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INCREASING POWER DENSITY BY ADVANCED MANUFACTURING, MATERIALS, AND SURFACE TREATMENTS

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ABSTRACT

Track vehicle Final Drive torque transferring capacity is constrained by the availability of packaging space, weight constraints, and material / heat treat properties. These constraints create a paradigm where as the increase in load due to weight growth is inversely related to life due to fatigue. Funded under Phase II SBIR contract W56HZV-13-C-0056, Loc Performance Products, Inc. (Loc) developed manufacturing processes aligned to key selected materials and surface treatments to break through this paradigm. The results of the SBIR efforts produced an optimized Final Drive design that addressed the increasing Gross Vehicle Weight (GVW) of the Bradley Fighting Vehicle while maintaining the current Final Drive packaging space, reducing lifecycle cost and maximizing performance in terms of power density and extending the life of the product.

INTRODUCTION

Historically, combat vehicles have increased in weight over the years in an attempt to address the evolving threats targeting our Warfighters. These weight increases commonly drive costly driveline upgrades and, if not addressed, could hinder the mobility performance of the fielded vehicles. One of the key mobility driveline elements is the Final Drive. This element transfers the torque produced by the power pack to the track through the carrier sprocket assembly. The Final Drive is commonly limited by its power density. Power density is defined as the amount of power (time rate of energy transfer) per unit volume.

Utilizing the production gear set designs, Loc established a performance baseline of life cycle fatigue as a function of applied torque. This baseline was used to compare the following gear set configurations:

- 4320H (Production Baseline)
- 4320H (combined with SuperFinishing)
- Ferrium C61
- Ferrium C61 (combined with SuperFinishing)

Performance testing focused on two types of fatigue to establish the performance baseline. The first fatigue type Loc evaluated was Bending Fatigue. For this type, Loc utilized an internally designed Bending Fatigue Test Stand. The second fatigue type Loc evaluated was Surface Fatigue. For this type, Loc utilized it's internally designed Final Drive Dynamometer. Both the Bending Fatigue Test Stand and the Final Drive Dynamometer produced consistent results for characterizing the technology configurations identified above.

TECHNICAL PROBLEM

In materials science, fatigue is the weakening of a material caused by repeatedly applied loads. If the loads are above the materials threshold, microscopic cracks will begin to form at the stress concentrators such as the surface inclusions, persistent slip bands, and grain interfaces. Eventually a crack will reach a critical size at which time the crack will propagate suddenly, fracturing the gear tooth. This condition is commonalty observed in high-cycle fatigue situations.

Currently, gear design power density is limited by the existing available packaging space, weight constraints, and material / heat treat properties. These constraints limit the power capabilities due to fatigue failures. Therefore, to increase the power density of a Final Drive unit while holding weight and volume constant leaves little trade space for improvements if options are limited to conventional gear materials and methods.

GENERAL METHODOLOGY

As noted above, two test conditions were studied to establish performance characteristics of the various sample configurations.

The first performance testing focused on bending fatigue. Utilizing Loc's Bending Fatigue Test Stand; performance characterization was documented for the following gear set configurations:

- 4320H (Production Baseline)
- 4320H (combined with SuperFinishing)
- Ferrium C61
- Ferrium C61 (combined with SuperFinishing)

In total, ~90 samples have been tested [(4) test configurations, 5-6 samples per test configuration, (4) load conditions]. These samples were tested in high-cycle fatigue conditions to generate the fatigue performance data. Fatigue performance is commonly characterized by an S-N curve, also known as a Wöhler curve. See Example graph below in **Figure 1: S-N Life Cycle Fatigue Plot**. This plot graphs the magnitude of a cyclic stress (S) against the logarithmic scale of cycles to failure (N). Loc generated S-N Life Cycle Fatigue Plots predicting cyclic stress (S) against cycles to failure (N) for all sample configurations and compare/contrast these plots to evaluate the impacts of Ferrium C61 and SuperFinishing.

