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Application of the Hopkinson Split Bar Test to the Investigation of the Influence of Neutron Irradiation on Dynamical Mechanical Properties of Some Steels

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1. Introduction

Neutron irradiation has an adverse effect on the mechanical propertie of low alloy steels. This effect is mainly characterised by a large increase in the brittle — ductile transition temperature (neutron embrittlement). One of the ways how to establish this transition is based on the konwledge of the dependence of the flow stress σ_f upon temperature T and strain rate $\dot{\varepsilon}$ in non-irradiated and irradiated conditions [1]. This way enables one to interpret the radiation embrittlement in terms of the plastic deformation mechanism defined by T and $\dot{\varepsilon}$.

Several investigaters [2, 3] have shown that in the temperature-strain-rate spectrum of low alloy steels we can observe several regions which reflect different mechanismus of plastic deformation. In the case of irradiated materials, the question arises of what kind is the influence of neutron irradiation on the mechanisms of plastic flow in the entire spectrum of strain rate and temperature. Literature reviews [1.2] show that the effect of strain rate on the post-irradiation plastic deformation of steels has not been investigated systematically at high strain rates. Especially at strain rates higher than about 10 s^{-1} sufficient data are lacking. One of methods for determining the flow stress σ_f at high strain rates is represented by the Hopkinson Split Bar Technique (HSBT) [4]. Recently this method has been applied more often for the research of materials used for reactor pressure vessels [5, 6].

The present paper studies the influence of irradiation on the dependence $\sigma_f(\dot{\varepsilon})$ in broad spectrum of temperatures with the aim of ascertaining the incidental change in the mechanism of plastic flow.

2. Material and experimental procedure

For the experiment, nearly pure iron (AREMA) and two low alloy structural weldable steels with chemical composition given in Table 1, were chosen.

From these materials penny-shaped specimens, $1.4.10^{-2}\,m$ in diameter and $l_0=2.10^{-3}\,m$ thick, were prepared. These specimens were irradiated in the VVR-S reactor in Řež. In Table 2 there are data on total dose of neutrons φ, irradiation temperature and the range of test temperatures given.

Table 1

Chemical composition of tested materials in %

Material	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	Ti
AREMA	0.07	0.27	0.20	0.014	0.009	—	—	—	—	—	—
STEEL 13030	0.18	1.22	—	0.016	0.012	0.17	0.33	—	—	0.055	0.028
STEEL 22 K	0.22	0.9	0·24	0.015	0.08	0.27	042	—	0.08	—	—

Non-irradiated and irradiated specimens were loaded by the HSBT in pressure. A detailed description of our experimental set-up and the method of data evaluation is given in [7]. Stress pulses with duration of 3.10^{-5} *s* and amplitudes ranging from 900 to 2000 *MPa* were used. Such amplitudes guarantée a strain rates of the order 10^3 s^{-1}.

From the experimental results the dependences σ_f $(\dot{\varepsilon}, T)$ for a permanent strain of 0.1% were constructed.

3. Experimental results

The results showed primarily that for all tested materials and test temperature the strain rate $\dot{\varepsilon}_2$ exists so that for $\dot{\varepsilon} > \dot{\varepsilon}_2$ the dependence $\sigma_f - \dot{\varepsilon}$ is linear:

(1) $$\sigma_f = \sigma_2 + \alpha(\dot{\varepsilon} - \dot{\varepsilon}_2)$$

respectively

(2) $$\sigma_f = \sigma_B + \alpha\dot{\varepsilon}.$$

Table 2

Irradiation and testing conditions

Material	Integral dose (n cm^{-2})	Irradiation Temperature (°C)	Testing Temperatures
AREMA	$1.35 . 10^{19}$	50—100	—100+450
STEEL 13030	$1.35 . 10^{19}$	50—100	—50+100
STEEL 22 K	$3.5 . 10^{19}$	150	—100+450

Equation (2) is typical for the behaviour of unirradiated materials in the given range of strain rates (8). It is generally accepted that in the region of the validity of (2) the plastic flow is governed by the damping of dislocation motion due to phonon viscosity and phonon scattering. Following e. g. (2), this region is denoted as region IV.

The stress σ_2 and strain rate $\dot{\varepsilon}_2$ represent boundary between regions II (thermally activated processes) and IV.

In Fig. 1—3 the courses of $\dot{\varepsilon}(T)$, $\sigma_2(T)$ and $\alpha(T)$ are plotted for AREMA steel for irradiated as well as non-irradiated state. The results indicate primarily that the neutron irradiation shifts the boundary line between regions II and IV in the direction of higher values of the strain rate. This shift decreases with increasing temperature what is also valid for the coefficient α.

