

Design of an Experimental Testbed for Evaluation of Carbon Fiber Reinforced Polymer Composite Gears

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Abstract:

Additive Manufacturing (AM) has the potential to disrupt the aerospace and automotive industries, with the ability to easily print complex geometries. However, the mechanical properties of the printed parts, such as porosity and surface roughness, are subpar. One remedy is to reinforce the thermoplastics that are often the sole printed material. This is done both by creating composites that have chopped fiber reinforcing materials such as Carbon Fiber (CF), or by designing parts with specific areas reinforced with continuous fiber CF. CF has a very high strength to weight ratio when it is in tension, which is most useful with continuous fiber layouts.

Carbon Fiber Reinforced Polymer (CFRP) gears will be designed for testing due to the CF's high strength and stiffness per weight ratios, and the previous research on gear wear testing. Primarily previous gear testbed designs are replicable. Fiber layouts with infill concentric rings will be designed, to determine increase in strength with additional rings. The fiber distribution will also be varied, comparing the fiber's layering in the outer layers, the middle layers, or evenly distributed among layers in the gear. The highest distribution will be used in a future work to test the number of carbon fiber layers, for the optimization of the reinforced fiber layers to price ratio. Finally, carbon fiber will be replaced with Fiberglass, Kevlar, and High Strength High Temperature Fiberglass, to study the way in which AM properties change with different reinforcing material.

Introduction:

Additive Manufacturing (AM) of advanced composites with increased strength and lifespans is changing the aerospace, automotive and robotics industries. Printing of Carbon Fiber (CF), Fiberglass, and Kevlar, through AM allows for the development of complex geometries. Carbon Fiber, Kevlar, Fiberglass, and HSHT Fiberglass will be printed using the Continuous Fiber Fabrication (CFF) method by utilizing the Markforged 3D printer. The use of AM for printing complex geometries is well documented, although there is a debate within the research as to which type of 3D printing is the most effective. According to Yu, et al. the use of Fused Deposition Modeling (FDM) to print the thermoplastic, and printing concentric rings of CF has the highest flexural strength. [7]

Previous testbed designs indicate that the most efficient way to test continuous wear is to use a distance sensor to continuously measure the distance between two gears while a force is being applied to them to ensure that they remain flush to each other. [3] Gear wear rate is best tested in this way because otherwise the gears would need to be stopped to take pictures to determine wear deformation, which changes the way they run. In order to test the wear rate and time to failure based on the speed and torque, a testbed was developed that consisted of a driving gear powered by a motor and a driven gear that applies resistive torque. This testbed measures wear rate by measuring the decreasing distance between the driven and driving gear, using a Linear Variable Differential Transformer (LVDT), which becomes smaller as the pitch point's tooth thickness decreases.

The concentration of reinforcement material needed to reach the optimal efficiency of 3D printed

gears for their price will be tested. This is an important question because the lower the optimal fiber reinforcement layering is, the less expensive the gear would be to manufacture. There is a range of layers that will have similar impacts on the wear rate and time to failure of the gears. We've seen from Mao, et al. that there is a transition torque at which point the gears rapidly accelerate to failure. [1] The range of torques to be used for our optimization testing would contain this transition torque. Optimizing the fiber layout design will increase the ease of development of 3D printed parts.

Related Work:

According to Mao et al., there was a 50% increase in load carrying capacity when Polyoxymethylene (POM) was reinforced with glass fiber, also known as GFR POM, compared to POM alone. [2] Mao et al. designed a test rig specifically for testing the wear rate of gears. From this test rig setup, it was determined that the transition torque marked the point at which the wear rate accelerated which caused thermal failure. The test rig was designed to test wear in a nonconventional way, based on tooth thickness. This was because in the thermal wear process, the gears can deform due to heat, and while they will melt out of shape, they won't lose any volume. Therefore, by measuring the "reduction in tooth thickness around the pitch point" there will be a more accurate assessment of the gear wear rate. [2]

In a second paper, from Mao et al., the wear of machine cut gears is analyzed in comparison to the previously studied POM gears. [1] Mao et al. also analyzed the ways in which different temperatures impacted the acetal machined gears, because the plastic deforms at different rates when it is exposed to

different temperatures. This is also relevant to the POM gears, the GFR POM gears, and our own Onyx and Nylon CFRP gears.

We see from Dickson, et al. that there are increases and plateaus in the max strength of fiber reinforced composites when compared to the increase in fiber layers, seen in Fig. 1. [3] Also, 3D printed parts generally have low mechanical strength due to surface roughness and porosity. Chopped fiber has previously been used to reinforce 3D printed parts. Lower layer heights have been shown to decrease the porosity.

