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Research paper

Low temperature creep in a high strength roller bearing steel

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ABSTRACT

Noticeable low temperature creep was established for a bainitic and a martensitic microstructure of the 100CrMnMo8 high strength roller bearing steel. The response revealed primary creep that differed between the microstructures, following a power law for martensite and the logarithmic description for bainite. The detected creep was pressure sensitive, higher in tension than in compression for the same stress level, following the strength differential effect (SDE) at material yielding. Two models were proposed where the stress variable for the pressure effect was based on the Drucker–Prager yield function and deviatoric creep strains were derived from a non-associated von Mises potential. Model parameters were determined from experimental series on the respective microstructure. When the models were evaluated against the experiments the accuracy was of the same order as the effects of different heat treatment batches and different load application rates. The importance of different material parameters in the descriptions was discussed.

1. Introduction

Low temperature creep is defined at temperatures below $0.3\Theta_m$, where Θ_m is the melting temperature in K. Unlike high temperature creep, it requires relatively high stresses to become noticeable, the total creep strain is often fairly small, typically much less than 1%, and it rarely leads to rupture. The overall behaviour of low temperature creep differs from that of high temperature creep, which generally exhibits three stages: primary creep with decreasing rate, secondary creep with constant rate and tertiary creep with increasing rate to creep rupture. Low temperature creep on the other hand typically displays only primary or transient creep.

The primary creep can usually be described by a power law equation (Bailey, 1935; Norton, 1929). For uniaxial conditions,

$$\epsilon^{cr} = A\left(\frac{t}{t^*}\right)^B \tag{1}$$

where ϵ^{cr} is the creep strain, A and B are material parameters for a given stress, loading rate and temperature, t is time and t^* is an arbitrary but known reference time. When $B = 1/3$, Eq. (1) becomes Andrade's creep law (Andrade, 1914). At low temperatures, the primary creep may follow a logarithmic curve,

$$\epsilon^{cr} = \alpha \ln\left(\beta\left(\frac{t}{t^*}\right) + 1\right) \tag{2}$$

where α and β are material parameters (Wyatt, 1953; Garofalo, 1965).

There are not that many investigations on low temperature creep in the literature and of these only a few focuses on high strength steels. Neu and Sehitoglu (1992a) studied creep in tension and compression in four different heat treatments of the railroad bearing steels SAE 4320. They analysed how stress and temperature affected creep and proposed a logarithmic model based on Eq. (2) that relates the creep strains to the deviatoric stress. Oehlert and Atrens (1994) examined low temperature creep in three high-strength martensitic steels. Through a series of tensile creep experiments, they investigated the influence of loading rate, strains and material strength on the parameters in Eq. (2). They found that the lower stress limit for creep was identical to the stress at the "first instantaneous plastic strain" . This stress level was independent of the loading rates investigated in the work. Liu et al. (2001) performed tensile room temperature creep experiments on SAE 4340 martensitic steel with four different heat treatments. They concluded that the accumulated creep strain in a given time period depends on the applied stress and the material hardness. Increased stress or reduced hardness led to larger creep strains. Bhadeshia (2012) also mentions the possible existence of low temperature creep in high strength bearing steels.

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Alden (1987) and Wang et al. (2001) studied low temperature creep in other materials and found logarithmic creep. Alden (1987) analysed strain hardening during low temperature creep of 304 stainless steel. Wang et al. (2001) performed room temperature creep experiments on some pipeline steels to study how the processing conditions influenced the creep deformation and strain-rate sensitivity. In general it appears that logarithmic creep prevails at low temperatures.

Creep deformation at low temperatures is primarily dependent on applied stress, creep time and temperature such as

$$\dot{\epsilon}^{cr} = \dot{\epsilon}^{cr}(\sigma, t, \Theta). \tag{3}$$

The time dependence in Eq. (3) typically follows Eq. (1) or (2). For secondary creep, where the rate is constant in time, Norton (1929) proposed a power law relation between creep rate and stress

$$\dot{\epsilon}^{cr} = C\left(\frac{\sigma}{\sigma^*}\right)^n. \tag{4}$$

In Eq. (4) n and C are material parameters, σ is the applied stress in tension and σ^* is a reference stress. In particular, the parameter C depends on the temperature with a relation often assumed to follow the Arrhenius' law

$$C = C^* e^{-\frac{Q_c}{R\Theta}}. \tag{5}$$

Here Q_c is the activation energy for creep in J/mol, Θ is the temperature in K and $R = 8.314$ J/(mol·K) is the universal gas constant. Eq. (4) with Eq. (5) is utilized also for describing primary creep. Frequently, the relations in Eq. (3) are assumed to be separable resulting in

$$\epsilon^{cr} = C^*\left(\frac{\sigma}{\sigma^*}\right)^n \left(\frac{t}{t^*}\right)^B e^{-\frac{Q_c}{R\Theta}} \tag{6}$$

for the power law time relation in Eq. (1).