A detail analysis of dependences $\sigma_2(T)$, $\dot{\varepsilon}_2(T)$ and $\alpha(T)$ leads to the following equations for irradiated as well as for non-irradiated materials:

(3) $$\sigma_2 = A - B\sqrt{T},$$

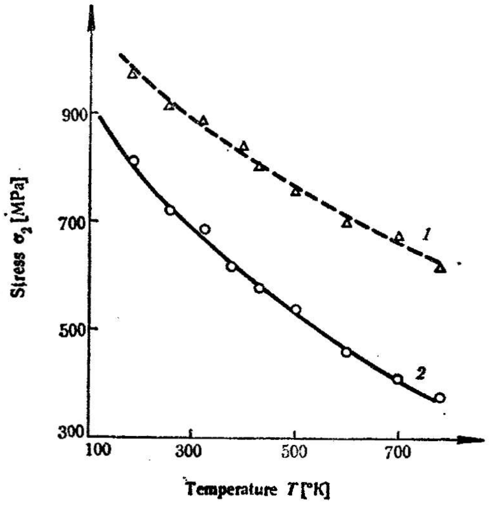

Fig. 1. Dependence of the stress σ_2 on the temperature

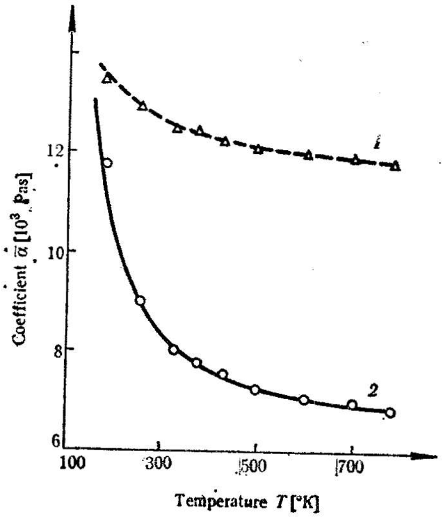

Fig. 2. Temperature dependence of parameter α

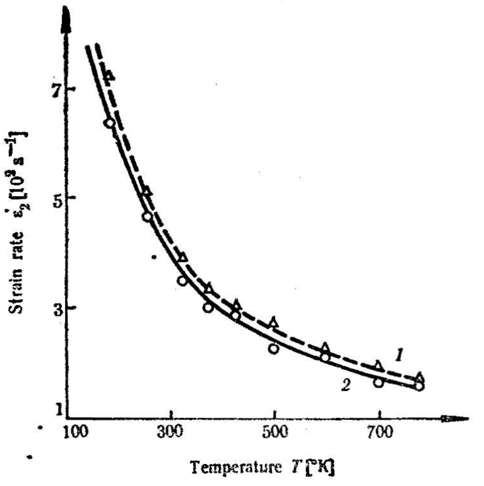

Fig. 3. The influence of temperature on the strain rate $\dot{\varepsilon}_2$

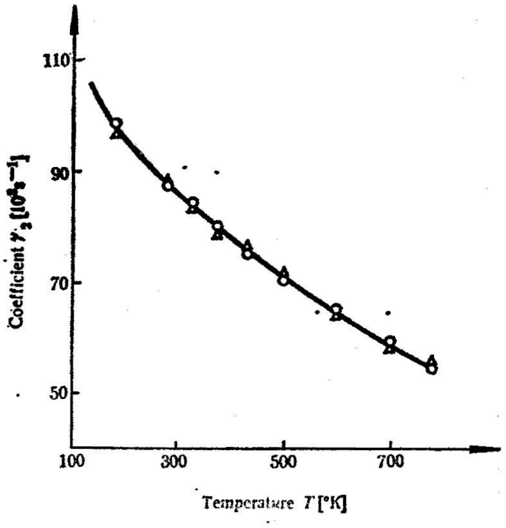

Fig. 4. Temperature dependence of viscosity parameter γ_2

$$\dot{\varepsilon}_2 = a + b/T, \tag{4}$$

$$\alpha = T/(c + dT)^{-1}. \tag{5}$$

The values of parameters A, B, a, b, c, d are given in Table 3. Equation (1) may be re-written in more often used form

$$\varepsilon = \dot{\varepsilon} + \gamma_2(\sigma_f/\sigma_2 - 1) \tag{6}$$

where $\gamma_2 = \sigma_2/\alpha$ is parameter viscosity [8].

