Single Tooth Bending Fatigue Testing at any R Ratio

Matthew Wagner, Aaron Isaacson, Kevin Knox and Thomas Hylton

Introduction

A bending fatigue failure in the root region where bending stresses are highest is often considered the most catastrophic failure a gear can experience. Consequently, evaluation of the bending fatigue performance (stress to life relationship) of different gear materials subject to various manufacturing processes and subsequent post processing treatments is of significance to gear and transmission designers.

One method for establishing bending fatigue performance is the single tooth bending fatigue (STBF) test. An example of a fixture used to implement this type of test is shown in Figure 1. Although this test has the advantage of being relatively simple, one limitation is that it is not directly representative of typical gear applications. The test load is unidirectional and the root areas of the tooth under test are subject to tensile stresses only, with no ability to load the test tooth root fillet in compression. This paper outlines the need for an STBF test that can accommodate reversed loading, followed by the development of a new test fixture design to execute this type of test.

Related Work

Using STBF testing to evaluate the bending fatigue strength of gear teeth has been documented in literature dating back over 60 years (Ref. 1). A few inherent advantages in this type of test are that it eliminates unwanted failure modes, uses relatively simple fixturing, and uses readily available fatigue testing equipment to apply the necessary loads.

Some variations in STBF fixture design exist, however the tooth loading method shown in Figure 2 generally applies regardless of the particular implementation. The test gear is mounted on a spindle in a test fixture and the gear teeth

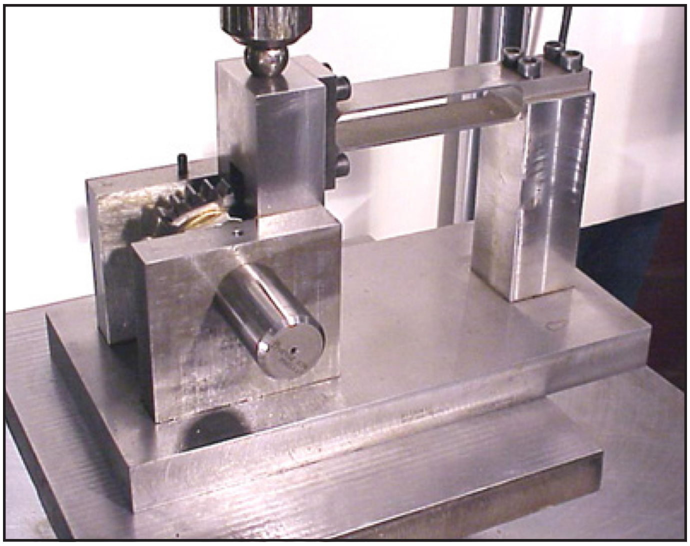
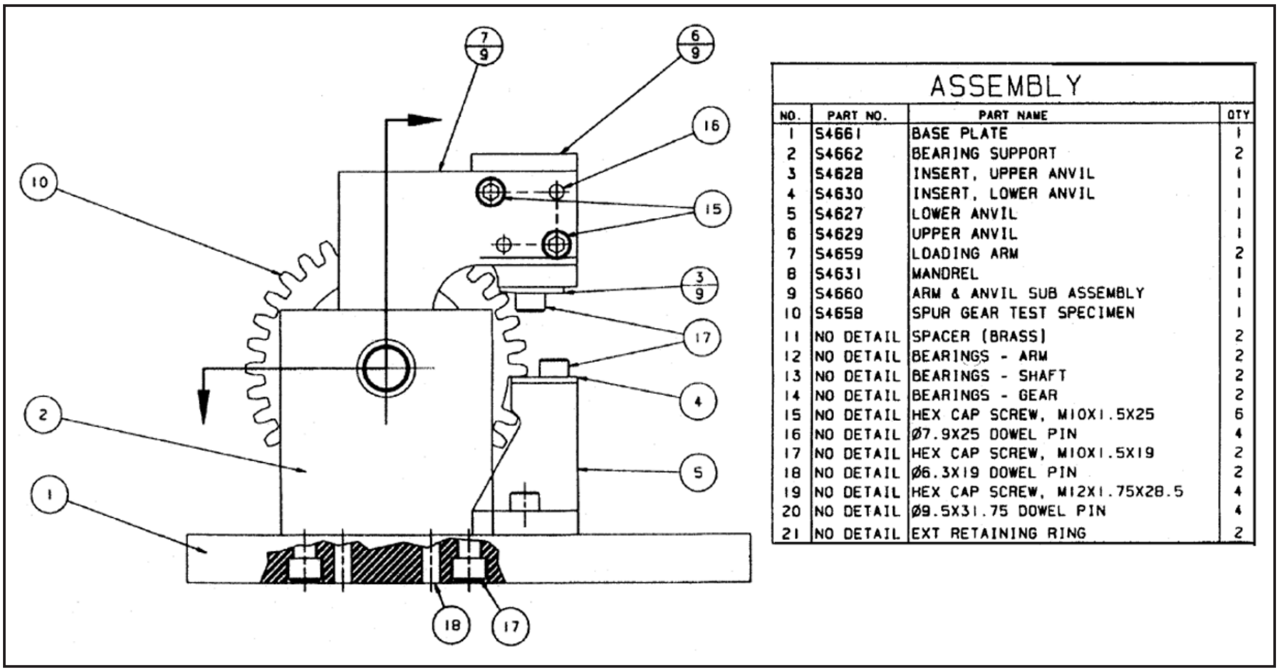


Figure 1 Single Tooth Bending Fatigue Test Fixture.



ASSEMBLY

NO.	PART NO.	PART NAME	QTY
1	S4661	BASE PLATE	1
2	S4662	BEARING SUPPORT	2
3	S4628	INSERT, UPPER ANVIL	1
4	S4630	INSERT, LOWER ANVIL	1
5	S4627	LOWER ANVIL	1
6	S4629	UPPER ANVIL	1
7	S4659	LOADING ARM	2
8	S4631	MANDREL	1
9	S4660	ARM & ANVIL SUB ASSEMBLY	1
10	S4658	SPUR GEAR TEST SPECIMEN	1
11	NO DETAIL	SPACER (BRASS)	2
12	NO DETAIL	BEARINGS - ARM	2
13	NO DETAIL	BEARINGS - SHAFT	2
14	NO DETAIL	BEARINGS - GEAR	2
15	NO DETAIL	HEX CAP SCREW, M10X1.5X25	6
16	NO DETAIL	Ø7.9X25 DOWEL PIN	4
17	NO DETAIL	HEX CAP SCREW, M10X1.5X19	2
18	NO DETAIL	Ø6.3X19 DOWEL PIN	2
19	NO DETAIL	HEX CAP SCREW, M12X1.75X28.5	4
20	NO DETAIL	Ø9.5X31.75 DOWEL PIN	4
21	NO DETAIL	EXT RETAINING RING	2

Figure 2 Loading Schematic for STBF Test [6].

under test are held between two independent anvils (Figure 2, items 3 and 4). The entire fixture is placed in a universal fatigue test frame and the anvils are subjected to cyclical loading until a bending failure occurs or a run out limit is reached. Several teeth on each gear can be tested to provide multiple data points from each test gear. This type of fixture is well documented in literature (Refs. 1–5) and established test standards (Ref. 6). Some variants of this method can also be found in literature, such as application of three-point loading (Ref. 7) or testing of asymmetric gears (Ref. 8), however all of the methods discussed thus far load the test tooth in one direction only.

