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CHARACTERISATION OF THE MATERIAL BEHAVIOUR OF CATHODE STEEL COLLECTOR BAR AT HIGH TEMPERATURES AND LOW STRESS LEVELS

Femi Fakoya[1,2], Donald Picard[1,3], Guillaume Gauvin[1,2], Houshang Alamdari[1,3], Richard Beeler[4], Mario Fafard[1,2]
[1]NSERC/Alcoa Industrial Research Chair MACE[3] and Aluminium Research Centre – REGAL, Laval University, Quebec, QC, G1V 0A6, Canada
[2]Department of Civil and Water Engineering, Laval University, Quebec, QC, G1V 0A6, Canada
[3]Departement of Mining, Metallurgical and Material Engineering, Laval University, Quebec, QC, G1V 0A6, Canada
[4]Alcoa Primary Metals, Alcoa Technical Center – 100 Technical Drive, Alcoa Center, PA, 15069-0001, USA

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Abstract

The study of the deformation behaviour of the collector bar at conditions experienced within the aluminium reduction cell is of great importance to optimizing the efficiency and increasing the life span of the cell. This paper communicates the results of an experimental program carried out on the steel collector bar material (AISI 1006) to investigate its behaviour in relation to its thermal, mechanical and the creep properties. Tests were carried out in compression at low stresses, 0.5 to 2 MPa and high temperature, 900 °C. Different behaviour was observed at low stresses below 2 MPa, which can be characterised by time and applied stress level. For the test at 2 MPa, a conventional creep curve with dominating secondary creep region was obtained. Oxidation and corrosion were factors considered due to the aggressive environment of the test condition. Metallographic inspection showed effect of oxides on tested sample.

Introduction

A long lifespan of the aluminum reduction cell is required as cost factors are related to relining and loss of production time. The longevity of the cell at operating conditions is determined by the first material to fail inside the steel shell [1]. Cathode heaving and degradation of its lining are two key factors influencing the performance and lifetime of the cathode due to the effect of thermal and sodium expansion of the cathode assembly against the strong steel shell [2].

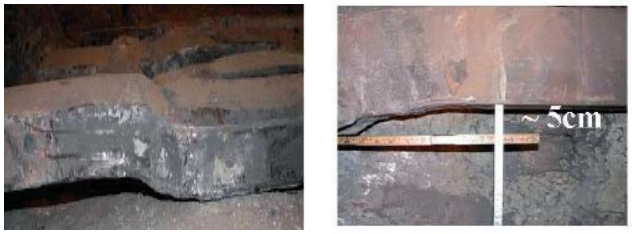
Autopsies showed that cathode heaving induces a considerable deformation profile in the collector bar (Figure 1), majorly due to the temperature gradient and lower constraints at the end of the bar. This leads not only to elastic contractions but also creep of the cathode collector bar at high temperature. The total strain can be expressed such that:

$$\boldsymbol{\varepsilon^t = \varepsilon^{th} + \varepsilon^e + \varepsilon^{cr}} \quad (1)$$

$\boldsymbol{\varepsilon^t}$ denotes total strain, $\boldsymbol{\varepsilon^{th}}$ thermal strain, $\boldsymbol{\varepsilon^e}$ elastic strain and $\boldsymbol{\varepsilon^{cr}}$ creep strain [1,2].

The creep/relaxation behaviour is a nearly incompressible phenomenon. The deformation along the transverse section of the collector bar causes a decrease in the stress level at the steel/ cast iron/ cathode block interface, thereby further increasing the electrical resistance induced at this interface. This contributes to the overall contact voltage drop (CVD) in the cathode assembly hence reducing the energy efficiency of the cell.

In order to have a good prediction for the material behaviour of the collector bar at operating temperature (around 960 °C), it is necessary to identify parameters not only for thermal expansion and elastic behaviour, but also for the creep behaviour.



(a) (b)

Figure 1: Deformation of the collector bar: (a) deformed collector bar, (b) measurement of deformed collector bar after service life. Extract from [2].

