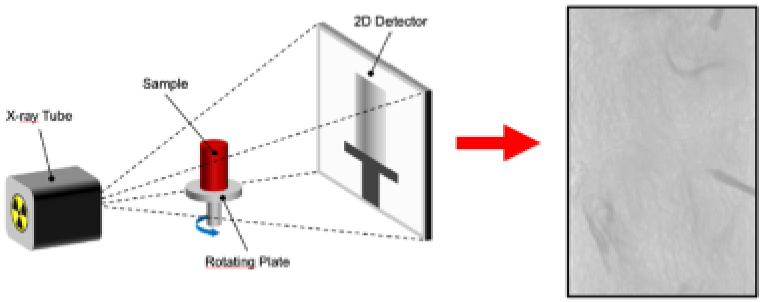


Figure [23] Dispersion Analysis using micro-CT scanner [21]

To calculate a quantitative course of fiber dispersion using the X-ray images, the image processing software ImageJ is used for the analysis of the individual scans. As said before, the scans are gray scale images, this means that the mean value refers to the mean gray value in the defined image section. Specifically, this number is the sum of the gray values of all pixels in the selected area of study divided by the number of pixels. The maximum gray scale value corresponds to white, this is because the grayscale only contains information about the brightness of the image. The maximum and minimum values were added to the parameters in ImageJ. These values are not directly related to the calculation of fiber dispersion, however, these values affect the mean grey value, which is the one variable used in the calculation of fiber dispersion. The features used in ImageJ helping to calculate the fiber dispersion of every pitch of the extruder screw are the SD and COV. The SD of a data set indicates how far each value lies from the mean. Using this SD and the mean gray value, the COV can be determined. A high value of the SD means that the gray values are far from the mean gray value in the defined area. On the other hand, a low SD value means that the gray values are relatively close to the mean gray value. It is common that a low SD also leads to a low COV. If both SD and COV values are low, it could be said that the sample has a high level of dispersion. Inversely, a high value in both tools means that the fibers of the sample are poorly dispersed. While doing the experiments, it was observed that the samples exhibit a much more homogeneous gray scale value toward the end of the extruder screw. Using the example scan in Figure [23] it can be explained how the fiber dispersion level can be observable. A high fiber dispersion will be seen in the scans as a gray area. In the example, most of the area examined is completely gray, with no significant variations in the grayscale. It could be said that the fibers of the sample are well dispersed. On the other hand, it could be seen some agglomeration of fibers that lead to a stronger gray color as illustrated in the following image.

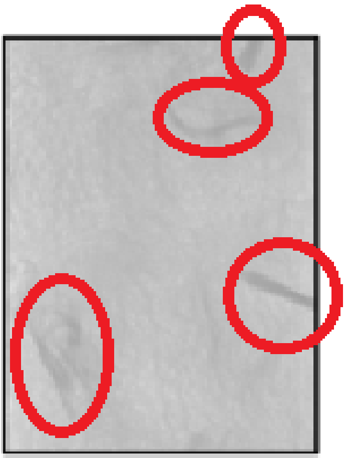


Figure [24] Observable Fiber Dispersion

Figure [24] shows agglomerations of fibers in the X-ray scanned image. These agglomerations mean that the fibers are not well dispersed. Since they are located in bigger groups, the ray-X scan translates this on a darker gray scale. In areas closer to the feed hopper, more undispersed fiber bundles can be seen. That makes sense because the dispersion of fibers increases continuously along the length of the extruder screw. Dispersion rate increases with every rotation of the screw channel. In pitches close to the feeding zone, big and more agglomerations of fibers can be seen along the whole scanned area, meaning a poorer dispersion level. The dispersion rate appears to be higher at the beginning of the screw starting from the tip and slowly decreases towards the end of it. The results showed that a dispersion close to 100% was achieved in the first pitches of the screw. However, a 0% dispersion was seen for pitches 13-15. This verifies the behavior explained in section 4.1 in which it was said that only pitches 1-15 of the screw are analyzed. There is no point on studying the pitches after the 15th one since a 0% dispersion is found after pitches 13-14. A full course of dispersion (from 0% to around 100%) is then studied along the length of the extruder screw. It is curious to mention that the pitches with the highest dispersion rate are the ones with lower thickness.

4.4 Analysis of Fiber Length

This part of the study is the most time-consuming one and it is divided in two parts. The first part of this analysis consists of a matrix removal and downsampling of the fibers to then obtain scanned images of them. The second part of this analysis consists of a post-processing study and fiber detection using a code program for further examination of the results and respective conclusions. The polymer Engineering Center at UW-Madison, has developed a fiber length measurement technique adapting different features from various measurement methods. This new procedure ensures reliable results by sampling between 10 000 and 100 000 fibers. The material and tools used in this first part of the fiber length analysis are the following ones:

Figure [25] Tools used in Fiber Length Analysis

Figure [26] Sample Holders

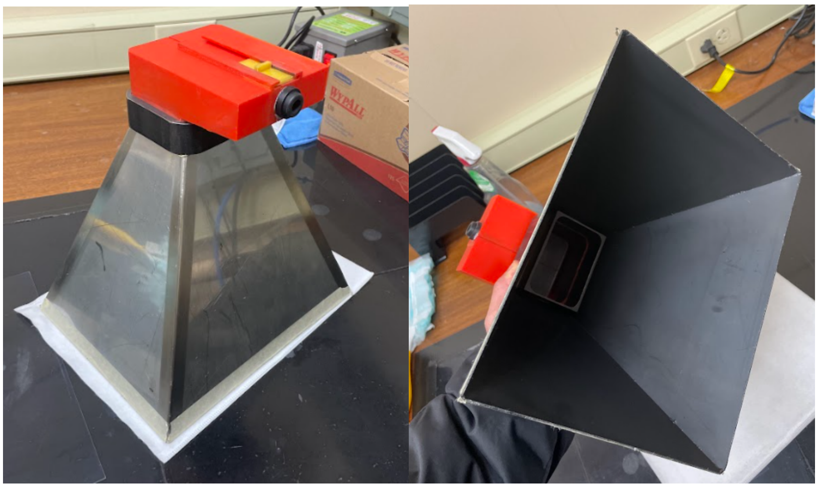


Figure [27] Fiber Dispersion Chamber

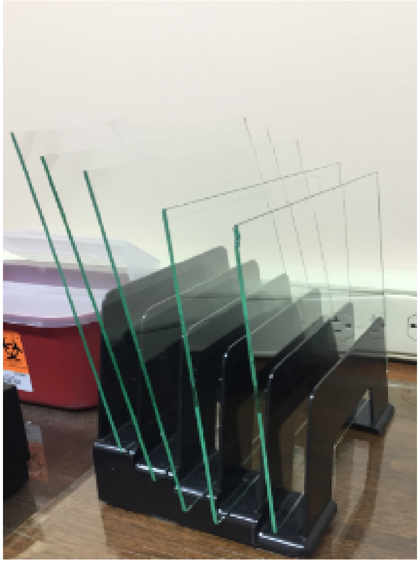



Figure [28] Glass Sheets

Figure [29] Epson Perfection V750 PRO Scanner

Figure [25] shows some of the tools used in this part of the experiment. From left to right, it can be seen the sample holder and respective cap, syringe, bondic glue, UV flashlight, brushes, tweezers and a Petri dish. The sample holders can also be seen in Figure [26] with numbers written in them as labels. The fiber dispersion chamber is what can be seen in Figure [27] which has two holes; the top one, in which the fibers are deposited, and the lateral one, from where the compressed air is blown. The way it will be used will be explained with more depth next. Finally, Figure [28] shows the glass sheets used to capture the fibers from the chamber. Those sheets are then placed in the scanner illustrated in Figure [29] to take pictures of the fibers.

To start with the fiber length analysis, a 30mm diameter disk is cut from each one of the pitch samples and placed inside of the sample holders. The samples are heated in an oven up to 500ºC for 2 hours. This technique is called pyrolysis, in which the high temperature will remove the matrix in each one of the samples. Since the matrix is removed, the result after this step is a bunch of fibers that fill the whole sample holder. A representative subsample is then extracted using the glue. To do so, the sample holder cap is placed on top of the sample holder. The cap has a small hole in the middle of it which represents the syringe guide. The needle is introduced through the sample guide until touching the bottom of the sample holder. Then, the glue is injected while moving the syringe all the way up with constant pressure, ensuring that the glue is injected during the whole path followed by the needle. It is important that the glue is being injected all the time because fibers from the whole sample should be extracted instead of only the fibers at the bottom of the sample holder. After this, the cap of the sample holder is removed and the resin is cured with the UV flashlight for 5 to 10 seconds. Once cured, the mass of fibers glued is transferred into a Petri dish. This means that the rest of the fibers that have not been glued by the process just described are going to be discarded. This division may need the help of the tweezers, by grabbing the head formed by the glue with them and carefully striking the reminder fibers that are not glued with the brushes. The resulting sample of fibers is then placed in a new Petri dish for a new pyrolysis. The oven is heated at 500ºC for an hour and a half. The goal of this second pyrolysis is to remove the resin used to take that sample of fibers.

