LONG-TERM CREEP MEASUREMENTS OF 302 STAINLESS STEEL AND ELGILOY®

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INTRODUCTION

Mechanisms incorporating loaded elastic elements to provide a known force over long periods of time must account for the potential of stress relaxation leading to a change in force and concomitant change in mechanism performance. If the intended period of operation is many years, it is impractical to test elastic components for a period equal to the lifetime of the mechanism in order to determine the adequacy of the material choice and design. Instead, designers must rely on an assumed constitutive relationship and data collected at shorter periods of time. When the elastic load is small compared the yield stress of the material, the long-term stability may be dominated by internal stress relief or thermally activated phase transitions. At loads of a significant fraction of the yield strength, however, the behavior will be dominated by the external load and response of the material to that load, typically by dislocation motion.

Creep at temperatures in excess of half the melting temperature of the material or at stresses very close to the yield stress have been extensively studied[1, p983]. The restriction to these temperature and stress regions is the result of both the common range of application of the data and the limitations of instrumentation used in studies. For some applications of very high precision or very long service, an understanding of very low levels of creep at lower temperatures and stress is desired. At these lower loads and room temperature, however, there is much less data since applicable experiments require the stable measurement of very small strains over long periods of time. Here the term creep is used to refer to the irrecoverable time-dependent plastic deformation while the recoverable time-dependent strain is referred to as anelasticity.

Models adapted from other temperature and load regions include logarithmic strain followed by linear strain, and strain-induced hardening (Bailey-Norton) models. At moderate time scales, there is considerable similarity between these models. But at long times they provide very different estimates of dimensional change.

To help establish a constitutive relation applicable to precision instrument design, we have carried out a series of measurements at time scales ranging from tens of days to periods exceeding six years. Measurements have been using both UNS30200 stainless steel and the proprietary Elgiloy®spring steel (40 Co - 20 Cr - 15 Ni -7 Mo - 2 Mn)[2].

EXPERIMENTAL METHOD

A gravity-loaded dilatometer was constructed as shown in figure 1. The wire segment of nominal 150 mm length is held between two clamps. The lower clamp is connected to a beam which is constrained by an air bearing and contains a weight pan which is used to provide an axial load to the wire. The position of the beam is measured relative to the upper clamp by a transducer. In early tests the transducer was an LVDT. This was later changed to a capacitance gauge in order to avoid potential friction should the core of the LVDT contact its bore. The entire experimental apparatus, including capacitance gauge measurement electronics, is placed on an air-isolated table in a temperature controlled chamber [3] which maintains the apparatus environment at a nominal 20 ℃ with a stability of order 0.01 ℃. After the load is initially applied to the wire, the capacitance gauge is adjusted so that the subsequent creep will be within the range of the gauge. For this reason, there is no direct measurement of the elastic dilatation of the wire, which is large compared to the creep and outside the measurement range of the capacitance gauge. The initial measurement data is also affected by the small changes in temperature that accompany these manual adjustments. Thermal equilibrium of the instrument is obtained within 24-36 hours of the initial loading and adjustment. As a consequence, very rapid anelastic effects cannot be accurately measured.

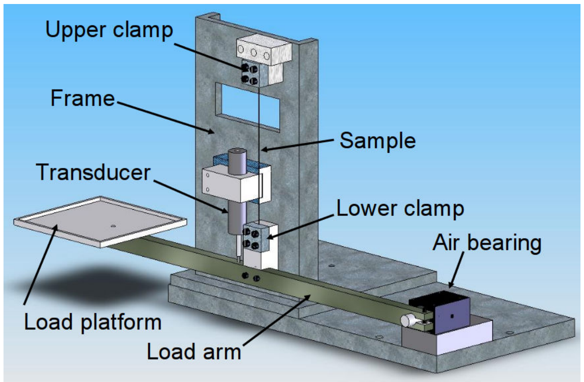

FIGURE 1. Apparatus used to measure long-term creep of wires under axial load.

