Plastic Deformation and Creep of Two Ductile Cast Irons, SiMo51 and SiMo1000, during Thermal Cycling with Large Strains

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Abstract. Cyclic deformations of two ferritic, ductile cast irons, SiMo51 and SiMo1000, were studied in air and Ar using a new method, SRTC (stress relaxation with thermal cycling). Locked specimens were thermally cycled up to 800 °C with isothermal holds, varying temperature interval, heating/cooling rates and hold times. A description of the mechanical response to thermal cycling of a locked specimen is given.

1. Introduction

The development of truck diesel engines towards high power efficiency and low emissions has increased the temperature in the exhaust manifolds reaching the upper limit of the currently used material, SiMo51. This has led to several studies [1-6] and a new Al-rich material, SiMo1000, developed by Georg Fischer Automotive, is now available. The two materials are compared with a new method, evaluating plastic deformations and creep during thermal cycling. A parallel-coupled, two-specimen system with individual temperature controls and a common total strain has been used [7, 8]. Our method has a serial coupling of a lower cold head, middle hot gauge and an upper cold head, keeping the total strain zero. Studies on creep properties of cast irons appear lacking and, in general, monotonic creep is well described in literature compared to cyclic creep [9], being the focus of the present paper.

2. Materials

The SiMo51 and SiMo1000 materials, Table 1, were cast by Castings P.L.C, West Midlands, UK and Georg Fischer Eisenguss GmbH, Herzogenburg, Austria, respectively.

Table 1. Chemical composition in wt% (Fe balance).

| Alloy     | C  | Si  | Mn  | Cr  | Ni  | Mo  | Mg  | Al  |
|-----------|----|-----|-----|-----|-----|-----|-----|-----|
| SiMo51    | 3.17 | 4.15 | 0.40 | 0.10 | 0.04 | 0.86 | 0.052 | -  |
| SiMo1000  | 3.57 | 2.72 | 0.25 | 0.07 | 0.84 | 0.81 | -   | 3.08 |

Both materials have a ferritic matrix with dispersed graphite nodules and Mo-carbides at the grain boundaries. For SiMo51, the nodules are spherical, as desired, but for SiMo1000 many of them, admittedly deviate in shape, Fig. 1. At high temperatures in air, the Si-rich SiMo51, and the Al-rich SiMo1000, form protective layers of SiO2 and Al2O3, respectively.

Plates, Fig 2a, of 370 mm length and 20 mm thickness were cast between cylinders of matching lengths and Ø60 mm, separated by the width of the plates, 150 mm. The cylinders and 75 mm of each end were removed to produce defect-free material, 220x150x20 mm\textsuperscript{3}. Tensile test specimens of 131 mm total length were produced with 51.5 mm long grip sections of Ø12 mm and two R7 radii, reducing the central gauge to Ø7 mm. The gauge was circumferentially ground with p320, p600 and p1200 sand papers.
3. Test Rig and Gas Chamber Setup

A well-equipped test rig was used, built on a load frame of an Instron 8561 machine. It is equipped with an Instron 100 kN alignment fixture, a 25 kN Instron load cell, water-cooled, hydraulic, specimen grips, an EDC-580V Dooli controller and a Laser Xtens compact TZ, ZwickRoell, non-contact laser extensometer. A gas-tight test chamber with a gas-supplying system allows tests in controlled atmospheres. A 5kW induction system from Teknoheat is installed for heating the specimen through a circumferencing coil, Fig 2b.

An S-type thermocouple was spot-welded to the specimen, according to the TMF-validated code of practice [10]. The strain was measured in the central part of the gauge length using the speckle laser extensometer. The measurement length was set to 5.5-6 mm, with visible access of the specimen between the windings of the induction coil.