A glass sheet is then cleaned with a microfiber cloth until it is fully transparent. Sometimes the sheet is not clean enough, which will lead to the use of glass cleaner. The cleaned glass sheet is placed on a black mat background on the table. Afterwards, the chamber is located on top of the glass sheet. It is important that the chamber, as well as the glass sheet, is properly cleaned to avoid cross-contamination of fibers from different samples. Unlike the glass, the chamber is cleaned with compressed air through the lateral hole of the chamber. After having the glass sheet and chamber in place, the sampled fibers from the second pyrolysis are deposited through the hole located on top of the chamber. To do so, the tweezers or the brushes may be used to help get the fibers through the hole. Since there are more fibers in the Petri dish than the ones that should be placed at once in the chamber, it may be necessary to prepare 3 or 4 glass sheets depending on the sample size. Each one of the glass sheets will represent a sample scan. The fibers are separated in various glass sheets to ensure the scans are not fiber-overwhelmed, guaranteeing this way a good dispersion of them. After the fibers are deposited through the hole at the top, this hole will be closed and compressed air will be blown through the lateral hole with 2-4 short bursts of air. The air blown and the shape of the chamber, as shown in Figure [27], will make the fibers fly from the tunnel at the top through the chamber's body, dispersing the fibers all over the glass sheet. More than one burst of air is blown to ensure proper dispersion. The result of this procedure will be a glass sheet full or dispersed fibers all over its area. Thanks to the black mat background, those fibers could be seen at a glance. If a group of agglomerated fibers is identified, the brushes should be used to disperse the group into individual fibers. As explained before, the process will be repeated until all the sample fibers from the Petri dish are subjected to the experiment, taking in most cases between 3 and 4 glass sheets. Afterwards, the chamber is lifted carefully to not move the fibers from the glass and the frame is slowly transported to the scanner. As done with the chamber, the scanner is also closed carefully to avoid current air that could affect the dispersion of the fibers. The brushes and tweezers should be cleaned with compressed air before repeating this process with a new sample as they could contain glass fiber traces from the previous sample.

The second part of this analysis corresponds to the scanning of the glass sheets with the scanner shown in Figure [29]. Epson software will be used to perform the scans. When the scanner is closed , “Preview” feature is clicked. This feature will make a quick scan for around 15 seconds. After this preliminary scan, “Histogram” is clicked and some values are added to the input. Those values are 0, 0.23, and 49. The implementation of the values will change the scale of colors in the scan, making the fibers more visible in the final picture. When the values are set, “Scan” tool is pressed and the scanner will be running for 2 minutes. When finished, a directory is selected and the picture is labeled for easier post-scan identification. Before, it was explained that samples are divided in different glass sheets, the first scan of a sample will be labeled with the number of the sample and “001”. Meaning that the second scan will be “002” and so on.

The pictures are later processed with Photoshop. This is the last step of the images before measuring the fiber length of the fibers on them. Once the scan is opened in Photoshop, the canvas size is adjusted to 10 inches in both width and height dimensions. Afterwards, the threshold is also modified to a value between 45 and 60. A value should be found that gets rid of the noise on the background but still keeps the fibers in one piece. This change will make a significant difference in how the fibers are seen in the scan. If the threshold value is too high, most of the fibers will be incomplete or spittled, giving as a result, a wrong analysis of the fiber length.

On the other hand, if the threshold is too low, there will be a lot of noise in the image, especially in the edges. This value can change depending on the scan. A correct value of threshold is shown in Figure [30].

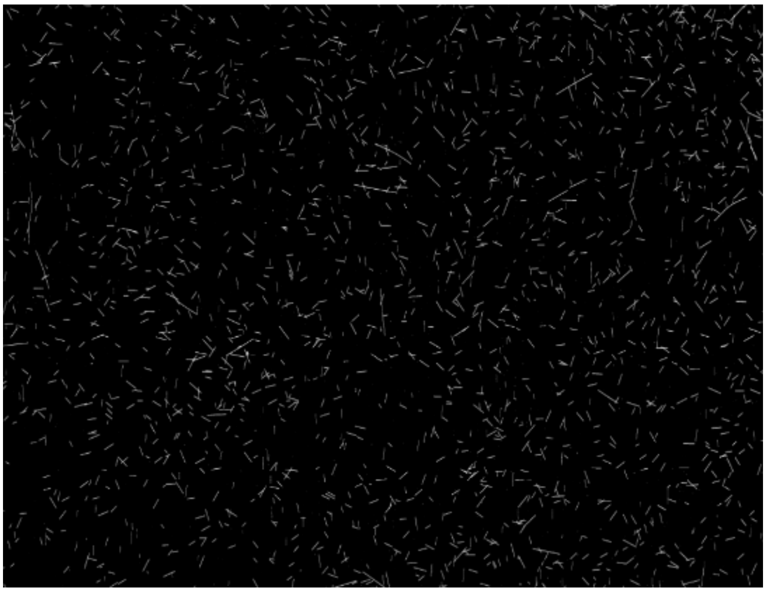


Figure [30] Scan with the correct threshold value

Once the image adjustments are done, it is time to start cleaning the scan. The “PaintBrush” tool will be used to erase any scratch, noise, and contaminant that could be considered as glass fiber. To start with, all the edges are erased. Most of the time, the scratches and noise will be in the edges. This is mostly because it is the place in which we grabbed the glass sheet when placing it in the scan. Moreover, some fibers are splitted because of the edges, meaning that those fibers should also be erased. Some contaminants could also be identified by its shape. They can look like fibers, but they are not. The shape of these contaminants are most of the times very curved, making in some cases, the shape of a semicircle. In the scans, fibers are straight lines, with minimal curves. Once semicircles are seen, they could be identified as contaminants and should be erased. Strong white dots should be deleted too. Sometimes, agglomeration of fibers makes it unable to identify the correct length of the fibers. This is because two or more fibers are perfectly aligned, creating a very long fiber. These agglomerations should also be deleted because they represent a fake long fiber that could modify the sample average length of the fibers, leading to a manipulation of the results.

When the images are fully processed with Photoshop and therefore free of scratch and noise, it is time to measure the length of the fibers. To do so, the Polymer Engineering center at UW-Madison has coded a Matlab program capable of analyzing the scan in search of fibers to then measure their length. There are some inputs that should be added to the code before running it. First, the number of the sample is added and then it is specified if the scan analyzed is the first one of the said sample. This is because the code creates an Excel sheet with the average length of the fibers in the analyzed scan, and if a sample is divided in more than one scan, the Excel of the last analysis should have the information and length data of the other scans from the same sample. This means that the average length of a scan is then transferred to the next scan values to create a global average length of the full sample and not of a specified picture. As said before, the program starts identifying all the fibers from the scan to then measure their length. The time to perform this analysis depends on the number of fibers found. Normally, it takes between 2 and 10 minutes per picture. Some of the times, when the fibers are small, the number of fibers in a single scan can reach 80 000, taking around 20 minutes to complete the length analysis. .

Once all the Excel sheets are created with the average fiber length of each sample, the study is then prepared to compare the obtained results and reach a conclusion. To start with, some tables will be created with the average length calculated by the program. Secondly, pultruded and coated pellets will be compared with a dispersion rate - fiber length graph from where the conclusions will be drawn.

5. Results

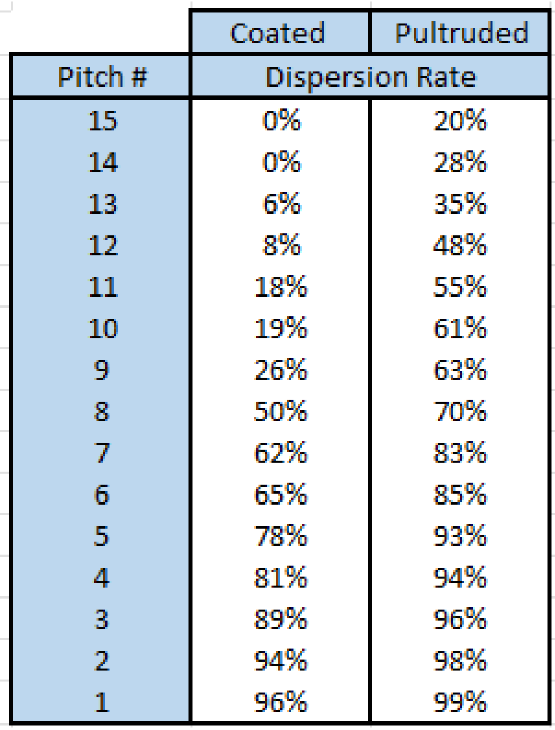
In this section, the results obtained in this study are going to be addressed. In order to get very accurate results, a big quantity of experiments are required to be done. However, it was confirmed that the accuracy of those results is not significantly affected when lowering the number of experiments. For this reason, four experiments in total were performed; two with pultruded pellets, and the other two with coated ones.

