NDT&E International 44 (2011) 708–717

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Sensitivity analysis of a directional potential drop sensor for creep monitoring

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ARTICLE INFO

Article history:
Received 3 June 2011
Received in revised form
30 July 2011
Accepted 1 August 2011
Available online 9 August 2011

Keywords:
ACPD
Creep monitoring
Resistivity
Anisotropy

ABSTRACT

Recent research efforts indicated that directional potential drop (PD) measurements could be exploited for in-situ creep monitoring. The present work investigates the sensitivity of such measurements with a square-electrode configuration to geometrical and material variations caused by creep. This measurement technique is based on a modification of the conventional PD technique as it measures simultaneously two resistance values in orthogonal directions. Under uniaxial stress condition, the ratio of the lateral and axial resistances is roughly proportional to the applied strain. Experimental tests showed that small anisotropic changes in the resistance ratio caused by directional effects of creep can be distinguished from potentially far larger isotropic changes caused by non-directional reversible and irreversible thermal effects. The sensitivity of the square-electrode PD sensor to geometrical and material variations was analyzed separately and the analytical predictions were validated by experimental tests in both cases. The directional PD technique was found to exhibit high sensitivity that allows the detection of elastic and plastic strains as low as 0.05%. Additional experimental results from an accelerated 400-hour creep test are presented to demonstrate the feasibility of this technique to monitor creep degradation in 304 stainless steel at 600 °C.

1. Introduction

During creep deformation, material damage accumulates with time as a function of temperature and mechanical stress. The specific form of degradation is material dependent, but in creep-resistant steels it might follow two main types of path [1]. First, there is transformation and precipitation of carbides from the initial microstructure. These precipitations might be in the form of tempered martensite and bainite or pearlite and ferrite, depending on the heat treatment used. Second, at a later stage of the degradation process, the presence of voids and microcracks becomes more evident. For creep-resistant materials used at high temperatures, creep rupture caused by cumulative damage is a common failure mode. The process starts by the nucleation and then growth of cavities at grain boundaries. The cavities tend to gather preferentially on grain boundaries approximately perpendicular to the applied stress [2–4]. Eventually these cavities connect together to form microcracks that propagate and join together in a later stage of degradation that leads to ultimate failure. This process leads to anisotropic texture in electric resistivity, which can be exploited for creep monitoring. In effect, the resulting preference in damage orientation introduces small but perceivable path-length differences for electrical current. This induced anisotropy is detectable by directionally sensitive sensors.

Most damage detection techniques have sufficient level of sensitivity for the purposes of damage monitoring, but the crucial issue is their selectivity, or the lack of it, to a specific material degradation mechanism. There are numerous variables to which a given sensor can be sensitive including microstructure evolution, carbide precipitation, hardening, plastic strain and elastic strain. Effective creep monitoring requires that the sensor sufficiently suppress changes that are primarily associated with thermally-activated microstructural evolution. Even prior to mechanical loading, the material contains various microdefects, such as microcracks, voids, inclusions, second-phase particles and other inhomogeneities [5]. Also, most steel components used in power plants accumulate an initial amount of cold work during their manufacturing. The presence of cold work induced texture and directional defects is expected to result in an initial material anisotropy that is detectable by sensitive probes as recovery and relaxation takes place during thermal exposure.

Because of the above described complexities, creep monitoring in general and detection of void precursors in early stages of creep in particular continue to be great challenges and also great opportunities for the nondestructive evaluation community.

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doi:10.1016/j.ndteint.2011.08.001

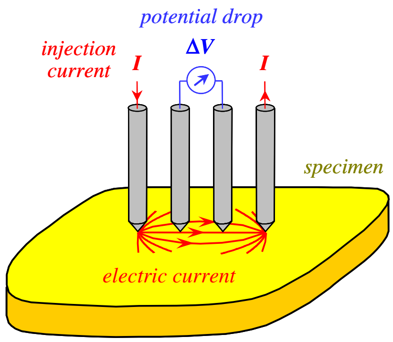

Fig. 1. Schematic diagram of a typical PD measurement with in-line electrode configuration.

The most popular techniques for creep detection include replica metallography, various forms of surface strain measurements, ultrasonic velocity, attenuation, backscatter, birefringence measurements, magnetic methods including Barkhausen and magneto-acoustic emission, hardness measurements, positron annihilation, small-angle neutron scattering, eddy current and various other electromagnetic methods. For a critical comparison of the most important techniques see the recently published comprehensive review by Sposito et al. [6]. From the point of view of the present paper, efforts to use electric potential drop (PD) measurements are the most relevant. PD assessment of creep damage was found especially promising early on in the degradation process [7,8]. PD creep assessment exploits changes in electrical resistivity due to microstructural evolution and damage accumulation throughout the creep life of the material [9]. Numerous studies indicated that electrical resistivity measurements can be used for volumetric creep damage monitoring [10–13]. Generally, long-term thermal exposure of low-alloy ferritic steels causes a perceivable drop in the electrical resistivity and simultaneous applied stress leads to even greater reductions. It was reported that during creep the electric resistivity tends to first decrease until about 40% of creep life [10]. Around this point, the resistivity stabilizes and eventually starts to increase as failure approaches. In summary, these recent studies indicate that PD techniques are well suited for monitoring creep degradation and that their main advantage over alternative inspection methods is their ability to monitor creep in early stages when most other NDE methods cannot yet detect the resulting damage [6]. Unfortunately, microstructural evolution, which is not necessarily creep-related, also contributes and sometimes dominates the changes in electric resistivity [14].

