

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

Justin John and Keyu Li
Oakland University

Huaxin Li
Vibracoustic North America (A Freudenberg-NOK Company)

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ABSTRACT

This particular study focuses on four specific gear steels: SAE 4320, SAE 8822, PS18, and 20MnCr5. Notched specimens are manufactured from the four materials. Three point bending experiments were conducted which include ultimate tests and fatigue tests. Part I is on ultimate test only. Part II will concentrate on fatigue testing.

In order to see how the carburization affected the fatigue performance of these steels, a residual stress test was performed on one sample of each steel by mean of the incremental hole drilling method. The compressive stresses were found in all four steels with minimum and maximum stress approximately equal. This suggests that the residual stresses are biaxial in the carburized steel case. The difference between the maximum and minimum stresses is within 37% for all steels. The residual stress after the carburization process were found to be highest in the 4320 steel and SAE 8822, followed by PS 18 and then MnCr.

1. INTRODUCTION

Notched samples are used as they simulate the geometry of the gear teeth and generate a stress concentration at the notch roots. Maximum stress exists at the notch roots where fatigue failure usually occurs first [1, 2]. The notch geometry is the same for all samples of the four steels, as well as other dimensions of the testing samples. Except the compositions of the four steel materials, the other variables are intentionally kept the same for sample dimensions and preparation and testing conditions which are discussed below.

2. TEST SAMPLES AND FIXTURES

The three point bending specimen seen below in Figure 1 is a common design used for fatigue testing and is intended to simulate a tooth notch of a ring gear [3, 4, 5]. The geometries of the specimens were intended to produce a core hardness value and a case-to-core

thickness ratio comparable to that of a heavy-duty truck's hypoid ring gear. For each of the four steels, twenty five three-point bending specimens are created for testing. The bars were then machine ground in order to produce a uniform surface finish. The steel samples were sent out to be carburized. Carburization occurred at a normal carbon potential of 1% and quenched in oil. Oven temperature was 1700° F.

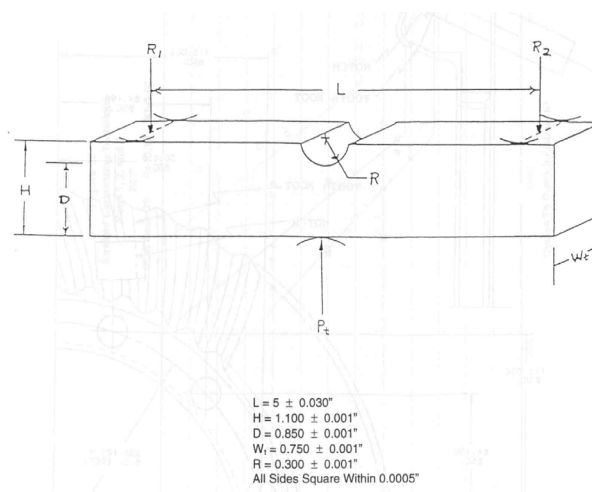


Figure 1 The geometry of the 3 point bending specimen

Figure 2 below shows the final design of the sample fixture used for the three point bending application. An aluminum holder was designed for the three load supports. The fixture was designed with a "T" shaped cross section so that that load-testing machine could grip the fixtures during testing. The supports were located on the aluminum holders with steel pins and were joined together by using heavy duty double sided tape. This tape ensured that the fixture would not drop to the floor when the specimen broke. At the top of the supports is the point of loading for the specimen. The three supports are topped with hardened steel rollers that are contained within brass bearings so that line contact is made with the specimen (thus creating the three point bending condition).

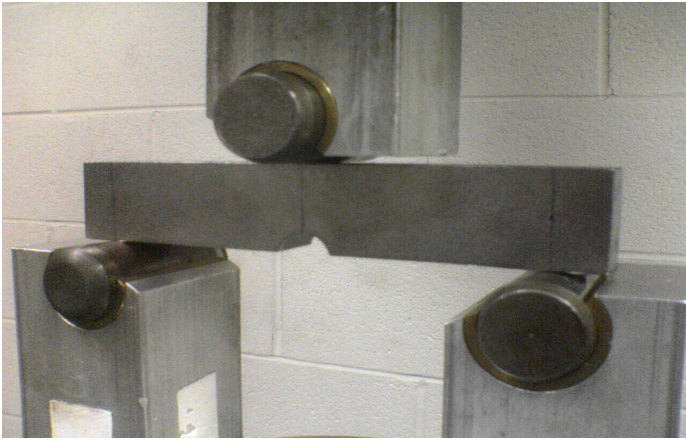


Figure 2. The three-point fixture loading a test specimen.

