WHITE PAPER
FDM

Fatigue Behavior of Select Stratasys FDM Materials

Introduction

FDM® technology users in many industries commonly ask how fatigue-resistant polymer FDM materials are. Because of this, Stratasys has performed a study on ULTEM™ 9085 resin, FDM® Nylon 12CF, and Antero™ 840CN03 to determine their fatigue properties. The samples for these tests were printed by Stratasys on an in-house F900® 3D printer and tested externally by a certified testing facility.

Importance of Fatigue Data

When designing parts for applications that include various dynamic loading and unloading cycles, it is important to understand the fatigue resistance of the material being used. Fatigue resistance is the material's ability to withstand cyclic loading cycles without failure, or more simply, how many times it can withstand the load and unload of a given stress before failing. This material property can be very important for larger assemblies such as an airplane wing or for smaller FDM printed parts like ducting in a fuselage or a bracket in an engine bay where there can be a constant cyclic load applied to the part.

Failure from fatigue stress will occur at a lower level than the strength-at-break threshold and can lead to sudden and unexpected failures. Understanding the fatigue resistance can help determine the material's applications in environments with fluctuating stress and strain. It can also help determine a part's potential life expectancy in these environments. This data typically shows what the long-term life expectancy of the material may be, as well as the point at which a part is expected to fail due to cyclic loading. Knowing a material's fatigue strength will help identify its realistic load capability and help predict the lifespan of the part.

Testing Method

Before testing could start, it was important to have a good understanding of what type of test method must be followed. For this study, ASTM D7791 Procedure A was selected.

ATSM D7791 Procedure A

This standard is used to find the uniaxial fatigue properties of rigid and semi-rigid plastics and was chosen because there is no current fatigue testing standard specifically for polymer additive manufacturing. Additionally, this standard is popular with industries such as aerospace and rail when evaluating the fatigue properties of polymer parts.

Procedure A was chosen because it focuses on testing samples in tension rather than compression which was found to be more common in similar literature. This procedure calls for a specimen with a circular or rectangular cross section, like one would see with ASTM D638 test coupons, which is loaded in a cyclic manner until failure. Because ASTM D7791 calls out a testing specimen with the dimensions, shape, surface conditions, and limitations of an ASTM D638 specimen, the ASTM D638 Type I tensile bar was selected for fatigue testing. This type of specimen was also used to collect the mechanical data available on the material data sheet, discussed later in the paper.

When following Procedure A, the sample is tested by first pulling the part in tension with a very low force. This is the starting point of the test and considered the minimum stress for the cyclic load. After the low stress is applied, the tensile force is increased until it has reached a given percentage, or stress level, of the strength-at-break of the material. This larger stress is considered the maximum stress for the cyclic load. The cyclic load is then applied to the part by fluctuating between the minimum and maximum stress levels while counting the number of cycles. When the sample begins to yield or suffers from failure due to rupture, the test is stopped, and the number of cycles is recorded.

After test completion, the fatigue strength of the material is displayed in an S-N curve by showing the stress (S) and the number of cycles the material lasted (N) on a graph. This graph uses a logarithmic scale on the X axis and provides an accurate assumption of the number of cycles a material can last at a given load.

Testing

After selecting the proper testing method, additional actions included completing the pre-test planning, finalizing the material selection, and determining the stress level for each material.

Pre-Test Planning

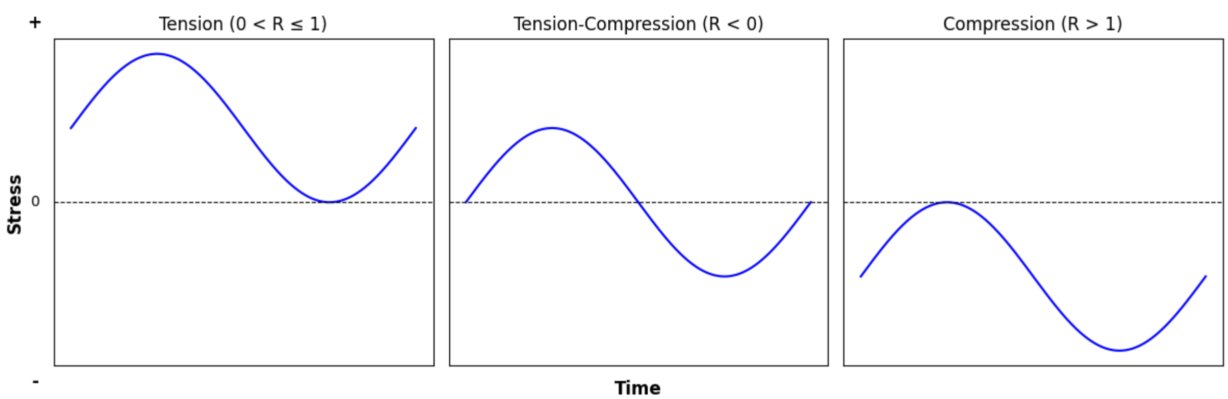
Prior to testing per ASTM D7791 it was important to understand the testing conditions required to achieve realistic results. These conditions include the stress ratio (R-ratio), frequency, and max cycle count.

R-Ratio

The R-ratio compares the minimum stress to the maximum stress and helps define the relationship between the tensile and compressive stresses during cyclic loading. Typically, there are three loading scenarios:

- Tension-to-tension: $0 < R \leq 1$, where both the maximum and minimum stresses are tensile, with the minimum stress being a fraction of the maximum stress.
- Tension-to-compression: $R < 0$, where the maximum stress is tensile, and the minimum stress is compressive.
- Compression-to-compression: $R > 1$, where both the maximum and minimum stresses are compressive, with the minimum stress being more negative than the maximum stress (i.e., larger in magnitude).

An R-ratio of 0.1 was selected for this fatigue testing. This means the loading will be in tension with the minimum stress being 10% of the maximum stress. These tests follow ASTM D7791, Procedure A, and are designed to closely represent a component that is cyclically loaded and unloaded in use.



Frequency

The test frequency determines the speed of the loading/unloading cycle. Assigning the correct frequency is especially important with polymers because an excessively high frequency can result in thermal buildup within the specimen causing inaccuracies in the data due to material softening or melting. Additionally, a frequency that is too low can cause overly long test time.

A frequency of 5 Hz was chosen for all materials because it is slow enough to avoid softening due to thermal buildup but quick enough to avoid excessive test time. This value also falls within the recommended frequency range called out by ASTM D7791.

Cycle Count

Before testing it is important to know the max cycle count. Choosing a cycle count that is too low can result in insufficient data, and choosing one that is too high may result in unnecessarily long tests. This study has a max cycle count of 1,000,000 cycles, sufficient to properly evaluate the material's performance while ensuring a reasonable test time.

Material Selection

Three materials were selected for fatigue-resistance testing. These include Nylon 12CF, ULTEM™ 9085 resin, and Antero 840CN03. They were selected because they are commonly used in industries with requirements for material fatigue properties such as aerospace, automotive, and rail.

ULTEM™ 9085 Resin

ULTEM™ 9085 resin is a high-performance polyetherimide (PEI) thermoplastic displaying excellent mechanical properties. It also has very good flame, smoke, and toxicity (FST) characteristics, making it suitable for use in the aerospace and rail industries. This strong and lightweight FDM material is extremely versatile and is seen in many applications through various industries.