As explained in this study, the fiber dispersion rate is higher in the first pitches of the screw and keeps going down until the pitches number 13 to 15, in which the dispersion rate could be considered as 0%. The dispersion rate obtained in the first pitches in both materials was around 100%. The more dispersed the fibers are, the better the quality and stability of the mechanical properties throughout the final part will be. Moreover, a high dispersion rate improves the uniform reproducibility of quality parts. On the other hand, a good dispersion rate always leads to a higher fiber breakage meaning that a high fiber length is expected for lower dispersion rates and a high dispersion rate will lead to shorter fibers. It is important to achieve a high length of fibers because it improves the mechanical properties, however, if the fibers break, the length of those fibers will decrease, leading to a lower mechanical performance of the finished part. For this reason, we could conclude that the ideal result will be a part which maintains a high fiber length and also a high dispersion rate.

It is worth mentioning that from both pultruded and coated pellets experiments, the same pitches were analyzed. However, not all the pitches from the screw were studied for the fiber length analysis. The analyzed pitches were mainly located at the beginning of the screw, starting from the tip, to demonstrate the different behavior between the two types of pellets at high dispersion rate. Furthermore, a couple of pitches from the middle and final part of the screw were studied. The experiments were performed at 30 rpm. In Appendix 1, it can be found all the scan pictures made by the CT scanner used for the dispersion analysis.

5.1 Fiber Dispersion Analysis

The first part of the analysis was focused on studying the fiber dispersion rate of coated and pultruded pellets. For this analysis, all pitches from 0 to 15 of the extruder screw were analyzed.



	Coated	Pultruded
Pitch #	Dispersion Rate	
15	0%	20%
14	0%	28%
13	6%	35%
12	8%	48%
11	18%	55%
10	19%	61%
9	26%	63%
8	50%	70%
7	62%	83%
6	65%	85%
5	78%	93%
4	81%	94%
3	89%	96%
2	94%	98%
1	96%	99%

Table [3] Dispersion Rate Analysis for Coated and Pultruded Pellets

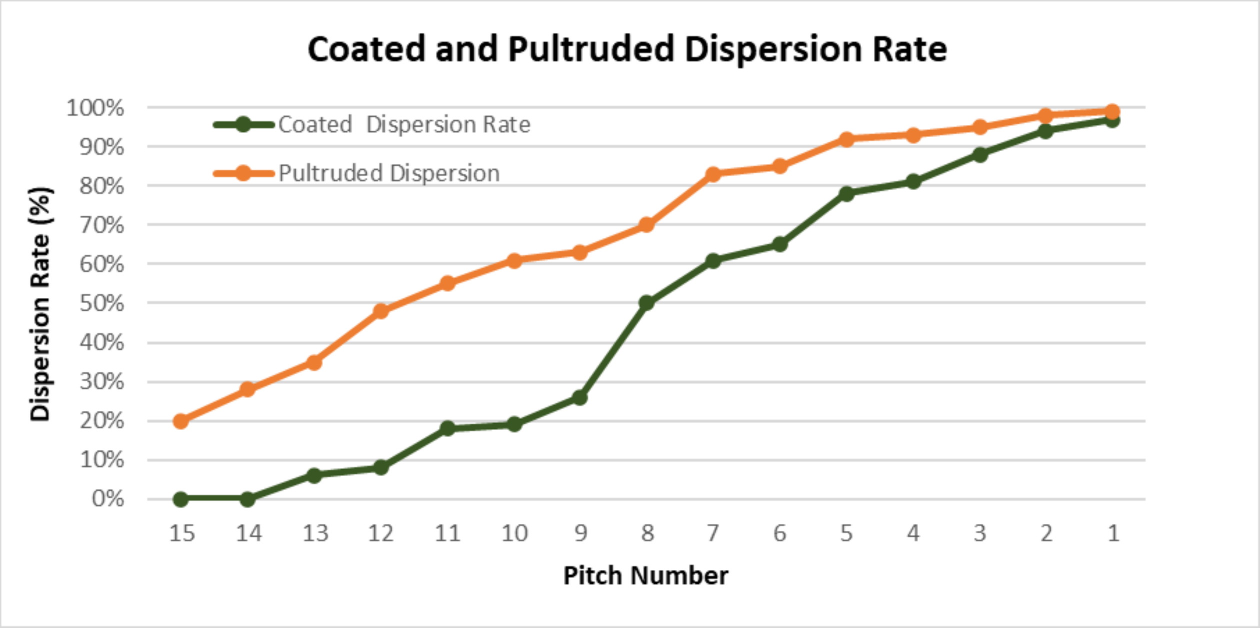
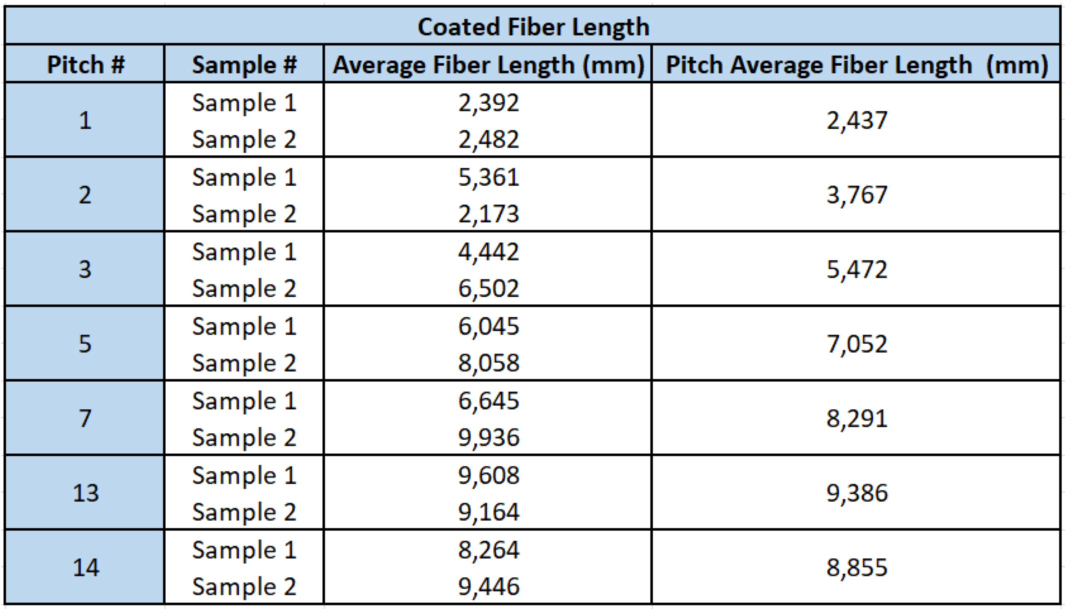


Figure [31] Coated and Pultruded Dispersion Rate Graph Comparison

Figure [31] shows a visual comparison of the dispersion rate for coated and pultruded pellets. Both types of pellets follow a similar behavior. As expected, the first pitches of the extruder screw will have a higher dispersion rate. During this study, the dispersion rate achieved in the first pitch was close to 100%. This rate starts to decrease progressively as the pitches get closer to the end of the screw. Pultruded pellets maintained a 90% dispersion rate until pitch number 5. On the other hand, coated pellets' dispersion rate was below 90% after pitch 2. Furthermore, a big difference in dispersion was noticed between pitches 8 and 9 unlike with pultruded pellets. These last ones maintained the decrease rate during the whole range of pitches. Finally, coated pellets reached 0% dispersion from pitch 14. Otherwise, pultruded ones kept a 20% dispersion rate in pitch 15. During the whole range of pitches, pultruded pellets had a higher dispersion rate than coated pellets for the same studied pitch.

5.2 Fiber Length Analysis

The second part of the analysis measured the fiber length using the fiber detection MatLab code with the scanned images of the samples after being processed with Photoshop. In this part of the study, not all the pitches were subjected to the study due to the amount of scanned images that this would entail. However, each pitch studied was analyzed twice for each one of the pellet types. The value used for the graphs would be the average length of both measurements.



