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Letter to the Editors

Thermally activated deformation of irradiated reactor pressure vessel steel

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Abstract

Temperature and strain rate change tensile tests were performed on two VVER 1000-type reactor pressure vessel welds with different contents of nickel in unirradiated and irradiated conditions in order to determine the activation parameters of the contribution of the thermally activated deformation. There are no differences of the activation parameters in the unirradiated and the irradiated conditions as well as for the two different materials. This shows that irradiation hardening preferentially results from a friction hardening mechanism by long-range obstacles. © 2002 Published by Elsevier Science B.V.

1. Introduction

The analysis of the thermally activated deformation (activation analysis) in crystalline material has proven to be a useful tool for understanding the mechanisms of the deformation processes (e.g. [1–3]). Assuming the dislocations move under the impact of an effective stress σ_{eff} through a wide spectrum of weak barriers the strain rate $\dot{\varepsilon}$ can be described by an Arrhenius rate equation

$$\dot{\varepsilon} = \dot{\varepsilon}_{\circ} \exp\left(-\frac{\Delta G}{KT}\right). \tag{1}$$

ΔG is the effective Gibbs free energy of activation for overcoming the given barrier spectrum, $\dot{\varepsilon}_0$ is a material constant and k and T are the symbols as usual. ΔG is a function of the effective stress and can be approximated by $\Delta G = \Delta G_0 - \sigma_{\mathrm{eff}} \cdot V^*$. The activation volume V^* has the dimension of a volume. Considering $\Delta G = \Delta H - T\Delta S$ with the activation enthalpy ΔH and the activation entropy ΔS, the activation parameters ΔH and V^* can be determined by means of the differential strain rate change and temperature change in a tensile test according to [2]

$$\Delta H \approx KT^2(\Delta \ln \dot{\varepsilon}/\Delta\sigma)_T(\Delta\sigma/\Delta \mathrm{T})_{\dot{\varepsilon}}, \tag{2}$$

$$V^* \approx KT(\Delta \ln \dot{\varepsilon}/\Delta\sigma)_T. \tag{3}$$

$\Delta\sigma$ is the change of the flow stress due to an instantaneous change of temperature (ΔT) and strain rate ($\Delta \ln \dot{\varepsilon}$), respectively.

Eqs. (2) and (3) are valid if the stress is a unique function of temperature and strain rates for a given structure.

The situation is more complicated in the case of dynamic strain ageing where an additional dislocation pinning mechanism is caused by moving mobile solute atoms to the dislocation during the waiting times of the dislocations at obstacles. Then the effective Gibbs energy of activation ΔG contains an additional strain ageing term ΔG_{dsa} and the activation parameters cannot be determined on the basis of Eqs. (2) and (3). However, the stationary and the instantaneous strain rate sensitivity provide useful qualitative information on the deformation processes also in this case.

Whereas there is a large number of papers concerning with the activation analysis for pure metals and solid

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solution systems, the use of the method for irradiation effects is unusual. The paper reports on the results of strain rate change and temperature change tests on irradiated low-alloyed Cr–Ni–Mo reactor pressure vessel steels.

2. Experimental

Two VVER 1000-type welds with different nickel contents were irradiated at VVER 1000 surveillance

Table 1
Chemical composition (in wt%, Fe balance) of the used VVER 1000 welds

Material	C	Si	Mn	Cr	Ni	Mo	V	S	P	Cu
Weld 1	0.08	0.42	0.74	1.86	1.59	0.61	0.01	0.0075	0.010	0.058
Weld 2	0.07	0.29	1.05	1.64	1.11	0.59	0.01	0.0084	0.017	0.106