The value of the output of the LVDT or capacitance gauge is recorded periodically. Because of the long period of measurement, it has been necessary to exclude from the fit some data that reflects transient failure of the laboratory air conditioning and compressed air supply. Some data has also been excluded during periods of large humidity swings in the building, since the capacitance gauge has some sensitivity to humidity and the chamber does not provide great attenuation of laboratory humidity variations.

EXPERIMENTAL RESULTS

Elgiloy®

A wire sample with rectangular cross section 0.1 mm by 1.0 mm and 149 mm length was loaded at 993 MPa. This is 90 percent of the published yield strength of the material [2], though specific properties are known to vary with the cold work and temper of the material. To determine the strength of the material used in these experiments, the transducer was replaced with a longer range LVDT and weight successively added to the weight pan to produce a stress-strain curve for the material up to tensile failure. Figure 2 displays the observed deviation of the measured strain from the linear response at loads below 0.5 GPa. From this curve, the 0.2% yield strength is near the tensile strength of 1.7 GPa and considerably above the load for the experiment. However, the material begins 0.01% microyielding below 700 MPa, well below the experiment load. It is clear, then, that at 993 MPa load there is sufficient stress to induce measurable dislocation motion.

The dilatation of the sample was measured for a period of 2333 days (6.4 years). A Bailey-Norton

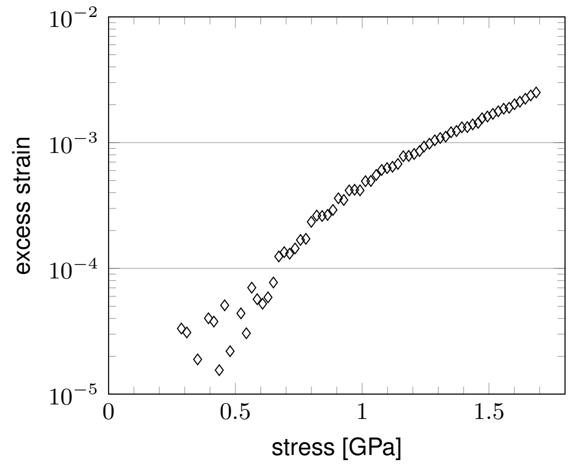

FIGURE 2. Excess strain of an Elgiloy® wire as a function of applied stress. Values below 5×10^{-5} reflect measurement noise.

(B-N) creep curve

$$\epsilon = Ct^n \tag{1}$$

with constant, C, was fit to the first 181 days of data (figure 3). The fit is a good one across most of the domain, with a RMS deviation of the data from the B-N fit across this interval of 1.2×10^{-6}. This value is small compared to the total creep strain and comparable to the instrument uncertainty. However, there is a significant deviation of the data from the B-N curve observed during the first five days of the test (figure 4). This is attributed to anelastic settling during which the response of the wire appears to be largely viscoelastic. Anelasticity is related to internal material damping and follows the expected exponential time dependence[1, p. 986].

The observed creep strain across the full period of the test is shown in figure 5. The periodic excursions of the experimental data above the plotted B-N curve represent periods during which the lack of environmental humidity control caused measurement errors in the capacitance gauge. To avoid compromising the integrity of the long term data, no major modifications of the experimental setup were made during the period of the experiment. Instead, data is considered valid only during the periodic intervals of stable humidity.

In addition to the B-N curve based on the first 181 days of data, two other extrapolations of the early data are shown. The linear extrapolation is based on an assumption that the sample is undergoing

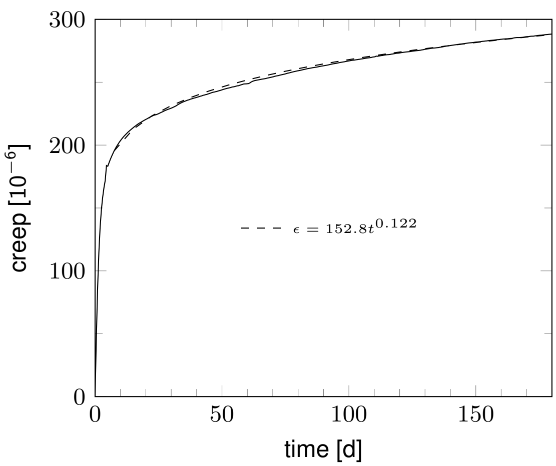

FIGURE 3. Initial creep of an Elgiloy® wire under 993 MPa *axial stress with best-fit Bailey-Norton creep curve.*

