

Fatigue Behavior of Stainless Steel Sheet Specimens at Extremely High Temperatures

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ABSTRACT

Active regeneration systems for cleaning diesel exhaust can operate at extremely high temperatures up to 1000°C. The extremely high temperatures create a unique challenge for the design of regeneration structural components near their melting temperatures. In this paper, the preparation of the sheet specimens and the test set-up based on induction heating for sheet specimens are first presented. Tensile test data at room temperature, 500, 700, 900 and 1100°C are then presented. The yield strength and tensile strength were observed to decrease with decreasing strain rate in tests conducted at 900 and 1100°C but no strain rate dependence was observed in the elastic properties for tests conducted below 900°C. The stress-life relations for under cyclic loading at 700 and 1100°C with and without hold time are then investigated. The fatigue test data show that the hold time at the maximum stress strongly affects the stress-life relation at high temperatures. When the results are plotted as functions of the time to failure, the test data suggest that creep dominates the failure of the sheet specimens at elevated temperatures.

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INTRODUCTION

Emissions from diesel engines can be reduced through use of a diesel particulate filter (DPF) that removes particulate matter from the exhaust gas stream. The accumulated particulate matter can then be oxidized through an active regeneration cycle. Active regeneration utilizes heat sources, such as electric heaters or fuel burning to initiate the combustion of the particulate matter. During an active regeneration cycle, the temperature of structural components can be extremely high. Thermal fatigue, creep and oxidation then become critical mechanisms to be considered for durability of the components.

Stainless steels are widely used for high temperature automotive applications due to consideration of high temperature performance, durability and cost. Much of the previous research on high temperature fatigue of stainless steels has focused on thick sections of austenitic stainless steels for use in power plants [1, 2, 3]. However, most austenitic grades may be less suitable for high temperature automotive applications due to their higher cost, poor oxidation resistance above about 850°C, and high coefficients of thermal expansion. For this reason, ferritic grades are considered for use in automotive applications. Further, exhaust system components are typically thin-walled structures with wall thickness of 3 mm or less. Relatively few researchers have

investigated the high temperature fatigue behavior of ferritic stainless steels with thin cross sections. For example, Ha et al. [4] investigated the thickness effect on high temperature bending fatigue life for ferritic stainless steel plates up to 800°C and found that increase in thickness from 1 to 2 mm deteriorated the fatigue life at a given stress level for the tested materials. Santacreu et al. [5] presented high temperature properties of an oxidation-resistant ferritic stainless steel sheet (1 to 2 mm in thickness) in comparison with those of austenitic grades up to 1000°C. In order to accurately predict the durability of the structural components of an active regeneration system, the fatigue, creep and oxidation behavior of thin stainless steel sheet material must be characterized accurately in a wide range of temperatures, stress levels and loading rates.

The purpose of this paper is to explore the effects of extremely high temperature on the fatigue life of a candidate stainless steel for an actively-regenerating DPF system. First, the material, specimen geometry and experimental set-up are presented. The experimental development of a transverse-flux induction coil to heat sheet specimens is then described. Next, the procedures for tensile and fatigue testing of the sheet specimens are presented. Stress-strain curves are shown for tensile tests conducted from room temperature to 1100°C at the strain rates from 0.0005 s⁻¹ to 0.05 s⁻¹. S-N and stress-time curves are then presented for cyclic fatigue tests conducted in air at room temperature, 700 and 1100°C with and without a hold time at the maximum stress. Finally, the results are discussed and the effect of hold time on the damage modes is investigated.

EXPERIMENTAL DETAILS

Material

A stainless steel with excellent high-temperature scaling resistance was selected as the primary candidate material for the structural components of an active-regenerating diesel emissions system. The stainless steel has primary alloying elements of aluminum, manganese, nickel and titanium and is magnetic at room temperature.

Specimens

Two types of specimens were created for quasi-static tensile tests and cyclic fatigue tests. The geometry of the tensile specimens was made according to ASTM E8 [6] and ASTM E21 [7] with the specimen shoulders elongated to accommodate the high temperature grips used for the elevated temperature tests. The geometry of the tensile specimen is shown in Figure 1. The tensile specimens were milled from sheet with a thickness of 1.9 mm. The material was used with an as-received finish on the specimen faces and an as-milled finish on the specimen edges for the tensile tests.