Coated Fiber Length			
Pitch #	**Sample #**	**Average Fiber Length (mm)**	**Pitch Average Fiber Length (mm)**
1	Sample 1	2,392	2,437
	Sample 2	2,482	
2	Sample 1	5,361	3,767
	Sample 2	2,173	
3	Sample 1	4,442	5,472
	Sample 2	6,502	
5	Sample 1	6,045	7,052
	Sample 2	8,058	
7	Sample 1	6,645	8,291
	Sample 2	9,936	
13	Sample 1	9,608	9,386
	Sample 2	9,164	
14	Sample 1	8,264	8,855
	Sample 2	9,446	

Table [4] Coated Pellets Fiber Length

Pultruded Fiber Length			
Pitch #	**Sample #**	**Average Fiber Length (mm)**	**Pitch Average Fiber Length (mm)**
1	Sample 1	2,697	2,992
	Sample 2	3,287	
2	Sample 1	3,789	3,103
	Sample 2	2,417	
3	Sample 1	3,051	3,008
	Sample 2	2,964	
5	Sample 1	3,033	2,876
	Sample 2	2,719	
7	Sample 1	3,124	2,959
	Sample 2	2,793	
13	Sample 1	5,871	6,905
	Sample 2	7,939	
14	Sample 1	6,806	6,774
	Sample 2	6,742	

Table [5] Pultruded Pellets Fiber Length

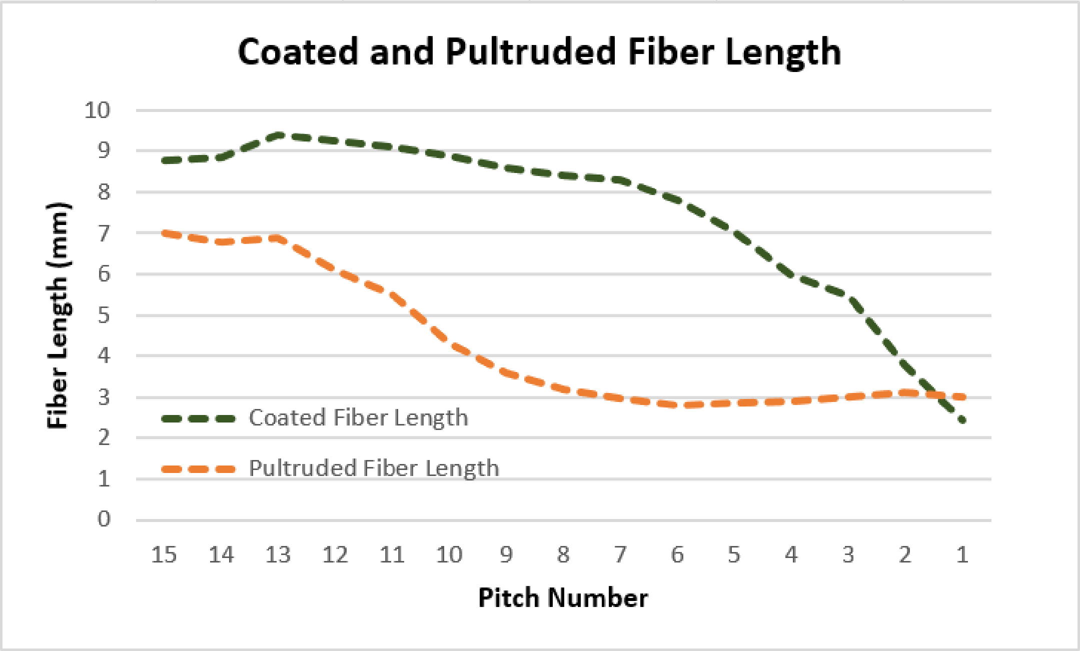


Figure [32] Coated and Pultruded Fiber Length Comparison

Figure [32] shows the fiber length comparison between coated and pultruded pellets. As expected, the fibers will be longer in the final pitches of the screw, when the dispersion rate is at its minimum. The pellets behaved differently depending on the manufacturing process. Coated pellets maintained a high fiber length between pitches 15 to 6, when the length of the fibers drastically fell. On the other hand, pultruded pellets have said length fall in the last pitches of the screw to then maintain a short fiber length between pitches 9 to 1. Their behavior therefore is opposite. Nevertheless, coated pellets have higher fiber length during the whole screw. The only exception is pitch number 1, in which pultruded pellets have a bit longer fibers.

6. Conclusions

In the previous section, the results of both analyses performed in this study were shown separately. However, the dispersion rate is directly related to the fiber length of the part due to breakage. Hence, at the moment of choosing the manufacturing process to create the pellets, both dispersion and fiber length should be taken into account. A high dispersion rate does not improve the mechanical part properties. Well dispersed fibers improve the quality and stability of the mechanical properties throughout the final part as well as improving the uniform reproducibility of quality parts. On the other hand, greater fiber length directly improves the mechanical properties and performance of the part. Hence, the best scenario possible will be long fiber length, maintaining as high dispersion rate as possible.

To start with, a Dispersion Rate - Fiber Length comparison is presented with coated and pultruded pellets. In said comparison, there is a clearer view of how both types of pellets behave. In the automotive industry, LFTs are present in most of the polymer-made parts of the car such as engine mounts and dashboards. Due to the variety of uses of LFTs, each one of them needs specific mechanical characteristics, which is implied by the fiber length, and therefore by the fiber dispersion rate of the part. For this reason, different scenarios of dispersion rate are going to be studied, leading to a conclusion of which manufacturing process is best for each one of the presented scenarios.