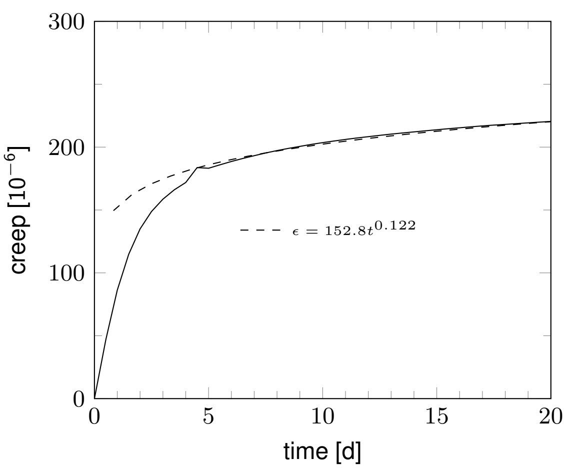

FIGURE 4. Early creep of an Elgiloy® wire under 993 MPa *axial stress with best-fit Bailey-Norton creep curve, showing anelastic settling during the first five days.*

classic secondary (steady state) creep , and uses the last 30 days of the early data to estimate the slope. It is clear that the assumption of secondary creep considerably overestimates the subsequent creep strain.

The logarithmic extrapolation follows the commonly accepted model of creep at temperatures well below the melting temperature:[1]

$$\epsilon = \epsilon_0 \log(1 + \nu t) \quad (2)$$

This model provides a much more reasonable estimate of the creep strain. It is, however,

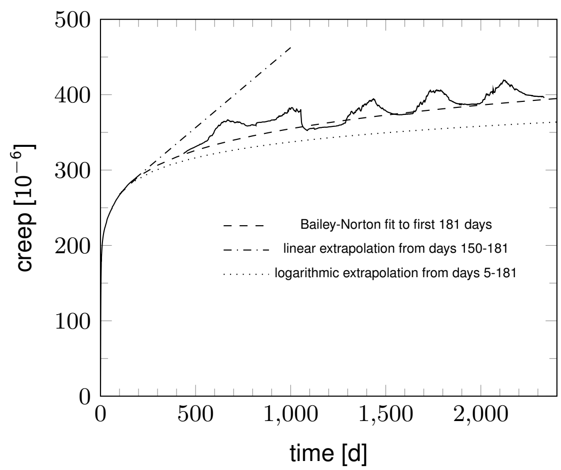

FIGURE 5. Long-term creep of an Elgiloy® wire under 993 MPa *axial stress with Bailey-Norton, linear, and logarithmic creep extrapolations based on the first 181 days of data.*

not as good a fit to the early data as the B-N (RMS 2.2×10^{-6} versus 1.2×10^{-6}) and underestimates the creep strain at 6.4 years by approximately 8%.

UNS30200

A sample of 0.1 mm diameter cold-drawn UNS30200 stainless steel wire with a nominal tensile strength of 2 GPa was tested under successive loads of 0.97 GPa, 1.17 GPa, 1.30 GPa, and 1.45 GPa. Table 1 summarizes the load, period of test and total accumulated creep strain. The intent of this set of measurements was to provide a basis for extending the simple form of the Bailey-Norton relation in equation (1) to the case of time-varying load.

