International Journal of Engineering Research ISSN:2319-6890)(online),2347-5013(print)
Volume No.3 Issue No: Special 1, pp: 101-105 22nd March 2014

Experimental investigation on fatigue failure of spur gear teeth under elasto hydrodynamic lubrication conditions

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Abstract-**This study consists of experimental study involve gear contact fatigue failure: gear pitting spalling). For pitting studies, several materials and surface treatments were investigated at various stress levels. These surface treatments included (i) hobbed and shaved (baseline)(HS), (ii) chemically polished(CP) and (iii) shot peened and plastic honed(SP+PH). Pitting fatigue lives of chemically polished gears were greater than those of baseline specimens. Both shot peened and plastic honed gears and ground gears were shown to have greater pitting fatigue lives than baseline gears. The improved pitting fatigue life of ground gears over baseline gears appears related to the improved involute profile shapes of the specimens.**

Keywords— Gear pitting, Hobbed and shaved , Chemically polished, shot peened and plastic honed, oordinate measurement Machine.

I. Introduction

Within geared transmissions, gear failures occur in many ways and often without advanced notice. While engineers have developed, over the years, a greater understanding of these failures, there is still a need for a thorough understanding of how involute gears fail and how they can be made to last longer. There are many types of gear failures, each influenced by a variety of gear, surface, lubricant and contact parameters. This study focuses on one of these failure modes, namely gear pitting (spalling).Pitting develops over time from recurring contact stresses between the teeth of two gears during rotation. Pitting can be described as visual surface fractures on the gear teeth usually preceded with hairline cracks that develop on or below the tooth surface. Once gear pitting has initiated, gear noise may become more prevalent and the gear surface continues to degrade until complete gear failure has occurred.

Kaneko [1] did an extensive study on gear pitting with various carbon and alloy steels. In the study, quenched and annealed gears made of CrMO steel alloy and a carbon steel were subjected to various loads in a power circulation loop configuration similar to the FZG machines described later in this thesis. Flame hardened and induction hardened test specimens, which were ground afterward to remove heat treatment deformations, were also made of the same two materials. The hardened specimens were able to endure higher loads and the CrMo steel alloy had greater pitting fatigue life than samples made of carbon steel. Also in the study, NiCrMo and NiCr carburized steel gears were subjected to pitting tests and endured the highest loads. The NiCrMo carburized steel specimens had greater contact fatigue lives than those made of NiCr carburized steel.

In a study by Townsend *et al* [2], the pitting fatigue lives of spur gears was studied using two different materials while keeping other variables, such as speed (10,000 rpm), hardness (HRC 62), and inlet lubricant temperature (170ºF ± 5ºF), constant. Specimens manufactured from the AISI M-50 steel had 50% longer pitting contact fatigue lives than those manufactured from Super Nitralloy (5Ni-2Al). In addition to having longer contact fatigue lives, the AISI M-50 specimens had more wear than the Super Nitralloy gears. In the study, these differences in contact fatigue lives, as well as wear, were noted as not being statistically significant.

In a study by Bluestein [3], the influence of contact stress variations on gear pitting fatigue life was studied extensively. Bluestein, along with the sponsor of his study, produced a variety of successful gear contact fatigue experiments. In those experiments, various torque loads were applied to the gear specimens in order to determine the influence of contact stress amplitudes on the pitting contact fatigue life of the gears. In addition to contact stress variations, the influence of various surface treatments on the contact fatigue life of the specimens was also studied. All of these surface treatments were also tested at different torque settings. In Bluestein's experiments [3], tests at each test condition were repeated several times in order to provide statistically meaningful sets of data. With this data, the probabilities of pitting failure under each load for each surface treatment were calculated. Additionally, Weibull analysis was applied for various sets of data in order to provide a failure analysis comparison between identically loaded gears with different surface treatments.

II. Material and Methodology

The spur gear specimens utilized for experimental testing in this study work had identical gear geometries to those utilized by the sponsor during the phase-one study and those tested in the study by Bluestein [3]. Design parameters of the test gear pair is shown in Table 1. All tested gear specimens were heat treated to a surface hardness value of 60 HRC with a case depth of approximately 1.3 mm. The test gears were made of AISI 8620 and AISI 4620M steel alloys.

International Journal of Engineering Research
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ISSN:2319-6890)(online),2347-5013(print)
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Table 1: Basic design parameters of the spur gear pair.