FDM Nylon 12CF

Nylon 12CF is a polyamide (PA) 12 that has been reinforced with 35% chopped carbon fiber by weight. The addition of carbon fiber imparts exceptional flexural strength properties giving it a very high stiffness-to-weight ratio while maintaining the toughness seen in an unfilled nylon with no added fibers.

Antero 840CN03

Antero 840CN03 is a polyetherketoneketone (PEKK) based thermoplastic filled with 3% carbon nano tubes (CNT) by weight. The CNTs give the material electrostatic discharge (ESD) properties. It has excellent mechanical properties while also displaying high heat and wear resistance. Additionally, this material demonstrates strong chemical resistance with minimal off-gassing. It is often seen in industry as a lightweight replacement for aluminum and steel parts. These attributes along with the ESD properties make it a very popular material for industries like aerospace.

Stress Level

Stress level is the most important test parameter to be decided on. It indicates the amount of stress applied to the part during testing and is a percentage of the material's strength at break.

Strength at Break

Determining the tensile strength at break is critical when evaluating the fatigue properties of a material. The strength at break is the amount of tensile stress that must be applied to a part before it breaks. This value is typically found when testing a material in tension following the ASTM D638 standard. For this study, the strength at break was the value displayed on the Material Data Sheet (MDS) for the given material.

Stress Level Selection

Each material had custom stress levels selected for testing to ensure the most representative S-N curve possible. Because each material will exhibit different responses to different stress levels, it is important to ensure that the level selected is not too high or too low. For example, with Nylon 12CF printed in XZ, there would be no difference in performance in a stress level of 20% and 40% for fatigue testing. Both stress levels will show that the material was able to reach 1,000,000 cycles. This overlap could lead to an S-N curve that does not effectively capture or display the material's fatigue response. Therefore, instead of following a fixed stress level percentage such as 20%, 40%, 60%, 80%, Nylon 12CF was assigned a specific set of stress levels to accurately reflect its performance characteristics to promote a clear and accurate analysis. This same method was followed for ULTEM™ 9085 resin and Antero 840CN03 to help create the most representative S-N curves.

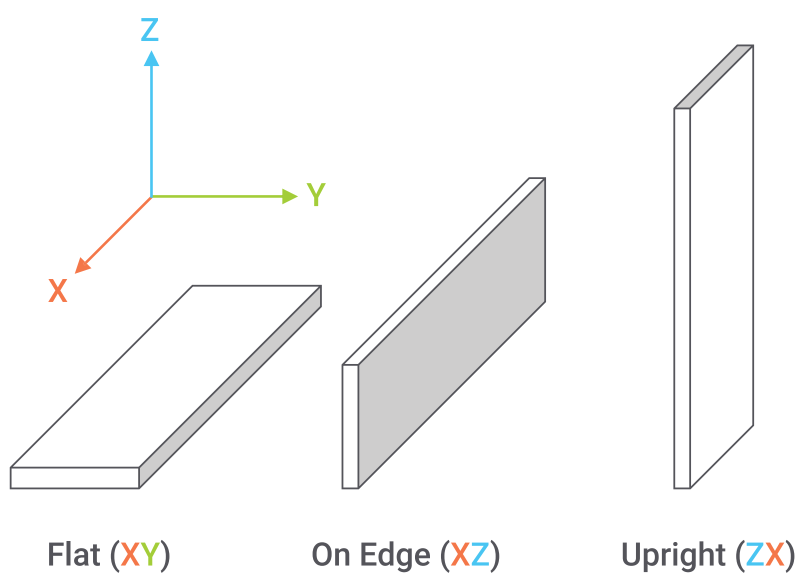
Printing and Sample Selection

All printing was performed on three different in-house F900 machines with each machine printing all three materials. Antero 840CN03 used a T20F tip with a 0.254 mm (0.010 in.) layer height, ULTEM™ 9085 resin used a T16 tip with a 0.254 mm (0.010 in.) layer height, and Nylon 12CF used a T20C tip with a 0.254 mm (0.010 in.) layer height. Each build had ten ASTM D638 Type I tensile bar coupons with a purge tower to reduce any instances of stringing, blobbing, or voids, which ensured the best possible print quality. Type I tensile bars were used because they have a uniform rectangular cross-sectional area and follow the ASTM D638 test method design per ASTM D7791 requirements. All samples were prepared following the testing procedure highlighted in the "Stratasys Materials Test Procedure" white paper. This was done to ensure the mechanical performance of the parts printed to test fatigue properties align with the performance outlined in the respective material data sheets.

Because of the anisotropic mechanical properties of FDM printed parts, two orientations were printed. The first was On Edge (XZ) and the other orientation was Upright (ZX). These orientations can be seen in the picture below displaying the different printing orientations. Printing in both orientations highlighted the highest and lowest fatigue performance expected, with XZ showing the highest and ZX showing the lowest. In total, 30 specimens were printed for each material in packs of 10 across three different F900 printers in both the XZ and ZX orientations. Of those 30 specimens, a total of 12 specimens were tested with four randomly selected from each build. From these 12 specimens, three were again randomly selected for each stress level. This allowed three specimens in each orientation to be tested at all four stress levels. Once printed, each sample was conditioned at standard laboratory conditions of 73 ± 4 °F (23 ± 2 °C) and 50 ± 5% relative humidity for at least 40 hours prior to testing. While testing, if the tester felt a specimen failed due to a reason outside of the scope of testing, such as improper loading of the specimen or the environmental conditions of the testing lab fell out of spec, another coupon was randomly chosen to take its place and marked with a number and a letter (e.g., 1b).

Print Orientation

Parts created using FDM are anisotropic as a result of the printing process. Below is a reference of the different orientations used to characterize the material.