3. TECHNIQUES AND METHODS

The nominal stress in the beam is calculated using classic beam theory with the key material properties shown in fig. 1. The stress concentration at the notch root of the beam is defined as the ratio of the maximum stress at the notch root to the nominal stress. The load can be calculated given the other parameters.

$$\sigma_{nom} = \frac{3PL}{2WD^2} \quad (1a)$$

$$K_t = \frac{\sigma_{max u l}}{\sigma_{nom}} \quad (1b)$$

$$\therefore P = \frac{\sigma_{max u l} WD^2}{6 \left(\frac{K_t}{2} \right) \left(\frac{L}{2} \right)} \quad (1c)$$

The stress concentration factor, $K=1.628$, was looked up from standard handbook of stress concentration factors for bending of a bar with a U-shaped notch on one side [6].

3.1 Ultimate test method

For the heat treated/carburized case on the surface, the ultimate load was calculated using eq. (1c) as 15.62 kips. The ultimate load for the original steel at the core of the sample is determined as 8.48 kips. The plan for the loading of the MTS machine is that loading will begin from zero and the load will quickly increase until approximately 6000 pounds or 26.7 kN. From that point on gradual increases will be made until failure. The ultimate strength test requires two objectives to be met. One is that the ultimate strength required to crack the carburized case has to be recorded. The other objective is that displacement data has to be recorded as load is being applied to the specimen. Once the displacement data is taken, then stress strain curves can be generated for the materials. In order to collect this data, a data acquisition program was created that would measure the output

voltage coming from the testing MTS machine for both load and displacement of the specimen to electronically save data in tabular form.

The ultimate tests and fatigue tests will be run on a MTS (Material Test Systems) 810 Fatigue Test Machine with a 55 kip capacitance. The MTS (Material Test Systems) 810 machine is a servo-hydraulic mechanical testing machine that is typically used for tensile tests and fatigue testing. The machine consists of an oil-driven hydraulic power source, an upper and lower jaw that are used to grip a sample or a fixture and a heavy duty load frame that allows the two jaws to move up or down during setup and testing. The MTS machine used for the purpose of this research was capable of loading a specimen up to 250 kN in tension or compression. The ultimate tests that were performed on the four steels were done on an MTS machine at the ArvinMeritor Corporation in Troy, Michigan whereas the fatigue tests were performed on a MTS machine at the main campus of Oakland University.

The first step in testing was setting up the MTS machine for three point bending conditions. The upper jaw, which was static during any testing, was used to adjust the height of the test. The lower jaw is the component of the MTS machine that applies load. The three point bending fixtures that were previously described in Chapter 3 were clamped down in the jaws and were kept in place by hydraulic pressure. The bottom jaw held the two-point fixture while the top jaw held the one point fixture. This was done so that the specimen could be laid flat on the two-point fixture rather than having to balance the specimen on the one-point fixture. The fixtures were then aligned so that the bottom two load points would be equidistant from the central upper load point. This spacing would provide the specimen a uniform load. Once the fixtures were put in place, the sample had to be properly placed into the fixture. The specimen had to remain straight and had to be equally spaced so that the load would remain uniform. In order to ensure that the specimen would be straight and equally spaced during testing, all of the specimens were marked with graphite at the specimen center, and 63.5 mm to the left and right of the specimen. Lines were drawn at these measured intervals so that the specimen could be placed in the fixture and then checked from the front and the back. If the lines were aligned with the three point bending fixture at the front and back, then it was determined that the specimen was indeed straight and was ready for testing.

The MTS machine setup was calibrated with a load cell and a data acquisition computer. The load cell was placed between the two jaws and a command was sent through the controller to apply a specified amount of load to the load cell. Once the jaws had applied the force onto the load cell, the data acquisition computer obtained the load measurement from the load cell. The measurement from the load cell was then compared to the controller command and the value from the controller

was found to be within 10% of the value from the load cell.