Parameter	Pinion	Gear
Module (mm)	4.23	
Center Distance (mm)	91.50	
Number of Teeth	17	26
Pressure Angle (deg)	22.5	
Face Width (mm)	14.00	20.29
Pitch Diameter (mm)	71.97	110.07
Base Diameter (mm)	66.49	101.69
Outside Diameter (mm)	80.02	117.11
Root Diameter (mm)	62.87	99.95
Start of Active Profile (mm)	67.92	105.33
Circular Tooth Thickness (mm)	7.81	5.65

As can be expected from the wide variety of gear surface treatments tested in this study, the average initial roughness amplitudes varied with each surface treatment. In Table 2, the average *Ra* values obtained with the Talysurf surface profiler before testing are listed for each of these surface treatments. The surface roughnesses for the CP specimens were significantly less than those for the HS specimens, as well as all other specimens in this study. It should be noted that the tests performed in this study with the HS, CP, and SP+PH specimens were performed with the same batch of gears produced by the sponsor during the phase-one study.

Table 2: Average initial *Ra* roughness values for various surfacetreatments

Surface Treatment	Average Initial Roughness - R_a (μm)
HS	0.35
CP	0.10
SP+PH	0.33
GD8	0.38
GD4	0.39

Table 3: Test Load Levels and their related normalized torques and contact stresses.

Load Level	Normalized Torque	Normalized Pitch Line Contact Stress	Normalized Maximum Contact Stress
L1	3.81	1.55	1.62
L2	3.27	1.46	1.53
L3	2.67	1.35	1.42
L6	1.94	1.20	1.26
L4	1.73	1.16	1.22
L5	1.20	1.03	1.09

The torque levels and their corresponding maximum pitch line contact stresses were normalized by dividing these values by a reference torque *TR* and reference contact stress *σR*, respectively. These reference values were identical to those used by Bluestein [3]. The normalized values for input torque and pitch line contact stress for each of the load levels tested during these experiments are shown in Table 3 .A test was concluded when the specimens failed under one of the three criteria defined prior to the test program. These failure criteria are as follows:

1. Total area of pits on a single tooth is greater than 3.8 mm2 (0.00589 in2)
2. Total area of pits on all teeth greater than 16 mm2 (0.025 in2)
3. Maximum surface wear on any of the measured teeth exceeds 25 μm (0.0010 in) for SP+PH tests and 12 μm (0.0005 in) for all other tests.

The first two failure criteria were included in the pitting database as tests with successful pitting failures. The tests with the third failure criterion were included in the database as tests with excessive wear. The majority of successful tests resulted in a single tooth pitting failure (the first criterion). The area of the surface pits was obtained utilizing calibrated software, which measured the dimensions of tooth pits at a 5X magnification. Confidence intervals, similar to those in Bluestein [3], were also calculated when at least five data points were available at each test load level. The equation used for calculating the confidence interval is

$$C = \bar{x} \pm z\left(\frac{p}{\sqrt{n}}\right)$$

where is the confidence interval, is the mean (i.e. 50% confidence interval), the value is 1.645 for a 90% confidence interval, is the standard deviation, and is the number of data points. Tests suspended for wear were not considered in these confidence intervals.

Experiment Test Set - Up

Experimental contact fatigue tests utilizing spur gears were performed using three similar FZG gear test machines. These FZG machines create a four-square power circulation loop, within which specified test torque loads are applied. A schematic of the FZG machines used for testing in this thesis is shown in Figure 2.1. The FZG machines have two gearboxes each. The reaction gearbox on the motor side includes a reaction gear pair which has a greater face and hence very low contact stresses and greater life expectancy than the test gears. The reaction gearbox used a more viscous gear lubricant to offer greater wear protection to the reaction gears. The test gear pair is installed in the test gearbox farthest from the motor. This allows greater accessibility to the test gears for easier visual and measured inspections.

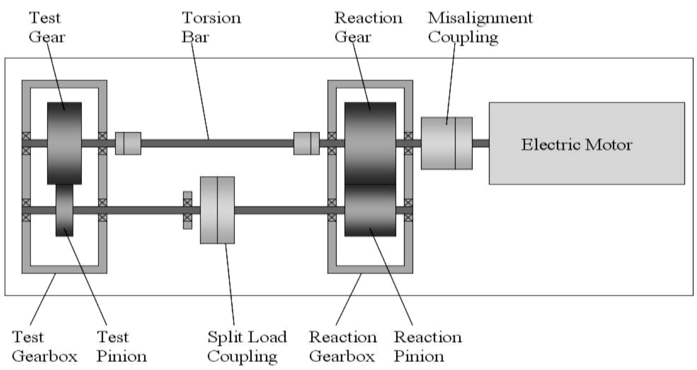

Figure 1: A detailed FZG schematic from Bluestein [3].