Tests were carried out in air and in Ar+1%H2. In the latter case, a test chamber, Fig. 2b, was used maintaining a flowrate of 90 ml/min probing the outgoing gas for leakage with an oxygen sensor. The chamber is formed between two ceramic plates with grooves matching a quartz tube. Holes in the plates provide gas in/outlet and a channel for the thermocouple. BN-rings, ceramic paper and springs provide gas-tight sealing to the specimen heads and rubber rings seal the ceramic plates and quartz tube. More details about the setup can be found in [5].
4. Stress Relaxation with Thermal Cycling, SRTC

SRTC is related to TMF OP (out of phase) since the phase shift of temperature and stress is the same. However, an important difference is that TMF-tests are employed in strain-control [8] whereas SRTC uses fixed specimen length. Thus, in a standardized TMF-test, the strain in the middle region of the specimen gauge length is controlled, following a pre-chosen time-strain profile, synchronized to a pre-chosen time-temperature profile. In SRTC, the specimen length is fixed by locking the positions of the grips. As thermal stresses may exceed the yield strength, rapid, uncontrolled, plastic deformations can be seen during SRTC. In TMF OP tests, on the other hand, such plastic peaks are avoided by piston motions.

The SRTC test-procedure can be described as follows. During heating to the start temperature, also serving as the lower hold temperature, the specimen is kept at zero stress. After temperature stabilisation, the specimen is locked in its position. Then, thermal cycling with temperature holds begins.

Fig. 3 illustrates the first one and a half thermal cycles indicating transitions between elastic (blue) and plastic (red) deformations, showing $\sigma(T)$ in a) and $\epsilon(T)$ in b), respectively. Path 1-4, can be considered as “initiation” whereas the succeeding path, 4-12, is the loop being repeated during further cycling. As seen, the initiation results in a large compression followed by a loop containing three plastic regions, 5-6, 9-10 and 11-12, as well as two creep regions, 3-4 and 7-8. However, region 9-10 may not be present, if the stress path 8-9-10-11 is slightly lower than in Fig. 3a. Then, it is replaced by a purely elastic path, 8-11.

![Fig. 3. The first 1.5 cycles, with elastic regions (blue) and plastic regions (red).](image)

An analysis shows that the slope in the elastic regions of Fig 3a) is $-\alpha E$, the product of heat expansion coefficient and elastic modulus. As both vary with temperature, the elastic regions are slightly curved.

Due to intense recovery at high temperatures, the deformation hardening is low (point 2-3, exaggerated here). During cycling, the stress returns to point 12, close to point 4, as it is determined by the yield strength. For strain, cycling is different. Point 12 is clearly separated from point 4 and the specimen “climb” in accumulated strain (as illustrated) or in accumulated compression.

5. Results and Discussions

5.1 Test matrix

In the present SRTC-tests, symmetric cycles were adopted using the same heating/cooling rates as well as the same upper/lower hold times, Fig. 4. In all cases, the upper hold temperature, $T_{\text{high}}$, was 800 °C. The lower hold temperature, $T_{\text{low}}$, ramping rates, hold times, $t_{\text{hold}}$, and atmospheres (air or Ar+1%H₂) were varied according to Table 2. The last series, varying the hold
time, was carried out both in air and in argon. By varying the hold time in an inert atmosphere, the purely mechanical effects can be analysed, undisturbed by oxide formation. The unique No. of tests in Table 2, is 2+3+5=10 for each material. By repeating each unique test for two materials, 40 tests are required. By some extra tests, 46 test were made in total.

Table 2. Test matrix.

| T_(low), (°C) | T, (°C/min) | t_hold, (min) | Atm. |
|--------------|-------------|---------------|------|
| 100          | 200         | 3             | air  |
| 300          | 200         | 3             | air  |
| 500          | 200         | 3             | air  |
| 500          | 200         | 6             | air/Ar |
| 500          | 200         | 12            | air/Ar |

5.2 Influence of temperature interval

The results from the first 1.5 cycles for SiMo51 and SiMo1000 are shown in Figs. 5 and 6, respectively. The figures present paths of $\sigma(T)$, $\varepsilon(T)$ and $\sigma(\varepsilon)$ to form complete pictures. The yield strength data for SiMo51, [5], and SiMo1000, provided by Georg Fischer Eissenguss GMBH, although from other batches, are included. The time evolution is indicated by arcs. As seen, $\sigma(T)$ and $\varepsilon(T)$ show variations on the path described in Fig. 3. The third plot, $\sigma(\varepsilon)$, shows that each TMF-cycle forms a loop with an area corresponding to the absorbed energy.