An ultimate load test had to be performed for each material so that a plan for fatigue testing could be developed. Samples of each material were placed in a three point bending fixture and were loaded at a rate of 0.067kN/second. This procedure was repeated for two trials and then averaged to get a final ultimate load. The ultimate load that was generated was used as a point of reference when planning the fatigue tests which would be loaded no more than ultimate load. Based on the assumptions made previously and other experimental deductions from past research, the endurance limit of most steels takes place at approximately 33% of ultimate load.

Setup criteria had to be consistent for all tested samples during fatigue testing. This included how to apply the initial load, the tuning of the MTS controller, and the frequency of the test. Once the specimen was properly lined up in the fixture as described in a previous section, a low-level, compressive set point (less than 1 kN) was used to bring the jaws slowly together so that the specimen would have minimal impact once the upper and lower jaws came into contact with the specimen. If a high load was initially commanded during setup, then the specimen would have been impacted once the upper and lower jaw came into contact. This may have caused a spike in loading on the sample; therefore the slow initial loading was used in every test. Once the sample was in contact with both jaws, via the three-point fixture, the load was set at the necessary set point.

The controller was connected to an oscilloscope and a data acquisition card so that the commanded load and feedback load levels could be monitored during testing. The reason for monitoring the output of the controller was to ensure that the load and command would maintain stability and accuracy during testing. The oscilloscope was set to show the feedback load signal so that the sine wave could be monitored. If the feedback signal ever became erratic, the controller's tuning could be adjusted in order to bring the test back into original parameters.

3.2 Residual stress measurement method

The most widely used practical technique for residual stresses is the hole-drilling strain gage method. The secondary quantitative measurement technique uses radiation diffraction to measure the amount of residual strain within an object. Two primary techniques exist under the diffraction measurement category. X-ray diffraction and neutron diffraction both rely on the physical properties and interactions between electro-magnetic radiation and matter. However, neutron diffraction measures residual strains at greater depths at 1.5 mm and below while x-ray diffraction measured surface and very shallow surface due to its limitations of chemical itching. For the requirement of this experiment, the

maximum residual stresses exist between the surface and 1 mm below surface. The best suited measurement method is resistance strain rosette and hole drilling methods.

The resistance strain gage method is used in this project according to the ASTM Standard E837. The detailed procedures are documented in Measurement Group's Bulletin 304. With the resistance strain gage method, a specially configured electrical resistance strain rosette (two strain gages are perpendicular to each other, and the third in between the two gages) is bonded to the surface of the test object, and a small, shallow hole is introduced through the center of the rosette, using a precision drilling apparatus, Measurement Group's RS-200 Milling Guide. Three strain gages in the rosette measure three strain components simultaneously during the drilling. The relieved strains are related to the residuals stresses in the following equation

$$\begin{bmatrix} \sigma_1 \\ \tau_{13} \\ \sigma_3 \end{bmatrix} = \begin{bmatrix} A+B, 0, A-B \\ A, -2B, A \\ A-B, 0, A+B \end{bmatrix}^{-1} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{bmatrix} \quad (2)$$

Where the relieved strains in directions of 0, 45 and 90 degrees can be measured by 3 strain gages 1, 2 and 3. And the Coefficients Matrix (CM) is constructed from the coefficients A and B. The coefficients can be calculated using elasticity theory and finite element method and recorded in numerous published resources [7]. The residual stresses are computed from the above equation provided the measured three strains and the coefficients A and B.

Residual stress distribution through the subsurface of the object is measured by using incremental hole-drilling technique. When a thin layer of material is removed, relieved strains at that layer are measured. With multiple layers of material removal incrementally into the surface, the relieved strains are measured in the multiple layers. The residual stresses distribution in the multiple layers can be calculated by using "one layer method", "averaged stress method", "integral method" and finite element method [7, 8, 9].

4. TEST RESULTS AND DISCUSSIONS

4.1 Ultimate test results

The ultimate loads for each material are listed in Table 1 below. Two ultimate strength tests were completed for each material so that an accurate representation for ultimate strength could be generated. Table 1 also shows the averaged ultimate bending stress as well as the average displacement that occurred at the center of the specimen during loading. In actuality, the stress-displacement measured for PS18, 8822, and 4320 had well defined yield points before failure while MnCr did exhibit some plastic deformation after hitting the yield strength before finally failing.