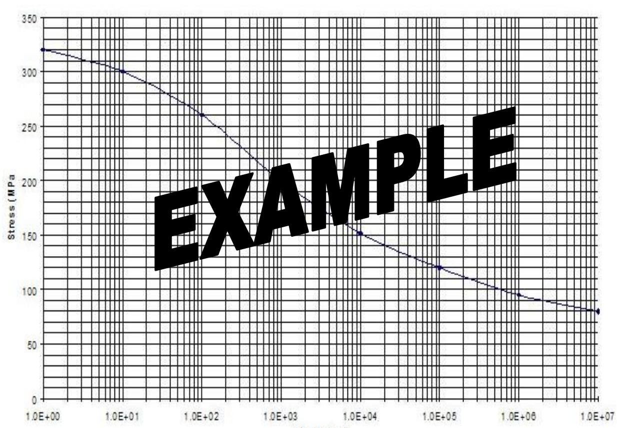


Figure 1: S-N Life Cycle Fatigue Plot

Utilizing Loc's Bending Fatigue Test Stand, the impact of Ferrium C61 material and SuperFinishing on gear life under extreme operating loads were analyzed. See **Figure 2: Gear Bending Fatigue Stand**. This stand actuates a single gear set across the Highest Point of Single Tooth Contact (HPSTC), loading the teeth in a uni-directional fashion. This test method is consistent with the primary operational use for Final Drive gearing.

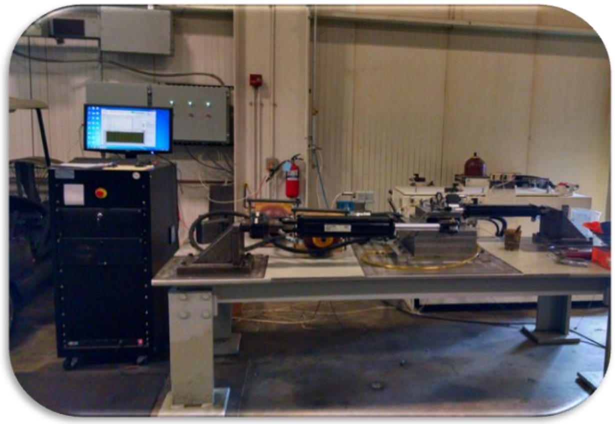


Figure 2: Gear Bending Fatigue Stand

Each gear set sample generates a single point on the plot. This point is generated when a failure occurs. The typical gear failure mode is a crack in one of two of the gear teeth. These cracks characteristically propagate across the root of one gear tooth. See **Figure 3: Common Gear Set Failures** for an illustration of this failure mode. These failures are detected when the stand identifies a loss in force during cycling or a sharp spike in rotational acceleration detected by the load cell or accelerometer.

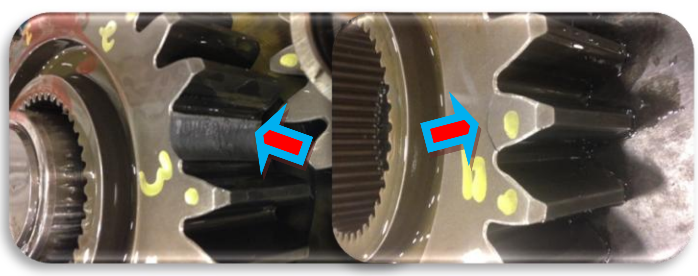


Figure 3: Common Gear Set Failures

By testing and analyzing the fatigue data on numerous samples using survival analysis and polynomial regression, S-N curves were derived for the purpose of data comparison. These curves provided empirical evidence to support the position documented in the conclusion of this report.

In conjunction to the Bending Fatigue Test, Loc has conducted Surface Fatigue Testing. This testing was conducted on Loc's internally designed Final Drive Dynamometer. **See Figure 4: Loc Final Drive Dynamometer.** This testing served to evaluate the effects of Isotropic SuperFinishing (ISF) on gear efficiency as well as gear life. C61 was not tested for improvements in surface fatigue life since surface fatigue is related to surface hardness, surface finish, torque, rpm and lubrication. For comparison all parameters were common except surface finish.

In total, (2) tests were conducted on (2) Final Drive pairs; [(4) sets of gears (4320H w/ISF average Ra 5 microinches & w/out ISF average Ra 30 microinches)] were tested to determine their effective life. Utilizing 15W40 lubricant, all samples were tested in high-cycle fatigue conditions to generate the materials performance data. Loc assessed the impact of ISF on life cycle surface fatigue using ANSI/AGMA 912 Mechanisms of Gear Tooth Failure and ANSI/AGMA 1010 Appearance of Gear Teeth as a guide.