Comparing Figs. 5 and 6, it is obvious that the two materials behave similar. In the elastic regions, $\sigma(T)$ is nearly linear, as explained in section 4. Around 700 °C, anomalies are seen due to the Curie temperature. The yield stress data of SiMo1000 seem to fit the curves of $\sigma(T)$ quite well. For SiMo51, the present batch seems to be of superior quality compared to reference 5. Difference in applied strain rates may also account for some discrepancy, as it affects yield strength [11]. As the stress curves join each other at high temperatures, the deformation hardening is low and the recovery processes fast. Therefore, the tests also provide yield strength data as a function of temperature, in one single test.

Focusing on $\varepsilon(T)$, it is apparent that the creep during $T_{\text{high}}$, can readily be seen whereas it is barely seen during $T_{\text{low}}$. The cyclic strain paths are quite different for the various temperature intervals. The cooling paths are similar but the heating paths differ. The plastic region 9-10, in Fig. 3 is clearly seen at 500-800 °C, barely seen at 300-800 °C and missing at 100-800 °C. This indicates that the yield strength, Fig. 3a, is exceeded, slightly touched and completely missed in the first, second and third intervals, respectively.

A discrepancy between $\sigma(T)$ and $\varepsilon(T)$ can be seen, especially for the 300-800 °C and 100-800 °C curves. $\sigma(T)$ during cooling is curved below 400°C, indicating plastic deformation whereas $\varepsilon(T)$ shows no such signs, being completely flat. A probable explanation is that deformation occurs outside of the measuring zone. The first heating compressed the hotter measuring zone, making it stronger than its surroundings. Then during cooling, the strain of the surroundings is missed by the extensometer. This is supported by barrelling seen on long-lasting specimens.
Fig. 5. SiMo51, first 1.5 cycles at 100-800, 300-800 and 500-800°C. Yield strength from reference 5. The inserted arcs with arrows indicate the direction of time evolution.

Fig. 6. SiMo1000, first 1.5 cycles at 100-800, 300-800 and 500-800°C. Yield strength from Georg Fischer Eissenguss GMBH.

To further understand the deformation behaviour over the segments of a cycle, the plastic strain rate during the first two cycles was evaluated for the tests at 500-800 °C, Fig. 7a. In the first (initiating) cycle, the strain rate shows a compressive and a tensile peak. The second cycle starts with a tensile peak directly followed by a compressive peak. By inspecting Fig. 7b, it is obvious that the change in deformation direction is attributed to a change from tensile to compressive stress. As the selected T_{low} resulted in large plastic strains and high tensile stresses, the fatigue life became very short, in many cases only a few cycles. However, by plotting the fatigue cycles to fracture, Fig. 7c, it is evident that the tensile peak (9-10 in Fig. 3) is very dominating at 500-800°C, moderate at 300-800°C and absent at 100-800°C. It is also evident that the second cycle is merely repeated by further cycling. At 500-800°C, tensile strain is accumulated and at 100-800°C compressive strains are accumulated. The tensile peaks during cooling (5-6 in Fig. 3) are always present.
Returning to the strain rate, its peak magnitudes are close to tensile test rates, $10^{-3}$ s$^{-1}$. Thus, the plastic peaks are quite tough for the material. Inspecting the hold at $T_{\text{high}}$, (not seen in the figures) reveals that the compressive peak preceding the hold is smoothly replaced by creep. In the beginning of the hold, the magnitude of the true strain rate is about $10^{-4}$ s$^{-1}$, falling to about $10^{-5}$ s$^{-1}$ after about a minute. At $T_{\text{low}}$, with high tensile stress, small stress relaxations are only seen at 500°C, since creep is not activated at 300 or 100°C.