Initial tests performed by a sponsor used Dexron III automatic transmission fluid as the lubricant. Another variation, Dexron VI, was used in pitting tests performed by Bluestein [3]. Dexron VI was also used for all testing performed for this thesis study. Although there were concerns for potential disparities in the

ISSN:2319-6890)(online),2347-5013(print)
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results from the use of these two lubricants, these differences were found to be insignificant when fatigue data for these two lubricant variants were compared. For this reason, the test data sets for each lubricant have been combined into one data set.

After the spur gear pairs were installed within the FZG machines, the lubricant was used at the start of each test, and the same fluid was used throughout the test until the test was completed. During the progression of a test, any metallic debris that might be produced due to wear or small pits on the pinion surface were separated from the oil bath through a magnet placed at the bottom of the gearbox.

III. Results and Discussions

In previous testing preformed by Bluestein [3], the majority of experimental tests were performed at higher torque values. These high torque values produced a large number of successful experiments in a relatively short period. In order to obtain confidence data for lower torques and contact stresses, the majority of testing included in this thesis involved lower loads. All tests performed in this study had procedures and failure criteria that were consistent with the original study.

For the tests using Hobbed and Shaved (HS) gears, there were a total of 50 successful tests (46 pit failures and 4 suspended tests). Of these successful tests, 8 tests (5 pit failures and 3 suspended tests) resulted from this study. One suspended test occurred at load L6, and the rest of the tests occurred at load L4. Stress-life (S-N) charts for normalized contact stress of the HS tests is shown in Figures 2.

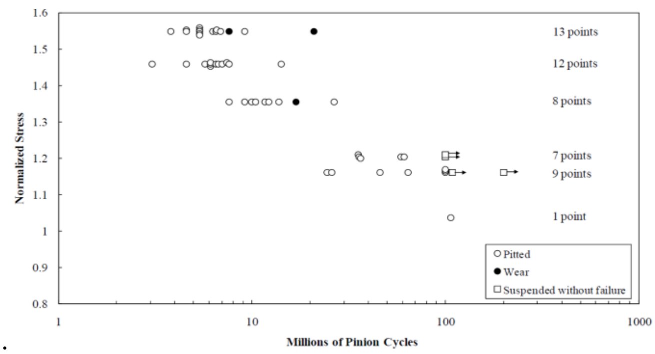

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Figure 2: Normalized pinion pitch line stress versus pinion cycles for HS gears.

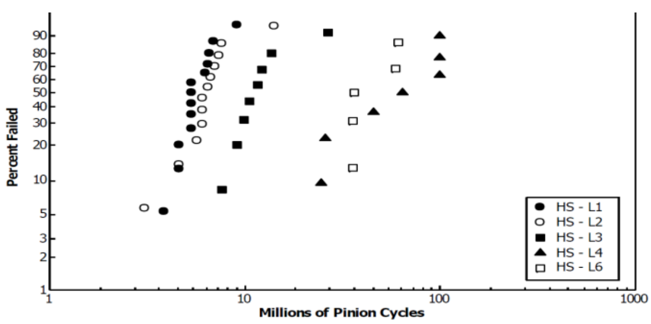

Figure 3: Weibull distributions of HS pitted tests at different load levels.

In Figure 3, Weibull distributions were calculated for each of the load levels of the HS tests.

Compared to the large number of HS tests, the total number of successful Chemically Polished (CP) tests was only 32 (30 pit failures and 2 suspended tests). The S-N charts for these data points are shown in Figure 4 . Six of these tests (5 pit failures and 1 suspended test) at load L6 resulted from experiments in this study. Although there were a smaller number of CP tests, the number of tests was great enough to calculate the confidence intervals at L6. Previously, in Bluestein [3], the confidence intervals were calculated for loads L1, L2, and L3. In Figure 5, the data points and confidence intervals in this study along with those determined previously are shown. As performed for the HS test results, Weibull distributions were also calculated for CP tests at various loads. If there were five or more successful pit failures at a particular load, Weibull distributions were calculated. When comparing the CP 50% Confidence Interval test results with the HS 50% Confidence Interval, the contact fatigue life of CP gears is substantially longer than the life of HS gears at all load levels. With the addition of the HS and CP test points obtained in this study, a better comparison between the two surface treatments at lower loads was possible.

