

Axial and Bending Fatigue of a Medium Carbon Steel Including Geometry and Residual Stress Effects

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ABSTRACT

This paper discusses the effects of changes in specimen geometry, stress gradient, and residual stresses on fully-reversed constant amplitude uniaxial fatigue behavior of a medium carbon steel. Axial fatigue tests were performed on both flat and round specimens, while four-point rotating bending tests were performed only on round specimens. All the tests were performed using shot peened and unpeened flat and round samples, to investigate the effects of compressive residual stresses on fatigue behavior. The specimens in the rotating bending tests experienced longer life for a given stress amplitude than in the axial test. Shot-peening was found to be beneficial in the long life region, while in short life tests the shot-peened samples experienced a shorter life than the unpeened samples under both axial and bending test conditions. Specimen geometry had a minimal effect on fatigue life and the difference observed between the behavior of round and flat samples is thought to be due to slightly different hardness levels of the two specimen geometries. The data generated from the aforementioned tests and conditions and the effects observed and their implications on fatigue behavior and life predictions are analyzed and discussed in this paper.

INTRODUCTION

Most mechanical components and structures, particularly those in the automotive industry, are subjected to cyclic loading, and therefore prone to fatigue failure. As a result, evaluation of material cyclic deformation and fatigue behavior is a prime consideration in the design and durability analysis of such components and structures.

Most material fatigue data have traditionally been generated under rotating bending conditions. More recent data, however, include axial fatigue data under strain-controlled or load-controlled conditions. Since bending fatigue data are sometimes the only available data for use in axial fatigue applications, it is important to be able to related bending fatigue to axial fatigue data.

For a given stress amplitudes, specimens have been shown to experience longer life under rotating bending fatigue, as compared to fully-reversed axial fatigue. Stephens et al. [1] suggest that fatigue limits determined for axial fatigue testing should be between 10% and 25% lower than fatigue limits determined from rotating-bending fatigue testing for a given material. Lin et al. [2] performed a study comparing constant amplitude rotating bending fatigue and completely reversed

constant amplitude axial fatigue test results for ferrous and copper based powder metal alloys. The results showed that for quenched and tempered ferrous alloys, about 10% higher fatigue limit was observed in rotating bending compared to axial fatigue. Their results also showed that the quenched and tempered specimens' fatigue limit was around 32% of the ultimate tensile strength.

Theoretically, there should be little or no difference due to specimen geometry effect on axial fatigue behavior between flat and round test specimens with similar gage section volume (i.e. no size effect), if both geometries are subjected to the same stress or strain in either load-controlled or strain-controlled test. The only difference between a round specimen with a circular cross section and a flat specimen with a rectangular cross section may be due to an edge effect (i.e. a stress concentration) in the flat specimen at the corners.

Shot-peening is a process in which compressive residual stresses are applied to the surface to improve fatigue resistance. It can improve fatigue life under axial loading conditions by shifting surface cracks to sub-surface. Under bending conditions, compressive surface residual stress from shot-peening reduces the effect of the applied tensile stress at the surface of the specimen. However, depending on the magnitude and depth of the compressive residual stress, the type and magnitude of the loading, and material ductility and strength, shot-peening may be detrimental to fatigue life (i.e. in the low cycle fatigue region). This is because shot-peening plastically deforms the specimen surface, removing some of its ductility, while ductility is the controlling property in low cycle fatigue.

This paper first discusses the experimental program carried out in this investigation including material, specimens, test equipment, and test procedures used. Then, monotonic and cyclic deformation behaviors and properties are presented. This is followed by a discussion of observed fatigue behavior, including effects of specimen geometry, stress gradient, and residual stress effects on fatigue life.

EXPERIMENTAL PROGRAM

MATERIAL AND SPECIMENS

The steel used was a medium carbon steel. Heat treatment was done following final specimen machining and polishing. Both flat and round specimens were used in strain-controlled axial and rotating bending fatigue tests. The flat specimens had a hardness of 45 HRC while the round specimens had a hardness of 50 HRC. Only the round specimens were used in rotating bending tests. The specimen configuration and dimensions used are shown in Figure 1 and conform to dimensions recommended by the ASTM Standard E606 [3].

