Potential Drop Creep Strain Monitoring

Joseph CORCORAN ¹, Peter CAWLEY ¹, Peter NAGY ²
¹ Imperial College, London, UK
² University of Cincinnati, Cincinnati, USA
Contact e-mail: joseph.corcoran07@imperial.ac.uk

Abstract. For practical engineering applications creep occurs in an inherently harsh, high-temperature environment. There is a strong industry demand for continuous measurements to allow a better understanding of component integrity in a situation where outages allowing inspection are infrequent; in the UK the expected inspection interval is 2+ years. A potential drop strain sensor has been developed that has very robust sensor hardware lending it to in-situ creep monitoring of power station components. A background to the sensor is presented in this paper, along with a resistance-strain inversion which is then demonstrated on accelerated creep test components. Additionally a brief overview of site trials of the technology in power station components is given.

1. Introduction

Creep is one of the most serious high temperature damage mechanisms [1]. Many conventional power stations have been in use for over 100,000 hours and are therefore reaching the end of their design life. At this stage assessment of integrity is important to safely extend asset life and also minimise costly outage time by better informed and targeted inspection [2].

The strain, or more specifically the strain rate, of a component is well known to provide valuable information on creep integrity and has been suggested for use in remnant life estimate calculations [3–5]. A permanently installed creep strain sensor has been developed with simple and robust hardware. The use of a quasi-DC inspection current provides enhanced noise performance [6, 7] whilst supressing the skin effect [6, 8, 9] that would otherwise undermine measurements in the ferromagnetic materials of interest to the electricity generation industry. The use of alternating currents greatly increases the noise performance of the measurement technique, relative to the DC alternative, lends the technique to continuous, remote monitoring.

This paper provides background to the sensing principle, provide an analytical strain inversion and then demonstrate the technique on accelerated creep test components.
2. Low-frequency, square configuration potential drop measurements

A square configuration of electrodes is fixed to the surface of a component and two successive measurements are taken as shown in Figure 1. First, as shown in blue, a known current is injected through the electrodes forming one side of the square and the potential difference is measured across the remaining two electrodes. In this way a transfer resistance is measured indicative of the resistivity in the $x_1$ direction. The roles of the electrodes are then exchanged and a resistance measurement is made in the $x_2$ direction, as indicated in red.

![Square electrode configuration potential drop measurement](image)

(a) Initial, unstrained configuration  (b) Configuration following strain

**Fig. 1.** Square electrode configuration potential drop measurement (a) before and (b) after strain accumulation.

The electrodes may be permanently fixed to the surface of the component, usually taking the form of studs welded to the surface of a pipe. As the component deforms through creep strain the initially square geometry will deform to some new altered geometry. The resulting change in the distances between the electrodes will influence the measured transfer resistances – which can then be used to infer the accumulated strain.

The penetration depth of an ACPD measurement is limited by the electromagnetic skin effect which is a known function of both frequency and permeability. In the ferromagnetic materials commonly used in the power industry the permeability will vary as a function of many variables which will in turn influence the skin depth and so resistance measurements. By using very low, quasi-dc frequencies (here 2 Hz) the current distribution will tend towards that of a DC measurement where the penetration depth is limited by the smaller of the electrode separation or the component thickness. In the case of thick walled power station components, the current penetration is limited by the electrode separation and the influence of the ‘back wall’ is considered negligible. In this regime the measurement is no longer dependent on the magnetic permeability.

The transfer resistances arising from a four-point, rectangular configuration, potential drop measurement will be a function of the distances between electrodes, and therefore strain, but also resistivity. An analytical expression for the transfer resistances has previously been provided [6]. By normalizing the resistances to their initial, undeformed, values, $R_{10}$ and $R_{20}$, they can be written in terms of the strain, $\varepsilon_1$ and $\varepsilon_2$, in the orthogonal $x_1$ and $x_2$ directions.

\[
\frac{R_1}{R_{10}} = s \frac{\rho}{\rho_o} \left( \frac{1}{1 + \varepsilon_2} - \frac{1}{\sqrt{(1 + \varepsilon_1)^2 + (1 + \varepsilon_2)^2}} \right)
\]

\[
\frac{R_2}{R_{20}} = s \frac{\rho}{\rho_o} \left( \frac{1}{1 + \varepsilon_1} - \frac{1}{\sqrt{(1 + \varepsilon_1)^2 + (1 + \varepsilon_2)^2}} \right)
\]

(1)
where, \( s = 2 + \sqrt{2} \approx 3.41 \).