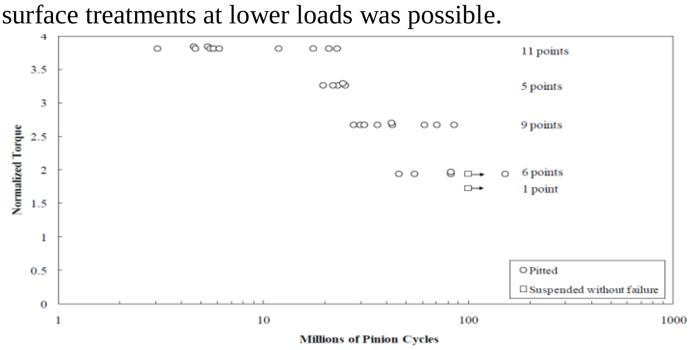

Figure 4: Normalized pinion torque versus pinion cycles for CP gears.

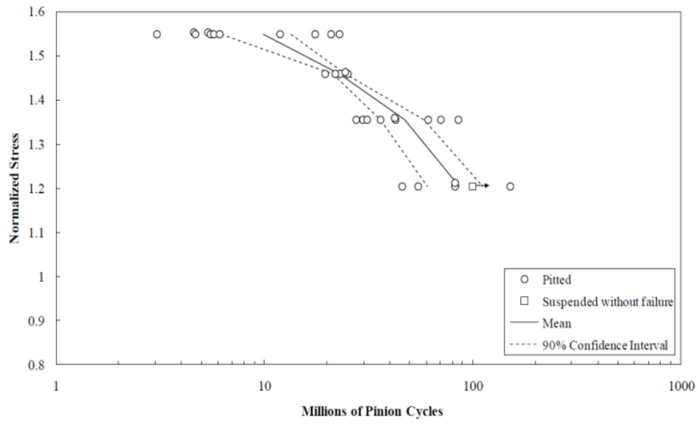

Figure 5: CP pitted and suspended tests with 90% Confidence Intervals.

A large portion of surface treated specimens included in this study were Shot Peened and Plastic Honed (SP+PH). Combining the tests in this study with those previously conducted by Bluestein [3], the total number of successful tests for SP+PH specimens was 15 with 12 tests occurring from pit failures and 3

International Journal of Engineering Research ISSN:2319-6890)(online),2347-5013(print)
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tests suspended. In addition to these successful tests, 5 tests reached the 25 m wear failure criterion. Of the successful SP+PH tests, 8 pit failures, 1 suspended test, and 4 wear failures occurred during this study. The S-N curves for normalized pinion torque and normalized pinion contact stress of SP+PH specimens are shown in Figure 6 and Figure 7, respectively.

For the SP+PH surface treatment, the limited number of tests did not allow for the calculation of confidence intervals at most load levels. However, Figure 8 shows a comparison between the SP+PH data points along with the confidence intervals for both HS and CP gears. Most of the successful SP+PH tests had a greater contact fatigue life than the 50% confidence interval for HS gears. From this figure, it is observed that 13 of the 15 successful tests had a greater number of cycles than the corresponding 50% HS confidence interval at the same load level. When trying to make a comparison of SP+PH specimen results with CP confidence intervals, the task is difficult due to the small number of successful data points. Although load level L3 has 8 data points, the data points range from the lower 90% HS confidence interval to above the upper 90% CP confidence interval.

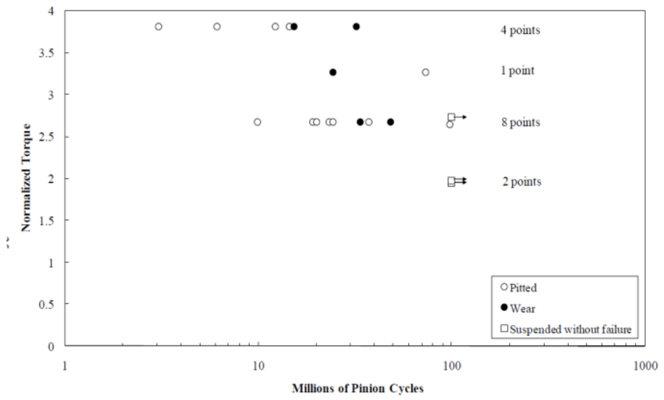

Figure 6: Normalized pinion torque versus pinion cycles for SP+PH gears.

