

Fatigue Performance and Residual Stress of Carburized Gear Steels Part II: Fatigue Performance

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ABSTRACT

Part II of the paper focuses on fatigue tests of four specific gear steels: SAE 4320, SAE 8822, PS18, and 20MnCr5. Fatigue life, S-N curves are experimentally generated for all steels at low cycle fatigue and high cycle fatigue. The failure stresses at cycle one and slope of the linear portion of S-N curves are determined based on the experimental data. Endurance limits were tested. Uncertainty in the fatigue data is analyzed in details and values of sigma are calculated. Design curves were estimated based on the fatigue test results.

1. INTRODUCTION

Fatigue life in powertrain applications is an important concept to understand since powertrain components are often subject to high stress cyclic loading [1-3]. Fatigue is a failure mode that takes place in gears that are subjected to dynamic and fluctuating loading conditions. The *American Society of Metals* states that fatigue failure is estimated to account for at least ninety percent of all service failures that are due to mechanical causes. The origin of fatigue failure arises from the initiation and propagation of cracks in materials perpendicular to the direction of applied stress. There are three basic circumstances that may lead to eventual fatigue failure, e.g., the maximum tensile stress of considerably high value, a large variation between the maximum and minimum load conditions, and a large number of cycles of applied stress variation [4]. In addition to these three major factors, there are many other variables such as stress concentration, corrosion, temperature, overload, metallurgical structure, residual stresses, and combined stresses that can affect the fatigue life of a material. Fatigue failure can also be accelerated with the inclusion of certain geometric elements such as sharp corners or notches in the specimen or at a metallurgical defect point such as an inclusion.

Engineering fatigue data is presented by means of a basic S-N curve. The S-N curve is a plot of bending stress, S , on the Y-axis against the number of cycles to complete fracture, N , on the X-axis (unless N is otherwise

indicated). Since the number of cycles can be potentially infinite, a logarithmic scale is generally used for the X-axis. The values of stress do not necessarily have to be adjusted for stress concentration and are usually plotted with values of the amplitude of the stress cycles, range of the stress cycles, maximum or minimum of the cyclic stresses [4, 5]. In this paper, S is defined as the range of the nominal stress which is calculated using the load range between the max and min load. The S-N curve is chiefly designed to portray the stress to cycle characteristics of a material at high cycle operation ($N > 10^5$). Higher applied stresses correspondingly result in a lower fatigue cycle life ($N < 10^4$ or 10^5). Fatigue tests at small stresses can last 10^7 cycles for ferrous metals and 5×10^8 cycles for nonferrous metals. Many ferrous S-N curve plateau at some level of stress where the material can hypothetically endure an infinite number of cycles without any observable failure. This plateau is an inherent property of steels and is often called the endurance limit or fatigue limit. This statement, however, is only valid in cases where no external variables such as temperature and corrosion affect the system. The S-N curves of non-ferrous metals like copper and aluminum never becomes horizontal in which endurance strength is set at a very high number of stress cycles on the scope of 10^8 cycles.

2. TECHNIQUES AND METHODS

In order to define the S-N fatigue curves for comparison purposes for the four gear steels: SAE 8822, SAE 4320, PS18, and MnCr, great care was taken to keep all testing parameters as consistent as possible and to follow a test plan that was accepted in academic circles as well as industry. The American Society for Testing and Materials published ASTM E 739 – 1980 which was the first test that was considered for this experiment [6]. This style of test uses a linear S-N model and the least squares method in order to build a statistical analysis of linearized fatigue data. The assumptions for this test are that the cycles to fatigue are log normally distributed and that the variance of log life is constant over the tested range. This test also requires that six to twelve levels of stress be used during fatigue testing for research purposes and

twelve to twenty-four levels for reliability tests. Furthermore, the amount of replication at each level is dependent on the final use of the data.