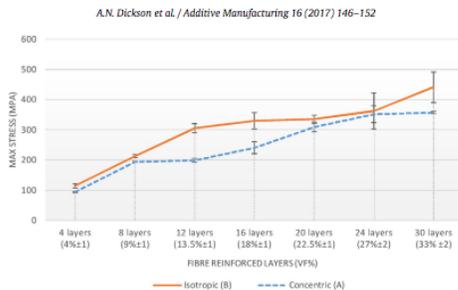


Fig. 1 Dickson, et al. max stress graph

Dickson, et al. also compared the isotropic and concentric fiber patterns preset by Markforged, and tested their tensile strength. Glass fiber reinforced Nylon with isotropic and concentric fill was used to test different amounts of layers. The 3D printed part had 32 total layers, and was tested with 4, 8, 12, 16, 20, 24, and 30 layers of Fiberglass, and it was determined that 12-16 layers was the most efficient.

A study by Kurokawa, et al. on CFR polyamide 12 considered factors such as load capability, noise, and water absorption of the CFRP. [9] A noted distinction in this study was that the CFRP gears were manufactured using injection molding, but some of the factors recorded are intrinsic to CFRP gears, such as light weight, noise reduction, and the degree of freedom with the gear geometry.

A fifth study, on the use of Fused Filament Fabrication (FFF), which is where a 3D printed deposits a thin fiber layer by layer was completed by Blok, et al. [8] The use of carbon fiber embedded in thermoplastics was analyzed for the optimal design, and they determined that CF should not be used in the outermost layers or thin features.

Experimental Procedure:

Testbed Design:

The testbed would require a motor to apply the torque and speed to the driving gear. A Variable Frequency Drive (VFD) would be needed to control the torque and speed of the motor. A Linear Variable Differential Transformer (LVDT) would be used, similar to the Mao et al. paper, to measure the distance that the driven gear moves closer to the driving gear

due to wear of the gears. A Data Acquisition (DAQ) system would be used to collect the data from the LVDT. NI LabView, is used to interface with the DAQ and record data. Finally, a braking mechanism is needed to provide resistive torque to the driven gear.

The motor needed to be a three-phase motor in order to change the speed and torque. This motor required a three-phase VFD, which would be the device responsible for controlling torque and speed so that both factors could be accounted for simultaneously. This was compounded by the need for the AC motor to be compatible with the DC outlet voltage, the VFD is able to make up for this difference.

The LVDT was required to measure the change in distance between the driven and driving gears. In order to read the data from the LVDT, a DAQ system needed to be incorporated into the design. The DAQ needed to be able to take in differential and singular analog input channels.

There was also the matter of allowing the LVDT and the driven gear to move as the gears wear. This was solved by designing a base to be mounted to a rail-carriage system. Constant force between the gears was maintained by a weighted pulley system. This base would include the LVDT, shaft for the driven gear, and a brake. A spring-lever arm system was the solution to this problem, with a rubber part to directly apply continuous friction to the shaft, at different forces, as seen in Fig. 2.

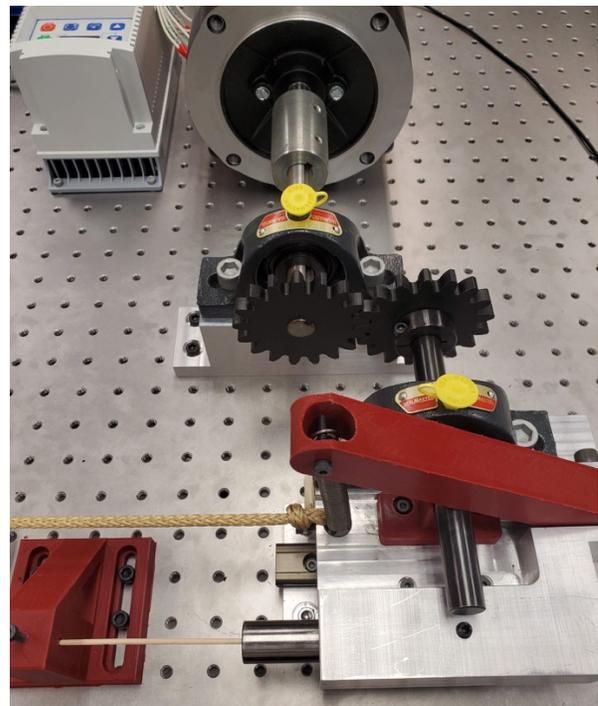


Fig. 2 Testbed

Gear Design Parameters:

Continuous CF has been proven to have superior mechanical properties to unreinforced thermoplastics. [4] However, while it is assumed that more layers will make a stronger gear overall, it is unclear what the increase in the wear rate will be. One aspect of gear design to be tested is the number of concentric rings in the outer shell of the gear. This is an important characteristic when determining the cost effectiveness of increased carbon fiber density. Therefore, one and two rings of carbon fiber will be tested, see prices referenced further.