Results

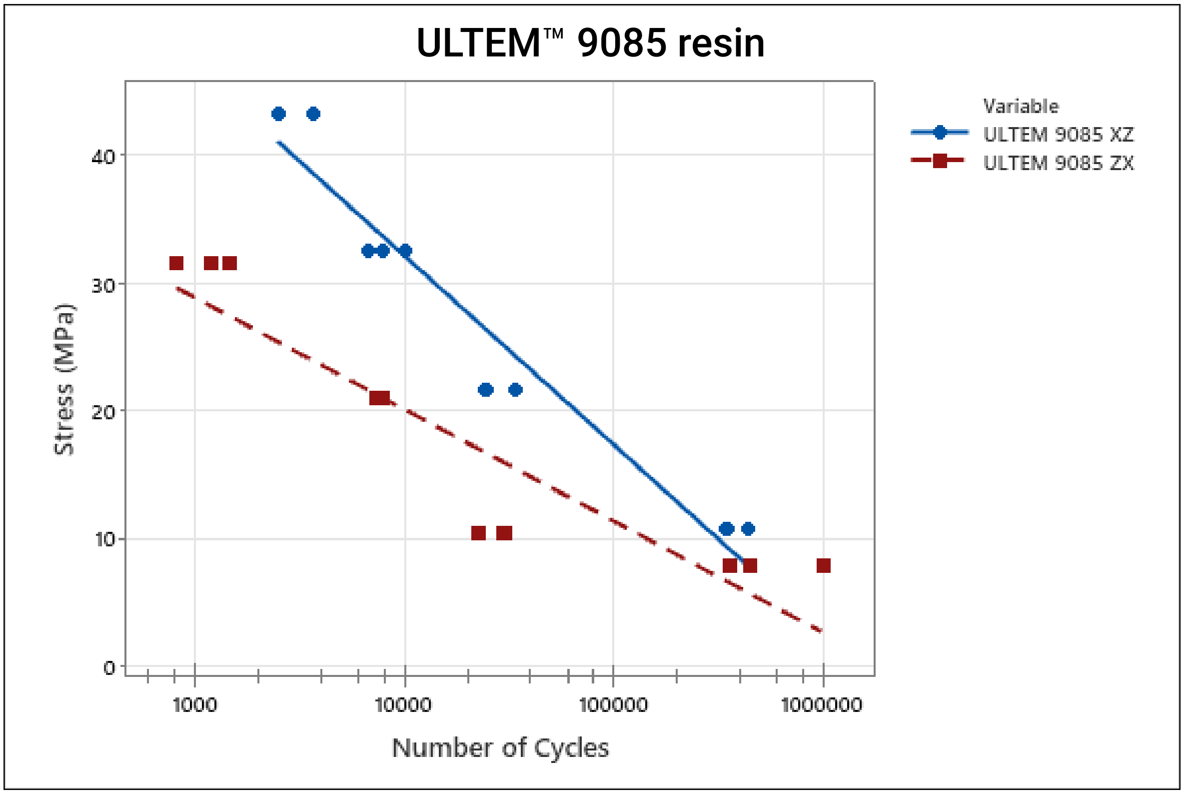
Results for all three materials can be seen in the following tables and graphs. The tables show the stress level, minimum stress, maximum stress, specimen, cycle count reached, and average cycle count for all coupons tested at the given stress level. Each material shows a graph with an S-N curve presented in two ways. The first graph shows the stress vs. number of cycles for both the XZ and ZX orientations combined to show how each orientation compares. Next, a graph for each orientation is presented showing the percentage of ultimate tensile strength, or the strength-at-break, vs. the number of cycles. From the results, one can see that all materials have their own unique fatigue properties that make them suitable for their respective applications.

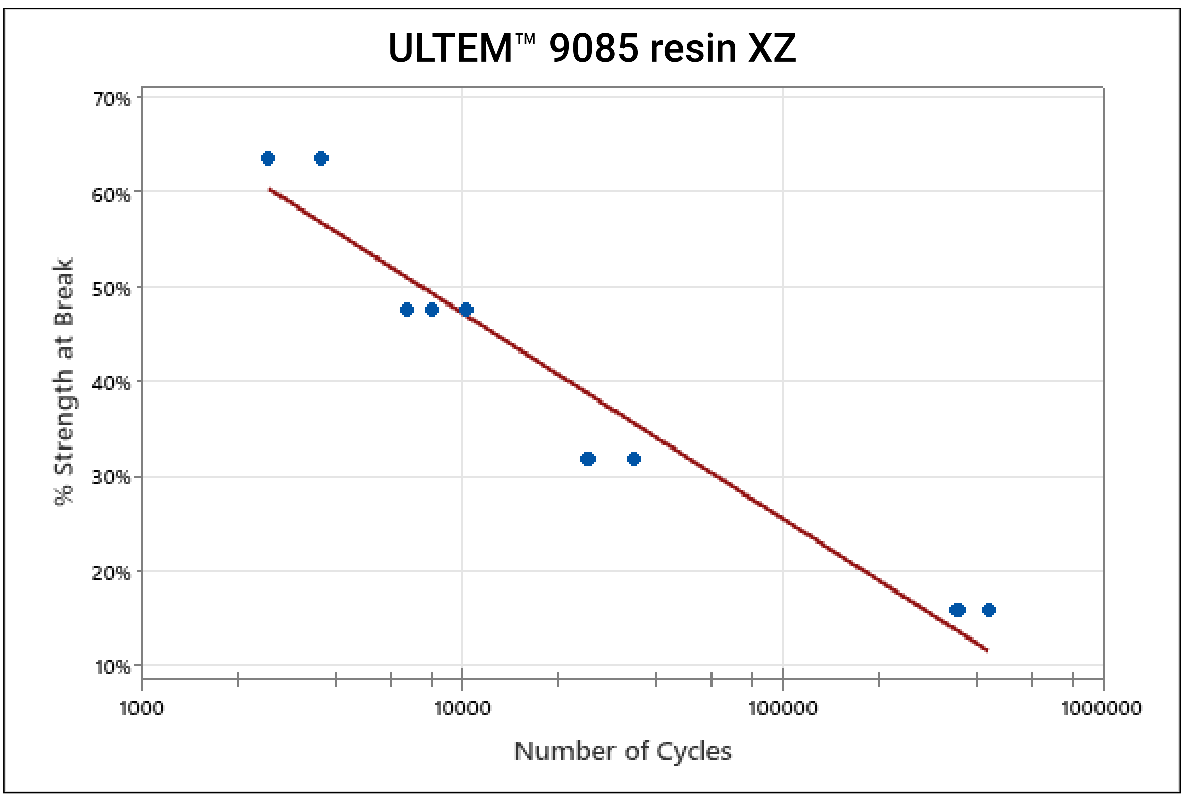
ULTEM™ 9085 Resin

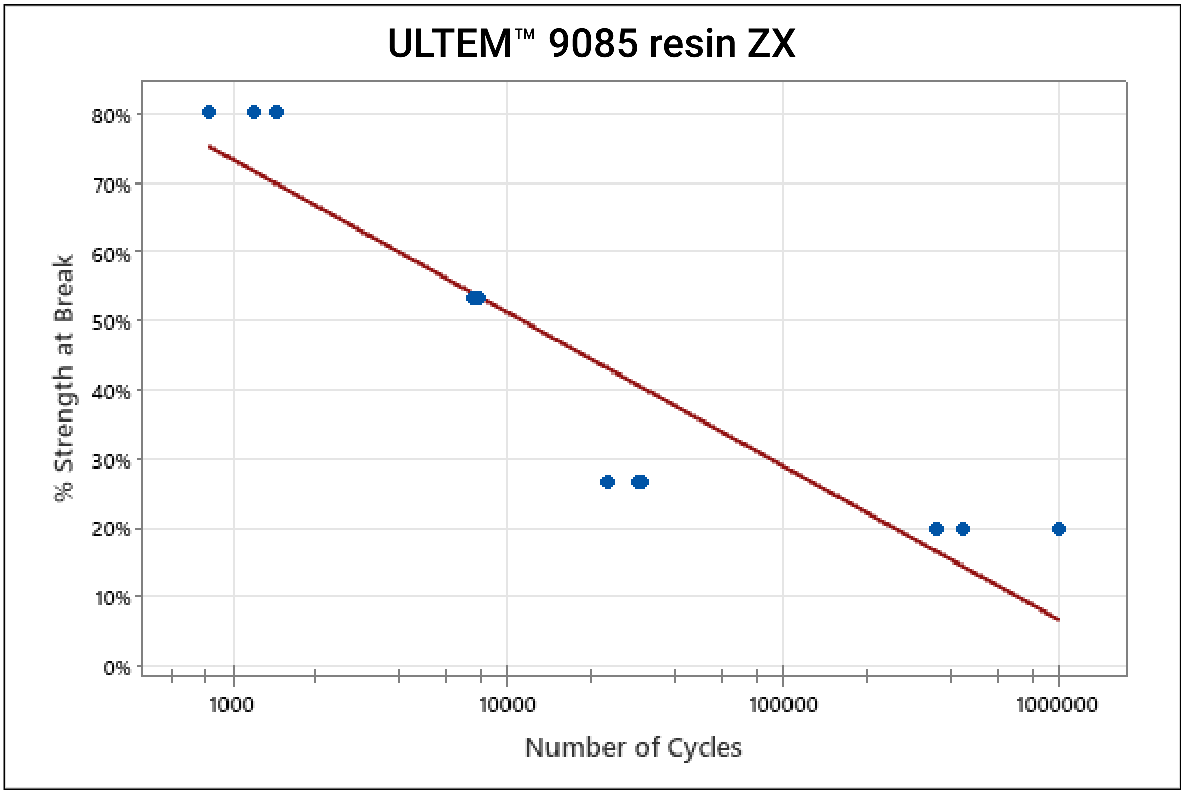
ULTEM™ 9085 resin samples in XZ and ZX were conditioned and tested at four different stress levels. Below are the tables for each orientation and the S-N curve generated from the data set.

