Monotonic and Cyclic Stress Strain Cuves with Temperature Dependence for Cast Iron Brake Disc

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Abstract

Cast iron is a material that has been commonly used to create automotive components of varying complexity for a long time since it is relatively inexpensive and easily formed into complex shapes. The investigation of their strengths or structures is also essential in engineering design. Without the characteristics of material, it is unable to fulfill the stress analysis under the loads. Therefore, the objective of this work is to investigate the characteristics of the monotonic and cyclic stress strain curves with temperature dependence for automotive engineering brake discs. This is because a cast iron brake disc is commonly used and subjected to high thermal loading. With the computer based machine and the heater unit, it is able to investigate material responses at the elevated temperature. Furthermore, the techniques to obtain deformation on the brake disc specimens, while subjected to high temperature, are revealed.

1. Introduction

The stress-strain curve for one direction of loading only in a uniaxial load test is called the monotonic stress strain curve (MSSC) in which the tensile or compressive loads can be applied. Typically, the MSSC responses in tension and compression for ductile material are similar. However, it is not for brittle material such as cast iron since it consists of two main substances: graphite (carbon) flakes and matrix ferrous metal. Both of these constituents have a significant influence on the stress-strain response of the material. This is because of the weak bonding between the graphite flakes and metal matrix which causing gaps or voids to open in the material under tension. Therefore, the compressive strength of cast iron is two or three times higher than its tensile strength. In order to capitalize on this anisotropy, the cast iron product should be designed to be loaded in compression wherever possible. With such different behaviours in tension and compression of material, Gilbert [1] performed tests to obtain tensile and compressive strength at the room temperature. Furthermore, the essential engineering material data

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were investigated such as Young's modulus, thermal conductivity, specific heat and thermal expansion on a variety of gray cast irons which were classified using tensile strengths according to the relevant British Standard [2].

A different stress-strain curve from the MSSC can exist if the material is subjected to a cyclic load. This is called the cyclic stress strain curve (CSSC) and has a very important on the fatigue characteristics of a material [3]. This is because the CSSC indicates the peaks during cyclic steady state loading. It also provides a more meaningful definition of the mechanical behaviour under cyclic loading at different strain levels. In practice, there are many procedures to determine the CSSC of a material as reviewed by Landraf et al. [4]. One of them is called the incremental step test in which the strain-controlled amplitude is increased gradually at each cycle and reduced gradually after reaching the desired maximum. Gilbert [5] investigated the cyclic strain response of grade 300 cast iron at room temperature. He found that the peak tensile stresses decreased gradually and the peak compression stresses increased with each strain cycle until failure. This is due to the effect of the repeated opening and closing of gaps between graphite flakes and metal matrix.

Even though the material properties at room temperature were investigated and useful for engineering application, the influence of elevated temperature also degrades its features such as yield strength, stress strain behavior etc. Therefore, the material properties at high temperature are taken into account in the design stage. For example, a brake disc is subjected to the high thermal and mechanical loads during the operation. Furthermore, it was found that the effect of mechanical stresses in brake disc were minor and could be neglected in comparison with the thermal stresses [6]. Thus, it is quite necessary to determine the strength of cast iron in tension and compression at elevated temperature. In addition, the behaviour of cyclic stress strain curves at high temperature are also investigated in the present work.

2. Specimen Design and Analysis

Specimens were machined from the BMW specification 600 36.0 back-vented brake disc supplied by Rover cars as indicated in Figure 1. The nominal composition of the grade 150 cast iron consists of carbon (3.70-3.90%), Silicon (1.80-2.20%), Magnesium (0.50-0.80%), Phosphorous (0.08% Max.), Sulphur (0.12% Max.), Chromium (0.20% Max.), Copper (0.25% Max.), Molybdenum (0.10% Max.) and Nickel (0.20% Max.) by weight [7]. Although the specimen cannot follow the British Standard specification, the results from the FE investigation demonstrate that the design is satisfactory. Therefore, the cross-section of the specimen is square, giving larger cross-sectional area than for the corresponding circular cross-section. The square cross-section specimen can therefore support a higher load in compression without buckling. In addition, it provides a flat surface that can be used to mount a strain gauge.