Figure 4: Loc Final Drive Dynamometer

Each gear set sample generates a single data point. This point is generated when a failure occurs. The typical gear failure mode is micro abrasions and gear tooth surface pitting. See **Figure 5: Surface Fatigue Gear Set Failures** for illustrations of micro abrasions and gear tooth surface pitting. These failures are detected during visual inspection thru the port hole in the housing. Testing was paused and observations were made every 100,000 cycles to allow for gear tooth examination and photographic documentation. Due to significant profile shift, wear started at the addendum of the pinion and the dedendum of the gear (location of highest sliding velocities) as documented in the results.

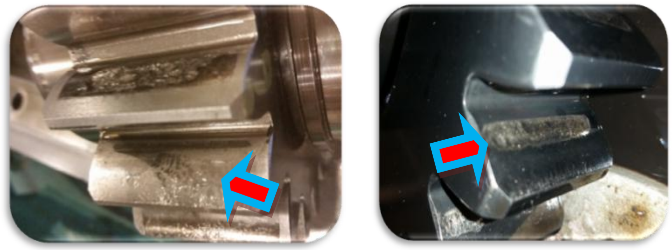


Figure 5: Surface Fatigue Gear Set Failures

Data Decomposition Methodology

<u>Bending Fatigue Stand Test Data Decomposition</u>

1. Torque is converted to stress utilizing ISO 6336.
2. Data is plotted in Excel with the X axis as log10 (cycles) and the Y axis as stress and then using a polynomial trend line to curve fit the data.
3. The baseline 4320H data is then compared to published data for 4320H gearing (SAE 2007-01-1006) to sanity check the data.
4. Performance curves for C61 and ISF technologies were then compared to the baseline 4320H performance.

<u>Mechanical Final Drive Dynamometer Surface Fatigue Test Data Decomposition</u>

1. Evaluate gear surface condition utilizing ANSI/AGMA 912 Mechanisms of Gear Tooth Failure and ANSI/AGMA 1010 Appearance of Gear Teeth.
2. Document finding at 100,000 cycle intervals.
3. Suspend test if surface fatigue fractures exceed guidelines for acceptable wear.
4. Compare life in cycles of baseline 4320H material to 4320H with ISF.

<u>Mechanical Final Drive Dynamometer Efficiency Test Data Decomposition</u>

1. Evaluate gear efficiency utilizing two torque sensors
   a. Torque sensor #1 was placed on the input side of the loaded drive
   b. Torque sensor #2 was placed on the output side of the slave drive.
2. Collect and document torque lost across both drives by subtracting Torque sensor #2 from Torque sensor #1 and divide by input torque which yields the power loss across the two drives.
   a. Data collection on time interval
   b. To derive individual drive power losses, the value above must be divided by two
   c. Efficiency calculated as 100 minus the % power loss

3. Efficiency values of baseline 4320H were compared to values with ISF.

Decomposed Test Results

Bending Fatigue, Baseline Gear Set (4320H)

The Bending Fatigue graph shown in **Figure 6: Common 4320H SN Curves** demonstrates a negative correlation between load condition and the sample life cycle. In other words, as the load increases the life cycle decreases. Additionally, the baseline material has a failure rate correlation equal to an R^2 value of 0.9512. The SuperFinished gears R^2 value is equal to 0.9655 which indicates a slightly higher correlation. These correlation coefficient values were derived by applying a "best fit" curve to the sample data points is a statistical measure of the degree to which changes to the test load value variable relates/predicts the change to the life value. SuperFinishing is believed to have a slightly higher failure rate correlation and increased life cycles due to the fact that the SuperFinishing process removes macro surface defects left during processing which could contribute to stress concentrations and failures. Closer examination of the data scatter showed that SuperFinishing did not change the mean value of the curves. In other words, the ISF mean curves and the baseline curves approximately overlay one another graphically illustrating minimal impact. The main benefit of the reduced data scatter as measured by R^2 result is improved B10 prediction values.