The stresses in fatigue testing are characterized by an R value as defined in Equation 1. In the authors' experience an R value of 0.1 is typically used in STBF testing, in other words the stresses are cycled from 10% of the maximum to 100% of the maximum tensile stress. Although the exact R ratio may vary, the methods previously described are inherently limited to testing with positive R values. For reasons which will be discussed in more detail, this is not always fully representative of the stresses the gear tooth experiences in practice.

$$R = \frac{Stress,\ min}{Stress,\ max} \qquad (1)$$

Where the following sign conventions are used for stress:
Root tensile stress (+)
Root compressive stress (-)

Given this limitation, the alternative to unidirectional STBF testing has been to use running gear bending fatigue testing, which is also well documented in literature (Refs. 1, 3, 9, 10). This type of test uses rotating meshing gear pairs operating under a load, often in a four-square / back-to-back arrangement. The running gear bending fatigue test has the advantage of subjecting the gear teeth to actual operating conditions, however it also has some significant disadvantages compared to the STBF test. The first is cost, since running gear test equipment is more complex, and also requires more test gears for a given number of desired data points. More significantly, the gear design must be carefully evaluated so unwanted failure modes such as pitting, wear or scuffing do not occur before the desired bending failure is generated (Refs. 1, 3).

The Need for STBF Testing at Negative R Ratios

The STBF test method's inability to realistically simulate loading of a tooth in mesh has relegated it to a comparative assessment role. As such it has typically been used for evaluating the relative performance of various gear materials and manufacturing processes. The difference between STBF data and running gear bending fatigue data is for two primary reasons discussed in (Ref. 11). First, STBF testing forces a failure on specific teeth on the gear, while running gear tests effectively use all of the gear teeth and develop a failure on the weakest member of the population. This is a statistical issue which can be addressed with the methodology shown in (Ref. 11).

Second, in STBF testing the limitation of using a positive R ratio means that the stress is cycled from a maximum to some percentage of that maximum. For this reason, the tensile stress is never fully released in an STBF test in the same way as when a gear tooth exits the mesh in a running application. In some cases in running gear applications, depending on geometry and speed, the root fillet may also be subject to a small amount of compression as the adjacent tooth is loaded, resulting in a slightly negative R ratio in practice. An example of measured root fillet strain alternating between tension and compression through a rotating mesh cycle is shown in Figure 3. For this reason, a positive R value STBF test may yield "optimistic" results when compared to running gear data at the same maximum stress level. This was one motivation to develop an STBF test that can be used to test under negative R ratios. Furthermore, in some applications such as idlers (Ref. 10) or planet gears (Ref. 13), teeth mesh with more than one mating gear during a rotation and thereby experience fully reversed stresses (R = −1.0). In these cases, very generic derating factors have typically been used (Ref. 14) to relate non-reversed stress allowables to design parameters for fully reversed stresses. The desire to establish more specific derating factors further emphasizes the motivation to develop an STBF test method that can use negative R ratios.

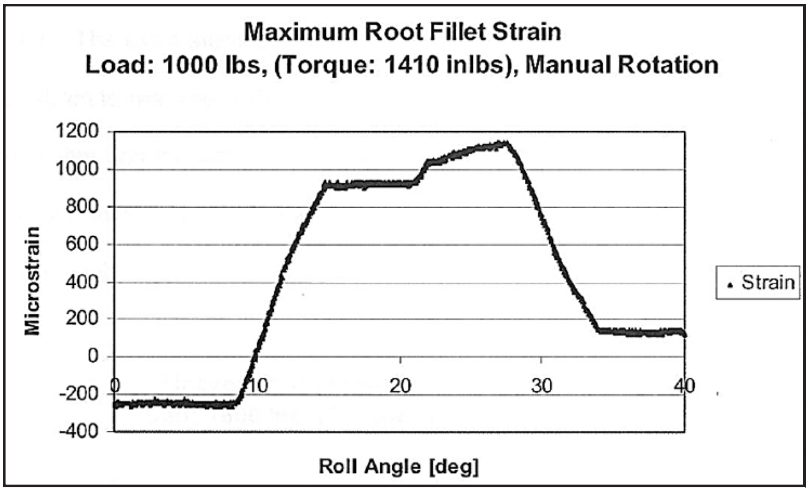


Figure 3 Root Fillet Strain vs. Roll Angle (Ref. 12).

Documentation of STBF methodology that can accommodate negative R ratios is scarce in open literature. One method is shown in (Ref. 15), where the load is reversed via torsional oscillation. Few details are provided, however this type of test does not appear to be compatible with commonly available tension and compression type fatigue test frames. Specifically designed test gears that utilize a splined bore are also required. A second method outlined in (Ref. 16) uses a servo motor to oscillate a mating gear against a fixed test gear. This test method was developed for polymer composite gears with a maximum test torque of 14 N-m, which was well below the loads required in the authors' testing. A running gear test method which allows negative R ratios is shown in (Ref. 10) and was shown to be successful, however this methodology was not practical for the authors' work for reasons which are described below.

Testing of Production Gears

A final comment on motivation for this work involves the ability to use production gearing in bending fatigue testing. When gear testing is undertaken to understand fundamentals such as material properties, specifically designed test gears are frequently used. In the literature cited, this was most often the case. If running gear tests are to be used, this has the advantage of allowing the test gear designer to make their best attempt to "force" bending failures by controlling various gear design parameters. Design of STBF test gears is more straightforward due to the limitation of possible failure modes.