ULTEM™ 9085 resin XZ					
Stress Level	Min Stress MPa (psi)	Max Stress MPa (psi)	Specimen	Cycle Count	Average Cycle Count
16%	1.082 (157)	10.82 (1570)	1	343,898	376,448
			2	351,385	
			3	434,062	
32%	2.165 (314)	21.65 (3140)	1	24,737	27,728
			2	34,107	
			3	24,339	
48%	3.247 (471)	32.47 (4710)	1	7,922	8,272
			2	10,165	
			3	6,728	
64%	4.330 (628)	43.30 (6280)	1	3,625	2,867
			2	2,479	
			3	2,497	

ULTEM™ 9085 resin ZX					
Stress Level	Min Stress MPa (psi)	Max Stress MPa (psi)	Specimen	Cycle Count	Average Cycle Count
20%	0.7874 (114.2)	7.874 (1142)	1a	355,695	601,232
			4	1,000,000	
			5	448,000	
27%	1.052 (152.6)	10.52 (1526)	1	29,601	82,685
			2b	30,340	
			3	22,744	
53%	2.104 (305.2)	21.04 (3052)	1	7,362	7,567
			2	7,823	
			3	7,517	
80%	3.156 (457.8)	31.56 (4578)	1	1,183	1,148
			2	1,444	
			3	816	


ULTEM™ 9085 resin
Variable
ULTEM 9085 XZ
ULTEM 9085 ZX
Stress (MPa)
0
10
20
30
40
1000
10000
100000
1000000
Number of Cycles


ULTEM™ 9085 resin XZ
% Strength at Break
10%
20%
30%
40%
50%
60%
70%
1000
10000
100000
1000000
Number of Cycles