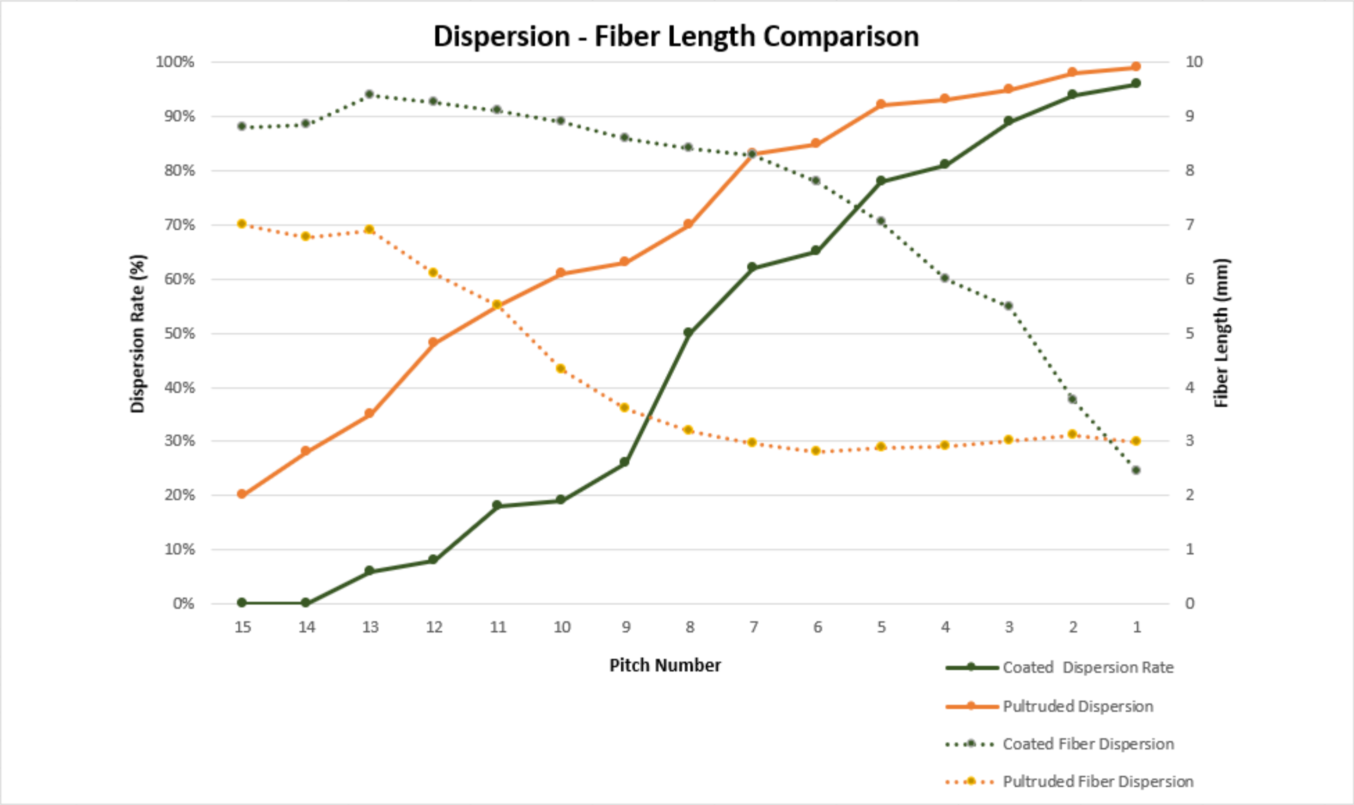


Figure [33] Dispersion - Fiber Length Comparison

Figure [33] shows the Dispersion - Fiber Length Comparison for coated and pultruded pellets. The Y-axis in the left shows the dispersion rate percentage, which applies to the solid lines of the graph. On the other hand, the Y-axis on the right represents the fiber length in millimeters, which applies to the dash lines of the graph. Finally, orange lines symbolize pultruded pellets and the green ones symbolize coated pellets. The theory says that the more dispersed the fibers are, the shorter the fibers will be due to breakage during the extrusion. The graph shows that the greatest fiber length occurs when the dispersion is at its lowest. In contrast, the shortest fiber length for both types of pellets coincide with the highest dispersion rate. This phenomenon can be seen in all pitches of the screw as the graph shows that the solid lines go up the closer we get to the tip of the screw, in which the first pitches are located. The dash lines go down the closer we get to the same pitches mentioned before. The studied pellets have opposite behaviors. Coated pellets have lower dispersion rate but longer fibers and pultruded pellets have higher dispersion rate but shorter fibers.

Next, different scenarios are going to be presented in order to compare and decide the correct manufacturing process needed depending on the specifications wanted by the company which orders the part. Coated pellets are “Stamax”, and pultruded ones are “Celstran”.

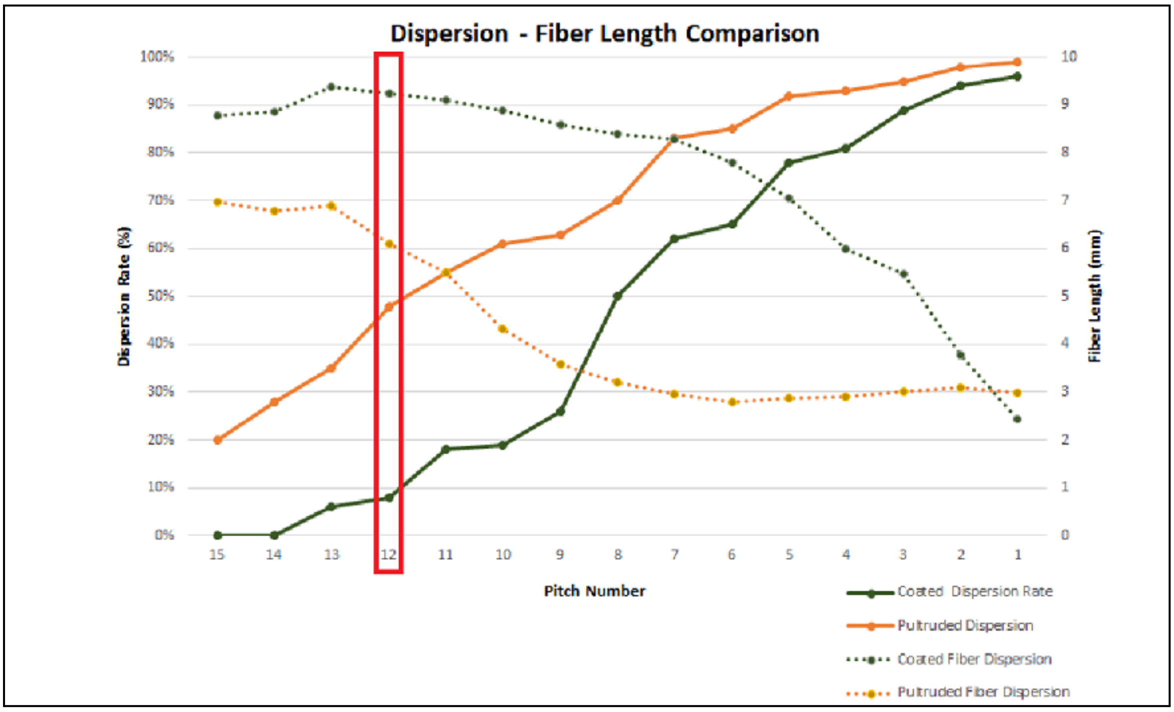


Figure [34] Comparison for a L/D of 16

Figure [34] shows the results obtained for an L/D of 16, which is pitch number 12. Coated pellets have a very long fiber length at this point, which could be aligned with strong mechanical properties. However, its dispersion rate is 8%, making the part completely useless. With this level of dispersion, the fibers are located in groups and some of the fibers are not processed, since the solidified pellets can still be seen at this point. Pultruded pellets offer a 48% dispersion rate, which could be acceptable. The fiber length is not as high as in coated pellets, but enough to ensure good part performance. For this reason, pultruded pellets should be chosen if the aspect ratio needed for the part is 16.

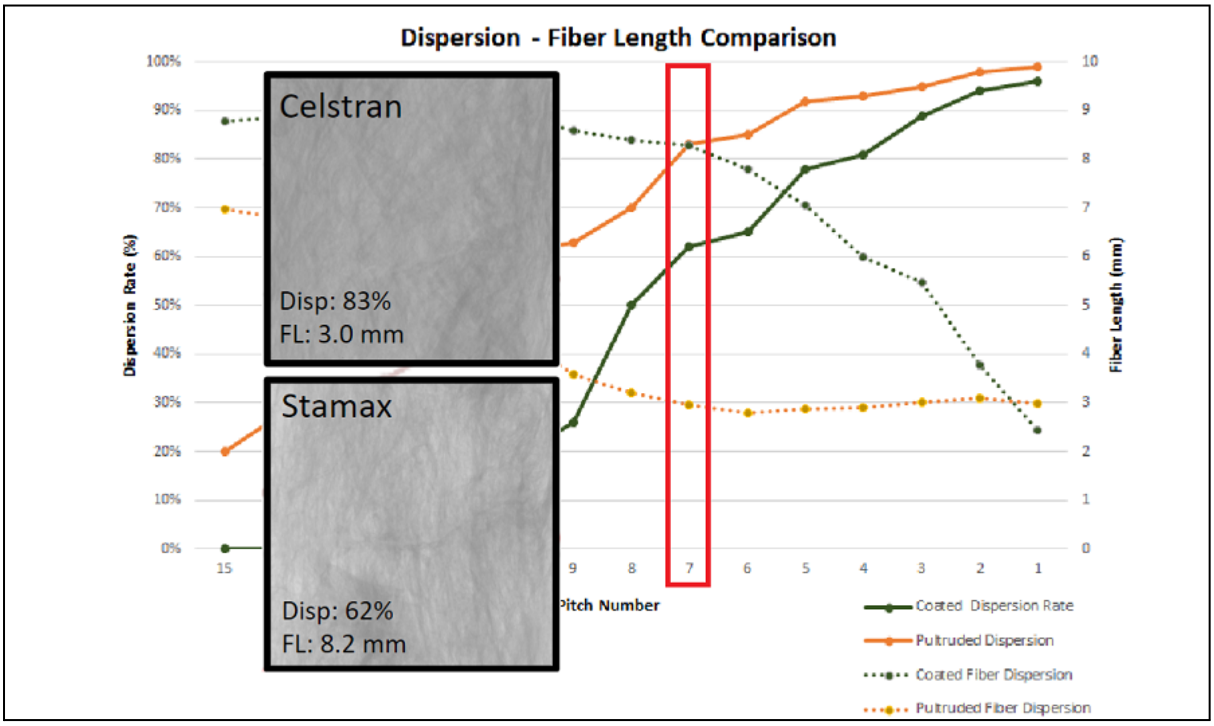


Figure [35] Comparison for a L/D of 21.5

In Figure [35], pitch 7 is studied, which represents an aspect ratio of 21.5. Coated pellets provide a 62% dispersion rate and 8.2 mm fiber length whereas pultruded ones provide a 83% dispersion rate with 3 mm fiber length. With this aspect ratio, the fiber length of pultruded pellets is too low to be considered as an option if we compare it to coated pellets. Coated pellets provide a very high fiber length at a relatively similar fiber dispersion. This leads to the conclusion that the fiber length is the differential variable for this specific case. Coated manufactured pellets should then be chosen if the required aspect ratio is 21.5.