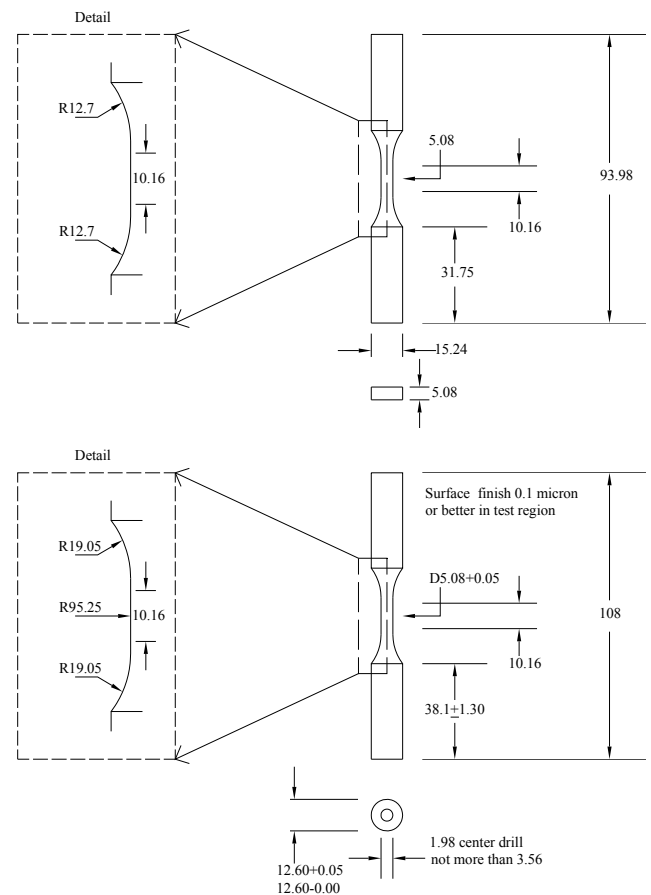


Figure 1: Specimen configuration and dimensions (mm) for round and flat specimens.

The specimens were machined using CNC machines. Three different grits (400C, 600C and 1200C) of silicon carbide sand-paper were used to polish the surface of flat specimens after machining and polishing marks coincided with the specimens' longitudinal direction. The edges of all the flat specimens were slightly rounded using sand-paper. The round specimens were polished by a polishing machine. Three different grits of aluminum oxide lapping film 30 μ m, 12 μ m, and 3 μ m were used. Polishing marks coincided with the longitudinal direction of the specimen. The polished surfaces were carefully examined under magnification to ensure complete removal of machine marks within the test section. Then all of the round and flat specimens were heat treated, while only half of them were shot-peened at a commercial machine shop prior to testing.

TESTING EQUIPMENT AND PROCEDURES

Closed-loop servo-controlled hydraulic axial load frames in conjunction with digital servo-controllers were used to conduct the axial tests. Hydraulically operated grips using universal tapered wedges for flat specimens and collets for round specimens were employed to secure the specimens' ends in series with the load cell. Total strain was controlled using an external controller used as

ASTM class B1 [4]. The extensometer had a gage length of 0.30 inch. In order to protect the specimens' surface from the knife-edges of the extensometer, a polymer coating was used to 'cushion' the attachment.

Significant effort was put forth to align the load train (load cell, grips, specimen, and actuator). Misalignment can result from both tilt and offset between the central lines of the load train components. Strain-gaged bars with two arrays of four strain gages per array that were arranged at the upper and lower ends of the uniform gage section were used [5] to align the load train.

All monotonic and axial fatigue tests were performed using test methods specified by ASTM standards E8 [6] and E606 [3], respectively. Strain amplitudes ranging between 0.275% to 1% were utilized for both peened and unpeened specimens in strain-controlled fatigue tests. Test data were automatically recorded throughout each test. Two control modes were used. Strain control was used in all tests with plastic deformation. Load control was used for the elastic tests. The reason for the change in control mode was due to the frequency limitation on the extensometer.