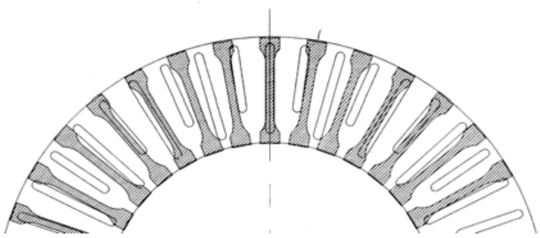

Figure 1 Layout of specimens on the rubbing surface

Due to the relatively short gripped ends, it was decided to load the specimen through holes drilled in the specimen in order to prevent any slippage. In the experiments, the specimens were subjected to both tension and compression loads. The wedge action specimen grips were designed to prevent any backlash as the load changes from tension to compression as described below. Therefore, the same specimen design could be used for testing under both uniaxial and cyclic loads.

3. Test Equipment

3.1 Dartec test machine

Specimens were tested in a servo-hydraulic Dartec test machine. During operation the current load and crosshead displacement can be displayed and recorded as a function of time. The output signal from the load cell is in the form of a voltage that is dependent on the setting of the Dartec machine. Setting these values depends on the maximum load expected and the resolution of the output data required. Therefore, before testing specimens, the ultimate tensile strength of the material should be firstly estimated in order to obtain the most appropriate setting of the load cell.

3.2 Induction heating unit

For testing at elevated temperatures, it is vital to find equipment to heat the specimen and maintain it at a constant uniform temperature. With the Dartec machine, tests at elevated temperature can be carried out inside an oven. However, the maximum temperature achievable with this oven is only 200 °C. In addition, the length of the specimen and grips is too short to load them inside the oven. For this reason, a Quasar solid state induction generator and a heating coil together with a Raytek control unit was chosen. The infra-red detector directs a laser beam on the specimen and converts the infra-red energy measured from the reflection into an electronic signal of the current specimen temperature, Figures 2 and 3. However, due to the limitations of the induction heater temperature control unit, maintaining a constant temperature below about 250 °C proved impossible. Therefore, specimens were tested at temperatures of 300, 350 and 400 °C only as well as at ambient temperature.