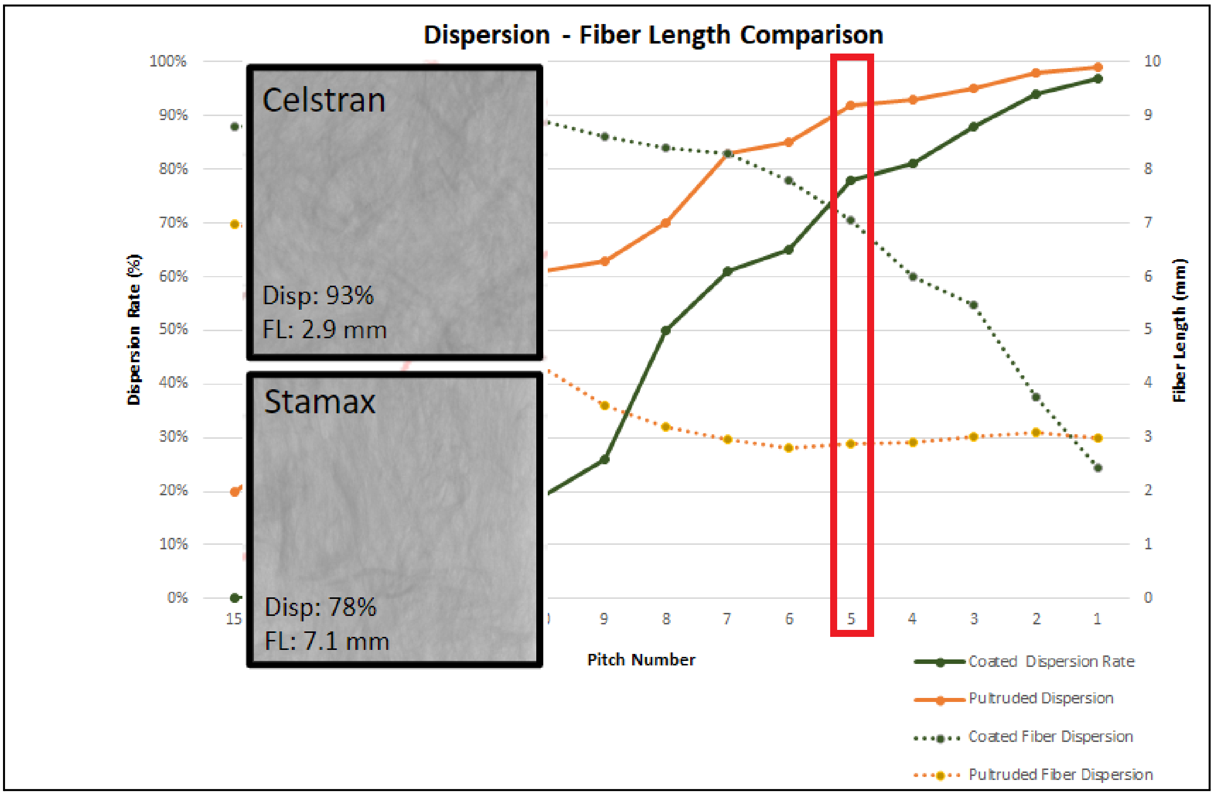


Figure [36] Comparison for a L/D of 24

If the required aspect ratio is 24, which represents pitch number 5, coated pellets will provide 7.1 mm fiber length at 78% fiber dispersion. Moreover, pultruded ones will provide 2.9 mm fiber length at 93% fiber dispersion. As in the past scenario, pultruded pellets offer very short fibers. However, the dispersion ratio is higher than in coated pellets. Nevertheless, the dispersion ratio in coated pellets is very high too, since this type of pellets get increasingly closer to pultruded ones in dispersion the closer the pitches are to the screw tip. For this reason, coated manufactured pellets are still the chosen ones if the required aspect ratio is 24.

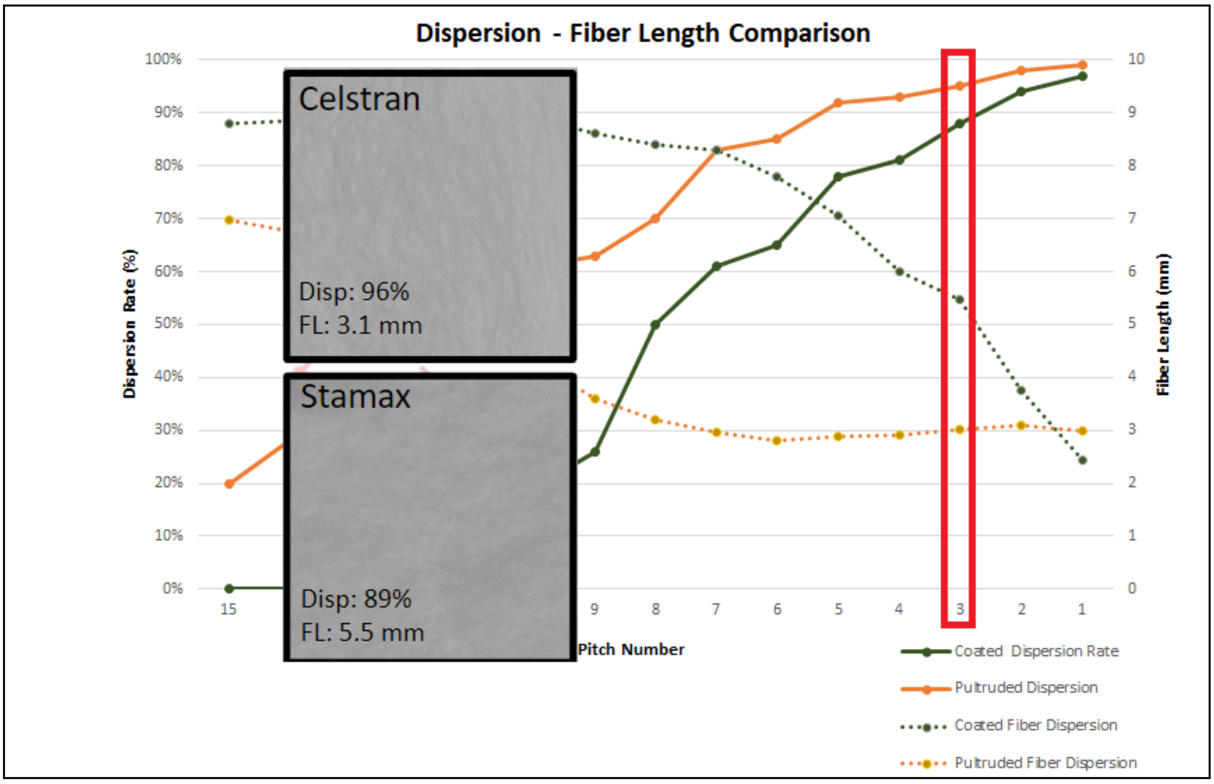


Figure [37] Comparison for a L/D of 27

For a required aspect ratio of 27 which represents pitch number 3, pultruded pellets offer 3.1 millimeter fibers at a 96% fiber dispersion. Figure [37] shows how pultruded pellets maintain an approximately 3 millimeters fiber length through the first 7 pitches of the extruder screw while the dispersion rate keeps increasing. On the other hand, coated pellets offer 5.5 mm length for the fibers at a very high 89% fiber dispersion. In this case, the decision to make should be easy to decide. The first 3 pitches of the screw provide a very similar and high dispersion rate for both types of pellets. However, even though the fiber length of coated pellets decreases, it is still higher than the pultruded fiber length. For this reason, coated pellets should be chosen if the required aspect ratio is 27.