The geometry of the specimens for cyclic fatigue tests was made according to ASTM E466 [8] for load-controlled cyclic fatigue testing. Due to the extremely high temperatures of the

tests, the recommendations in ASTM E606 [9] for strain-controlled cyclic fatigue testing were also considered for the design of the specimen. The final specimen size and geometry was determined in part by the guidelines from the ASTM standards and from practical consideration of the available experimental set-up. The geometry of the specimen for fatigue is shown in Figure 2. Following machining of the fatigue specimens, the width of the gauge section of each specimen was measured with a shadowgraph to the nearest 0.001 mm. The thickness of each specimen was carefully measured with micrometers to the nearest 0.01 mm at three points in the gauge section with the smallest thickness measurement used to calculate the stress in the gauge section as suggested in ASTM E8 [6] for tests of sheet materials. The specimen was then polished in accordance with the procedure recommended in ASTM E466 [8]. The edges of the specimens were longitudinally polished with lapping compound to a surface finish of Ra 0.2 µm, which is the surface roughness recommended in the procedure. The faces of the specimen were longitudinally polished with lapping compound only to a surface finish of Ra 0.4 µm to strike a balance between adherence to the standard and the cost of specimen preparation.

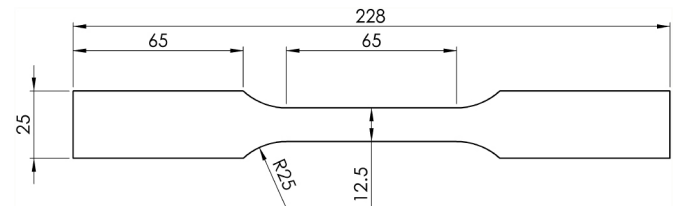


Figure 1. Geometry of the tensile specimen (all units in mm).

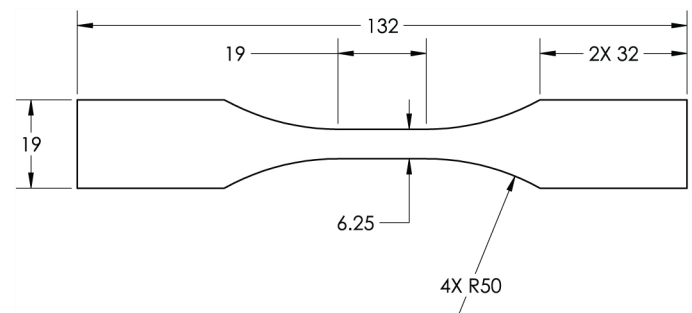


Figure 2. Geometry of the fatigue specimen (all units in mm).

Induction Coil Development

Induction heating was used to achieve the testing temperatures. In general, iron-based alloys have a Curie temperature of around 770°C [10] that can affect the ability of the metal to be heated by induction heating. However, no decline in the effectiveness of induction heating above this temperature was observed for the candidate material. Specimens were heated with a 5 kW induction system operating at 250 kHz. Induction heating is usually used for specimens with a round cross-section. A typical induction heating set-up has the coil axis parallel to the longitudinal axis

of the round specimen. However, the tests discussed in this paper were conducted on sheet specimens with a thin rectangular cross-section. Use of a coil designed for round specimen usually resulted in poor temperature gradients in the rectangular specimen. Therefore, a transverse-flux coil was designed where the coil axis is perpendicular to the specimen. The transverse-flux coil design was optimized to minimize the variation in temperature in the gauge section along the length of the specimen and across the specimen face. The temperature was measured at the center five locations along the length of the specimen for multiple revisions. The final coil geometry reduced the temperature variation along the length of the gauge section to less than 5% of the target temperature within a 12 mm gauge section for up to 1100°C. The final transverse-flux coil design is shown in Figure 3. The transverse-flux coil also minimizes non-uniformity of heating that occurs at the edges of the specimen when using a circular coil designed for round specimens [11].

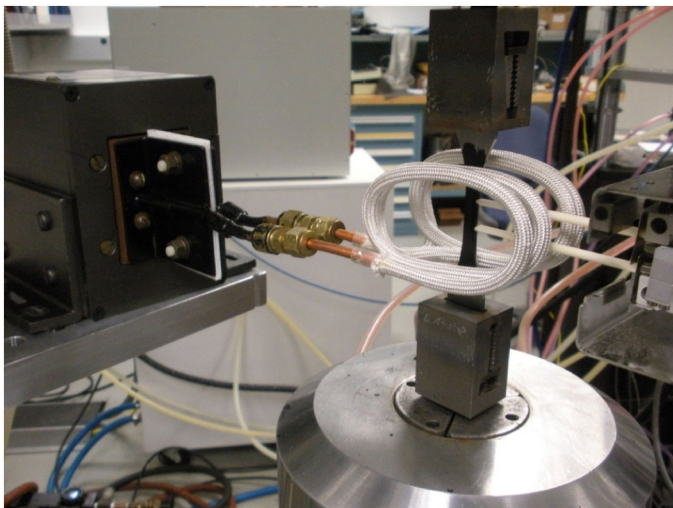


Figure 3. Transverse-flux coil used for sheet specimens for tensile and fatigue tests.