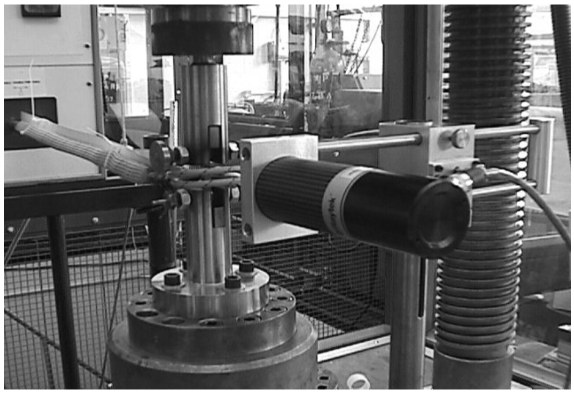

Figure 2 Infrared detector and induction heating furnace

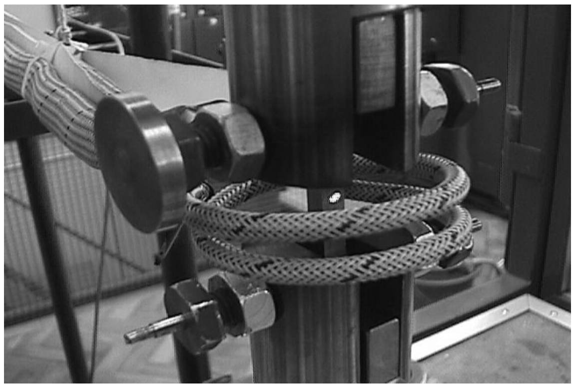

Figure 3 Induction coil for high temperature testing

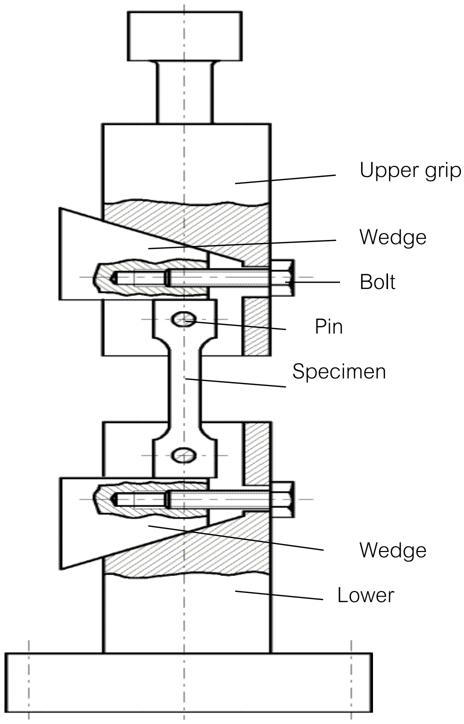

Figure 4 Side view of grip assembly

3.3 Grip design

The lower and upper grips were made of high carbon steel (EN 30B) in order to stand high loads during the tests without plastic deformation. The wedges inside the channels together with the pins were used to apply a compression pre-load against the top edge of the specimen as indicated in Figure 4. The wedges were fastened with small bolts so as to obtain good contact and eliminate any gaps between the wedges, the specimen and the pins. The grips can therefore transmit the loads from the crosshead of the test machine to the specimen without backlash while changing the load direction. The pins were made of ground silver steel and they have high accuracy on diameter for ensuring good contact with the specimen. Mild steel was used for the wedge because its strength is sufficient for testing at high load.

For testing at elevated temperatures, short bushes made of glass ceramic [8] were used to thermally insulate the specimen from the grips, Figure 5. By increasing the diameter of the hole in the specimen from 4 mm to 6 mm, these short bushes with inner diameter of 4 mm could be interference fitted inside the specimen using a heat shrink technique. Since the bushes are then in fact integral with the specimen, the effective hole size is again 4 mm as optimised by the FE analysis.

To complete the insulation for the elevated temperature tests, the wedge height was reduced by 3 mm in order to insert glass ceramic wedge insulators as indicated in Figure 5. The insulator thickness is 3 mm with the same width and length as the base of wedge. Furthermore, the same insulator material was used for the 2 mm thick washers located at the end of the threaded sleeves. The purpose of this design is to prevent the thermal energy transferring from the specimen to the grips thus maintaining the specimen temperature as uniform as possible.

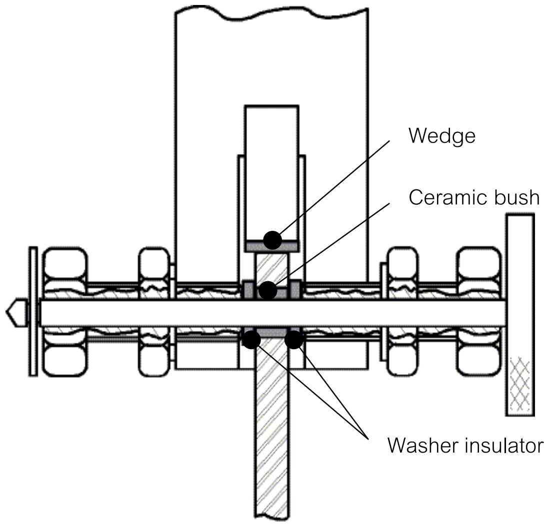

Figure 5 Front view of grip assembly for elevated temperature

3.4 Strain Gauge

The gauge is fixed to the object surface. In the uniaxial room temperature tests, Cu-Ni foil strain gauges with a gauge factor of 2.13 and electrical resistance of 120 Ohm were used for investigating the strain response of the specimen. The maximum limiting strain for this strain gauge is of the order of 2%. The strain gauge was fixed halfway along the gauge length of the specimen and aligned in the direction of loading. The response of the strain gauge was monitored by means of a strain gauge meter which with the correct setting of the gauge factor gives a maximum output of two volts equivalent to 20000 microstrain.