In order to determine the proper distribution of CF layers, varying distributions of fiber will be tested: outer layers, middle layers, or evenly distributed layers. The reinforced fiber layers will be referred to as, the outer, middle, and evenly distributed layers, referenced as A, B, and C respectively, as seen in Fig. 3.

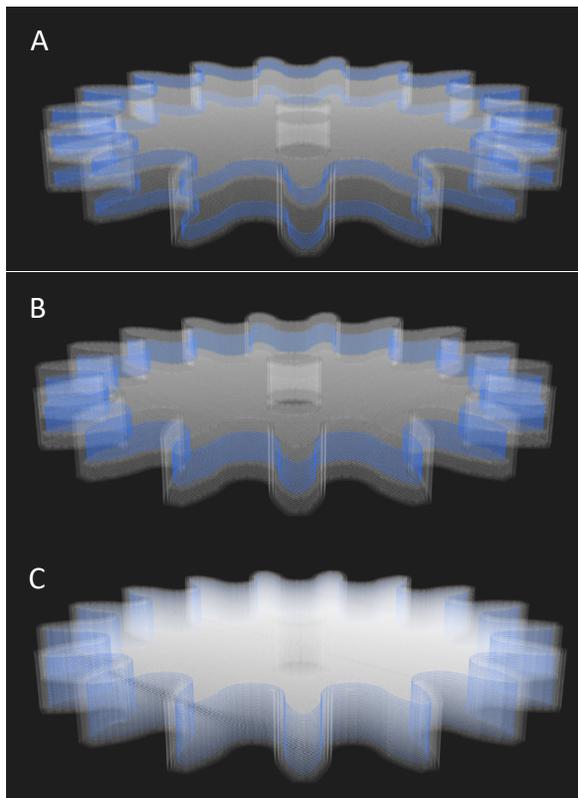


Fig. 3 Gear Distributions A, B, and C

For these tests, other gear design parameters will be kept constant, including module, tooth number, face width, and tooth profile. For preliminary tests, both the driving and driven gear were identical besides their mounting methods. Using KISSsoft design software, a gear with 17 teeth with a module of 4mm and a face width of 8mm. The tooth profile used was 1.25 / 0.38 / 1.0 ISO 53:1998 Profile A, seen in Fig. 4. The driven gear was secured to its shaft via axial

compression from a screw. The driving gear was designed to have a protruding key in its shaft hole so that it could slot onto a shaft with a keyway, which is what was coupled to the motor.

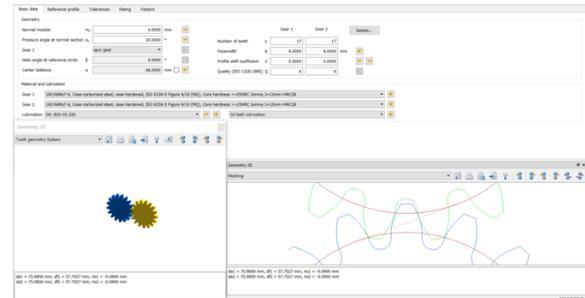


Fig. 4 KISSsoft Software used for gear design

We are proposing to run a similar test, increasing the fiber layers for a gear with 64 total layers to have 10, 20, 30, 40, and 50 layers of carbon fiber and to see if gear wear exhibits similar characteristics. This gear would have one fill ring. The current gear design contains 64 layers to be extruded. The tests are comprised of gears where the carbon fiber ring will be in 10 out of the 64 layers, at increments of 10, up to 50, also compared to a control with no layers of reinforcement.

Finally, different types of fiber, Carbon Fiber, Fiberglass, Kevlar, HSHT fiberglass, will be used in the tests. Running the tests on different materials will determine whether the characteristics are related to gears or a specific material.

Results:

Utilizing NI LabView and the NI DAQ, a program that obtained the data on the change in position and torque output of the motor was developed, seen in Fig. 5.

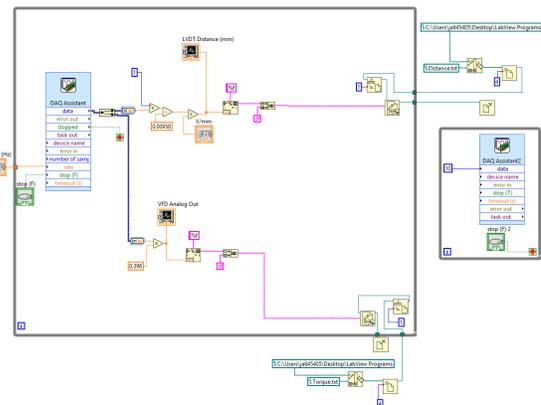


Fig. 5 NI LabView Program

Preliminary testing has shown the testbed is successful in maintaining angular velocity while powering gears under load. Wear distance and motor torque are both

successfully recorded throughout the process. The torque plot in Fig. 6 was obtained by running the program and applying oscillating torque on the motor shaft by hand. The position plot in Fig. 6 was obtained by running the acquisition program and adjusting the position of the LVDT.