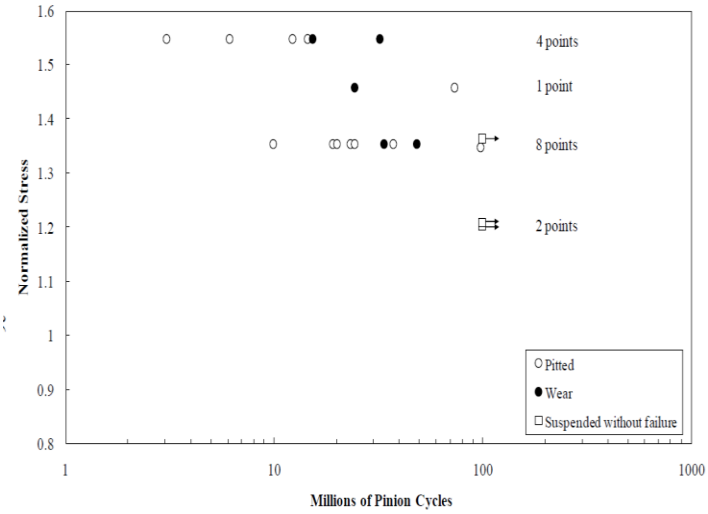

Figure 7: Normalized pinion pitch line stress versus pinion cycles for SP+PH gears

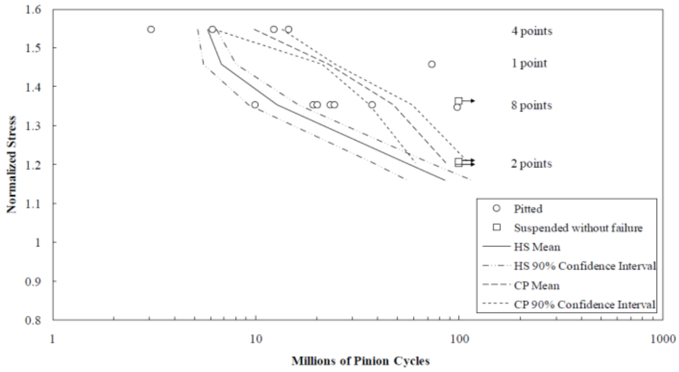

Figure 8: Pitted and suspended SP+PH tests versus 90% Confidence Intervals for HS and CP pinions.

Another method of comparing SP+PH specimens with those from HS and CP tests is with the creation of a Weibull distribution for each of the specimens at the L3 load. In Figure 9, Weibull distributions for each of the three surface treatments are shown at load level L3. From this figure, it appears the SP+PH specimens have a greater contact fatigue life at the same load as the HS gears; however, these SP+PH specimens do not have contact fatigue lives as great as those from the CP tests. A better comparison between SP+PH gears and CP specimens can be made when comparing Weibull distributions of the two surface treatments at different load levels.

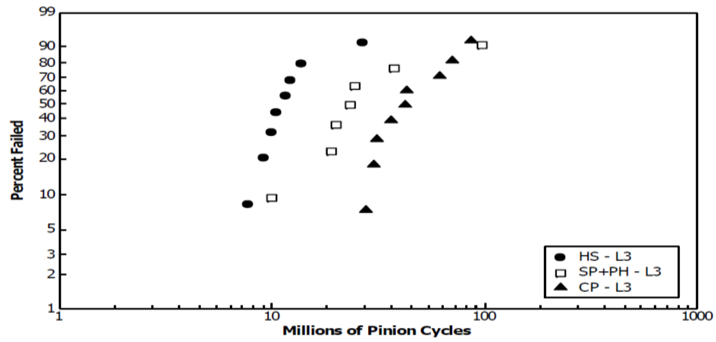

Figure 9: Weibull distributions of HS, SP+PH, and CP pitted tests at load level L3

IV. Conclusion

Based on the tests results presented in the previous section, the following conclusions can be listed in regards to the effects of surface treatments and material variations on fatigue pitting of gears:

1. At lower load levels, the expected fatigue life for CP gears was significantly longer than that for HS gears at the same load. However, the difference in measured fatigue life was not as great at higher contact stress conditions.

2. SP+PH gear specimens showed a greater tendency to wear, much more than HS and CP gears at the same loads. Although the amount of acceptable wear was doubled for SP+PHtests, 25% of the tests still exceeded that increased wear limit.

3.Available tests suggest SP+PH specimens have greater fatigue lives than HS gears at the same loads. Further testing is needed to better determine the significance of these differences between SP+PH gears and tests for HS and CP specimens at loads other

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