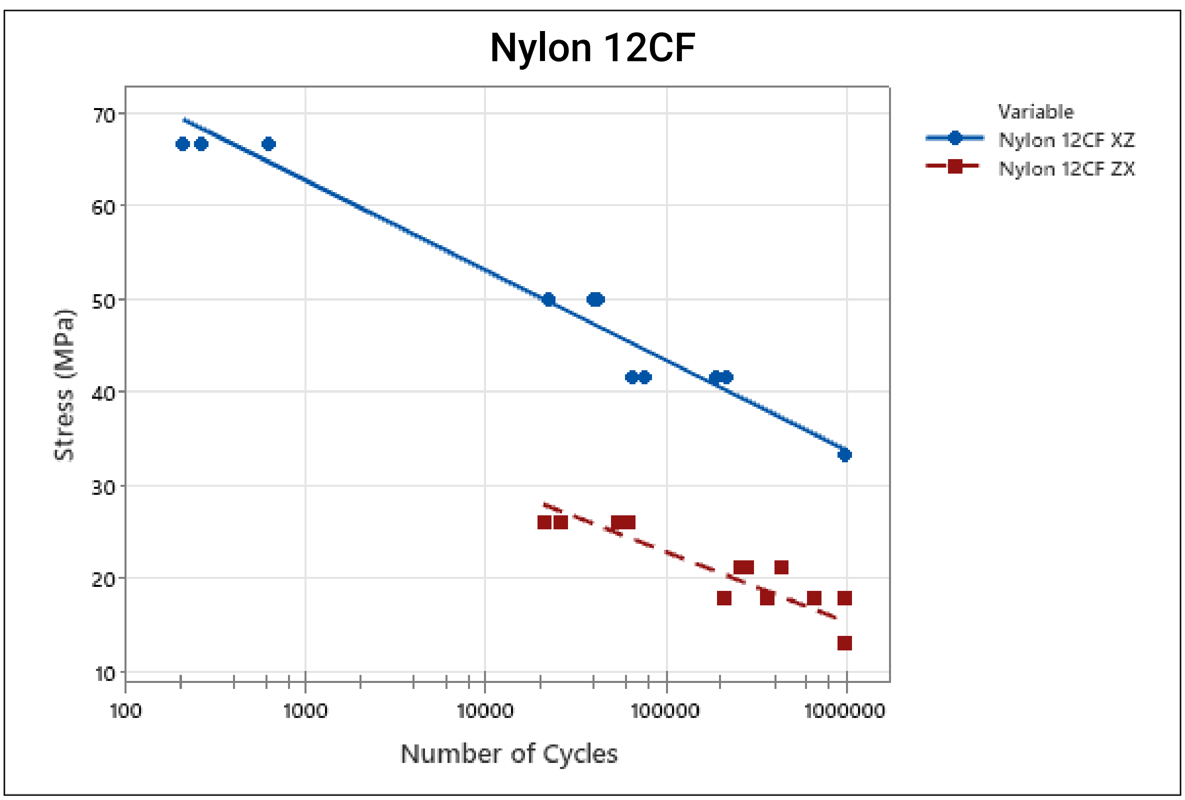


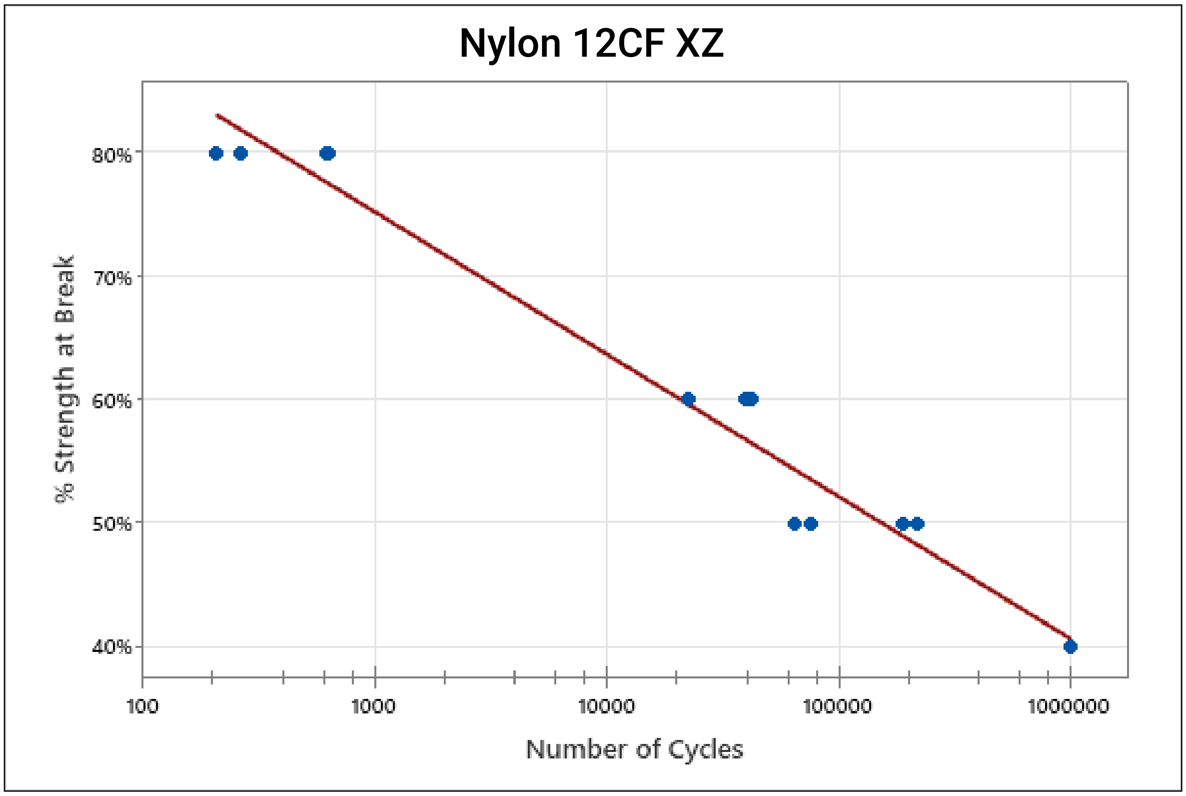
Nylon 12CF

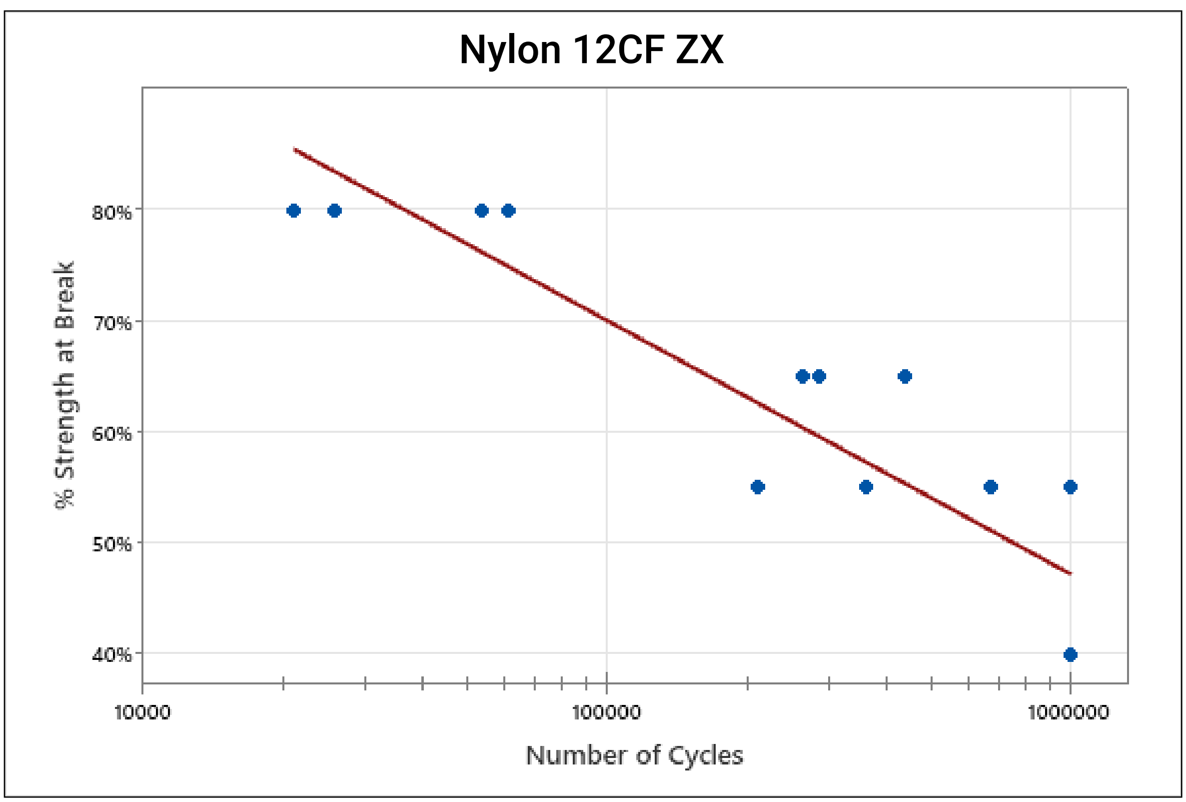
Nylon 12CF samples in XZ and ZX were conditioned and tested at four different stress levels. Below are the tables for each orientation and the S-N curve generated from the data set. Both the 50% and 80% stress levels had four specimens tested instead of three. This still satisfies the ASTM D7791 standard where it states at least three samples must be tested per stress level, but it is acceptable to test more than three.

Nylon 12CF XZ					
Stress Level	Min Stress MPa (psi)	Max Stress MPa (psi)	Specimen	Cycle Count	Average Cycle Count
40%	3.337 (484)	33.37 (4840)	1	1,000,000	1,000,000
			2	1,000,000	
			3	1,000,000	
50%	4.171 (605)	41.71 (6050)	1	188,135	135,769
			2	215,324	
			3	75,324	
			3b	64,293	
60%	5.006 (726)	50.06 (7260)	1	39,406	34,455
			2	41,797	
			3	22,163	
80%	6.674 (968)	66.74 (9680)	1	262	427
			2	616	
			3	622	
			1b	206	

Nylon 12CF ZX					
Stress Level	Min Stress MPa (psi)	Max Stress MPa (psi)	Specimen	Cycle Count	Average Cycle Count
40%	1.31 (190)	13.1 (1900)	1	1,000,000	1,000,000
			2	1,000,000	
			3	1,000,000	
55%	1.801 (261.25)	18.01 (2612.5)	2	211,055	561,546
			3	1,000,000	
			1b	672,352	
			2b	362,776	
65%	2.129 (308.75)	21.29 (3087.5)	1	440,110	329,854
			2	285,492	
			3	263,959	
80%	2.62 (380)	26.2 (3800)	1	25,929	40,479
			2	61,136	
			3	21,036	
			3b	53,816	




Nylon 12CF XZ
% Strength at Break
80%
70%
60%
50%
40%
100
1000
10000
100000
1000000
Number of Cycles