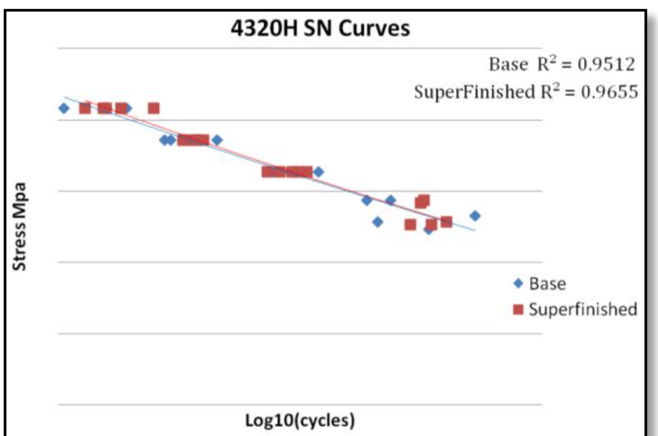


Figure 6: Common 4320H SN Curves

As a means to validate testing procedures/test methodology, the test data was plotted and compared against the 4320H SN curve published in SAE2007-01-1006. The curve comparison can be seen in **Figure 7: Common 4320H SN vs SAE Publication.** This comparison illustrates a positive correlation between the Loc test samples and the published data.

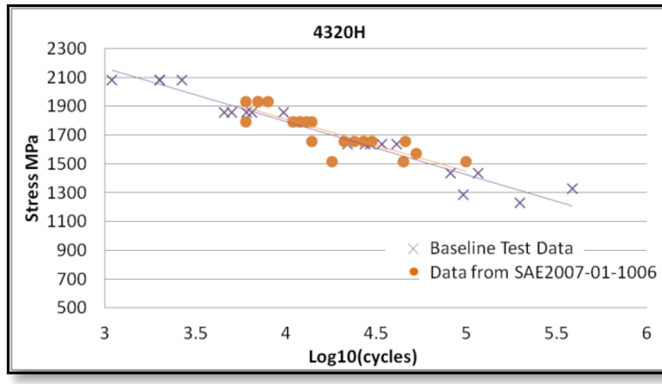


Figure 7: Common 4320H SN vs SAE Publication

Bending Fatigue, Ferrium C61

The Bending Fatigue graph shown in **Figure 8: Ferrium C61 SN Curves** also demonstrates a less linear negative correlation between load condition and the sample life cycle. Additionally, the non-SuperFinished C61 gears have a failure rate correlation value slightly lower than the baseline 4320H. The non-SuperFinished C61 correlation value is an R2 of 0.8414. Conversely, the SuperFinished gears had a higher failure rate correlation value of R^2 of 0.921. Since, the correlation coefficient values were again derived in the same manner as the baseline using a "best fit" curve to the test sample data points; it is believed that the improved failure rate correlation and increased life cycle is due to the fact that the SuperFinishing process removes macro surface defects left during processing which could contribute to stress concentrations and failures.

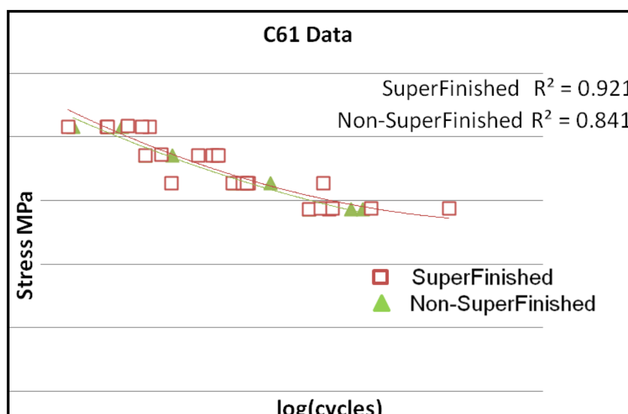


Figure 8: Ferrium C61 SN Curves

Bending Fatigue, Composite S-N Life Cycle Fatigue Plot

The final graph show in **Figure9: Composite S-N Plot** shows the difference between the current baseline material and C61. The test data clearly shows a significant life cycle improvement at the high load and a moderate improvement at the low loads. C61 yielded 8 times the life of the baseline material at high loads and approximately 1.6 times the life at low loads that were tested.