The Japanese Society of Mechanical Engineers published the next test that was considered: the JSME S 002 – 1981. This test requires that fourteen specimens be used for each material during the fatigue tests. The specimens are divided so that eight samples are used to develop the finite portion of the curve and so that six specimens are used for the endurance limit using the staircase method. The eight samples that are used for the finite portion of the curve are further divided into four equally spaced stress levels. This allows each stress level to be tested with a minimal sample size of two specimens. The staircase method only requires one specimen per level so that the fatigue limit is determined by taking the average of the last stress level of failure and the first stress level of suspension, or non-failure. This test assumes that the finite life region of the S-N curve is linear; therefore the data is analyzed by the least squares method. Both test methods are adequate, however, since a good endurance limit is needed and since specimens are limited, the JSME test was chosen. The JSME test will be slightly modified by adding one extra test sample to each of the four levels so that a statistical analysis suggested in ASTM standards can be completed on the data.

3. FATIGUE TEST PROCEDURES AND DATA

The notched samples designed in part I of the paper are used for test tests. Originally, there were twenty-five samples for each material. Two samples were spent for residual stress measurement, three samples were spent for ultimate testing, and the remaining twenty samples were designated for fatigue testing. Some additional spare samples were applied toward machine calibration or were spent as backup parts during various stages of testing.

The same three-point bending fixture designed in Part I of the paper is used to apply bending loads to the notched samples. The mechanics of how the notched specimen will react to the applied forces is shown below. This analysis was completed in order to determine the types of stresses found in the cross sectional area at the base of the notch. Illustrated below in Figures 1 (a)-(b) is the free body analysis of the three point bending specimen used in this research. The maximum bending stress is at the notch root which is equal to nominal stress, S , of an un-notched bar multiplied by the stress concentration factor. The nominal stress analysis can be completed using a simply loaded bar shown in Fig. 1 (b). The reaction forces, R , and applied forces from the fixture, P , are determined.



Figure 1a. Bending stress relationship within a notched bar

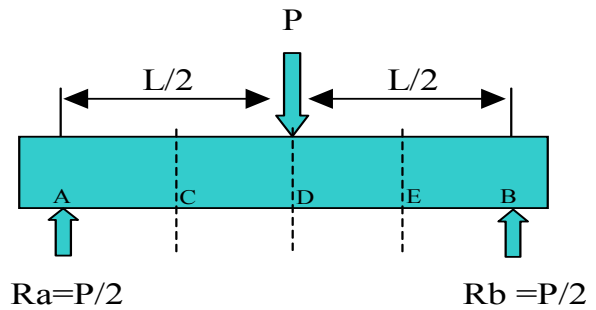


Figure 1b. Applied and reactive force free body diagram

The maximum bending moment and shear stress are at the middle of the bar. The maximum bending moment and nominal stress S and the maximum stress can be calculated as follows.

$$M = \frac{P \cdot L}{4} \quad (1a)$$

$$S = \sigma_{nom} = \frac{MD/2}{I} = \frac{3PL}{2WD^2} \quad (1b)$$

$$\sigma_{max} = \sigma_{nom} \times K_t \quad (1c)$$

As shown above, stress as shown in the S-N curve is designated by nominal bending stress, S . By taking Equation 1a and 1b and the load range, $P_{max} - P_{min}$, the bending stress can be plotted on the S-N curve. This method is the most usual approach for calculating stress on the S-N curve.