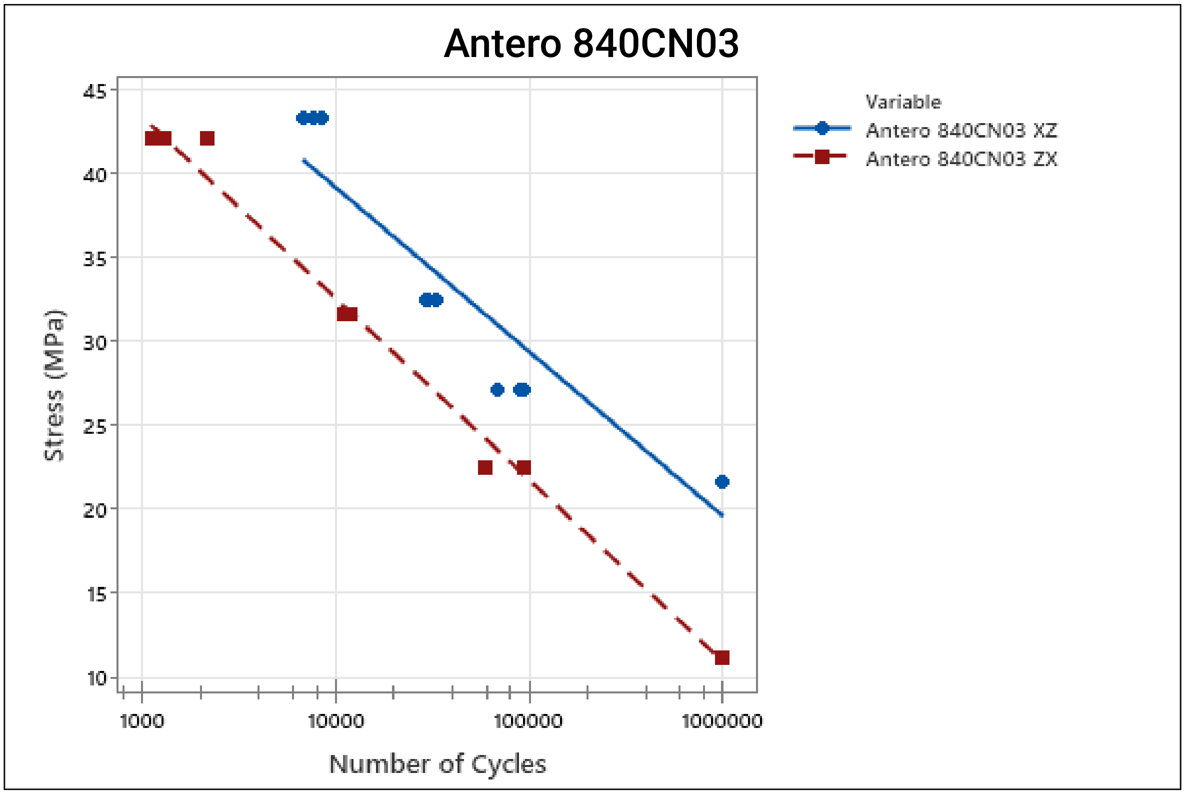

Nylon 12CF ZX
% Strength at Break
80%
70%
60%
50%
40%
10000
100000
1000000
Number of Cycles