3.5 Data acquisition unit

The PC based 'Labtech' data acquisition unit consists of an integrated hardware and software system that transforms analogue input voltage signals into the digital data that can be recognised by the software in the computer. Therefore, the strain signal from the strain gauge meter and the load signal from the load cell can be recorded at the same time as the crosshead displacement from the Dartec machine. This allows the load and displacement response of the specimen to be investigated as well as the relation between the crosshead displacement and the strain.

3.6 Strain-Stroke Calibration

Since strain gauges could not be used on specimens heated to elevated temperatures using the induction heater, it was necessary to establish a relationship between the crosshead displacement of the Dartec and the strain in the specimen. It could then be assumed that this relationship holds for elevated temperature as well as for the room temperatures tests. This assumption is reasonable because the factors that affect the crosshead displacement - specimen strain relation such as the compliance of the Dartec and the grips should not be affected by the local heating of the specimen itself.

In the first condition, the load rate of the machine was set at 300 Ns^{-1} and a compression load was applied up to a certain value without fracturing the specimen. During loading, the strain signal and the load signal were recorded by the data acquisition unit. At the same time, the displacement of the Dartec crosshead was also recorded. When the load reached its maximum value, the applied load was reduced to zero. The next step was the investigation of the strain-stroke relation under tension. Before starting, all the signals (the strain, the applied load, and the load was applied at a rate of 300 Ns-1 until the specimen broke.

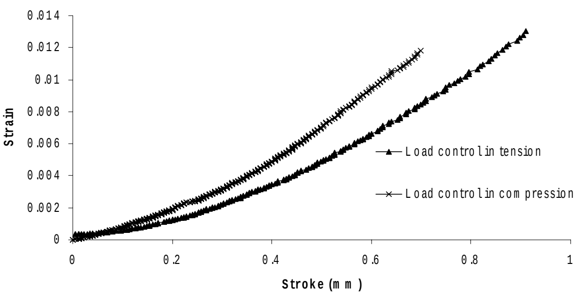

Figure 6 Relation between the specimen strain and the crosshead for the load control

Figure 6 also reveals that the relation between the strain and stroke in compression is different from that in tension. The main reason is that in tension the load was applied directly through the pin, resulting in slight deformation of the pin. In compression, there is less pin deformation because the compressive force was directly applied to the top of specimen, causing lower crosshead displacement in compression than in tension for the same specimen strain. Since the mean strain rate is in the range of acceptable value at a nominal stress rate of 8.33 $MPas^{-1}$, the load rate of 300 Ns^{-1} was used to investigate the stress-strain curves of the cast iron material in the monotonic tests described below.

4. Monotonic Testing

4.1 Method

Since the load history of a specimen may have significant influence on its stress-strain response, a specimen should only be tested once for each condition and then should not be used again in order to obtain further material data. Therefore, separate specimens were used for tests under tension and compression at each temperature (25, 300, 350 and 400 °C).

From the results of the strain-stroke calibration described above, the relation between the stroke of the crosshead Dartec machine and the strain in the specimen was used to obtain the current strain from the measured crosshead displacement. The load was divided by the cross-sectional area of the specimen to give the nominal stress. The monotonic stress-strain curve (MSSC) could then be generated from these results for both tensile and compressive loading at different temperatures.

4.2 Results

The stress-strain curves at the four different temperatures are shown in Figure 7. These graphs reveal that the cast iron response is dependent on temperature with higher temp

eratures producing higher strains for a given level of stress as expected. Furthermore, the stress-strain curves in compression are higher than those in tension at all temperatures. This results from the fact that the cast iron is composed of two components: graphite flakes and pearlite matrix. In tension, the graphite flakes cause voids to open in the matrix, resulting in a higher strain for a given level of stress compared with compression where the graphite flakes absorb and transmit the compressive load to the surrounding pearlite matrix.