Often however, it may be necessary to test production gears to gain insight into the performance of an existing gear design or manufacturing process. In these cases a representative test gear design may also be employed, however the best practice if possible is to use existing production gears in order to fully capture any inherent variables that may not be well understood. Using production gears in running gear tests can be a challenge, especially due to the fact that under running conditions bending fatigue may not be the dominant failure mode of the gear under consideration. Also, modifying existing rotating gear test equipment to accommodate a preexisting gear design can be costly due to geometry or power limitations. In the past, the only other option has been to use unidirectional STBF testing with production gears, while accepting the limitation of using R values that are not fully representative of the final application.

The work described here was motivated by the desire to test several production gears with widely varying geometries under unidirectional and fully reversed conditions. Implementing running gear bending fatigue tests with the range of sizes under consideration would have been impractical, and would have likely resulted in unwanted failure modes.

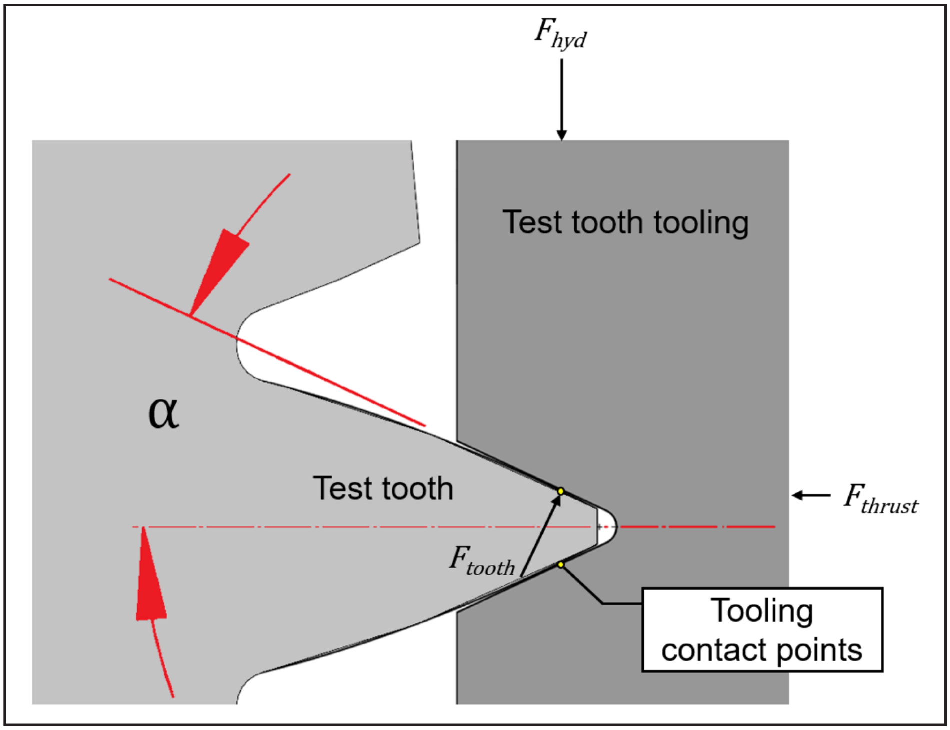


Figure 4 Test Tooling Angle and Contact Points.

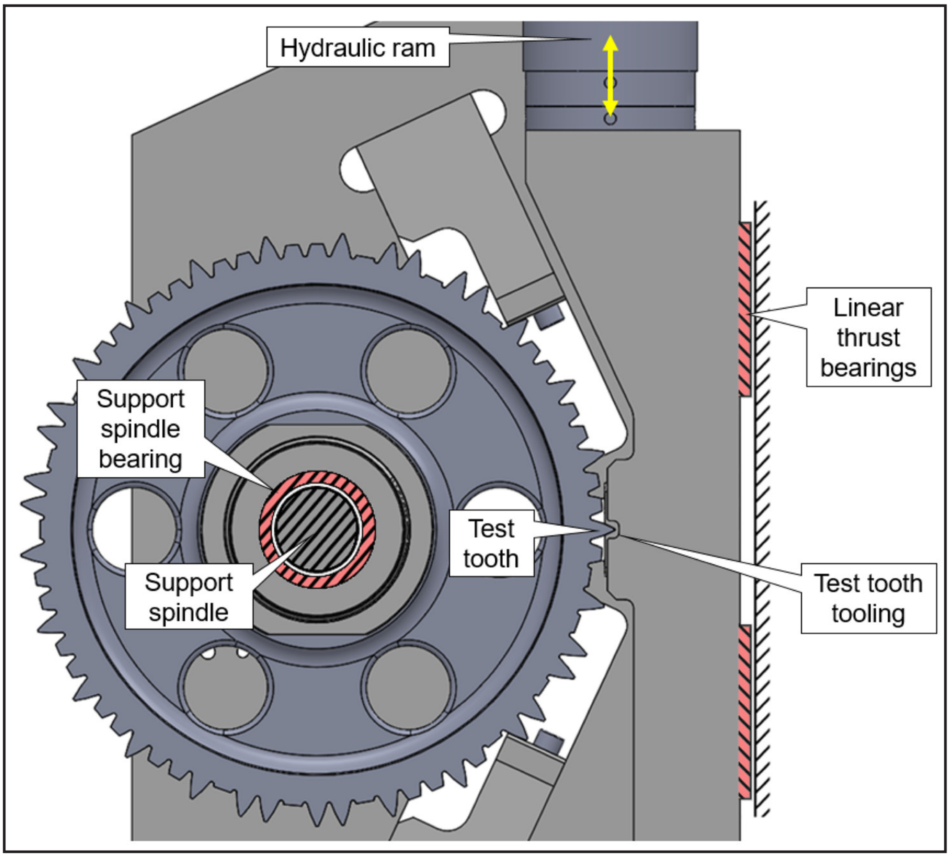


Figure 5 STRBF Fixture Layout.

Single Tooth Reversible Bending Fatigue Fixture Overview

An overview of the tooling used to interface with the test tooth on the newly developed Single Tooth Reversible Bending Fatigue (STRBF) test is shown in Figure 4. A v-shaped feature in the tooling contacts the test tooth on both flanks. The tooling v-notch half angle (α) is chosen such that the contact point is at an appropriate roll angle to induce a bending failure, but not too close to the tooth tip as to cause chipping. The tooling is loaded hydraulically (F_{hyd}) in the vertical direction in both compression and tension to apply a load to both the upper and lower flanks of the tooth respectively.