![Graph showing thermal cycling of SiMo51 and SiMo1000](image)

**Fig. 7.** Thermal cycling of SiMo51 (blue) and SiMo1000 (red). a,b) First two cycles at 500-800°C and c) all cycles to fracture at various temperature intervals.

5.3 Influence of heating and cooling rates ($\dot{T}$)

As indicated in Table 2, the heating/cooling rate was varied in the 2nd test series. The plastic strains of the second cycle segments 1-2, 2-3, etc, identified by the points in Fig. 8a, and the stress extremes, appearing in points 3 and 5, were analysed. As seen in Fig. 8b, the clearest trend is for segment 2-3, decreasing with increasing cooling rate. This is expected as a higher cooling rate gives less time for plastic deformation. As a consequence, the tensile stress at 3, $\sigma(3)$, increases with cooling rate, Fig. 8c. Due to the increased stress, the creep strain at 3-4 and plastic strain at 4-5 also increase with increased cooling rate. Admittedly, SiMo51 at 300 °C/min deviates from these trends. The compressive stress at 5, $\sigma(5)$, Fig. 8c, and the plastic strain at 5-6, Fig. 8b, are almost constant, indicating unaffected stress- and strain paths, 11-12 in Fig. 3, due to efficient recovery. A constant $\sigma(5)$ also gives a constant high-temperature creep at 1-2, representing about 10% of the total strain during a 500-800 °C cycle.

The compressive stresses in Fig. 8c) represent the high-T yield strength. Clearly, SiMo1000 is stronger than SiMo51 at high temperatures. At low temperatures, SiMo1000 receives higher stresses. As a result, the stress amplitude is higher for SiMo1000 compared to SiMo51.
5.4 Influence of hold times and atmosphere

The 3rd test series (Table 2) was carried out with hold times of 3, 6 and 12 minutes, cycling between 500°C and 800°C in air and in Ar. The curves for 3 and 6 min overlap well, Fig. 9, demonstrating reproducible results, not affected by oxidation. The fractures are very sudden, seen as instant load drops, without any preceding softening. As much of the stress relaxation happens prior to the high temperature hold (segment 5-6, Fig. 8) and because of a fast stress relaxation at 800°C, the tested hold times are too long to have a noticeable effect due to creep.

It should be pointed out that the short exposure times used in the present study do not allow thick layers of oxides to form. This means that the effects of oxides becomes minute on the testing method. Hence, it can be concluded that SRTC test can be performed in air, as long as the number of cycles are kept low. When carrying out SRTC in Ar, no decarburization or oxidation could be observed. When carried out in air, both SiMo51 and SiMo1000 showed surface decarburized graphite nodules replaced by Fe-oxides. For SiMo51, Si-rich shells were formed around the original nodules. For SiMo1000, Al-rich shells were instead formed.
6. Conclusions

Two ferritic nodular cast irons, SiMo51 and SiMo1000, were tested by SRTC (stress relaxation with thermal cycling). Fractures were sudden and occurred after a few cycles, only. Depending on the temperature interval, two to three plastic deformations occur per cycle. The smallest one gives the highest total deformation. SiMo1000 generally experiences higher stress amplitudes than SiMo51.

Recovery processes at high temperatures, 800 °C, are rapid and the specimens follow the yield strength curve as a function of temperature allowing the yield strength curve to be determined over a large temperature interval, using a single specimen. As a consequence, the stress at the high-temperature hold is merely the yield strength, not affected by the lower hold temperatures or heating/cooling rates. The maximum tensile stresses at the lower hold temperatures, on the other hand, increase with cooling rate and naturally also with decreasing hold temperature.

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