Other factors that may influence creep deformation are associated with the initial conditions at creep load start, *e.g.* the loading rate, and the microstructure. Langdon (2005) quantifies the microstructure of the material in terms of grain size. For instance, low temperature creep experiments of pure aluminium suggests different deformation mechanisms as the grain sizes gets finer (Shen et al., 2011). For high strength steels containing retained austenite, low temperature creep can also be attributed to time-dependent phase transformations (Neu and Sehitoglu, 1992a). Bhadeshia (2012) notes in his review that such phase transformation should result in logarithmic creep.

Various mechanisms have been proposed for creep in metals, including dislocation glide, diffusional creep, and dislocation creep that involves dislocation and diffusional flow (Gittus, 1975). A deformation mechanism map proposed by Ashby (1972) is a way of representing the dominant deformation mechanism in a specific material at a given set of load conditions. At low temperatures, dislocation glide or motion is often the responsible creep mechanism when no time-dependent phase transformation is involved (Neu and Sehitoglu, 1992a; Oehlert and Atrens, 1994; Liu et al., 2001; Bhadeshia, 2012; Alden, 1987; Wang et al., 2001). Alden (1987) describes the low temperature creep in 304 stainless steel as pure glide creep. When the inelastic deformation of metals is a consequence of dislocation glide, the shear strain rate has been expressed by the Orowan equation,

$$\dot{\epsilon} = \rho_m b v \tag{7}$$

where ρ_m is the mobile dislocation density, b the Burgers vector, and v the dislocation velocity. Eq. (7) can explain the decrease of creep strain rate for primary creep as a consequence of decrease in mobile dislocation density. Likewise, the creep strain rate can decay due to a decrease in the dislocation velocity or moreover as a combination of both (Oehlert and Atrens, 1994). Nabarro (2001) discusses the hardening and exhaustion models to account for dislocation glide at logarithmic creep.

Since low temperature creep is believed to be related to dislocation glide, it is connected to the onset of plasticity. However, dislocation glide can occur well below the macroscopic yield point and therefore creep strains can also be expected below these stress levels (Oehlert and Atrens, 1994; Liu et al., 2001). Neu and Sehitoglu (1992a) relate low temperature creep to the deviatoric stresses, which agrees with the high temperature creep description by Odqvist in 1934 (Odqvist, 1974).

Some high strength steels display a strength differential effect (SDE) with larger yield point and flow stress in uniaxial compression than in uniaxial tension (Chait, 1972; Rauch and Leslie 1972; Linares Arregui and Alfredsson, 2010). The monotonic experiments by Spitzig et al. (1975, 1976) with superimposed hydrostatic pressure on some high strength steels showed that the flow stress depended linearly on the superimposed hydrostatic pressure. The volume expansion after plastic straining was, however, less than 1/15 of the prediction of the associated flow rule (Spitzig et al., 1975, 1976; Linares Arregui and Alfredsson, 2010).

If a material contains a sizable amount of retained austenite, then stress induced transformation (SIT) of austenite to martensite with an accompanying volume change can cause an apparent difference in flow stress between tension and compression, i.e. SDE (Olson and Cohen, 1972; Neu and Sehitoglu, 1992b).

In the current study, low temperature creep was investigated for two different microstructures of a high strength roller bearing steel. The first microstructure was bainitic without any detectable retained austenite and the second was martensitic with 10 – 15% retained austenite. Linares Arregui and Alfredsson (2010) characterised the time independent elastic-plastic behaviour of these steels. Both steels exhibit high yield stresses and noticeable SDE. The onset of plasticity was modelled with a hydrostatic stress dependent yield surface, while the evolution of plastic strains followed a deviatoric non-associated flow rule. A non-linear elastic behaviour was also documented for the bainitic microstructure at high stress levels (Linares Arregui and Alfredsson, 2013).

The purpose of this work was to derive a mechanical model that describes low temperature creep in the two microstructures. The work comprised an extensive experimental program, determination of the creep characteristics and derivation of suitable mechanical creep models for the microstructures. The experimental goals were firstly to determine if low temperature existed in the current steels, secondly to establish at which conditions it did develop and thirdly to conclude if it is of scientific and engineering relevance. As the bainitic and martensitic materials experience SDE, creep experiments were made in both tension and compression. Following the dislocation glide mechanism, the series included experiments on several stress levels both below and above the yield point. Modelling and experiments focused on the normal bearing temperature at 75°C with some reference experiments at a higher and a lower temperature. The reference experiments allowed for calibrating the temperature description of the model.

Since the current steels displayed SDEs it was suspected that the behaviour of the low temperature creep could depend on both the hydrostatic and deviatoric stresses. Such behaviour has not previously been modelled and explicitly described in the literature. Inclusion of hydrostatic dependency of creep strains into the model required updating of Odqvist's hypothesis for pressure insensitive creep strains in three dimensions. Therefore, a new creep model that included different creep rates in tension and compression was derived based on existing models but facilitating exchange of the Odqvist hypothesis for pressure sensitivity of creep strains. From a modelling perspective there existed further experimental goals. The creep strains had to be quantified, including the magnitude