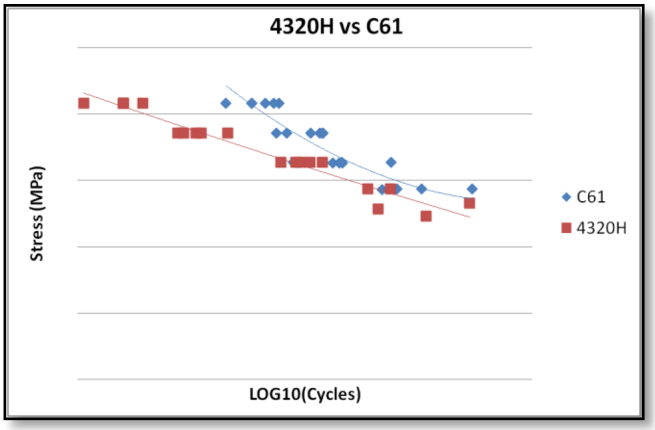


Figure 9: Composite S-N Plot

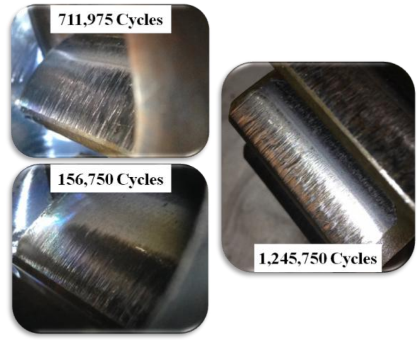
Note, both C61 and 4320H SN curves are both non-linear on a semi-log scale. The non-linearity is a function of case depth, core hardness and the direct positive relationship between hardness to tensile strength. In other words, increased hardness means increased tensile strength.

At very high loads the stresses below the case depth hardness play a major role. Since C61 has a core hardness of ~RC50 verses 4320H core hardness of RC35, the C61 provides greater tensile strength at high loads. At low loads, the core hardness is less at play. Instead, the case depth and surface hardness is the primary contributor. Since both C61 and 4320H were produced with roughly the same case depth and surface hardness, the life cycle results trend together with most of the difference attributed to variations in raw stock cleanliness and manufacturing processing.

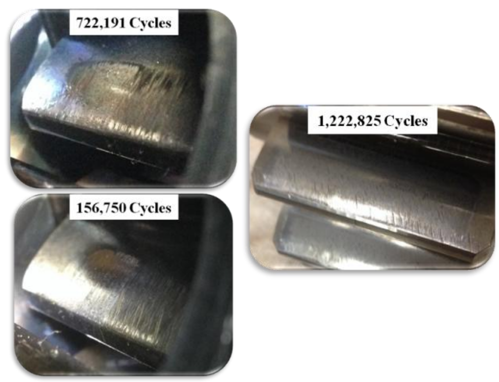
<u>Best Fit Curves to Data</u>
C61 shotpeened and SuperFinished
Stress(MPa)=2.903358E+02*log10(cycles)^2-3.310800E+03*log10(cycles) + 1.081675E+04
R^2=.921563

4320 shotpeened and SuperFinished
Stress(MPa)=1.413595E+01*log10(cycles)^2-4.984059E+02*log10(cycles) + 3.573462E+03
R^2= .9655437

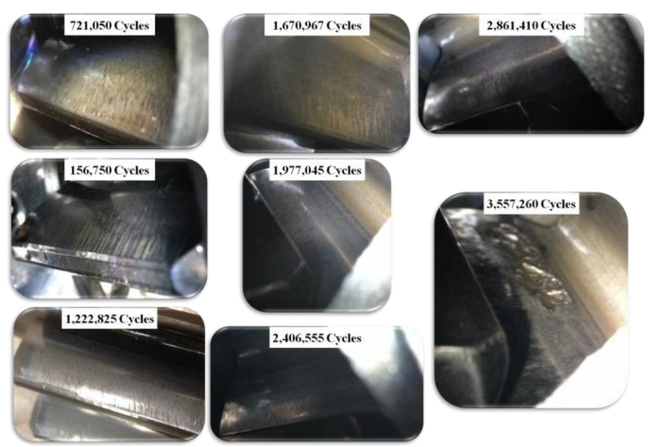
<u>Surface Fatigue</u>
The wear produced in the baseline gear design showed severe scuffing or surface fatigue failures as illustrated in the **Figures 10, 11, and 12**. To evaluate the impact of ISF on gearing, we employed the use of ANSI/AGMA 912 Mechanisms of Gear Tooth Failure and ANSI/AGMA 1010 Appearance of Gear Teeth; Terminology of Wear and Failure. Using these standards the gears were evaluated for wear and tooth surface failures. The figures clearly illustrate the relationship between cycles to surface fatigue as they relate to the selected test samples.