2. Directional PD measurement for creep monitoring

Most PD techniques measure the electrical transfer impedance of a conducting material with a pair of injection electrodes and a separate pair of sensing electrodes arranged in a line as shown in Fig. 1. In the so-called direct current (DC) or quasistatic mode the spread of the injected current inside the specimen is controlled by geometrical effects and the distribution of the electric resistivity of the material. Similar alternating current (AC) measurements can be conducted at increasing frequencies so that the frequency-dependent electromagnetic "skin" depth becomes first comparable and then smaller than the quasistatic penetration depth of the current distribution in the specimen. Because of this, ACPD measurements offer better control over the inspected depth in the specimen and yield larger, therefore more easily measurable, potential differences at lower levels of injection current. Furthermore, ACPD measurements can exploit phase-locked detection to increase the measurement accuracy. In order to minimize the spurious effects of large variations in magnetic properties, in this study we consider only low-frequency, essentially quasistatic, ACPD measurements when the skin effect is negligible and the injection current spreads throughout the whole cross section of the specimen limited only by the electrode separation just like in the case of DCPD measurements. For a comprehensive summary of the use of four-point potential drop measurements for materials characterization purposes see the recent review by Bowler [15].

It was recently suggested that in creep monitoring directional PD resistance measurements with square-electrode configuration offer many advantages over the conventional non-directional in-line electrode configuration [16]. A permanently installed sensor consists of the material to be tested and four thermocouple wires spot-welded to it as shown in Fig. 2. Let us assume that a uniaxial tensile load is applied in the x_1 direction. First, the "axial" transfer resistance $R_1 = V_1/I_1$ is obtained by injecting current I_1 at electrodes A–B and measuring the resulting in-phase voltage drop V_1 between electrodes D–C. Then, the "lateral" transfer resistance $R_2 = V_2/I_2$ is obtained by injecting current I_2 at electrodes A–D and measuring the resulting in-phase voltage drop V_2 between electrodes B–C. In this fashion, creep can be monitored through the variations observed in the resistance ratio R_1/R_2. It should be mentioned that, based on the Reciprocity Theorem, the injection and sensing electrodes can be exchanged without affecting the measured transfer resistances, which might be exploited to improve the measurement accuracy.

Generally, the measured electric resistances $R_{1,2}$ are complicated functions of both reversible and irreversible thermal, mechanical and thermo-mechanical (creep) effects in the material. For our current purposes, these effects can be modeled as follows:

$$R_{1,2}(T,\varepsilon) \approx R_{10,20} B_{1,2}(T) C_{1,2}(\varepsilon), \tag{1}$$

where R_{10} and R_{20} are the initial "intact" values of R_1 and R_2, respectively, $B_1 \approx B_2$ represents the very similar temperature dependence of the resistance in the two principal directions, T is the instantaneous temperature of the specimen, $C_{1,2}$ are functions that represent the strain dependence of the resistances in the principal directions and ε is the total axial strain that includes both elastic ε_e and plastic ε_p strain components. Since thermal expansion is negligible in comparison with the much higher temperature dependence of the electric resistivity, $B_{1,2}(T)$ can be approximated as a purely material effect:

$$B_{1,2}(T) \approx 1 + \beta(T - T_0)^m + \beta_{1,2}, \tag{2}$$

where β and m are the essentially isotropic coefficient and power of reversible temperature variation, respectively, T_0 is an arbitrary

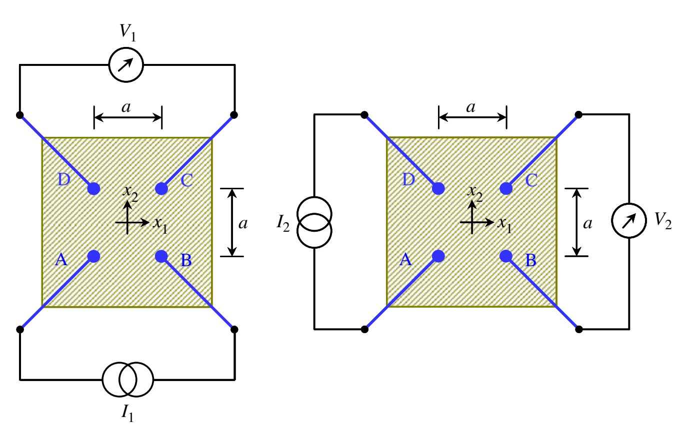

Fig. 2. Schematic diagram of directional PD measurement with square-electrode configuration.