One caveat of this of layout is that the force vector normal to the test tooth involute surface (F_{tooth}) is not parallel with the force vector for the applied hydraulic load. For this reason, there is a horizontal component of the test tooth load that needs to be accommodated on the tooling (F_{thrust}) to avoid side loading on the hydraulic actuator. Also, the effective test load on the tooth needs to be computed from applied load to take the off-axis loading into account. The relationships between applied load, thrust load and effective tooth load are given in Equations 2 and 3.

$$F_{thrust} = F_{hyd} \tan\alpha \qquad (2)$$

$$F_{tooth} = \frac{F_{hyd}}{\cos\alpha} \qquad (3)$$

Where:

α is tooling v-notch half angle
F_{hyd} is applied hydraulic load from test frame
F_{thrust} is resultant thrust load
F_{tooth} is load normal to tooth involute surface at tooling contact point

An overview of the remainder of the fixture is shown in Figure 5. A spindle is used to locate the bore of the gear, and the gear is allowed to rotate freely about its axis. Linear bearings allow the test tooth tooling to move vertically, but support the resultant thrust loads. The bearings on the gear spindle as well as the linear thrust bearings are Teflon based plain bearings specifically designed for use in high cycle, short stroke applications.

Similar to a typical unidirectional STBF fixture, a support tooth is used to react to the test load, however in this design two support teeth are used instead of one. When the hydraulic ram is in compression, the upper flank of the test tooth is loaded, and the lower support tooth reacts to the test load (Figure 6a).

Likewise when the hydraulic ram is in tension, the lower flank of the test tooth is loaded, and the upper support tooth reacts to the test load (Figure 6b). The support tooth contact point

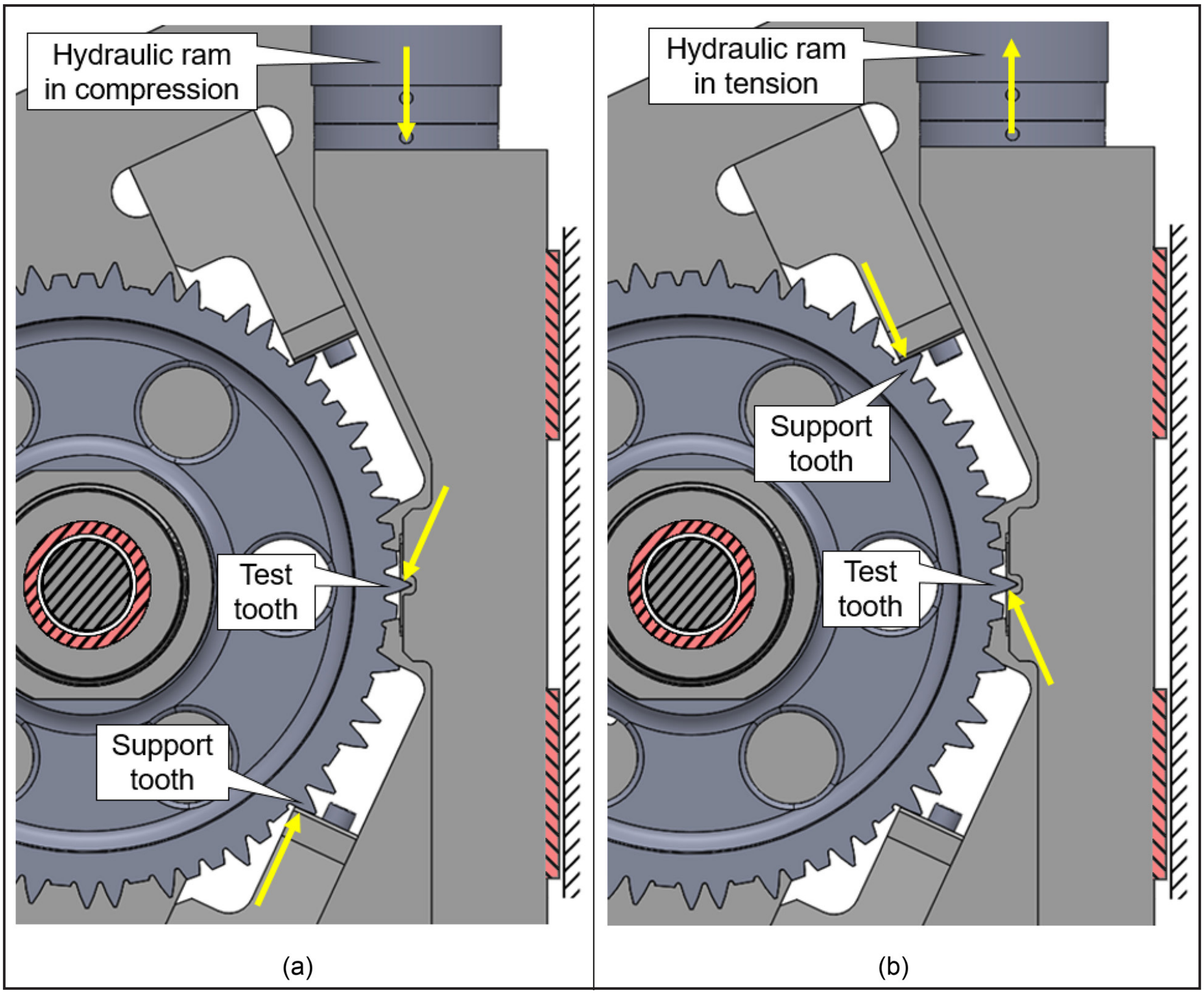


Figure 6 Fixture Load Path in (a) Compression and (b) Tension.

(Figure 7) is chosen to be at a lesser roll angle than the test tooth contact point in order to avoid support tooth failures. The support tooth contact point is also chosen so the line of action from the test tooth and line of action from the support teeth are collinear, which minimizes a component of the test load from being transmitted into the gear support spindle and bearings.

As previously shown in Figure 4, portions of the teeth adjacent to the test teeth need to be removed to allow for tooling clearance. A minimum amount is removed from teeth adjacent to the test teeth in order to minimize any possible effect on the stress distribution in the test tooth root fillets. As shown in Figure 7, teeth adjacent to the support teeth need more clearance due to the lower contact location of the support tooth tooling.

The test tooth and support tooth tooling sets were designed to be modular so the same base fixture would accommodate a range of sizes. The test program for which this method was developed, which is still ongoing, uses six different gear geometries ranging from 120 mm to 300 mm in pitch diameter. Figure 8 shows the STRBF fixture with the largest and smallest gear geometries.