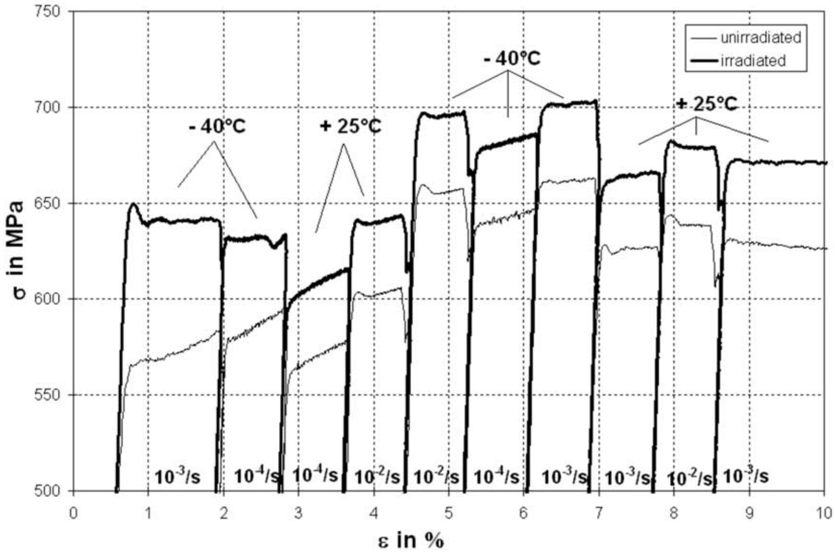

Fig. 1. Stress–strain-curve with strain rate and temperature changes for weld 1 in unirradiated and irradiated conditions.

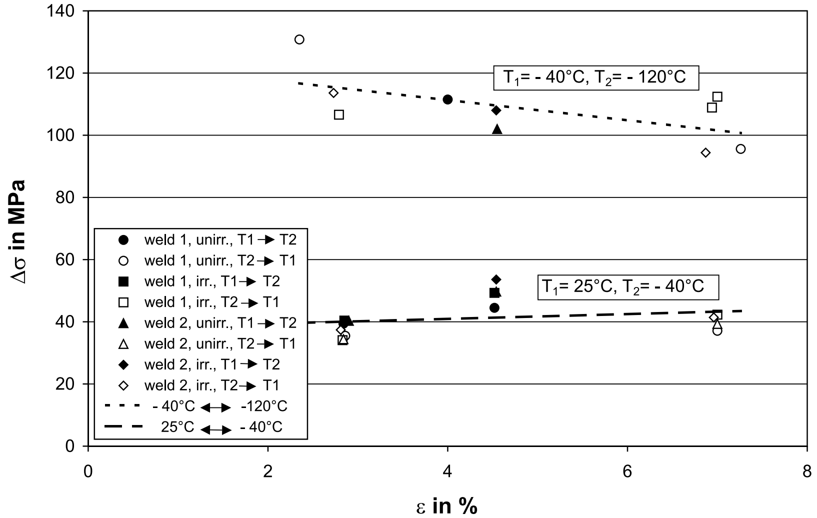

Fig. 2. Variation of the flow stress at temperature change tests between −40 and −120 °C or +25 and −40 °C, respectively.

positions during one reactor cycle up to neutron fluences of 4.3 and 3.2 × 10^{19} n/cm^2 ($E > 0.5$ MeV). The chemical composition is given in Table 1. Round bar tensile specimens 5 mm in diameter by 25 mm in nominal gage length were machined from these materials according to DIN and were investigated in the irradiated conditions and the unirradiated reference state on a servohydraulic test system (type MTS 810/50 kN) at a constant crosshead travel regime using an environmental chamber. The strain rate was varied over the range from 0.01 to 0.0001 s^{-1} and the temperature was changed over the range from −120 to +300 °C in different step widths and directions. The strain was directly measured by the crosshead displacement. At changing of temperature or strain rate the loading process was stopped, the specimen was partly unloaded and reloaded at the new temperature or strain rate.

3. Results and discussion

A typical example of the stress–strain curve obtained by the strain rate–temperature change tests is given in Fig. 1 for weld metal 1 in unirradiated and irradiated conditions.

