Interaction solute atom – dislocation during steady-state creep in ferritic 2.25Cr1Mo steel

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Abstract
Unusual behaviour was recorded at steady state creep curve for the ferritic steel 2.25Cr1Mo tested at T = 873K and under an applied stress of 103 MPa. The mechanism of deformation is interpreted from the superposition of two mechanisms: a) interaction of mobile dislocations with solute atoms, and b) viscous creep. The activation energy associated was 246 kJ/mol, which is consistent with the activation energy by diffusion of Cr atoms in the ferrite phase.

Keywords: creep, viscous glide, serrated flow, interaction solute atom- dislocations

1. INTRODUCTION:
At homologous temperatures higher than about 0.4, the solute atoms do not act as point obstacles for dislocation glide. Nevertheless, they can make the dislocation glide velocity lower, since they form atmospheres round them which must be dragged by the dislocations or, since they form a short range order, which must be destroyed by moving dislocations [1]. The drag of an atmosphere formed round a dislocation due to the elastic interaction between the dislocation and solute atoms was originally analyzed by Cottrell and Jaswon [2]. These authors proposed that the dragging process is the segregation of solute atmospheres to moving dislocations. Thus, the dislocation speed is limited by the rate of migration of the solute atoms.

It has been suggested that during the so-called Three-Power-Law regime, the deformation mechanism that controls the strain rate by creep during the steady-state is the viscous glide of dislocations [3].

\[
\dot{\varepsilon}_s \approx \frac{0.35}{A} G \left( \frac{\sigma}{G} \right)^3
\]

where \( \dot{\varepsilon}_s \) is the minimum creep-rate, G is the shear modulus, A is an interaction parameter which characterizes the particular viscous drag process controlling dislocation glide and \( \sigma \) the applied stress. Mohamed and Langdon [4] considered the dragging mechanism proposed by Cottrell-Jaswon and derived the following relationship,
where $e$ is the solute-solvent size difference ($e = (r-r_o)/r$, with $r$, the solvent radius, $r_o$, the solute radius), $C$ is the concentration of solute atoms ($C = C_o \exp (W/kT)$, where $C_o$ is the average concentration and $W$ the binding energy), $\nu$ is the Poisson’s coefficient, $b$ the Burger’s vector, $T$ the absolute temperature and $D$ is the diffusion coefficient for the solute atoms.

The aim of this paper is to show experimental evidence of the existence of a solute-dislocation interaction mechanism in the steel 2.25Cr 1Mo, during the steady-state on the curve of creep for a temperature and stress applied. The results found here are consistent with a creep strain mechanism controlled by the moving of dislocations interacting with atmosphere of solute.

2. EXPERIMENTAL:

The material used for the creep test was 2.25Cr1Mo steel. This is a creep-resistant steel, which is often used as re-heating tubes in the boilers in power plants. The chemical composition of the material is shown in Table 1.

| TABLE-1: Chemical composition of the steel used in this study (wt. %) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| C    | Mn  | Si  | S   | P   | Cr  | Mo  | Fe  |
| 0.16 | 0.4 | 0.3 | 0.01| 0.01| 2.23| 0.96| Bal.|

Creep samples 25 mm in gauge length and 5 mm in gauge diameter were machined directly from the tube. The creep test was performed in air with a loading beam capable of maintaining a constant stress, within 1% of the initial stress, up to strains of the order of 10% [5]. The experiment was performed at 873K under an applied stress of $\sigma = 103$ MPa. The test temperature was monitored with two thermocouples touching the specimen gauge section and held constant within ±1.5 K. The elongation of the specimen was measured by attaching fused silica rods, which extended out of the furnace, to the upper and lower grips. Since the lower grip was fixed, a measurement of the relative displacement of the fused silica rods, using an LVDT, gives the true elongation of the specimens, eliminating any influence of the loading train. The signals of the thermocouples and the LVDTs feed an A/D card connected to a slot of a PC. Data are recorded using a customized acquisition program.

3. RESULTS AND DISCUSSION:

An anomalous behavior during the creep test was recorded, through a diagram true strain by creep versus time at a temperature $T = 873$ K and applied stress, $\sigma = 103$ MPa. Fig. 1 shows the whole creep curve obtained during the test creep; while Fig. 2 illustrates the extended region of the “steady” stage, where variation of deformation over time during this stage is shown.
**FIGURE 1**

**Creep by tensile:** 2.25Cr1Mo steel

- $\sigma = 103$ MPa
- $T = 873$ K

Steady-state with serrations

Fig-1: Diagram true strain ($\varepsilon$) vs. time ($t$) for $\sigma = 103$ MPa and $T = 873$ K