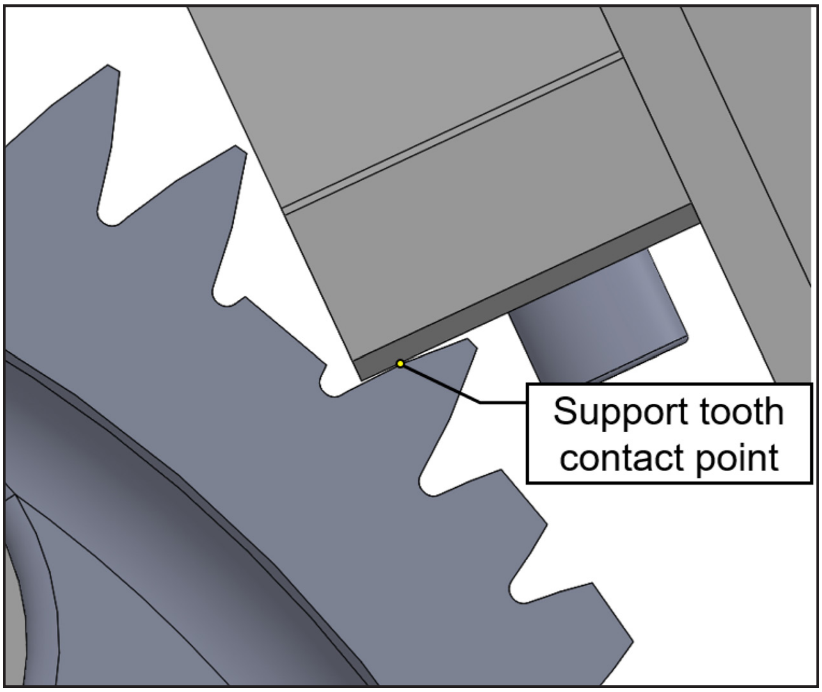


Figure 7 **Support Tooth Detail.**

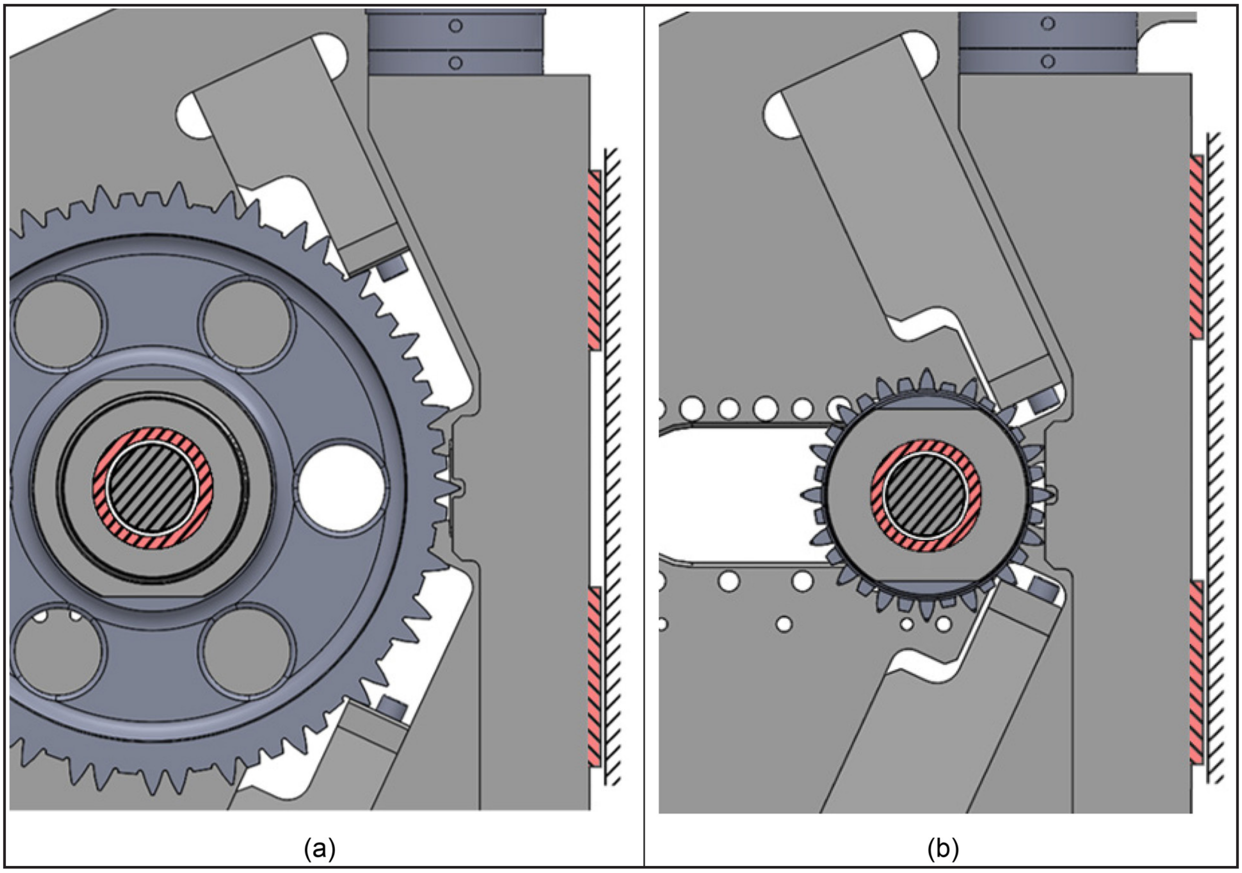


Figure 8 **STRBF Fixture with (a) Largest and (b) Smallest Gear Geometries.**

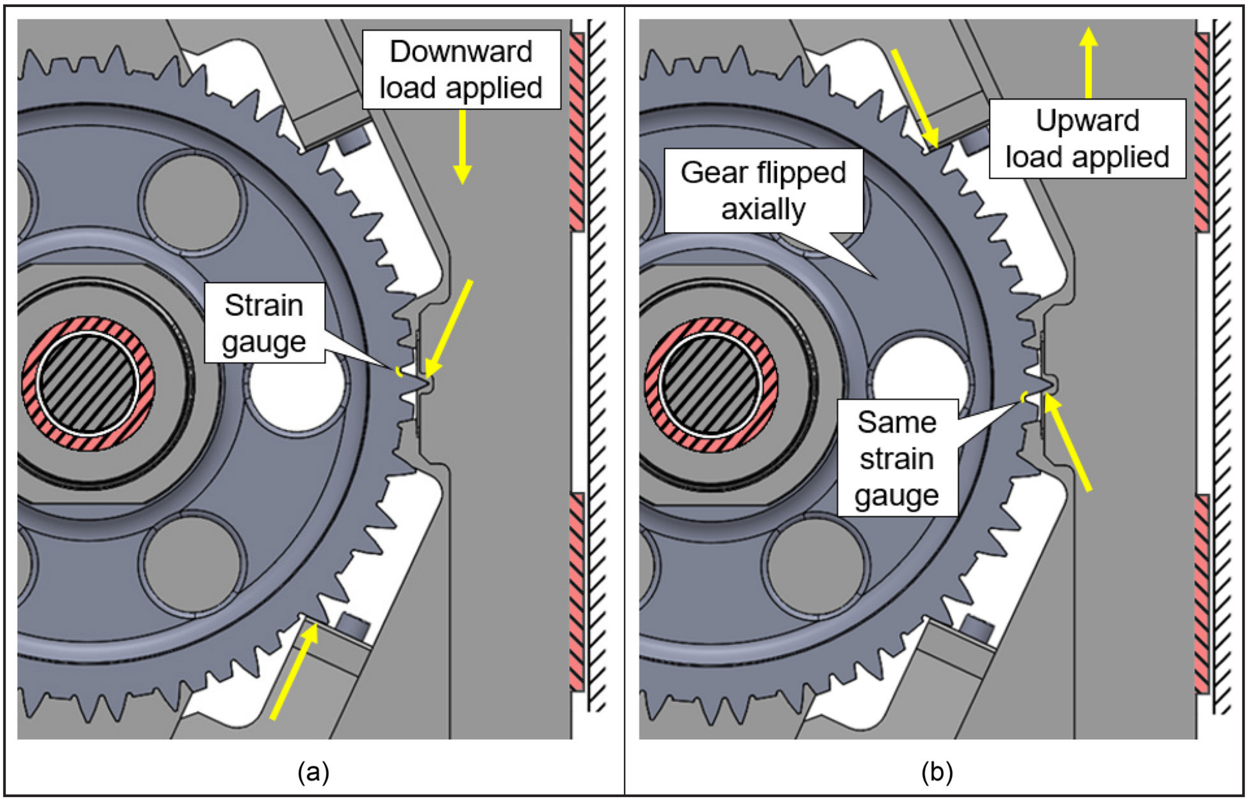


Figure 9 Fixture Calibration with Strain Gauge.

Calibration and Testing

Before testing, calibration of the fixture was carried out using a strain gauge applied to one root fillet of a test tooth. The gear was first installed to the fixture such that the strain gauge was oriented on the upper side of the tooth as shown in Figure 9a, after which a downward hydraulic load was applied to induce a tensile stress on the instrumented area. A relationship of applied load to strain was developed for this orientation. The gear was then flipped on its axis, so the same strain gauge from the first step was oriented on the lower side of the test tooth as shown in Figure 9b. Upward loads of identical magnitude to the first step were applied and a load to strain relationship developed for this orientation. Tooling adjustments were then made until both load vs. strain relationships were symmetric about zero.