As expected irradiation causes an increase of the stress level but the course of the stress–strain curve is similar for both conditions, apart from the sharp yield drop at the beginning of plastic strain in the case of the

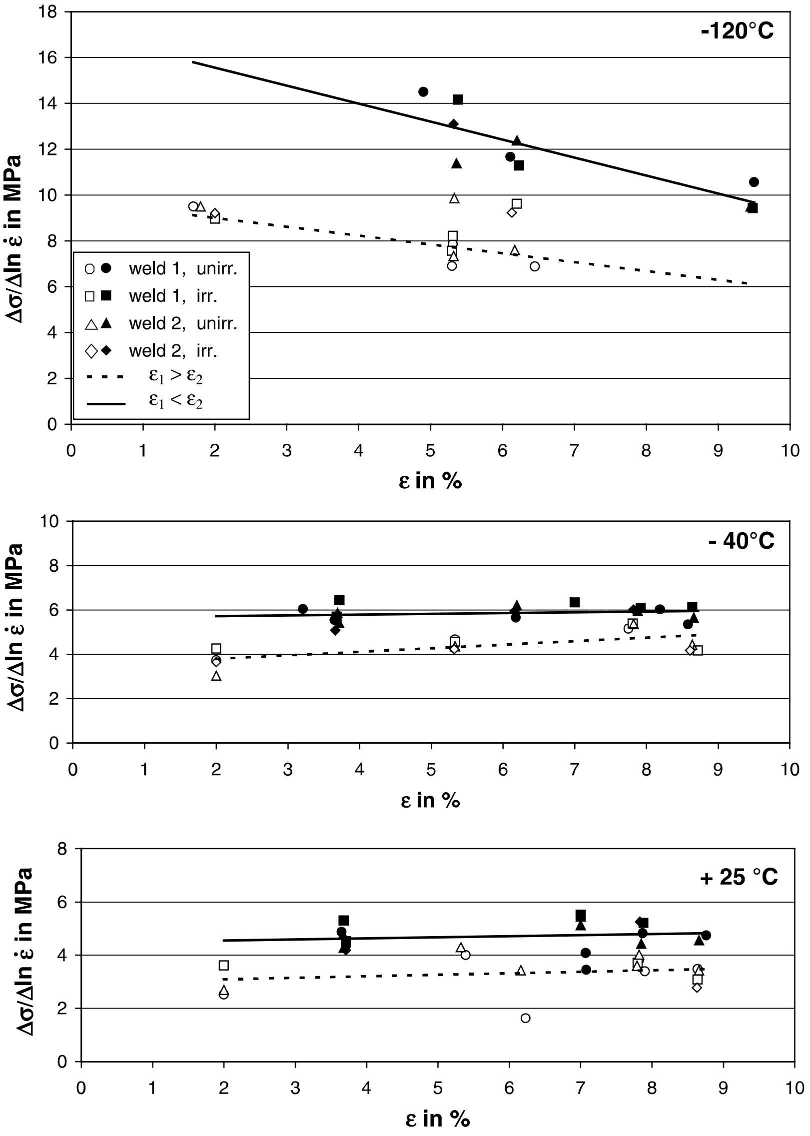

Fig. 3. Strain rate sensitivity $\Delta\sigma/\Delta \ln \dot{\varepsilon}$ versus strain at different deformation temperatures.

irradiated specimen. Yield point phenomena are always observed at the test temperature of −120 °C at the beginning of plastic strain or after larger strains at test temperatures of $\geqslant 25$ °C. However, the difference between the instantaneous stress change and the stationary stress change for strain rate or temperature changes are in general rather small. Some general features can be observed:

- The flow stress always decreases if the temperature increases. Conversely, the reduction of the temperature yields an increase of the flow stress. The amount of the flow stress change does not depend on the direction of the change and is only weakly influenced by the strain (Fig. 2). The latter means that the modified version of the Cottrell–Stokes law [1] $\Delta\sigma =$ const, found by Basinski and Christian [4] for iron, is approximately valid.
- The temperature history affects the flow stress change by a change in temperature. A first deformation at 160 °C effects an especially high change in the flow stress by a change over the lower temperature range (between 25 and −120 °C). This is discerned on unirradiated and irradiated materials but is more distinct in the unirradiated condition.
- Positive changes of the strain rate ($\dot{\varepsilon}_1 < \dot{\varepsilon}_2$) cause positive changes of the stress ($\sigma_1 < \sigma_2$) and reverse, apart from a few cases ($T = 160$ and 300 °C, $\dot{\varepsilon}_1 = 10^{-3}$/s, $\dot{\varepsilon}_2 = 10^{-4}$/s).
- The strain rate sensitivity $\Delta\sigma/\Delta \ln \dot{\varepsilon}$ (Fig. 3) depends on temperature, strain and the direction of the strain rate change. $\Delta\sigma/\Delta \ln \dot{\varepsilon}$ is larger for the change $\dot{\varepsilon}_1 \rightarrow \dot{\varepsilon}_2$ if $\dot{\varepsilon}_1 < \dot{\varepsilon}_2$ than reverse if $\dot{\varepsilon}_1 > \dot{\varepsilon}_2$. This is specially characteristic for the lowest temperature applied (−120 °C). The higher the temperature the lower is the strain rate sensitivity. Furthermore, the dependence