Steel has excellent strength properties at ambient conditions, but loses its strength and stiffness with increasing temperature. At high temperature, deformation becomes more pronounced even at low stress level as the yield strength is significantly lower. A more dominating creep effect begins to occur with time.

The temperature-dependent properties such as; thermal expansion, Young's modulus and creep data are required to model the creep behaviour response of structures at high temperature. For AISI 1006 steel, there appears to be limited data on these properties at very low stress level and high austenite temperature region. Carbon steel undergoes linear thermal expansion with increasing temperature. At a carbon content above 0.02 %, a phase change from ferrite to austenite associated to a contraction, starts at 730 °C and finishes between 800 °C and 900 °C for carbon content up to 0.3 %. For low carbon steel in tension, both yield strength and elastic modulus decreases significantly at higher temperatures especially above 300 °C. A thermal strain of up to 1.2 % with the occurrence of a phase change, an elastic modulus of about 13.5 GPa and a yield strength of 18 MPa (at a loading rate of 0.01 s^{-1}) has been predicted by different models and measured in different tests at 900 °C [3,4,5].

Compression test data on the collector bar material (AISI 1006) showed great influence and dependence of its deformation behaviour and mechanical properties on temperature up to 850 °C for strain rates ranging from 0.1 to 50 s^{-1}. At constant temperature of 850 °C, the yield stress increases with increasing strain rate such that, yield stresses of 50, 85 and 150 MPa were obtained for

strain rates of 0.1, 3, and 50 s^{-1} respectively [6]. A study on the creep rate of the collector bar at low loads ranging from 1 to 5 MPa [7], concluded that the collector bar slowly deformed under small forces experienced in the cell at temperatures above 700 °C. From several data provided in the literature, it can be concluded that the creep rate is around 0.002 % h^{-1} at 900 °C under a load of 1.3 MPa, a rate corresponding to almost 1 % creep in three weeks [7]. Thus, the expected effective contact pressures at the steel / cathode block interface of the cell may appreciably decrease over the years of the cell lifespan.

Continuous interest from the aluminium industry along with efforts of researchers to improve efficiency and maximize productivity, have seen the cell lifespan increase from 1000 days in the early years to close to 2500 days. To sustain the continuous increase in the lifespan and energy efficiency of the cell, the characterization of the material behaviour of the collector bar is a major factor that must be taken into consideration, especially for developing an accurate numerical model of the cell. However, there is a lack of relevant data in literature to fully characterize the deformation behaviour of the collector bar at operating condition. Hence, in this study, an experimental procedure was carried out in compression to investigate deformation behaviour of the collector bar particularly at high temperature and low stress conditions to obtain its thermal, elastic, and creep properties. The creep tests were carried out at constant stress levels of 0.5, 1, 1.5 and 2 MPa and at constant temperature of 900 °C.

Experimental Procedure

The test specimen used in this investigation is an AISI 1006 low carbon steel with typical composition of 0.080 % Carbon, 0.25-0.40 % Manganese, 0.050 % Sulphur and 0.040 % Phosphorus. The cylindrical shaped specimens are 86 mm long x 29 mm diameter and have a mass of 431.9 g. The compression creep test was carried out on an MTS landmark servo hydrodynamic test bench using three load cells with maximum capabilities of 250, 10 and 5 kN. The load cell was selected according to the test requirements. The required test temperature was attained in a flowing argon atmosphere of a three-zone resistance furnace, each with thermocouple as supplied by Winston Salem Thermocraft. The argon flow rate was 4 l/min. On line displacement data were taken by both the load frame displacement transducer (LVDT) and a precision linear encoder device (Heidenhain MT 1281). The test bench and specimen set-up was as depicted in Figure 2.