An image of the assembled STRBF fixture is shown in Figure 10. Testing was executed at frequencies up to 30Hz using R ratios of 0.1 and –1.0, with maximum applied loads ranging from 5kN to 80kN depending on the gear being tested. All unidirectional tests were completed using a downward (compressive) load on the hydraulic ram, however unidirectional tests could be conducted in either direction. Failures were detected by monitoring the minimum and maximum position of the hydraulic ram, which can be used to compute tooth deflection. An example of tooth detection data taken during a bending failure is shown in Figure 11. Root fillet cracks present after the deflection limit was exceeded were significant and visible without magnification.

Figure 10 STRBF Test Fixture.

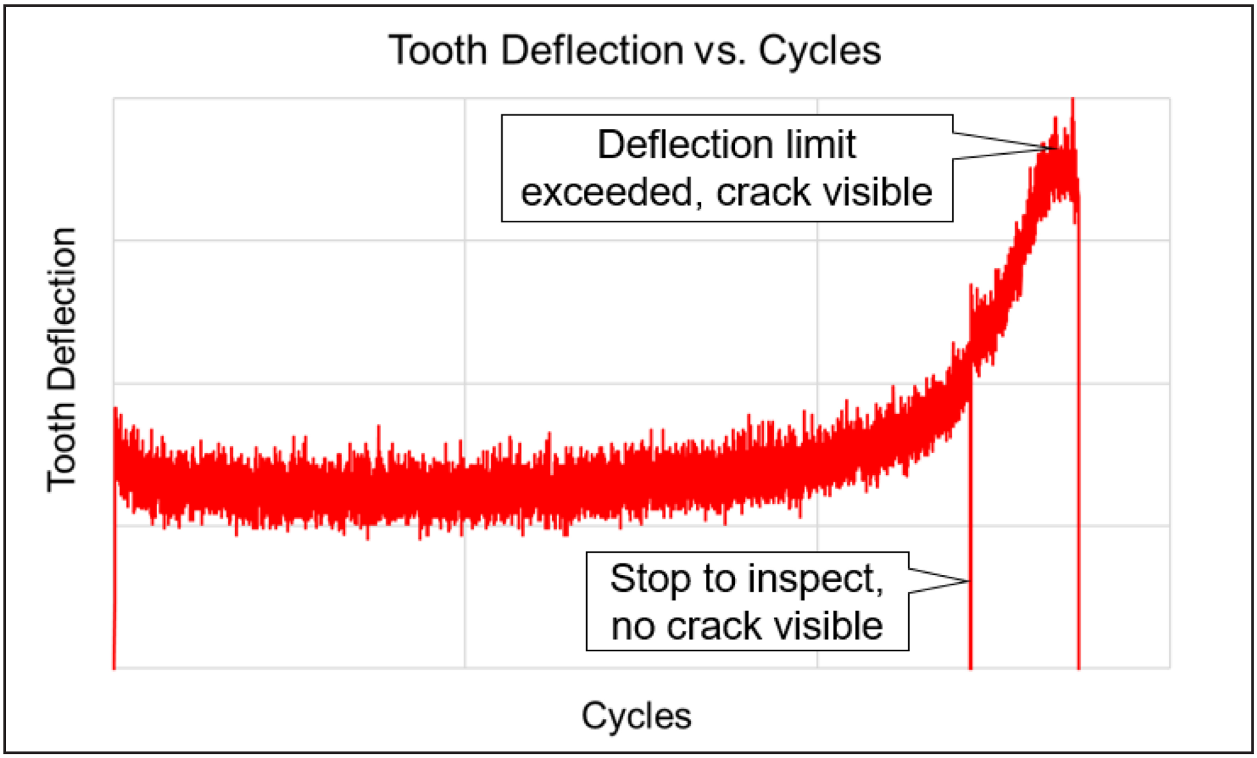


Figure 11 Example of Tooth Deflection Monitoring.