This parameter which is of principal significance of the phenomenological description of impact effects is independent of irradiation as follows from Fig. 4.

Table 3

Parameters of Eqs. (3) — (5). The values for irradiated materials are given in brackets

Material	A (MPa)	B (MPa $K^{-1/2}$)	a (s^{-1})	b (10^4 s^{-1} K)	c (10^{-3} Pa^{-1} s^{-1} K^{-1})	d (10^{-3} Pa^{-1} s^{-1} K^{-1})
AREMA	1230	31.1	9.44	11.4	—13.77	0.165
	(1320)	(24.7)	(10.8)	(12.2)	(—2.32)	(0.087)
22 K	1722	46.1	7.29	0.99	—1.68	0.048
	(1940)	(38.2)	(7.45)	(3.22)	(—0.707)	(0.027)
13030	1180	15.3	7.00	2.1	—0.59	6.08
	(2120)	(27.6)	(9.30)	(6.7)	(—1.42)	(4.2)

As it follows from (9), this quantity is also independent on the grade of recovery as well as strain ageing. The independence of γ_2 on irradiation is then of considerable significance in practical enabling its establishing in non-irradiated materials.

4. Discussion

As was already pointed out in the Introduction, there are several regions ($\dot{\varepsilon}$, T) which are controlled by different mechanisms of plastic flow. For our studies the most important ones are region II and IV which are schematically shown in Fig. 5. In the region IV the dependence $\sigma_f(\dot{\varepsilon})$ is described by Eq. (1) or Eq. (2). The coefficient α in Eq. (2) is related to the generalized dislocation drag coefficient for phonon viscosity and phonon scattering B by the expression

$$(7) \qquad B \sim \alpha N_m b^2$$

where b is the Burgers' vector and N_m is the mobile dislocation density. If we consider that B characterizes resistance to the motion of dislocations in otherwise perfect lattice, it becomes evident that the increase in coefficient α is a consequence of the decrease in the density of mobile dislocations. It is obvious in this connection that the shift of $\dot{\varepsilon}_2$ can by characterized by the relation $\dot{\varepsilon}_2 \sim 1/N_m$. The effect of T and $\dot{\varepsilon}$ on the plastic flow of metals can be also expressed in terms of dislocation motion. According to the theoretical analysis [10] the velocity of dislocation moving through the rows of barriers is given by

$$(8) \qquad v = \frac{Al^{-1}}{t_s + t_B}$$

where Al^{-1} is the average distance of dislocation movement after each thermal activation, t_s is the time a dislocation spends at the obstacle, and t_B the time of travelling between the barriers.

From this analysis it follows that both regions II and IV correspond to two different limiting cases. Region II is related to the case when $t_B \ll t_s$ and region IV to the opposite case. From this point of view the irradiation leads to the increase of time t_s. The time t_B is increasing function of temperature.

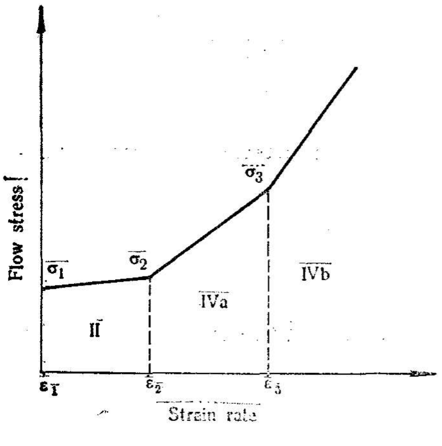

Fig. 5. Two regions II and IV of the flow stress versus strain-rate curve at given strain ε and temperature

5. Conclusions

This paper allows conclusions concerning the effects of neutron irradiation and temperature on the mechanical properties of low alloy steels at high strain rates.

(I) In agreement with the hypothesis made in [11] neutron irradiation does not effect the mechanism of plastic flow at high strain rates produced by HSBT.

(II) The dependence of σ_f—$\dot{\varepsilon}$ may be expressed by usual equation of theory of viscoplasticity:

$$\dot{\varepsilon}=\dot{\varepsilon}_2+\gamma_2(\sigma_f/\sigma_2-1)$$

where viscosity parameter γ_2 does not depend on the neutron irradiation damage.

(III) The neutron irradiation leads to the increase of the thermally activated region in the direction to higher strain rates. This shift decreases with increasing temperature.

(IV) The experimental results are in the agreement with theoretical conclusions of dislocation dynamics theory.

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