For the strain-controlled tests, the applied frequencies ranged from 0.15 Hz to 0.5 Hz in order to keep a strain rate about 0.02 mm/mm/sec. For the load-controlled tests, load waveforms with frequencies of up to 25 Hz were used in order to shorten the overall test duration. All tests were conducted using a triangular waveform with the exception of the tests run at 25 Hz, which used a sine waveform. In axial fatigue tests, failure was determined by a 50% load drop or by complete fracture of specimen.

A four-point rotating bending fatigue machine was used to perform the bending fatigue tests for unpeened and peened specimens. The machine was powered by an electric motor having a speed of 29 Hz. The machine was designed to create a uniform bending moment across the test section of the specimen. Weight was added to a hook below the center of the tests section to create the bending moment. A round strain-gage bar was used to verify the bending moment. Specimens were held in place by manually tightened tapered collets at both ends and it was ensured that only a torque was applied to the collet nut when tightening, to prevent any plastic deformation of the specimen prior to starting the test.

Bending moment levels ranging from 13.8 Nm to 9 Nm were used. The stress amplitude in rotating bending tests was determined from the following equation:

$$\sigma = Mc/I = (32M)/(\pi d^3) = [2.88 (W + 63.72)]/(d^3) \quad (1)$$

In rotating bending fatigue tests, failure was determined by complete fracture of the specimen.

EXPERIMENTAL RESULTS AND ANALYSIS

MONOTONIC AND CYCLIC DEFORMATION BEHAVIORS

The properties determined from monotonic tension tests were modulus of elasticity (E), yield strength (YS), ultimate tensile strength (S_u), percent elongation (%EL), percent reduction in area (%RA), true fracture strength (σ_f), true fracture ductility (ϵ_f), strength coefficient (K), and strain hardening exponent (n). The true fracture strength, σ_f , for flat specimens was calculated from $\sigma_f = P_f/A_f$ where P_f is the load at fracture and A_f is the final area after fracture. For round specimen σ_f was corrected for necking according to the Bridgman correction factor [1]. The strength coefficient, K, and strain hardening exponent, n, are the intercept and slope of the best line fit to true stress (σ) versus true plastic strain (ϵ_p) data in log-log scale.

The interposed monotonic stress-strain curves are shown in Figure 2. The difference in hardness between round and flat specimens can be observed in this figure. Ultimate tensile strength is often thought to be directly proportional to the Brinell hardness number. The round specimens compared to flat specimens have the same percent difference, about 13%, in both ultimate tensile strength and Brinell hardness. A comparison of the monotonic properties of the round and flat specimens can be observed in Table 1. From Figure 2 and Table 1 It can be observed that there is little or no difference between unpeened and shot-peened specimens for each geometry, as expected.

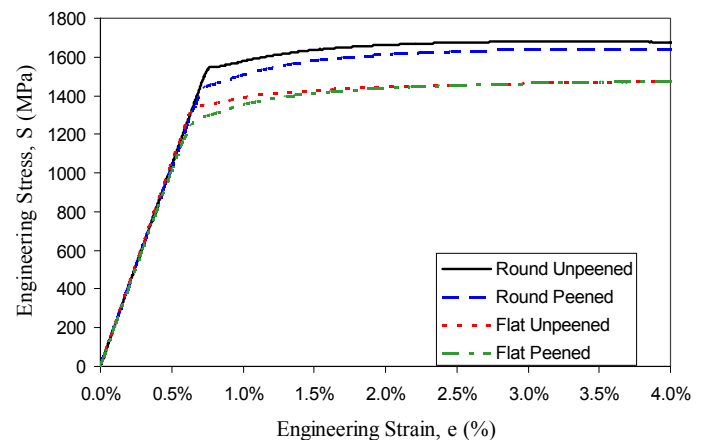


Figure 2: Monotonic tension stress-strain curves for round and flat peened and unpeened axial specimens.