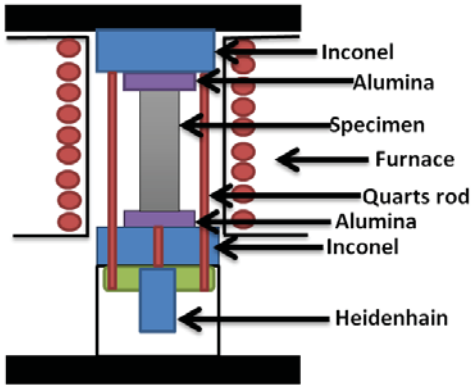


Figure 2: Schema of test set-up

For a test in compression, high precision in aligning sample within test set-up is essential to ensure a homogeneous stress distribution in sample. The test procedure was in accordance to ASTM E 209-00 and E 139-11. During the heating phase, the sample was subjected to an initial pre-stress load of 0.08 MPa while heating to the required test temperature (at 900 °C) and left at this isothermal condition for about 4 hours. This was to ensure proper contact at all surfaces, uniform temperature distribution in the set-up, and to achieve steady strain rate state (signifying maximum grain size and hence steady microstructure). Thereafter, the required test load was instantaneously applied and kept constant on the sample for the test duration. The thermal expansion, contraction due to phase change and scale oxidation behaviour of this material, took place prior to the creep test. The strain estimation as a function of time is based on the full length of the sample, i.e. the vertical relative displacement of the two circular faces of the sample.

Thermal Expansion and Phase Change

The test sample, AISI 1006 with carbon content of 0.08 % experienced a contraction, which started at 750 °C and ended at about 900 °C as shown in Figure 3. This suggests that the sample experienced both thermal expansion and phase transformation from ferrite to austenite state.

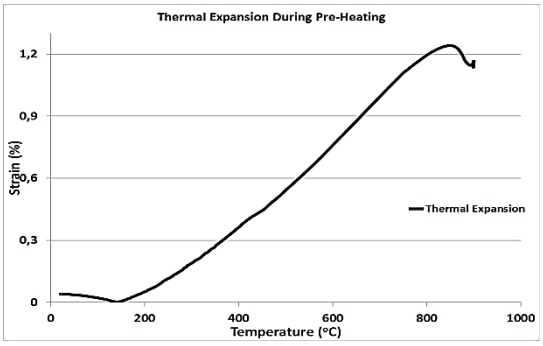


Figure 3: Thermal expansion and phase change during heating phase

At 900 °C, the phase transformation tends to reach an end. However, as the phase transformation occurs over a short temperature regime where both ferrite and austenite state seem to coexist, small ferrite phase may still exist at 900 °C. From this data, a maximum thermal strain of about 1.25 % was obtained. The coefficient of thermal expansion gives a value of 0.000015 per °C for this material and determined by the expression:

$$\alpha_{th} = \frac{\Delta l}{l_0 * \Delta T} \qquad (2)$$

where α_{th} denotes thermal expansion coefficient, l_0 initial length, Δl change in length and ΔT change in temperature.

Scale Oxidation Behaviour

Steels subjected to high temperatures in an oxidised environment leads to formation of oxide on their surfaces. Birosca et al. [8], carried out a study on the oxidation rate of low carbon steel at 650, 750, 900, 1000 and 1100 °C which showed that at all temperatures, the oxides thickness reaches a plateau level after relatively short oxidation time. Birosca et al. also concluded that

the higher the temperature level, the greater the oxide thickness [8].

In this work, an experiment was carried out to check for scale oxidation and metal loss due to the corrosive nature of the test condition in the furnace. Though argon gas was injected into the furnace chamber, the effect of the presence of some air could still be observed. Two samples, one coated with refractory material (SEALMET) and the other uncoated, were placed in the MTS test bench set-up as described above without any load. The temperature was raised up to 900 °C and kept constant for 24 h. Weight measurements were taken before and after the test as represented in Table 1.

Table 1: Measurements results of specimen for corrosion and metal loss test (grams).

Sample	Weight before coating	Weight after coating	Weight after test	Weight after cleaning	% weight loss
Coated	431.9	436.9	436.9	428.9	0.69
Plain	431.9	431.9	424.5	409.0	5.06

A metal loss of about 5.06 % in the uncoated sample compared to 0.69 % for the coated sample was observed. The amount of weight loss by the uncoated sample gives a reason to consider coating all samples prior to test. The scale oxides of the coated samples were observed to be more closely attached to the sample after the test in comparison to that of the plain sample, where most of its scale appeared to have fallen off during the test. Some blue and green stains were also observed on the coated material (Figure 4), indicating signs of corrosion leading to the metal loss. Based on these observations, in preparation for the creep test, all other samples were coated to reduce effect of corrosion, metal loss and also to ensure good strain measurement. Coating was applied by brush and special care was taken to ensure uniform coating on all samples used in the test.