Experimental Set-Up

Temperature was continually controlled throughout the duration of each test with a Micristar Model 828D temperature controller. For tensile tests, the temperature of the specimen was monitored by a chromel-alumel thermocouple welded on the specimen surface at the center of the gauge length. For fatigue tests, the temperature of the specimen was monitored by a two-color Raytek Marathon series pyrometer (range 600-1400°C) focused on the center of the specimen face with a spot size of approximately 6 mm. The specimen surface was painted with flat black high-temperature paint to improve accuracy of the infrared temperature measurement. Cooling was achieved through use of water-cooled hydraulic collet grips and natural convection away from the specimen surface. Titanium fixtures with mechanical wedges were used to adapt the sheet specimens to the collet grips. The specimen was carefully aligned in the titanium fixture before the specimen assembly was mounted in the testing machine. Gauge blocks

were used to center the specimen in the fixtures and the set screws to secure the wedges were tightened in an alternating pattern to avoid the misalignment of the specimen.

Tests were conducted on a servo-hydraulic frame outfitted with a 25 kN force transducer. Strain was measured via a high-temperature extensometer with vee-chisel ceramic extension rods. The servo-hydraulic frame was programmed with a closed-loop proportional-integral-derivative (PID) feedback controller. The PID values were manually adjusted at specimen temperatures of room temperature, 500, 700, 900 and 1100°C to optimize the load control response of the servo-hydraulic frame for a square wave form operating at 5 Hz and a triangular waveform operating at 20 Hz.

RESULTS

Tensile Tests

Tensile tests were conducted under strain control at room temperature, 500, 700, 900 and 1100°C in order to evaluate the elastic modulus, yield strength and tensile strength. The yield strength was determined by the 0.2% offset method. Strain rates of 0.0005 s^{-1} , 0.005 s^{-1} and 0.05 s^{-1} were used to evaluate the tensile properties at elevated temperature. Figures 4(a) and 4(b) show the tensile stress-strain curves for tests conducted from room temperature up to 1100°C. From Figures 4(a) and 4(b), it can be observed that the yield strength and tensile strength decrease with increasing temperature. For temperatures up to 700°C, the elastic moduli were determined by cycling the stress within the elastic range under load control, with a frequency of 1 Hz to minimize the creep effects at high temperature. Ten fully elastic cycles have been performed and the modulus was determined for each cycle and then averaged. For tests conducted at 900 and 1100°C, the elastic moduli were determined directly from the tensile stress-strain curves.

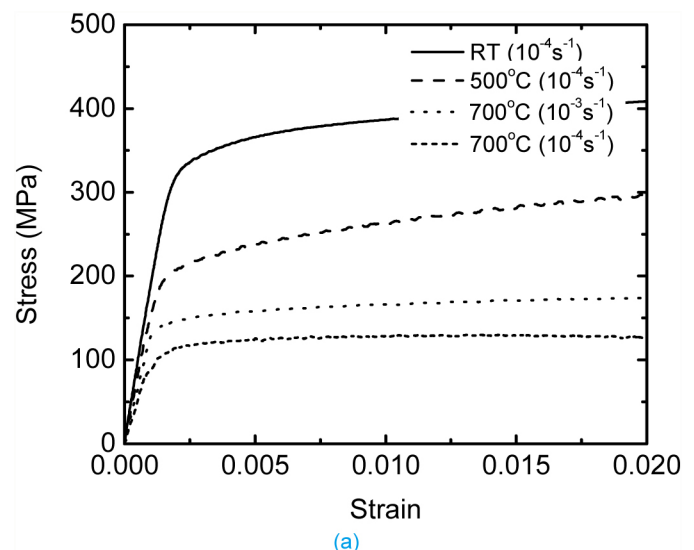


Figure 4. Tensile stress-strain curves at (a) room temperature, 500 and 700°C for strain rates of 0.0001 s^{-1} and 0.001 s^{-1} and (b) 900 and 1100°C for strain rates of 0.0005 s^{-1} and 0.005 s^{-1} .