**FIGURE 2**

- $\sigma = 103$ MPa

Fig-2: Steady state enlarged region showing the serrations on the experimental curve (see Fig. 1).
As can be seen, the steady stage shows a variation of the deformation over time in the form of an irregular wave alternating, overlapped on an average slope, which represents the deformation speed. After confirming and assuring that the behavior is characteristic of the material and not of some instrument or the environment, evidence shows that this is a deformation mechanism, which presents hardening by deformation and recuperation, similar to those observed during the tension tests, probably due to the effect of the interaction between mobile dislocations and solute atmospheres. This kind of behavior is unusual in creep diagrams. From the previous diagram a minimum speed of deformation or steady stage \( \dot{\varepsilon} = 1.5 \times 10^{-8} \text{ s}^{-1} \) was obtained. Maruyama et al. [6], examined the maps of deformation mechanism by creep in the steel 2.25Cr-1Mo for deformation speeds between 10\(^{-11}\) and 10\(^{-6}\) s\(^{-1}\) and a temperature ranging from 723 to 923 K and found that the minimum deformation speed by creep is related to the stress applied by a power-law with 3 < \( n \) < 5. Fig. 3 shows the diagrams obtained by Maruyama et al. and the result of the present work.

**FIGURE: 3**

![Diagram showing minimum creep rates as a function of creep stress normalized by Young’s modulus E for two heat treatments.](image)

Fig-3: Minimum creep rates \( \dot{\varepsilon} \) as a function of creep stress \( \sigma \) normalized by Young’s modulus E for two heat treatments obtained by Maruyama et al. In addition, broken line indicates the experimental point corresponding to this study.
From such results, we can infer that under our test conditions, the relationship between the tension applied and the minimum strain rate by creep is associated with a dislocation glide mechanism assisted by diffusion. However, the activation energies by creep obtained by Maruyama et al. ranged from 370 to 420 kJ/mol K. Chalmers [7] observed a type of slow creep (‘micro-creep’) on tin crystals which occurred at tensile strain rates below $10^{-8}$ s$^{-1}$ and at tensile stresses below 1.5 MPa. This author concluded that critical creep rate requires that

$$D \rho \approx 10^{-8} \text{s}^{-1}$$

(3)

3.1.- Interaction of solute atoms round moving dislocations:

Under an external force, the speed of a dislocation surrounded by a solute atmosphere is restricted to the speed of migration of solute atoms in atmosphere. Since diffusion speeds are slow compared with normal dislocation speeds, this process is likely to be important only in slow creep experiments. Cottrel has estimated that the critical velocity required to leave behind the solute atmosphere can be described [8] by

$$v_c = 4D/l$$

(4)

where the characteristic length $l (=A/kT)$ may be regarded as the ‘radius’ of the atmosphere and $D$ the diffusion coefficient. If the density of these dislocations is $\rho$ the corresponding critical creep rate is

$$d\gamma / dt = \nu \rho b = 4D\rho b / l$$

(5)

In our case, we might estimate the density of dislocations using the value that we have determined experimentally for the minimum speed of deformation by creep, $\dot{\varepsilon} = 1.5 \times 10^{-8}$ s$^{-1}$ and the diffusion coefficient $D$. Thus, to calculate the diffusion coefficient we use the $D_0 = 8.52 \times 10^{-4}$ m$^2$s$^{-1}$ [9] and a value for the activation energy $Q= 246 \pm 25$ kJ/mol K [10]. Thus, $\rho \approx 1 \times 10^{13}$ m$^{-2}$; which derives from a reasonable value for deformation by creep in the steady stage. It is interesting to highlight that the value of the activation energy by creep that we have used is very close to that obtained by Bowen et al. for the atom diffusion of Cr in alpha iron [9], which was $Q_D= 250$ kJ/mol °K. Peng et al. [11] studied the effect of dynamic strain aging (DSA) on the properties at high temperatures in the austenitic stainless steel 18-8 and attributed such behaviour to the interactions of atmospheres (C,Ni) and (C,Cr) with dislocations, at low and high temperatures, respectively. Taking into account the activation energy by creep obtained in this material, it seems reasonable to infer that the deformation mechanism by creep in the steady stage, in our case, would be composed of a viscous deformation mechanism, on which behaviour of the DSA type is overlapped and whose atmosphere is probably composed of Cr atoms.

4. CONCLUSIONS:

The anomalous behavior observed in the steady stage region of the creep curve obtained at T = 873K and $\sigma = 103$ MPa in the steel 2.25Cr1Mo, may be interpreted from the following observations:

1.- The steady stage region of the creep curve by tensile, obtained at $T = 873$ K and $\sigma = 103$ MPa, showed an anomalous behavior of the DSA type

2.- The anomalous behavior would be associated with an anchorage mechanism and release of mobile dislocations controlled by an atmosphere of Cr atoms.
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6. REFERENCES

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