(a) (b)

Figure 4: Corrosion test (a) Coated and plain sample after test, (b) Oxide scales detached off the sample

Compression Creep Test

Creep is a time dependent strain derived under constant stress and temperature. A typical creep curve can be characterised by three stages; primary, secondary and tertiary. In the initial stage "primary creep", the creep strain is relatively high but slows down with increasing time (decreasing strain rate) and eventually reaches a steady state "secondary creep" (constant strain rate). In the final stage "tertiary creep", the creep strain accelerates (increase in strain rate) towards failure. This final stage is mostly observed in a tensile test rather than compression due to the "Necking" effect.

Generally for metals under constant load, creep of the bar is expected to become noticeable at temperatures corresponding to 30 % of the melting temperature ($0.3T_m$) for pure metals and 40 % ($0.4T_m$) for alloy metals [9]. For the sample used in this study (AISI 1006), the melting point is approximately 1400 °C hence, the creep strain was expected to become evident at temperature starting from 566 °C and above. All creep tests were carried out in compression at constant temperature of 900 °C for four (4) different applied stress levels of 0.5, 1, 1.5 and 2 MPa. Each test was repeated three times to ensure repeatability. As a creep test in compression, and particularly at such low stress levels, the specimens were not expected to fail, hence tests were terminated once a significant amount of steady/secondary stage creep was obtained.

Experimental Results and Analysis

Creep tests were carried out in compression for a specified duration of time at constant temperature 900 °C and constant stress levels at 0.5, 1, 1.5 and 2 MPa. The recorded data were analysed and represented with a simple strain - time curve.

An initial creep test was carried out at 1 MPa for 24 hours with pre-heating stress at 0.3 MPa for 2 hours before commencing creep test (Figure 5).

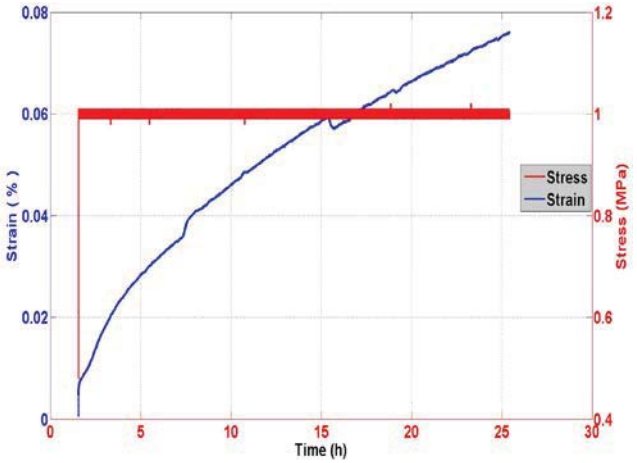


Figure 5: Initial creep test at 900 °C and 1 MPa for 24 hours

In Figure 5, the strain during thermal expansion was excluded. The obtained results showed an instantaneous elastic strain zone followed by a time dependent strain over the test period at constant load. The strain response was highly sensitive to changes in the surrounding temperature. Any little change in room temperature affects the temperature of the cooling water (used to protect the measuring devices) and hence the furnace temperature. A change in temperature as small as 3 °C within the furnace caused substantial increase in the strain and recovered back at normal furnace temperature. This corresponds well and can be associated with effect of thermal expansion occurring at slight temperature change during the creep test.

From calculations using a stress – strain plot of the elastic region and curve fittings, the elastic modulus was obtained at a value of 13.2 GPa. This compares well to given values in literature at same

temperature. The creep rate obtained at 0.0025 %/h also compares well to values given in literature [7].