During fatigue testing, the load P cycles between a maximum value P_{max} and a minimum value P_{min} . The bending stresses in the notched sample alternate between maximum and minimum values ($\sigma_{min} \leq \sigma \leq \sigma_{max}$). The components of a fluctuating stress cycle include a mean stress σ_m and an alternating stress σ_a , and a range of stress σ_r . These components will be used to properly plan fatigue testing. The stress range is the difference between the maximum and minimum stress in a cycle. The alternating stress σ_a is half of stress σ_r . The additional stress ratio, R of minimum stress to maximum stress, is used to set up a fatigue test and to accurately depict the collected data. The stress S is calculated according to equation 1b where P is alternating load taken as range of $P_{max} - P_{min}$. In the three point bending test, the load P must be compression all the time. The cyclic stresses on the notched side of the sample are always in tension. The mean stress is positive. To simulate real gear applications, an R value of 0.2 was chosen for all tests that occurred for this research. During fatigue testing, the mean load (or set point) and the amplitude (or span) of the cyclic loading must be programmed in the MTS machine. These load control values were determined by algebraic manipulation of the stress ratio R for a given maximum load value P_{max} . Fatigue tests were performed at four stress levels between the ultimate load and the theoretical endurance limit load which is

about one third of the ultimate load. Each level of stress will be tested on three samples. Each sample was tested to failure or suspension if number of cycles extends to greater than one million. The JSME test will be utilized for the endurance limit with six samples by employing the staircase method.

The MTS 407 controller was set up in order to provide test criteria to MTS machine. The controller not only sends commands to the load cell, but it is also capable of measuring conditions such as applied load, displacement of the lower jaw, and error between commanded and actual measures. For this series of testing, the controller was set to load control parameters with displacement monitoring. This meant that the test conditions would be applied based on a load command and displacement could still be read. In order to apply load to the specimens, the set point and span were input into the function generator of the controller based off of calculations from earlier sections of this thesis. The wave pattern was set to a sine wave and the tests were run until failure or until the specimen passed one million cycles. When the test lasted more than a million cycles, the endurance limit was deemed to have been reached and the test was suspended.

The last setup criteria, was the speed, or frequency, of the cyclic test. Basically, the testing frequency was defined in Hertz for the amount of complete load cycles would occur within one second. Fatigue testing theory suggests that the cyclic frequency has no affect on the test as long as the increase in temperature due to high rate of movement is controlled. The temperature increase, if high enough, could potentially change the results of fatigue testing. For the tests that were anticipated to be in the low cycle, finite,

portion of the curve a frequency of 10 Hertz was chosen. The reason for this choice was two fold. One was the safety concern because the low cycle tests were operated at a high range between maximum and minimum load. The second reason was due to machine performance and error. At high frequencies the controller would send out a signal to reach a certain load, but by the time the machine began to fulfill the load command, the controller would send out a new signal to load in the opposite direction. This caused the MTS machine to only reach a low cyclic load. The frequency had to be turned down to endure that the MTS machine could keep up with the controller commands. When a more advanced servo valve was purchased for the MTS machine, a high frequency of 35 Hz was used for high cycle testing which last more than a millions of cycles. Lastly, the controller was tuned independently for each high cycle test to ensure that the maximum and minimum loads were being reached.

4. FATIGUE RESULTS AND DISCUSSIONS

Fatigue test results are cataloged in Table 1 along with the corresponding S-N curves in Figures 2 (a-d). The table shows the range of load, $Pr = P_{max} - P_{min}$, the levels for the cyclic loads, and the corresponding bending stress that is calculated by using equation 1. The table also signifies where the fatigue test was suspended past one million cycles with a greater then symbol (>). The low cycle areas of the S-N curves are plotted using the least square fit of the cycle counts for each level of stress among all three tested samples. The endurance limit is plotted using the average value of the last stress level of failure and the first stress level of suspension.

Table 1. Fatigue test results for load and cycle count

Level	Load Range kN	Bending Stress MPa	Material	Cycles to failure or suspension (>)			
				1	2	3	Average
1	21.808	465.42	4320	1286206			>1286206
2	23.2	495.13		2006828			>2006828
3	24.128	514.94		2707704			>2707704
4	25	533.55		59770			59770
5	25.984	554.55		44035			44035
6	27.84	594.16		35434	39645		37540
7	30.97	660.96		15701	17616	12649	15322
8	34.8	742.70		8162	3940	4272	5458
9	37.12	792.21		1915	2244	1480	1880
Ø	57.88	1235.27		1			1