In both tension and compression, the most significant differences are between temperatures of 300 and 400 °C whereas the differences between the 20 °C and 300 °C curves are less significant given the much greater range of temperature. This might be due to the effect of micro-structural changes over this higher range of temperature. All curves show an increasingly non-linear relationship between stress and strain as the loads are increased due to the onset of plastic deformation.

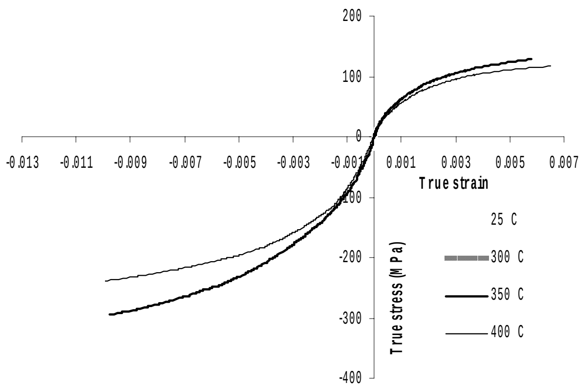

Figure 7 True stress-true strain curves for Rover cast iron disc material

5. Cyclic Testing

5.1 Method

In order to obtain the cyclic response of the present brake disc cast iron material, the multiple step test was used. In the tests, the cyclic strain amplitude started with a low value and then was increased to a higher value after successive intervals of 50 cycles as shown in Figure 8. The specimen was cycled at a frequency of 0.1 Hz using a sawtooth waveform as indicated in the Figure. In addition to testing at room temperature, this mode of testing was also used to find the cyclic response at elevated temperatures of 300 and 400 °C using the induction heating system. Therefore, three specimens in total were required for these tests.

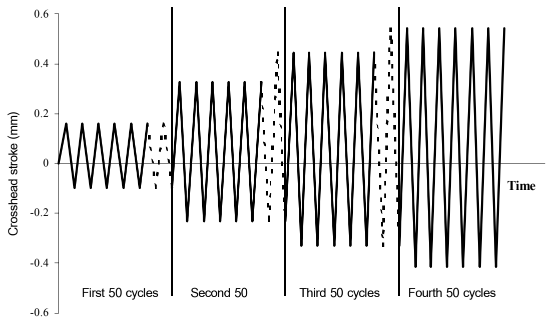

Figure 8 Cyclic crosshead stroke time histories

5.2 Results

All specimens broke in tension at the first cycle of the third strain amplitude except for the specimen that was tested at 400 °C which broke at the 11th cycle of the second strain amplitude. Therefore, there were no specimens subjected to the fourth cyclic strain amplitude conditions.

From the cyclic stress-time histories shown in Figure 9, the peak tensile stress decreases significantly with increasing cyclic strain amplitude whereas the absolute magnitude of the compressive stresses increases. This indicates a degree of cyclic softening in tension and cyclic hardening in compression. The magnitude of these effects is also temperature-dependent as can be seen from comparison of Figure 9 (a) and (b). A similar study on the cyclic behaviour of cast iron at room temperature attributed these characteristics to the greater opening of voids around graphite flakes under cyclic tension and the cyclic strain hardening of the pearlite matrix in compression [5].

The peak stress and strain in tension and compression at the end of each strain cycle can be used to form the CSSC's. These curves were compared to the MSSC's in Figure 10 for temperatures of 20, 300 and 400 °C. The results show that the MSSC's are above the CSSC's in tension due to cyclic softening whereas, in compression, the CSSC's give generally higher stresses for a given level of plastic strain due to cyclic hardening. However, it should be taken into account that the effect of cyclic load history for these experiments might be another factor to cause these differences in behaviour because a single specimen was tested with four different cyclic amplitudes. The effect of damage accumulation due to previous loading history is illustrated by the fact that the maximum tensile strain