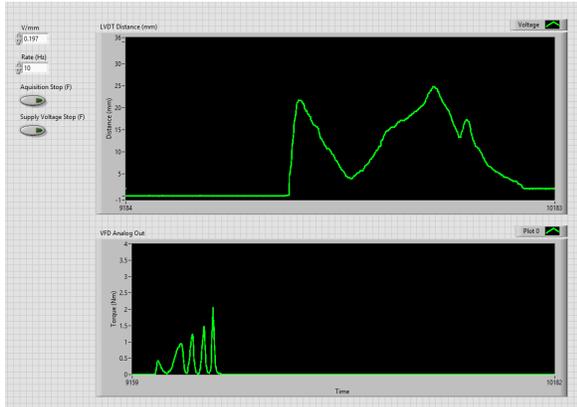


Fig. 6 NI LabView Data

An unloaded test of the 17 tooth, 4mm module gears described earlier was completed. They were run for several minutes, then the torque and LVDT response were re-plotted in Excel, see Fig. 7.

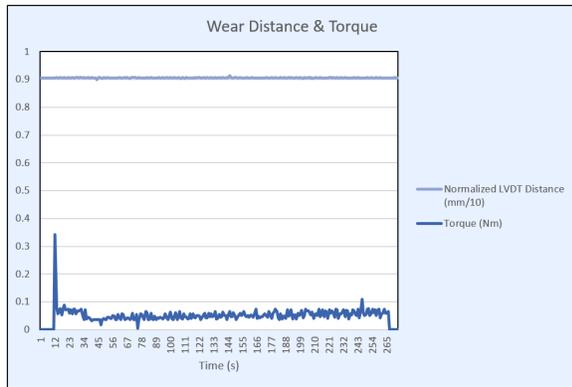


Fig. 7 Unloaded gear test

During the testing process, however, the SBR rubber pieces providing began to melt due to frictional heat. SBR rubber can withstand temperatures up to 93° C. Following this, the SBR rubber was substituted for ABS plastic, which can approach 210° C before melting. The ABS melted as well, though, when the motor ran at 1200 RPM for around ten minutes. The next planned step is to use PEEK to provide the frictional resistance. PEEK can withstand temperatures up to 340° C.

Optimization of the gear design is determined both by the of the gear but also by which gear is the most efficient for its price. The prices referenced are based on Eiger’s quotes on the individual gear’s

pricing. With the wear data, we will be able to create a formula based on wear rate and price to determine the best gear design.

Carbon Fiber Gears		
One Ring		
CF layers	Price for Single	Price for Set
0	\$3.35	\$6.70
10	\$4.71	\$9.42
20	\$6	\$12.00
30	\$7.29	\$14.58
40	\$8.58	\$17.16
50	\$9.88	\$19.76
60	\$10.87	\$21.74
Two Rings		
CF layers	Price for Single	Price for Set
0	\$3.35	\$6.70
10	\$5.85	\$11.70
20	\$8.28	\$16.56
30	\$10.71	\$21.42
40	\$13.13	\$26.26
50	\$15.56	\$31.12
60	\$17.69	\$35.38

Table 1 CF gear pricing

Conclusions and Future Work:

The development of the testbed allows for the testing of the gear wear rate for polymer gears of varying sizes. Without using the friction system, the testbed can wear gears at speeds up to 1200 RPM and 0.115 Nm of resistive torque. It has yet to undergo a long-period test of a gear set under these conditions, but presumably the time to failure would be fairly long, given the low torque value. While the lever arm braking system is effective at very low speeds, it experiences thermal failure at speeds of above 1200 RPM and torques above 0.748 Nm. The friction arm system was originally chosen over using a magnetic particle brake for reasons of simplicity and cost. It has become apparent, however, that a magnetic particle brake will be necessary for more rigorous gear testing. The magnetic brake will benefit the system by providing higher torque and more accurate control of the torque via a current-adjustable brake.

Additional future work will involve ensemble learning. Ensemble learning using neural networks has been shown to be able to predict failures in many

systems with parallels to gear train systems [6]. Machine learning has also been used to predict properties of AM materials, such as surface roughness. [7] Using the data acquired by tests run on this testbed, a novel ensemble learning algorithm will be trained to predict gear wear in AM CFRP gears.

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