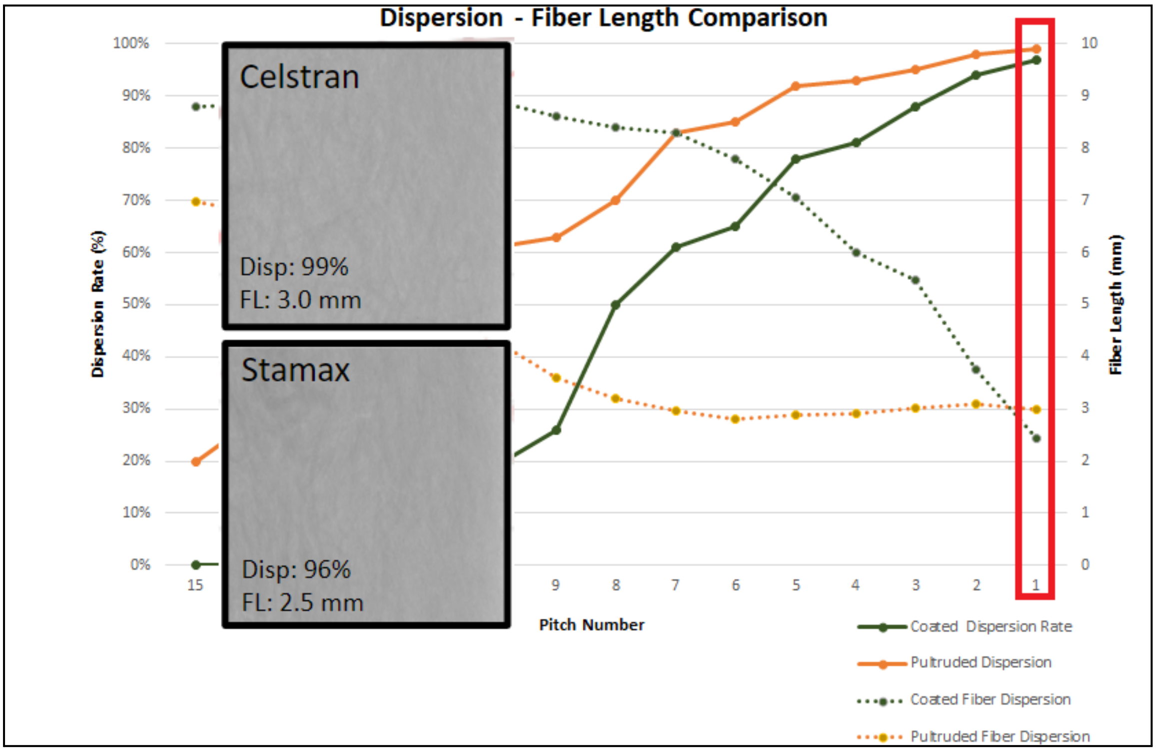
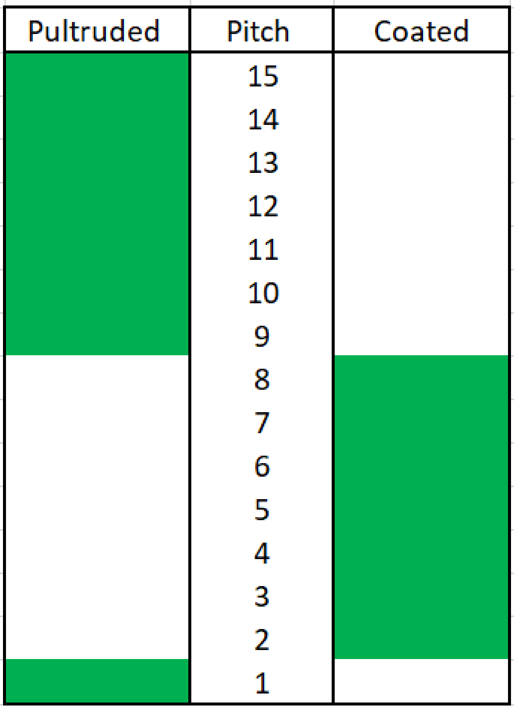


Figure [38] Comparison for a L/D of 30

The first pitch of the screw represents the higher aspect ratio which is 30. Moreover, in this pitch, it is expected to have the highest dispersion rate along the extruder screw. As pictured in Figure [38], the highest dispersion rate values occur at the first pitch. It can be expected therefore that the lowest fiber length is found in the same pitch. Pultruded pellets performed with 3 millimeters fiber length at a 99% fiber dispersion whereas coated ones provided 2.5 millimeters fibers at a 96% dispersion rate. As in the previous three scenarios, coated pellets were the chosen ones due to their fiber length despite having less dispersion. In this scenario, pultruded pellets had a better performance in both variables. Even though coated pellets dispersion is at its closest value to pultruded pellets one, their fiber length is lower. In this case, pultruded manufactured pellets should be the chosen ones for an aspect ratio of 30 because they perform at a higher dispersion and fiber length.

Finally, thanks to the dispersion scan pictures attached to the figures shown above, a clearer view of how fibers are agglomerated is presented. In Figure [35], groups of fibers can be seen by different tones of gray, being the darkest color, the groups of fibers that were not dispersed properly. On the other hand, in Figure [38], the fibers are well dispersed and can be seen by a smooth gray color along the whole scanned area, with no significant difference in the color.

To conclude this analysis it is going to be analyzed the decision-making depending on the pitch from where the part is going to be created. From pitch 15 to 9, the dispersion rate of coated pellets does not make it suitable for use even though its fiber length is at its highest values. Pitch number 8 makes the decision making not as easy. Figure [33] shows that the dispersion rate for coated pellets increases significantly, maintaining at the same time a very high fiber length. However, the dispersion rate for pultruded pellets is higher. What makes the difference in this situation is the 3 millimeters fiber length that pultruded pellets provide since pitch 8. For this reason, the decision-making changes from pultruded pellets to coated ones in the 8th pitch. From this pitch onwards, the decision will be to use coated manufactured pellets as explained in the previous scenarios. Finally, the last scenario showed that pultruded pellets performed better in the first pitch of the extruder screw, making them a better option. Figure [39] shows the best decision to make according to this study.



Pultruded	Pitch	Coated
🟩	15	
🟩	14	
🟩	13	
🟩	12	
🟩	11	
🟩	10	
🟩	9	
	8	🟩
	7	🟩
	6	🟩
	5	🟩
	4	🟩
	3	🟩
	2	🟩
🟩	1	

Figure [39] Decision Diagram

7. Security

Security was a paramount concern throughout the course of this project, particularly due to the nature of working with polymer fibers that could pose risks if they came into contact with the eyes. To mitigate this hazard, strict safety protocols were established and followed diligently. Safety glasses were used at all times while working with the polymer fibers, ensuring the eyes to be shielded from any potential contact or exposure with the fibers.

Furthermore, considering the potential skin irritation caused by the polymer fiber, proactive measures were taken to protect the skin. Lab coats were used at all times providing an additional layer of protection against any direct contact with the fibers. In addition, gloves were worn when working with the polymer fibers, minimizing the risk of skin irritation. The work environment was also well-organized with designated areas for handling the fibers. The room was also isolated from potential wind current ensuring that the fibers will not move in the air and land in our eyes or skin.

When performing the pull-out experiments, the extruder die needed to be extracted from the extruder after being heated. This task has to be made manually. To perform it, heat resistant gloves were used to ensure protection while holding and unscrewing the screws. In the event of an accident or emergency, first aid kits were readily available and easily accessible within the workspace.

Moreover, while cutting the pitches samples with a heated spatula after the extruder pull-out experiment, the heat from the spatula cuts the polymer by melting it. Breathing the gasses emitted from melting polymers can have damaging effects on human health. When polymers are heated to their melting point or beyond, they can release a variety of toxic gasses and volatile organic compounds (VOCs) into the surrounding air. These gasses can pose serious risks if inhaled, especially in environments with poor ventilation or prolonged exposure. One of the primary concerns is the release of hazardous gasses such as formaldehyde, acrolein, and hydrogen cyanide. The first one mentioned is commonly found in polymer fumes and can cause respiratory irritation, allergic reactions, and long-term health issues.

Acrolein is a highly toxic gas that can irritate the respiratory system and cause severe lung damage. Finally, hydrogen cyanide, a poisonous gas, can be released when certain polymers containing nitrogen are heated, and inhalation can lead to rapid breathing, dizziness, and even death in extreme cases. VOCs have been associated with respiratory problems, eye and throat irritation, headaches, and even neurological effects [27].

It is crucial to implement proper safety measures when working with melted polymers to minimize the risk of exposure to these harmful gasses. Adequate ventilation systems should be in place to remove and disperse the fumes effectively. Working in a well-ventilated area or using local exhaust ventilation can significantly reduce the concentration of toxic gasses in the air.

Personal protective equipment should be worn to minimize inhalation risks. Respiratory protection, such as a properly fitted mask or respirator designed for chemical fumes, can offer an additional layer of defense against harmful gasses. It is essential to select PPE that is specifically designed to filter out the particles and gasses generated by the melted polymers.

To conclude, it can be said that by being aware of the damaging effects of breathing the gasses emitted from melted polymers and implementing the necessary safety precautions, individuals can effectively protect their respiratory health and minimize the risks associated with working in such environments.

8. Challenges

During the course of this study, several challenges came up that made this study to offset from its planned path. These obstacles are going to be described in this section.

The majority of the challenges faced occurred during the pull-out experiments. To start with, a lot of screws from the flange broke while rotating the lever. This is because the torque needed to rotate it was very high. This torque was transferred from the screw to the flange, making sometimes the flange to rotate and therefore to shear the screws. Most of the screws broke close to their head. However, during one of the experiments, the failure of the screw occurred below its shank, making it impossible to take it off the threaded hole. The screw was stuck inside the hole and could not be taken with pliers. To fix this problem, a small portable saw was used to create a new drive on thread, so it could be unscrewed with a screwdriver.