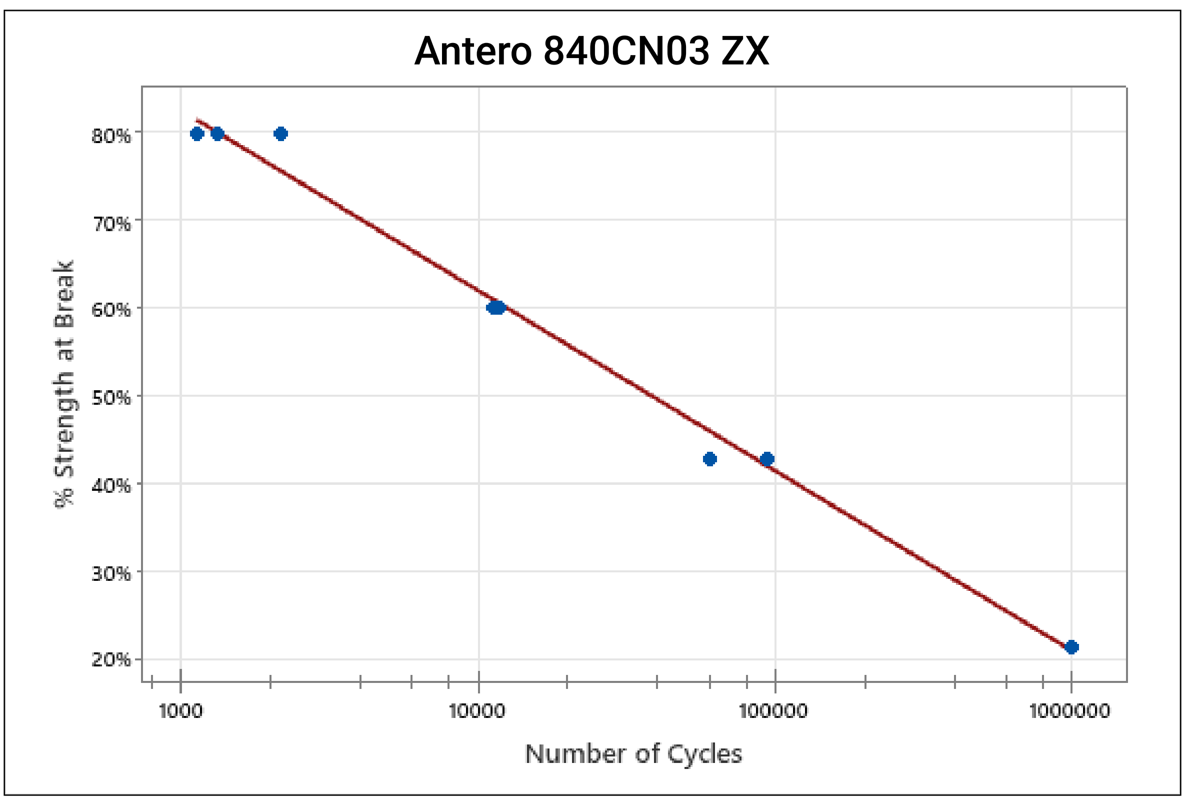
Antero 840CN03

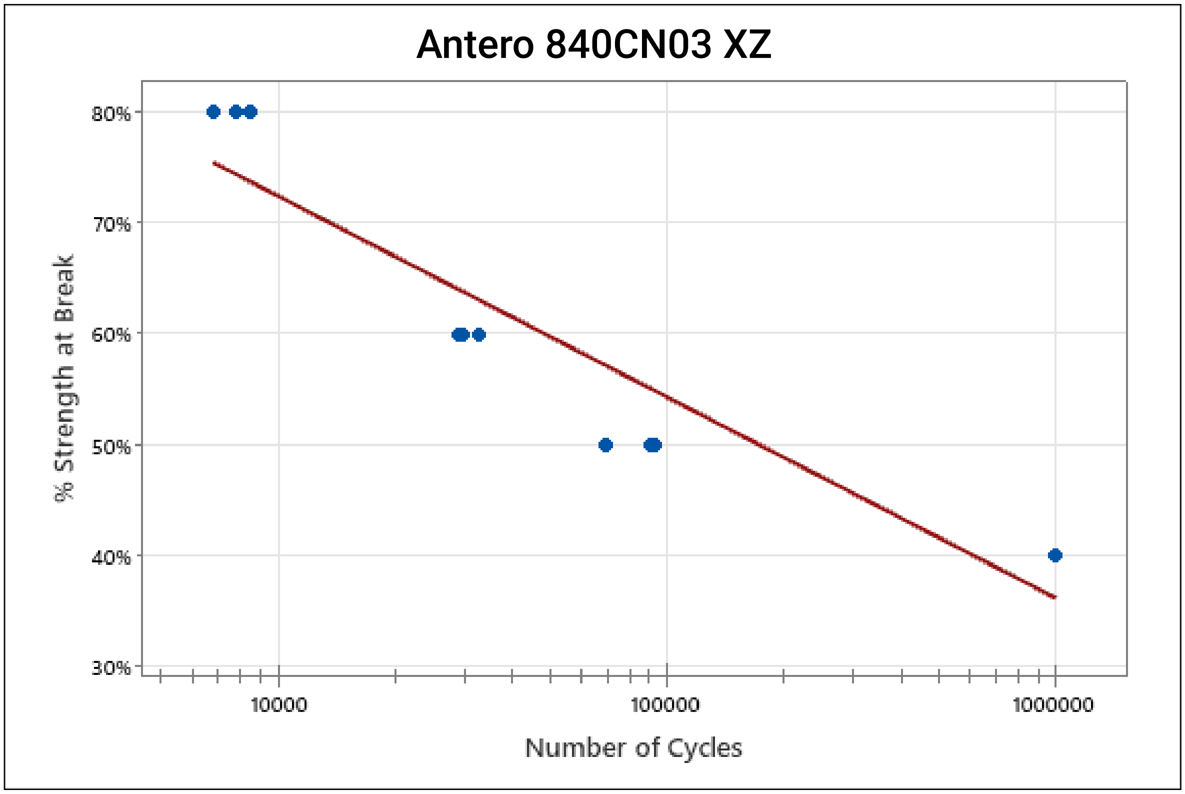
Antero 840CN03 samples in XZ and ZX were conditioned and tested at four different stress levels. Below are the tables for each orientation and the S-N curve generated from the data set.

Antero 840CN03 XZ					
Stress Level	Min Stress MPa (psi)	Max Stress MPa (psi)	Specimen	Cycle Count	Average Cycle Count
40%	2.165 (314)	21.65 (3140)	1 2 3	1,000,000 1,000,000 1,000,000	1,000,000
50%	2.706 (392.5)	27.06 (3925)	1 2 3	93,145 90,488 69,352	84,328
60%	3.247 (471)	32.47 (4710)	1 2 3	32,736 29,099 29,741	30,525
80%	4.330 (628)	43.30 (6280)	1 2	6,768 8,449 7,805	7,674

Antero 840CN03 ZX					
Stress Level	Min Stress MPa (psi)	Max Stress MPa (psi)	Specimen	Cycle Count	Average Cycle Count
21%	1.125 (163.2)	12.25 (1632)	1 2 3	1,000,000 1,000,000 1,000,000	1,000,000
43%	2.250 (326.4)	22.50 (3264)	1c 2 3	59,916 93,130 93,802	82,283
60%	3.156 (457.8)	31.56 (4578)	1 2 3	11,864 11,601 11,189	11,551
80%	4.209 (610.4)	42.09 (6104)	1 2 3b	1,328 1,123 2,176	4,627

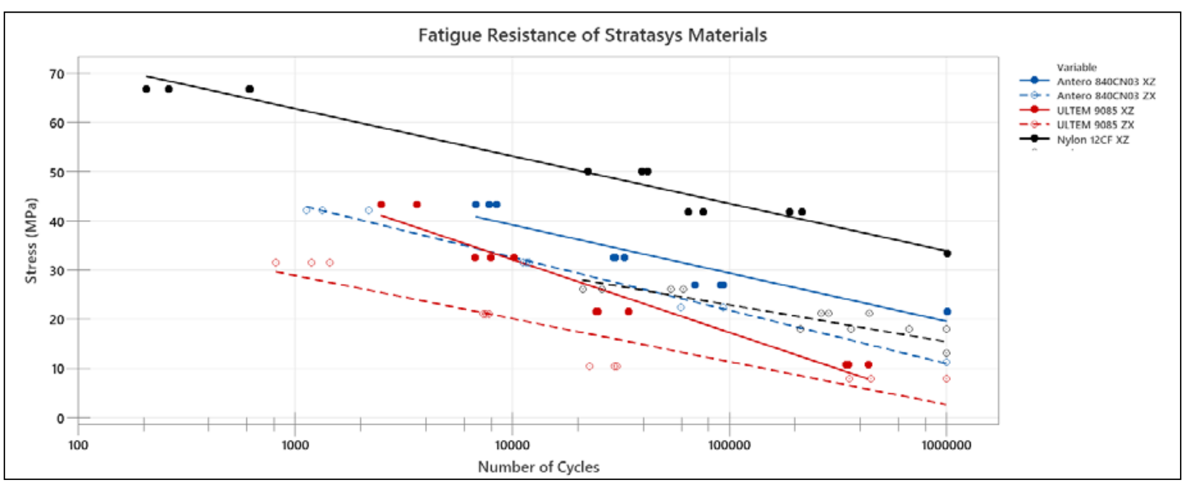

Antero 840CN03
Stress (MPa)
45
40
35
30
25
20
15
10
1000
10000
100000
1000000
Number of Cycles
Variable
Antero 840CN03 XZ
Antero 840CN03 ZX


Antero 840CN03 ZX
% Strength at Break
80%
70%
60%
50%
40%
30%
20%
1000
10000
100000
1000000
Number of Cycles



Combined Results

Finally, a table displaying all fatigue data from all materials was generated to display the fatigue properties across all materials.



Discussion

As seen in the results of the S-N curves and data tables, there is a difference in fatigue resistance for each material. The data collected can help show where these materials can be used and how parts can be designed to get the best out of their unique material properties paired with their fatigue resistance.

ULTEM™ 9085 resin

The results for ULTEM™ 9085 resin are similar to those seen in similar literature testing its fatigue performance. The XZ direction showed that a stress level of 16%, or 10.82 MPa (1,570 psi), reached an average cycle count of 376,448 cycles before failure. This showed that at a low stress ULTEM™ 9085 resin was still able to withstand many cycles. Additionally, at increasing applied stresses of 21.65 MPa (3,140 psi), 32.47 MPa (4,710 psi), and 43.3 MPa (6,280 psi), all showed large cycle counts.

The ZX direction showed similar results with slightly lower stress applied to the material at each testing percentage. At the 20% stress level, or 7.87 MPa (1,142 psi), this orientation had one run hit the 1,000,000 cycle runout while the other two samples had less than half of that. The potential reason for this is discussed later in this paper, but this could be due to print defects that caused the overall strength of the part to be less than what it should be for the two samples that broke early. Other stress levels still showed great fatigue resistance with an applied stress of 10.52 MPa (1,526 psi) reaching an average of 82,685 cycles, an applied stress of 21.04 MPa (3,052 psi) reaching 7,567 cycles, and an applied stress of 31.56 MPa (4,578 psi) reaching an average of 1,148 cycles.

From the fatigue resistance results, one can see that ULTEM™ 9085 resin shows good fatigue resistance in both the XZ and ZX directions. This makes ULTEM™ 9085 resin an excellent choice for applications within aerospace or automotive where parts are cyclically loaded in areas such as engine bays, internal cabins, or ducting. Additionally, pairing the FST and chemical resistance properties of this material with the fatigue resistance makes it stand out compared to other materials. If potential applications involve situations where there is low stress with high cycle counts of 10,000 or more, ULTEM™ 9085 resin could be an excellent fit.