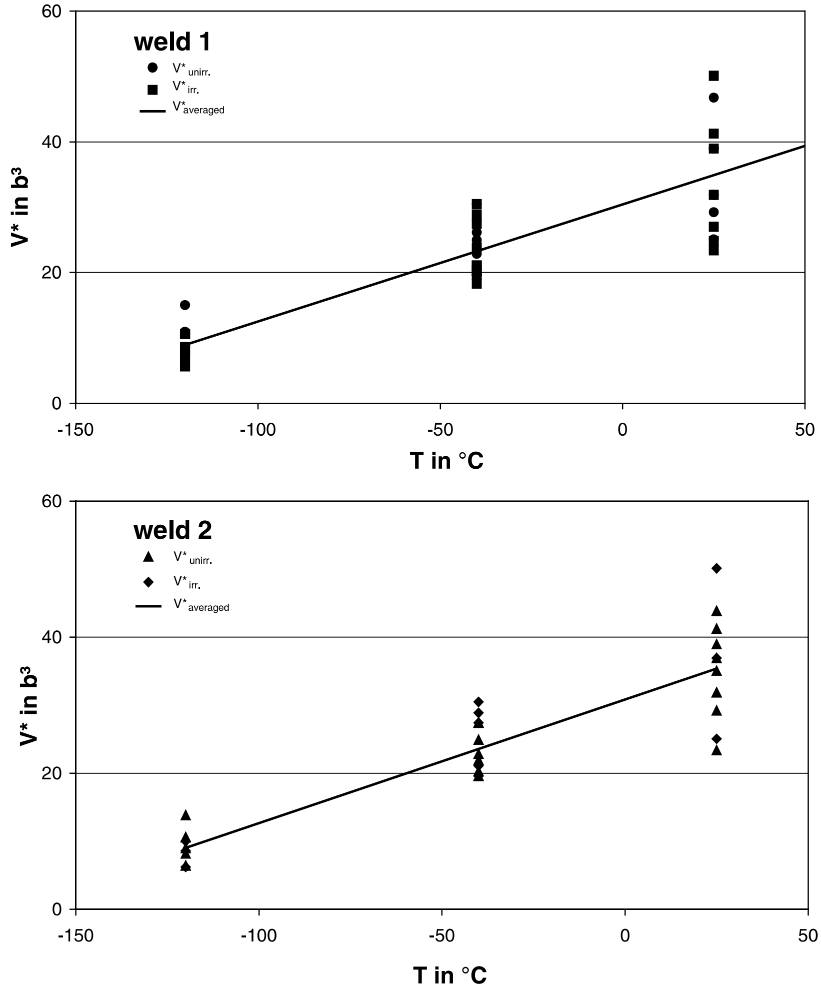

Fig. 4. Temperature dependence of the activation volume in units of the Burgers vector ($b = 0.3$ nm) of weld 1 (top) and weld 2 (bottom).

of the strain and the direction of the strain rate change are also reduced with decreasing temperature.

- Strain-aging effects appear at higher temperatures (160–300 °C), detectable by serrated stress–strain curves and very low or negative strain rate sensitivities.
- Strain hardening depends on the strain rate. The highest strain hardening is measured at the lowest strain rate (10^{-4}/s) and at low temperature (−120 °C). The effect is stronger for the irradiated material.