From the results obtained in the initial creep test, regions of primary or secondary creep could not be easily determined. Acquiring more data was necessary to understand the creep behaviour over a long period of time. Hence, the creep test duration was extended for a longer period of up to 250 hours. The test was carried out at constant temperature of 900 °C and at four different stress levels.

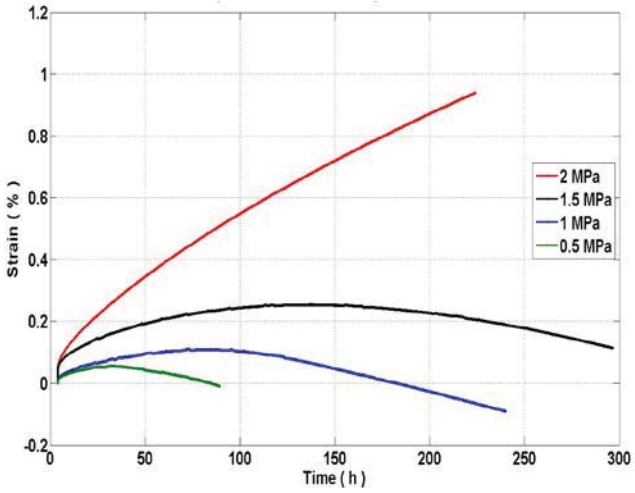


Figure 6: Strain at 900 °C and at four different stress levels

Figure 6 presents the time dependent strain data for the four stress levels: 0.5, 1, 1.5 and 2 MPa. For the first three stress levels, unconventional behaviour which can be characterized by time and applied stress level was observed. The case was different at 2 MPa where a conventional creep curve dominated by secondary creep region was obtained. Metallography analysis was carried out on the samples to understand the unconventional behaviour for stress level less that 2 MPa.

Metallography

A brief metallography test was carried out using SEM on a plain sample and test samples exposed to the creep test at all stress levels. Each sample was cut at about 5 cm along its longitudinal length and dissected into 4 uniform pieces along its circumference. Analyses on the outer surface of the sample before and after creep test at 2 MPa is as shown in Figure 7.

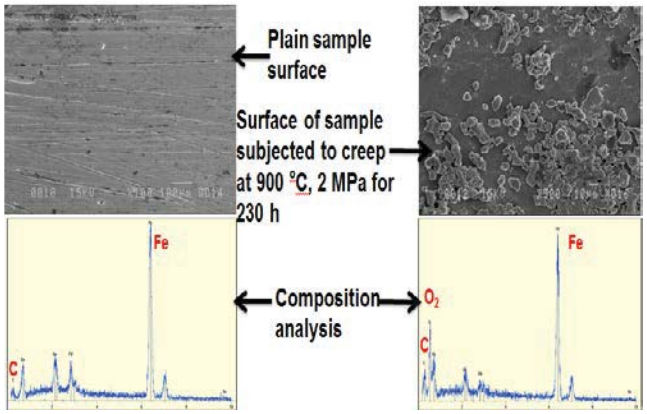


Figure 7: Metallography test on sample surface before and after creep test

The presence of oxygen and the effect of oxides were observed in sample subjected to the creep test at 2 MPa, as seen in Figure 7. Similar features were seen for all other samples analysed at different stress levels.

Discussion

Analysis of the initial creep test at 1MPa – 900 °C, represented in Figure 5 gave data which compared well in terms of the creep rate at 0.0025 %/h and the elastic modulus of 13.2 GPa to those obtainable in literature. However, this data was obtained from test carried out at a short duration of 24 hours and not considered long enough to accurately characterize the long-term behaviour of the collector bar at operating conditions. A clear instantaneous elastic and creep displacement region was observed, but primary and or secondary creep could not be easily identified and the controlling creep mechanism was not determined. The creep rate data compares well with literature, but information on the test duration and controlling creep region were not provided. This suggests that the duration of those tests might have been less than 24 hours.