Figures 10: Surface Fatigue (Baseline 4320H) Cycles vs Wear



Figures 11: Surface Fatigue (Baseline 4320H w/ ISF) Cycles vs Wear



Figures 12: Surface Fatigue (Baseline 4320H w/ ISF) Cycles vs Wear

The results of this study clearly show the benefits of ISF on surface fatigue failures. In short, to progress to the same level of surface wear the SuperFinished gears were tested 3X the number of cycles (~3.6 million) as compared to the non-SuperFinished samples (1.2 million).

Final Drive Dynamometer, Efficiency Plot

The final graph shown in **Figure 13: Composite Efficiency Plot** shows the impact of the SuperFinishing process on the current baseline 4320H gear design. The test data shows a significant reduction in heat generation as seen by the fluid to air delta. The drive losses were reduced 9% which is evidenced by the reduction in operating temperature.

Losses are determined by torque measured input to drive 1 and output torque of drive 2.

$$\text{Losses} = \frac{\text{Input torque-Output torque}}{2\text{*Input Torque}}$$

Assumes each drive contributes half the torque loss results

Technology	Efficiency	Losses
SuperFinished	98.42%	**1.58%**
Non-SuperFinished	98.27%	**1.73%**
Difference	0.15%	9%

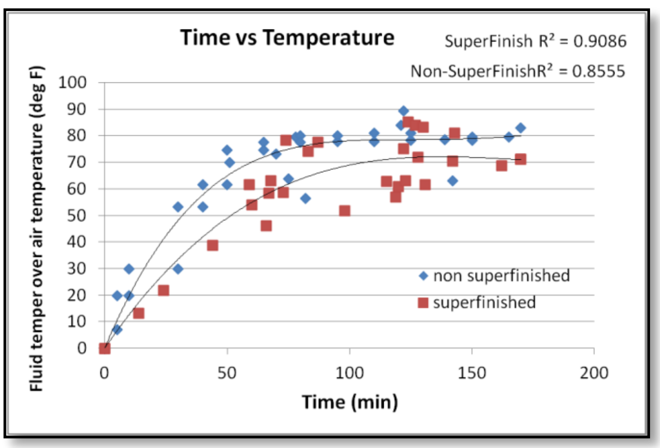


Figure 13: Composite Efficiency Plot

Conclusion

Loc's alignment of application, material (C61) and manufacturing processes offers a real option to increase Final Drive power density without a major redesign effort. The precision manufacturing and the high strength nature of Ferrium C61 allows for increased torque capability without increasing package space.

The Bending Fatigue Test highlighted Loc's improved design yielded approximately 8 times the number of life cycles vs 4320H at peak load and offers approximately 1.6 times the life cycles under decreased loads.

Additionally, this design benefited two-fold by ISF. First, and most significantly, SuperFinishing extended Surface Fatigue life. Testing concluded that the Surface Fatigue life extended to nearly 3x the number of cycles as compared to the baseline design. Finally, the SuperFinishing process has a modest impact on gear efficiency performance. A 9% reduction in energy losses and a significant lubricant to air temperature delta was recorded which is consistent with the measured decrease in power losses.

The technology developed for addressing power density needs for the future Bradley Fighting Vehicle is available for addressing similar needs on other military platforms that are challenged with vehicle platform weight growth. This technology presents an affordable option for increasing horsepower capacity of geared systems without adding weight, space, or requiring expensive structural vehicle upgrades to package larger, heavier geared solutions.

References

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