The activation volume V^* and the activation enthalpy ΔH, calculated by Eqs. (2) and (3), are presented as a function of the temperature in Figs. 4 and 5 and are given as mean values in Table 2 for both weld metals. In spite of the high scattering there is a clear trend: The activation volume and the activation enthalpy increase with increasing temperature. The strong temperature dependence of the activation parameters shows that the assumption of the activation analysis, i.e. the strain rate is controlled by the same dislocation mechanism, is offended. Thus, the activation parameters calculated are apparent or formal parameters but do not describe a real physical process. The values are, however, comparable with the values determined for iron and mild steels [5].

Definitely, there are no differences in the activation behaviour for both material conditions as for the two

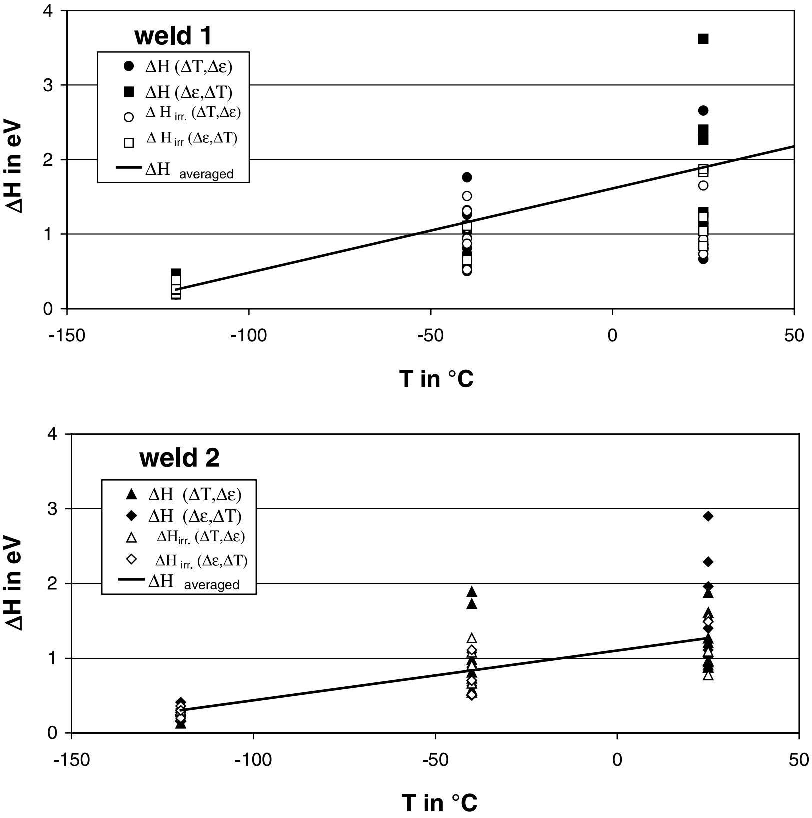

Fig. 5. Temperature dependence of the activation enthalpy of weld 1 (top) and weld 2 (bottom).

Table 2
Mean values of the activation volume V^* and activation enthalpy ΔH at the test temperatures −120, −40 and +25 °C

Material	Condition	−120 °C		−40 °C		+25 °C	
		V^* (b^3)[a]	ΔH (eV)	V^* (b^3)[a]	ΔH (eV)	V^* (b^3)[a]	ΔH (eV)
Weld 1	Unirradiated	9.10	0.26	22.9	1.02	35.1	1.14
	Irradiated	8.74	0.30	23.4	0.80	33.9	1.36
Weld 2	Unirradiated	9.3	0.25	23.1	0.97	35.6	1.20
	Irradiated	8.24	0.28	24.5	0.76	37.4	1.49

[a] Length of Burgers vector ($b = 0.3$ nm).

different materials. This is a clear proof that irradiation produces long-range obstacles and, hence, an athermal hardening effect. Two conclusions are obvious. First, as interstitials can essentially contribute to the thermally activated dislocation mechanisms in iron [6] one can conclude that the concentration of interstitials in the matrix is not changed by irradiation. Second, irradiation does not change the temperature dependence of the yield stress. Finally, the change of the Ni content in the weld metal does not imply a change of type and content of those obstacles which can be overcome by thermal activation.

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