Another faced challenge that took place during the last performed pull-out experiment was the breakage of the screw tip. This failure made it impossible to continue doing experiments until a new unit was purchased. The cone attached to the tip of the lead screw had axial and radial bearings. One of the bearings broke due to the strong torque, which caused the thread to disappear. Since there was no thread in the lead screw tip, the screw was not moving inside the extruder even though the lever was being rotated. Hence, if the lead screw can not move inside the extruder, the extruder screw will not be able to be pushed and therefore the samples can not be analyzed.

As explained in Section 4.2, the pitch samples are heated in the oven until they achieve a good deformability level. The oven was heated up to 165°C. However, during one of the fist experiments performed, the oven was set to 170°C, causing the sample to not only be deformable, but melted. This made the samples not useful for this study because the X-ray scanner can not measure the dispersion rate. All the samples of the mentioned experiment were therefore discarded.

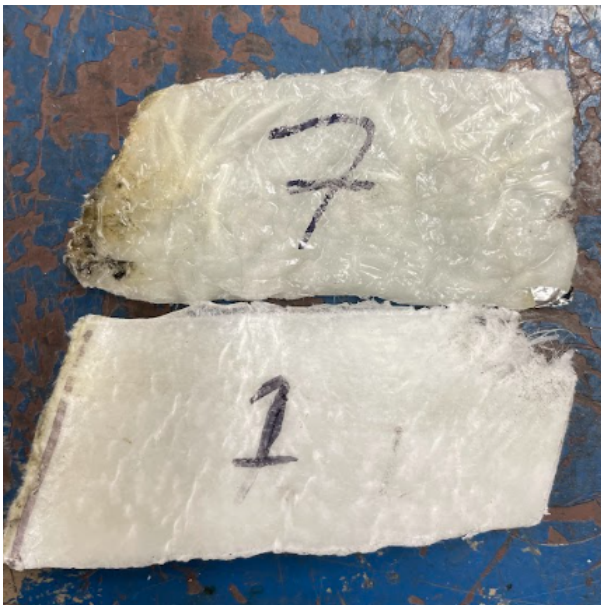


Figure [40] Sample Comparison

As seen in Figure [40] and explained above, the melting temperature was reached in the oven making the pitch sample to melt. The mentioned figure shows a comparison between a melted sample and a sample that was heated up to 165°C. It is clearly seen that sample number 7 melted, making the part wrinkle and change its color to transparent. Sample number 7 can not be scanned because the fiber dispersion rate is not measurable anymore.

9. Summary

In this study, the basics and characteristics of fiber-reinforced thermoplastics were explained, giving to LFTs all the attention throughout this analysis. The two different pellets manufacturing processes subjected to the study were mentioned as well as described the procedure to perform the analysis. Finally, the results were shown, and a conclusion of which manufacturing process is the best option depending on the aspect ratio needed was reached thanks to the creation of a Fiber Length - Fiber Dispersion Rate graph for coated and pultruded pellets.

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[27] Health Concerns of Plastic Fumes

[28] Occupational Safety and Health Administration

11. Appendix 1

11.1 Coated

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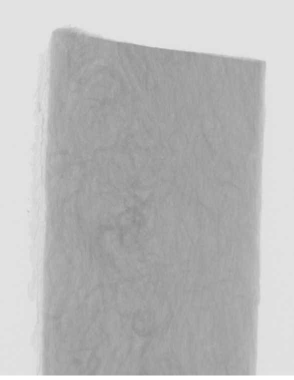
Pitch 2



Pitch 3

Pitch 4

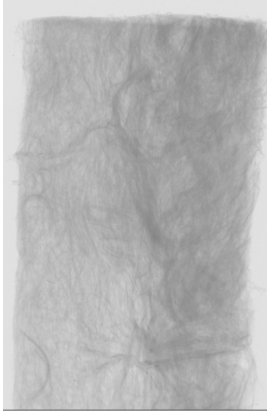
Pitch 5

Pitch 6

Pitch 7

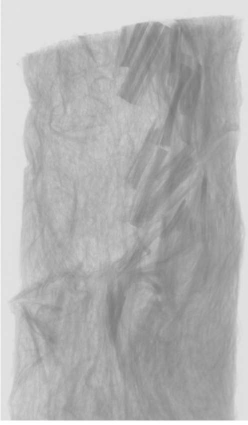
Pitch 8

Pitch 9



Pitch 10

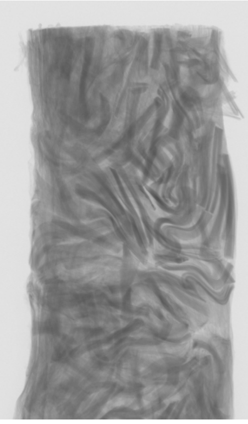
Pitch 11



Pitch 12

Pitch 13

Pitch 14



Pitch 15

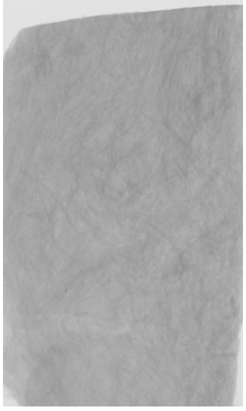
11.2 Pultruded


Pitch 1


Pitch 2


Pitch 3


Pitch 4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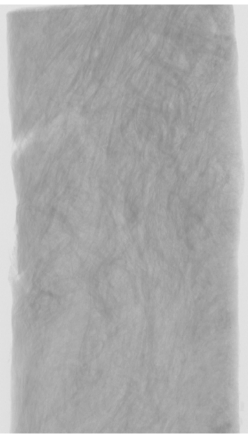
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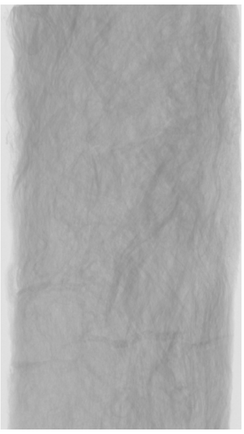
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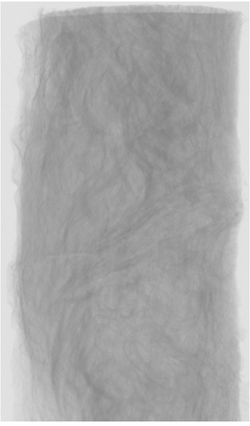
Pitch 8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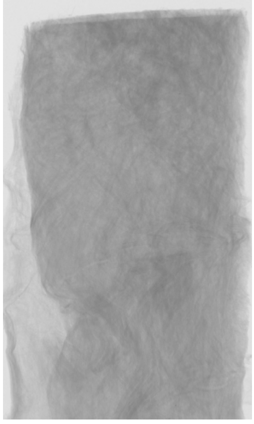
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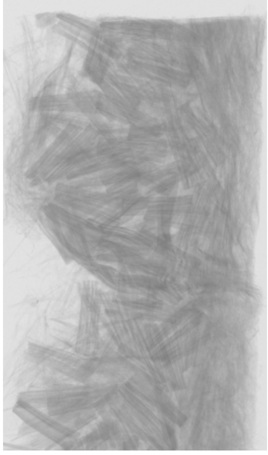
Pitch 11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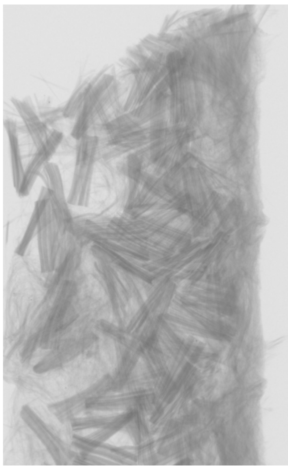
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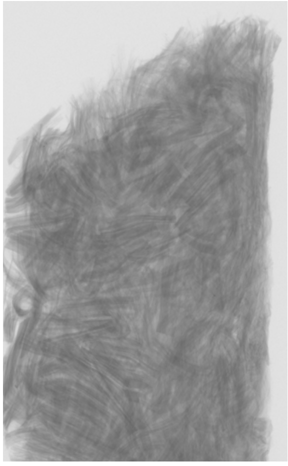
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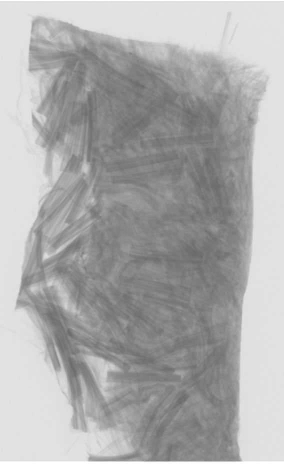
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