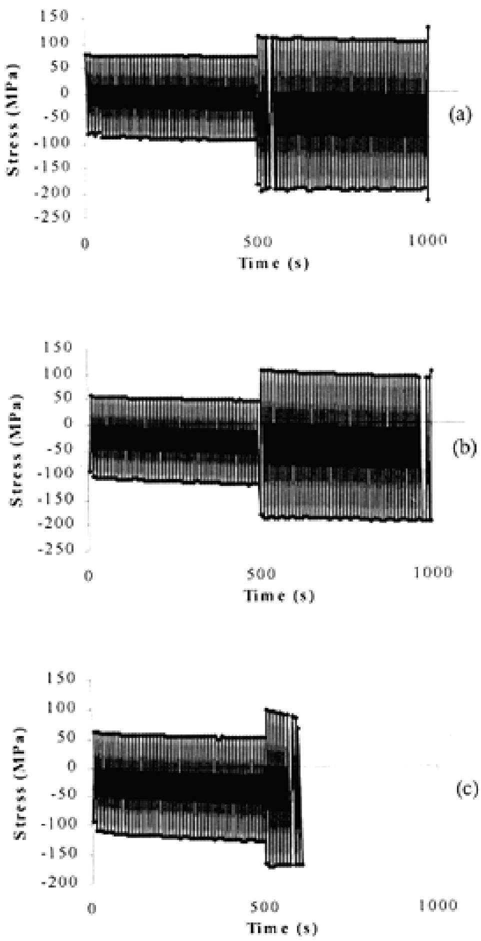

Figure 9 True stress-true strain curves for Rover cast iron disc material at (a) room temperature, (b) 300°C, (c) 400°C

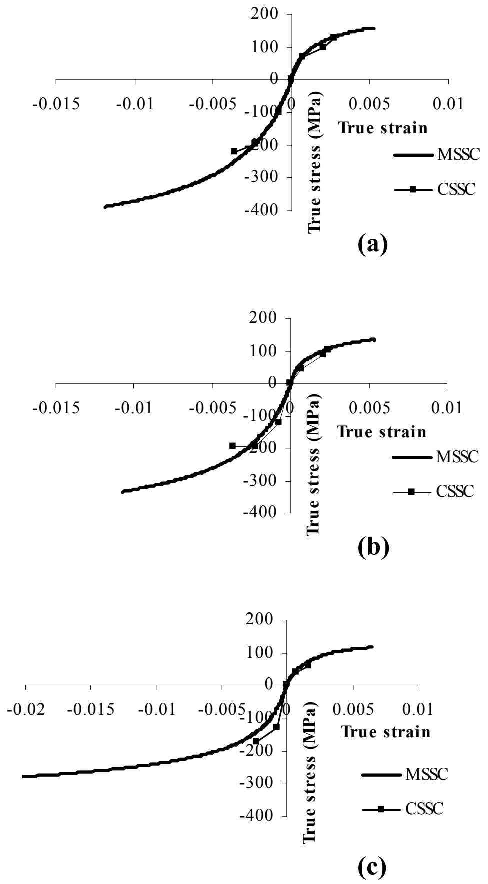

Figure 10 Comparison between CSSC and MSSC at (a) room temperature, (b) 300°C, (c) 400°C

for fracture under cyclic loading is lower than under monotonic loading at all temperatures.

6. Conclusion

The specimen grips fulfilled all the requirements to minimise the backlash for cyclic loading. Furthermore, they were used successfully with the induction coil for testing at elevated temperatures. However, a more direct method of measuring the specimen strain would be desirable e.g. Ettemeyer Speckle Interferometry (ESPI) [9] in order to eliminate the effect of the pin and wedge displacements.

The experimental MSSC's at various temperatures demonstrate that the stress-strain response of the brake disc cast iron is temperature dependent both in tension and compression. Furthermore, the temperature sensitivity increases significantly above 300 °C in both tension and compression. Therefore, errors induced by using the room temperature response will be much greater above 300 °C.

The effects of cyclic loading cause significant differences in the stress-strain response compared with monotonic loading. The cyclic load causes the material to harden in compression and to soften in tension especially at high temperatures. Furthermore, cyclic loading causes fracture at lower strains than under monotonic loading at the same temperature. However, the generation of accurate fatigue life data as a function of stress level and temperature was considered outside the scope of the present work.

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