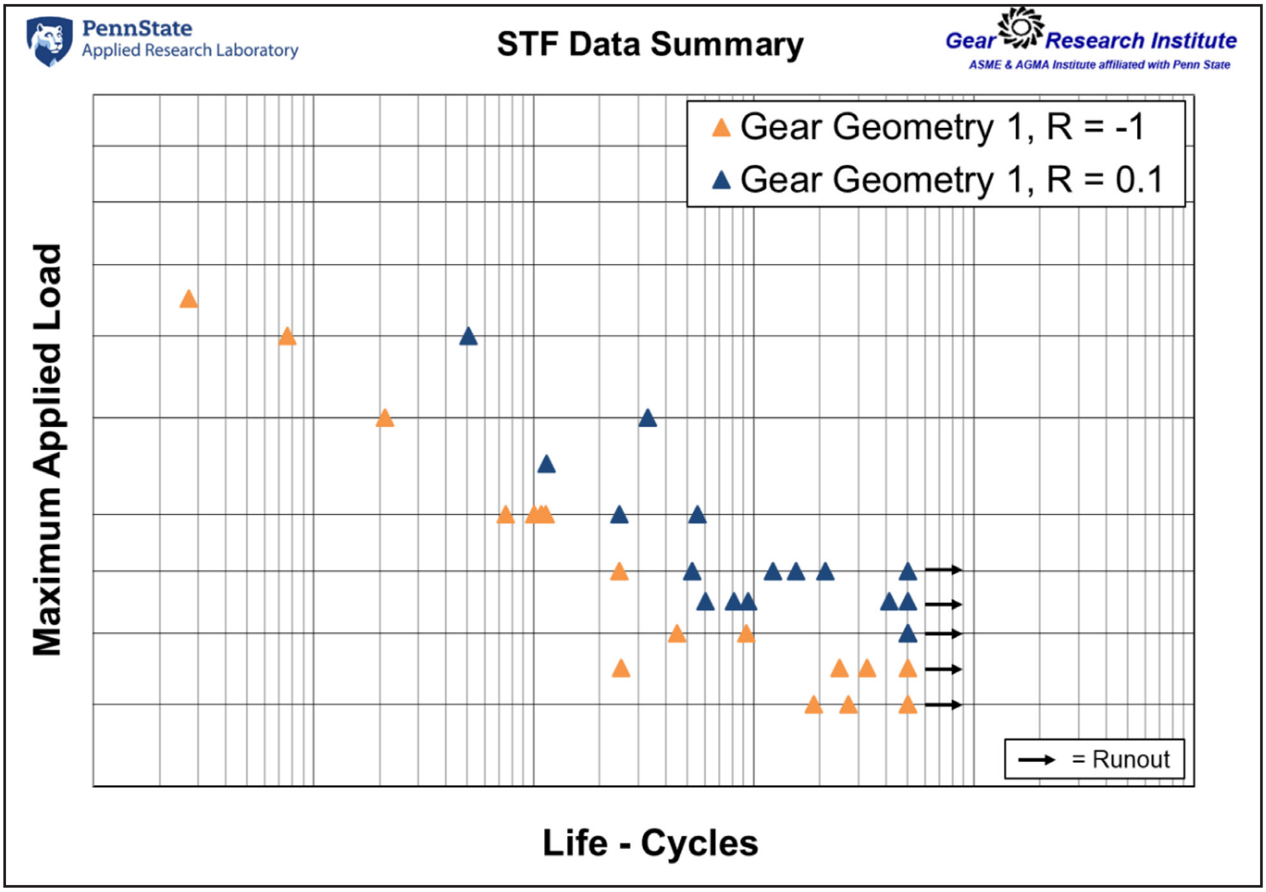


Figure 12 Example Data Set using two R Ratios - Gear Geometry #1.