At 0.5 MPa, obtained strain showed that the sample continues to creep in compression for duration of about 30 hours after which it tends to change behaviour with expansion occurring in the sample as time increases. Similar behaviour was observed for strain obtained at 1 and 1.5 MPa. At 1 MPa, this change in behaviour was seen to occur after about 100 hours and after 150 hours for 1.5 MPa where each peak was seen. After each peak, the material tends to experience a time dependent expansion. The rate of expansion seemed to reduce with increasing stress level as a higher expansion rate was observed at 0.5 MPa than that at 1 MPa and that of 1 MPa also higher than at 1.5 MPa. From all indication, this behaviour seems to be time dependent and a function of the applied stress level.

For strain obtained at 2 MPa, this behaviour was not observed, even after a long period of time. A clear creep profile was observed with a dominating secondary creep region (Figure 8). The creep profile at 2 MPa could be seen to be completely different from those obtained for lower stress levels right from onset. A creep rate of 0.0032 %/h was obtained.

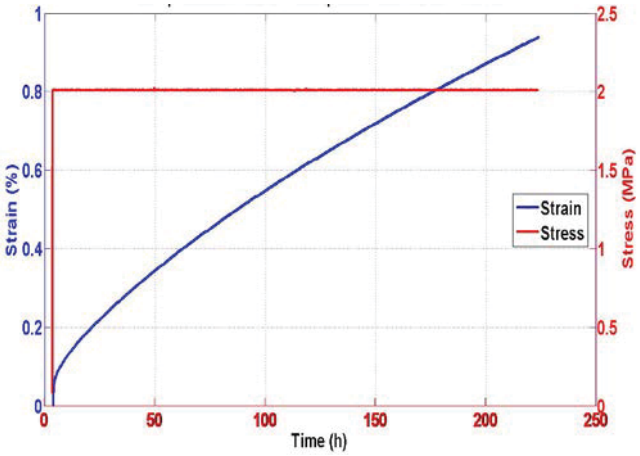


Figure 8: Strain at 900 °C and at 2 MPa

Though it was identified in literature that there is a threshold stress below which no creep occurs [10], this theory just describes a plateau level attained in the creep curve at which no deformation or expansion is observed for such stress levels. Hence, such a theory cannot be used to explain this behaviour. Moreover, due to the corrosive nature of the test environment, corrosion and oxides are factors that could be considered at this stage. Corrosion tests and metallography analysis showed formation of oxides in tested samples. These oxides could influence the friction conditions (hence stress distribution), heat transfer (temperature distribution) and tool wear during deformation, especially for a test in compression.

However, according to most literature [8], at constant temperature, the effect of corrosion reaches a stable state as the oxide thickness reaches a plateau. Only an increase in temperature increases the effect of oxide scale thickness and its behaviour obeys the parabolic law. This is not exactly as observed in these results and cannot be used to explain strain behaviour obtained at stresses below 2 MPa in this work.

For this material, a test at 900 °C falls in the temperature region where both ferrite and austenite phases coexist and where the microstructure is not stable. This could also influence deformation behaviour.

Conclusion

Creep tests were carried out at 900 °C and at four different stress levels to investigate the deformation behaviour of the collector bar material (AISI 1006) during cell operation. The effect of thermal expansion, phase change and corrosion were observed during the test as discussed. A typical creep curve dominated by secondary creep stage was observed at 2 MPa while different deformation behaviour could be seen at lower stresses. Metallographic inspection also showed presence of oxygen and effect of oxide scale on tested sample.

For proper understanding and explanation of the time dependent deformation profile and controlling mechanisms occurring at stresses below 2 MPa, a more detailed chemical and micro-structural analysis of the sample is essential and might provide a major headway

The impact of observed oxides in relation to friction conditions on the sample and to what extent it might affect the deformation behaviour of the sample will be investigated further as well as the effectiveness of the coating over a long period of time at different stress levels.

A complete phase change to full austenite region is said to occur at 915°C, tests at a higher temperature, above 915°C and at stress levels below 2 MPa could help determine if the unstable phase due to the coexistence of ferrite and austenite phase have major impact on the deformation behaviour.

Future activities include scheduled strength test in compression at ambient and 900 °C to obtain the mechanical properties such as the elastic modulus and yield strength. Also, creep tests at a particular constant stress and three different temperature levels (850, 900, 950 °C) will be carried out.

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