TABLE 1. Loading Schedule and Accumulated Creep Strain of UNS30200 wire

Sequence	Load [GPa]	Duration [day]	Total Strain [10^{-6}]
1	0.97	138	27
2	1.17	238	87
3	1.30	91	104
4	1.45	64	150

In its conventional form, the Bailey-Norton equation takes the constant multiplier to be a power function of the applied stress, and the time exponent to be temperature-dependent but independent of the stress:

$$\epsilon(t) = A\,\sigma^n\,t^m \quad (3)$$

It is straightforward to show that this can be placed in the form of a differential equation relating creep strain rate to creep strain.

$$\dot{\epsilon} = A\, m\, \sigma^n\, t^{m-1} = m\, A^{\frac{1}{m}}\, \sigma^{\frac{n}{m}}\, \epsilon^{\frac{m-1}{m}} \qquad (4)$$

This formulation provides an extension to varying stress which is plausibly connected to a physical mechanism of strain-hardening. This expression also allows the underlying Bailey-Norton form to be extended to the case of time varying stress. In the case of time-varying stress, it is straightforward to show the solution of differential equation 4 is

$$\epsilon(t) = A \left[\int_0^t \sigma^{\frac{m}{n}}\right]^n \qquad (5)$$

For any subsequent loading, then, the observed relative creep from the beginning of the test should have the form

$$\epsilon+\epsilon_a = \left[\epsilon_a^{\frac{1}{n}} + [A\sigma^m t^n]^{\frac{1}{n}}\right]^n = \left[\epsilon_a^{\frac{1}{n}} + \epsilon_{BN}{}^{\frac{1}{n}}\right]^n \qquad (6)$$

where t is the time from the beginning of the test, ϵ_a is the accumulated strain from previous tests, and ϵ_{BN} is the simple , time-dependent, Bailey-Norton expression for the current test.

The observed relative creep during the first 60 days of each test is shown in figure 6. Data at loadings of 0.97 GPa and 1.30 GPa have been corrected for variations in laboratory humidity, a correction which has introduced additional uncertainty into the data which can be seen in the apparent noise of the curve. The data taken with loads of 1.17 GPa and 1.45 GPa were taken during periods of better humidity control, with the later benefiting from an active humidity control that was installed on the test chamber.

The test data shows qualitative agreement with the strain hardening model. Both the 1.17 GPa and the 1.30 GPa tests show lower strain rates than the original test even though they are conducted at a larger load. This could not be case unless the previous creep had modified the material creep properties. It is not required, however, for the creep rate at higher stress to be smaller than the initial stress, only that it be smaller than would have been the case had it been applied to virgin material. Hence the larger creep rate observed at 1.45 GPa is not necessarily an anomaly in the context of Bailey-Norton-like creep. Indeed, Kassner suggests that the stress exponent, m,

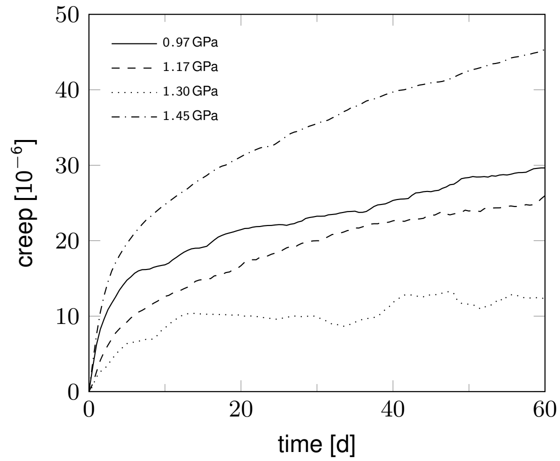

FIGURE 6. Creep of UNS30200 wire.

will likely be in excess of 5 at temperatures in the so-called “power law breakdown” region below half the melting point[4, p. 11]. If this is the case, then the contribution of stress to the creep rate will be more than seven-fold greater in the case of the last test than the initial loading. The creep at the higher loading is by contrast less than half that of the initial case.

While the observed creep rates are qualitatively consistent with the strain hardening model, they are not quantitatively consistent with a model based on equation (6) in which A, m, and n are simple constants independent of stress. To develop a more complete phenomenological constitutive model will require additional measurements, most likely at different stress applied to starting material which is in the same state.

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