Resistivity will change considerably as a function of temperature and also, to a lesser extent thermally activated material degradation. Fortunately, as the resistivity will be common to both orthogonal resistances, the effect will cancel when taking the ratio of the two. In order to invert the resistance data to strain, the ‘Normalised Resistance Ratio’ is adopted. The Normalised Resistance Ratio, \( NRR \), is given by,

\[
NRR = \frac{R_1}{R_{10}} / \frac{R_2}{R_{20}} = \frac{1}{(1 + \varepsilon_2)} - \frac{1}{\sqrt{(1 + \varepsilon_1)^2 + (1 + \varepsilon_2)^2}}
\]

(2)

Evidently, the resistivity terms cancel, suppressing the resistivity dependence. Madhi and Nagy [8] showed that Equation 2 can be approximated using a power approximation,

\[
NRR = \left( \frac{a_1}{a_{10}} \right)^s = \left( \frac{1 + \varepsilon_1}{1 + \varepsilon_2} \right)^s
\]

(3)

In the case of uniaxial loading in the \( x_1 \) direction this is trivial as \( \varepsilon_2 = -0.5\varepsilon_1 \).

\[
NRR = \left( \frac{1 + \varepsilon_{1\text{uniaxial}}}{1 - 0.5\varepsilon_{1\text{uniaxial}}} \right)^s
\]

(4)

or,

\[
\varepsilon_{1\text{uniaxial}} = \frac{NRR^{1/s} - 1}{0.5 NRR^{1/s} + 1}
\]

(5)

This resistivity independent inversion will be demonstrated experimentally.

### 3. Experimental Validation

Creep samples of 24 mm x 10 mm gauge cross section were produced. The potential drop creep strain sensor can be installed in an array formation, as shown on a test component in Figure 2 (a). Such an implementation provides complete coverage of the gauge length of the component. Additionally, it allows comparison between the potential drop method and extensometry to demonstrate the technique and inversion. Two studs were additionally spot welded to the back of the component and extensometry attached to them to transfer displacement outside of the test furnace where it can be measured using an LVDT. The studs were initially separated to cover an integer number of elements. As each of the potential drop array elements was initially the same size the engineering strain measured by extensometry should match the average engineering strain of the encompassed PD elements. In the schematic of Figure 2 (b) the studs used for mounting the extensometry cover the central 4 PD elements; the strain as measured by the LVDT, \( \varepsilon_{LVDT} \), should match the average of the strain as measured by the PD elements 3-6, \( \varepsilon_{PD3} - \varepsilon_{PD6} \).
Figure 2 shows the result of the strain inversion for each of the elements of the potential drop array for the duration of the experiment. It can be observed that the strain rate is considerably higher in the central array elements than those towards the ends. This is due to the widening of the dog bone specimen influencing the stress state. Towards failure, further strain localisation is evident until failure finally occurs at element 4. In this experiment a computer malfunction led to the missing data following 1100 hours. Element 1 of the array failed before loading started.

The average strain from the central four elements is compared to the control extensometry results in Figure 4. It can be seen that the strain inverted from the potential drop measurement is barely distinguishable from the independent extensometry measurements, thereby demonstrating the sensor performance.
Fig. 4. Comparison of the strain measured by LVDT and the potential drop inversion (NRR Inversion). The central 4 elements of the potential drop array were averaged to match gauge length of the extensometer.

4. Site Trials

Two site trials have been conducted to demonstrate the performance of the potential drop creep measurement system on operational components in a power station environment. A total of 32 sensors were installed; 20 at Ratcliffe and 12 at West Burton power stations, owned by E.ON and EDF respectively. Specially designed high-temperature hardware had to be developed to withstand the harsh power station environment, shown in Figure 5. Additionally, a prototype automated measurement system was developed. Current of 100 mA is used on site and therefore the measurement system can be battery powered, removing the necessity to install mains power cables and making it easy to install. It is programmable to service up to 4 sensors and to take measurements at user defined intervals. The full measurement system is shown in Figure 6.

Fig. 5. Labelled photograph of potential drop sensor design.
The site trials are being used to continuously update and improve the system. Current performance is very promising. Figure 7 provides example data from a signal sensor with the orthogonal resistances labelled as ‘1’ and ‘2’. A thermocouple installed in the vicinity of the sensor enables temperature compensation of the temperature effect on resistivity. The gradual divergence of the orthogonal resistances is a result of creep strain accumulation, indicating that the system performance is sufficient to clearly monitor creep strain rates even over a relatively short duration.

![Prototype measurement system with sensor cables being attached](image)

**Fig. 6.** Photograph showing sensors and measurement system installed at West Burton power station.

![Sensors protruding out of pipe insulation and cladding](image)

**Fig. 7.** Temperature compensated orthogonal normalised resistances from a sensor installed on a power station component.

## 5. Conclusions

A strain sensitive potential drop technique has been presented that has very robust sensor hardware, therefore lending itself to use in the harsh conditions of the 550 °C+ power station component environment. The use of quasi-DC inspection frequencies provides enhanced noise performance relative to the DC alternative, achieving excellent signal to noise at typically 100 mA.

A strain inversion has been provided and demonstrated on accelerated creep test components. Excellent agreement was shown between the strain measured by the potential drop technique and extensometry at temperatures of 620 °C.
Site trials are underway at two coal fired power station in the UK. Dedicated high-temperature sensor hardware has been developed in addition to battery powered, automated measurement and data logging equipment. Data recorded so far is very promising, with the influence of creep strain being clearly evident.

The sensor therefore offers the potential for monitoring creep strain, or more importantly, creep strain rate of a component. The interpretation of which can then be used for integrity assessment and remnant life calculations allowing improved component management and outage planning.

References