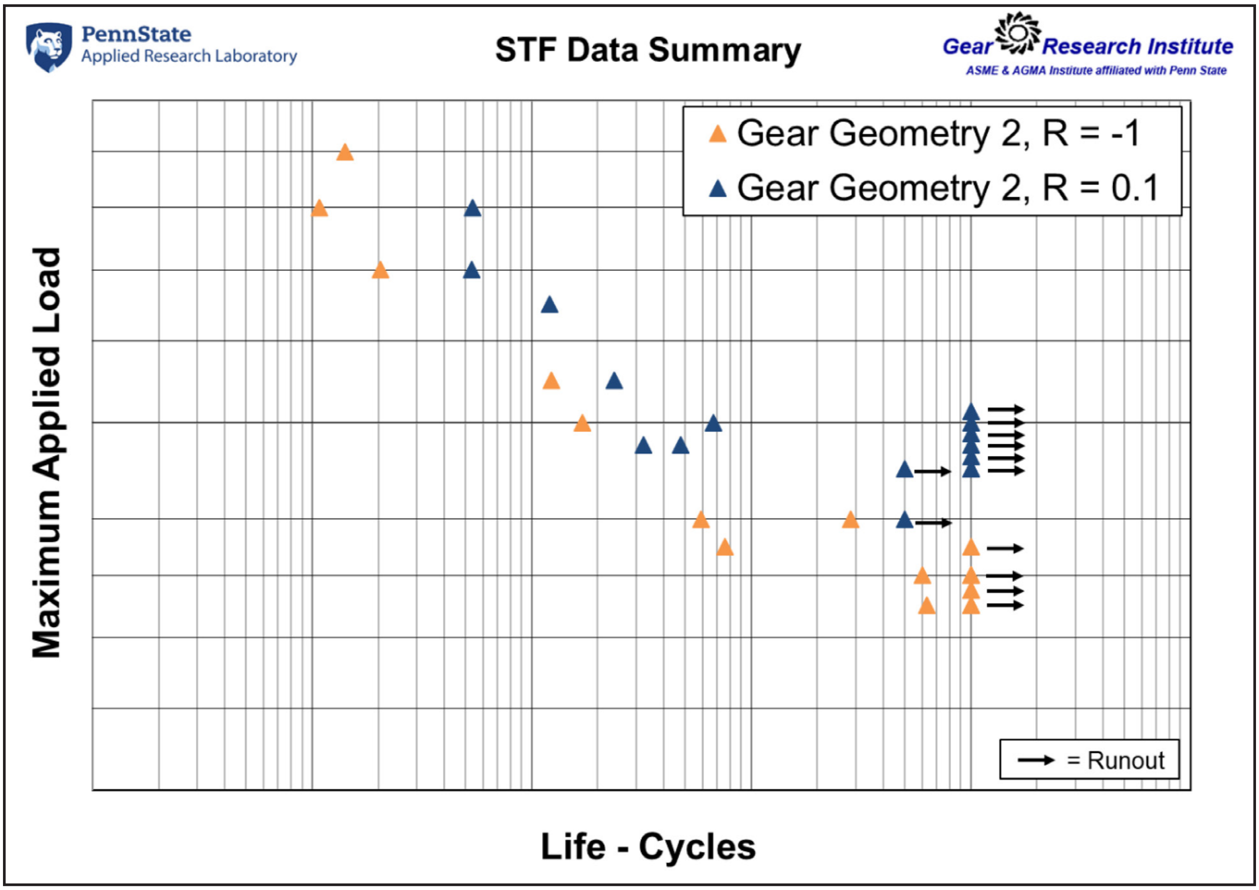


Figure 13 **Example Data Set using two R Ratios - Gear Geometry #2.**

Figure 12 and Figure 13 show non-dimensional examples of data comparing the unidirectional ($R = 0.1$) and fully reversed ($R = -1.0$) results from two different gear designs. Both plots utilize the same scaling on the Maximum Applied Load axes. In the data sets shown, the slopes of the finite life portions of the data sets from both R ratios are similar, however as expected the unidirectional finite life data sets are offset toward increased cycles to failure. The knees (intersections of finite life and infinite life slopes) in both unidirectional data sets also occur at fewer cycles and at higher loads than the knees in the fully reversed data sets, which leads to the fully reversed data sets having more long cycle failures. It should be noted that these trends are comments on the specific data sets presented here, however many factors such as residual stress, geometry, material cleanliness, etc. can influence bending fatigue performance. It was expected that the knees in the fully reversed data would occur at lower loads, since this is what is captured in the generic derating factors typically used for fully reversed loading on gear teeth [14].

Testing has shown that the actual derating factor can vary with various gear design parameters and may not be fully represented by the generic factors found in literature.

The test method outlined here has successfully generated unidirectional and fully reversed bending failures on a variety of gear geometries. All failures have been on test teeth only, with no support tooth damage observed. Also, no unwanted failure modes on the test tooth such as flank fracture have occurred. The program referenced is ongoing, and to date over 180 tests have been completed representing over 500 million fatigue cycles. Although this program uses R ratios of 0.1 and −1.0, any R ratio ($1 > R \geq -1$) can be implemented by altering the programming of the fatigue test load frame. No further changes to the fixture tooling or setup are required to accommodate other R ratios.

Summary and Future Work

In conclusion, this paper outlined the development of a new type of single tooth bending fatigue test method in which both tensile and compressive bending stresses can be applied to the test tooth root fillets, which allows fatigue testing at any R ratio applicable to gear bending fatigue testing ($1 > R \geq -1$). Using this method, negative R ratios up to and including fully reversed loading can be tested. The need for this type of test exists because traditionally used single tooth bending fatigue fixture designs are limited to applying tensile bending stresses only, which is not fully representative of running gears. The only alternative in the past has been to use running gear bending fatigue tests, which create several other challenges and are not always practical. This method was developed to allow testing of a range of sizes of actual production gears rather than representative test specimens. Loading the test tooth root fillet in tension and compression dictated the design of a novel fixture concept which is described in detail. The STRBF test method has been shown to effectively generate bending fatigue failures under unidirectional and fully reversed conditions on a variety of gear geometries. The development of this test method is a significant step forward in single tooth bending fatigue testing and has generated substantial interest from gear engineers from a variety of industries.

Future work for this test method includes testing of additional R ratios, specifically slightly negative R ratios representative of non-reversed gear applications. Additional gear geometries and materials are also planned for testing. Results will be compared to running gear bending fatigue test data in order to compare the results of both test methods.

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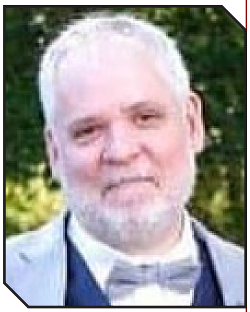
Aaron Isaacson is a Faculty Researcher and Head of the Drivetrain Technology Center at the Applied Research Laboratory - Penn State University and Managing Director of the Gear Research Institute. Mr. Isaacson holds B.S. and M.S. degrees in Mechanical Engineering and is currently pursuing his Ph.D. in Materials Science and Engineering with a focus on functional design and optimization of high alloy steel microstructures for rotorcraft gears in loss of lubrication environments. Mr. Isaacson has over 20 years of experience conducting gear performance testing. He has been principal investigator the Gear Research Institute Aerospace Bloc research consortium since 2013. His research interests include gear performance characterization, failure analysis, gear tooth friction and efficiency, ferrous metallurgy, additive manufacturing for drivetrain applications, tribology, gear metrology, gear health monitoring and custom testing applications.



Kevin Knox retired from Caterpillar Inc in 2020 after 31 years of service. He holds both M.S. and B.S. degrees in Mechanical Engineering from Iowa State University, with a specialty in the control and modeling of nonlinear dynamic systems. He held a variety of positions at Caterpillar, including supervising the transmission controls team and researching new machine concepts. He holds 13 patents related to his work in those areas. He spent most of his career involved with the dynamic modeling and analysis of engine rotating systems and has presented work on gear train systems to the ASME, SAE and IMAC.

Thomas F. Hylton II joined Caterpillar Inc in 2012 as the large power systems gear train design engineer. He holds a B.S. in Mechanical Engineering from Indiana University Purdue University Indianapolis. Prior to joining Caterpillar as the gear train designer. Thomas worked 2 years as a detailer/designer for core engine rotating components and large electric power diesel products. He also worked for 2 years with Butler America in a joint effort with Sikorsky Helicopters on gearbox designs for the CH53 heavy lift helicopter program. During his time with Caterpillar as the gear train design engineer he was responsible for developing, designing and maintaining 4 engine platforms of gear designs ranging from 27 mm bore to 280 mm bore engines across all applications. His current role has seen him shift into a Sr. Engineer position in 2020 focused on non-emissions regulations and compliance specializing in Components, Labeling, Loco/Industrial/Marine applications and Chemical compliance worldwide for LPSD product.