Nylon 12CF

The fatigue data for Nylon 12CF showed that the overall fatigue resistance of the material is strong in both the XZ and ZX directions. As expected, the XZ orientation can withstand larger stresses during cyclic loading. However, the ZX direction shows the ability to have larger cycle counts at a higher stress level relative to the strength at break.

Nylon 12CF was able to reach 1,000,000 cycles in both the XZ and ZX direction when applying a stress level of 40% of the strength at break for the given orientations. This indicates that in the XZ direction, a constant stress of up to 33.37 MPa (4,840 psi) can be applied cyclically without causing part failure for at least 1,000,000 cycles. In the ZX direction, this number is reduced to 13.1 MPa (1,900 psi).

For higher loading percentages, the ZX direction showed an impressive average of 40,479 cycles when loaded at 80% of the strength at break, or 26.2 MPa (3800 psi). The strong fatigue resistance of this material could be due in part to the high carbon fiber loading percentage. The small fibers along with the natural toughness of nylon may help reduce the number and severity of crack propagations during the test, leading to longer cycle counts. For the XZ direction at a 50% stress level, or 41.71 MPa (6,050 psi), the average cycle count was 135,769. At a 60% stress level, or 50.06 MPa (7,260 psi), the cycle count was 34,455. Finally, at an 80% stress level, or 66.74 MPa (9,680 psi), cycle count was 427. This shows that the fatigue resistance in this direction is still good and can withstand larger cyclic forces, but that it does not have the same ability to withstand as many cycles at high loading percentages as it does in the ZX direction.

When comparing the results of Nylon 12CF to the other materials tested, it shows that it has comparable or even favorable fatigue properties due to its ability to withstand very high cycle counts. This shows that if the printed part is subject to moderate to high stress levels and needs to withstand higher cycle counts, Nylon 12CF would be the optimal choice for the application. One particularly beneficial application could be unmanned aerial vehicles (UAVs), where a tough, strong, and lightweight material is needed, but stringent requirements for chemical resistance or flammability, smoke, and toxicity (FST) are not a top concern. Additionally, it shows that it would be a suitable material for other industries such as automotive where a printed part on a vehicle may not experience the highest stress levels but has constant cyclic loading during the movement of the automobile and therefore a printed part will need to be able to withstand moderate loads with very high cycle counts.

Antero 840CN03

Like Nylon 12CF, Antero 840CN03 showed strong fatigue resistance in both the XZ and ZX directions. With larger stress levels, Antero 840CN03 was still able to withstand larger cycle counts, showing the strong fatigue resistance of the material. One factor that may help this material is the 3% carbon nano tube loading by weight. The carbon nano tubes may help reduce the number of crack propagations and the speed at which they form, which would lead to increased fatigue resistance.

In the XZ direction, the runout limit of 1,000,000 cycles was reached with a stress level of 40%, or 21.65 MPa (3,140 psi). This shows that at almost half of its strength at break, it can withstand large cycle counts. When a large stress level of 80%, or 43.3 MPa (6,280 psi), was applied, Antero 840CN03 was still able to last an average of 7,674 cycles.

In the ZX direction, a stress level of 21%, or 11.25 MPa (1,632 psi), achieved the cycle runout of 1,000,000 cycles. This loading percentage was lower than what was seen in the XZ direction, but it still shows that this material will operate well with low-force cyclic loads in the ZX direction. As the stress level increased, the typical drop in cycle count followed, with an average cycle count of 82,283 at 43%, or 22.5 MPa (3,264 psi), 11,551 at 60%, or 31.56 MPa (4,578 psi), and 4,627 at 80%, or 42.1 MPa (6,104 psi).

The results from this study show that Antero 840CN03 displays strong fatigue resistance properties in both the XZ and ZX direction. Pairing this with the naturally strong chemical resistance, low off-gassing, and ESD properties achieved from the added carbon nano tubes makes Antero 840CN03 an excellent choice for many aerospace and defense applications. For applications where the stress on the part is high and the cycle count must be large, Antero 840CN03 is a great fit. This is especially true for applications where strong FST or ESD properties are required.

Potential Causes of Error

Additive manufacturing, including FDM, tends to create small voids or pockets within the part during the printing process. For FDM, this is caused by the raster incompletely filling the space from one bead to another. The result of this unfilled space leads to internal voids within the part and each collective layer printed on top of one another introduces more voids throughout the part. During testing, these voids could be areas of stress concentrations that can lead to small cracks. As testing progresses, these cracks can start to grow until they reach a critical size and cause failure. To mitigate these cracks, ensuring the proper printing conditions and material conditions is very important.

Another error source involves the material cooling rate during printing. Insufficient or excessive cooling from machine pauses during auto changeovers or poor part location in the oven can influence the part's crystallinity while printing. Crystallinity differences create areas of poorer layer adhesion where crystallinity is greater. These areas can be a weak point and lead to quicker failure during testing.

One final potential cause of error is the inclusion of micro particles. These particles act like voids and lead to localized stress concentrations that may promote crack growth, causing premature failure. This type of issue can be avoided by ensuring the printer oven is cleaned regularly to avoid any dust or other small particulates that may become airborne and embedded in the part during printing. Additionally, ensuring that the printer tip is within its service life is recommended to avoid the chance of degraded material or any other type of FOD being embedded in the part.

Environmental Conditions

One last consideration regarding material fatigue properties is the exposure to environmental conditions. Excessively high or low temperature, chemical exposure, or UV exposure have the potential to change the material's fatigue resistance. This study only conducted fatigue testing in lab environments, so it is important to consider the potential issues that may arise with other environmental conditions.

Conclusion

This study evaluated the fatigue properties of ULTEM™ 9085 resin, FDM Nylon 12CF, and Antero 840CN03, FDM materials that enjoy widespread use in the aerospace, automotive, and defense industries. The data shows that all three materials have fatigue properties similar to what was seen in literature performed with similar high performance FDM materials. The fatigue data presented in this study can help determine the expected lifespan and applicable stresses to parts made with these materials.

ULTEM™ 9085 resin showed good overall fatigue performance in both the XZ and ZX orientations. This fatigue performance combined with the material's other beneficial properties, such as FST and chemical resistance, makes ULTEM™ 9085 resin a very good choice for fatigue-prone applications.

Nylon 12CF also showed impressive fatigue performance in both the XZ and ZX orientations. Its ability to withstand high cycle counts at 80% of its strength at break in the ZX direction was especially impressive. In the XZ direction, it was still able to reach high cycle counts with larger loading percentages and was the best performer among all materials tested. The fatigue performance of Nylon 12CF along with its toughness makes it an excellent choice for various applications in automotive and tooling. Additionally, this material would work well for unmanned aerospace or defense applications such as UAVs.

Antero 840CN03 also showed very impressive fatigue properties similar to Nylon 12CF. In the XZ direction it reached the max cycle count of 1,000,000 at 40% of its strength at break. In the ZX direction, this number was lower but still an impressive 21% of the strength at break. Further testing showed that it maintained high cycle counts even at higher stress level percentages. The fatigue performance of Antero 840CN03 along with its chemical resistance, FST, and ESD properties make it an easy choice to use for many aerospace or defense applications.