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Continuous electron irradiation effect on plastic deformation of the steel T91 at different temperatures

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There was studied the deformation of the steel T91 exposed to electron irradiation at different temperatures. The deformation strength decreasing and the hardening ratio as function of relative elongation were defined in continuous irradiation mode. It was established the increasing of the steel plasticity as the result of the electron beam exposition.
Keywords: electron irradiation, yield stress, plastic deformation, hardening ratio, temperature dependence.

Вивчена деформація сталі T91 під впливом електронного опромінення при різних температурах. У режимі безперервного опромінення визначено зниження рівня деформуючої напруги, коефіцієнт зміцнення як функцію відносного видовження. Встановлено зростання пластичності металу в результаті впливу електронного пучка.
Ключові слова: електронне опромінення, межа плинності, пластична деформація, коефіцієнт зміцнення, температурна залежність.

Изучена деформация стали T91 под воздействием электронного облучения при различных температурах. В режиме непрерывного облучения определено снижение уровня деформирующего напряжения, коэффициент упрочнения как функцию относительного удлинения. Установлено возрастание пластичности металла в результате воздействия электронного пучка.
Ключевые слова: электронное облучение, предел текучести, пластическая деформация, коэффициент упрочнения, температурная зависимость.

Introduction

It's well known that plastic deformation or flow of metals and alloys, and strain hardening as well is observed in the full temperature range beginning from low (helium) values and up to pre-melting ones. This effect is induced by moving of dislocations and their interactions with structural and impurity defects of a crystal lattice. In some cases, interactions of moving dislocations with phonons, conductivity electrons and others [1] should be taken into account as well.

Dislocations while moving dissipate energy on conductivity electrons. This fact was established experimentally in changing from room-temperature sate to superconductivity [2]. Kinetics of dislocations is varied also in hard magnetic field [3], under exposition to electron and gamma irradiation [4] and to high current density electric pulses [5]. The term 'electro-plastic deformation of a material' was introduced for these effects [5].

The research purposed to investigate deformation of some hexagonal close-packed (HCP) crystals exposed to short electron beam pulses that have been done in the early 1960s allowed to demonstrate the step-down change of a deforming strength and increasing of plasticity [4].

The plastic flow of metals with FCC crystal lattice (Al, Cu) exposed to electron beam has been researched in the paper [6]. There were studied dependencies of strength loss, deformation ratio, the thickness of a sample and others [6].

However, steel has BCC crystal lattice, and the effect of its exposition to electron irradiation should be researched. The steel T91 is a constructive material of nuclear reactors. To understand its strength performances dependent on temperature and electron irradiation and to obtain data for analysis and defining of control methods of radiation-induced effect the research including the simulation of in reactor environment processes should be fulfilled.

Experimental technique

Polycrystalline samples of the steel T91 were researched. Its alloying constituents are summarized in the table 1. The samples were profile cut from sheets of 15 mm thickness after hot rolling. The rolling and the cooling was realized by following sequence: normalization at 1050°C during 15 min, water hardening down to room temperature, exposure at 770°C during 45 min and air cooling down to room temperature. Samples have active narrow region with dimensions of 1.9×0.75×30 mm between two broad regions for grips of a deformation machine.

The researched samples were divided into two sets. The first set was researched without the next processing. The second set was annealed at 650°C in argon environment during 3 hours with next cooling together with a kiln down to room temperature.

The plot of the sample loading was registered in load (P) – time (t) diagram with time resolution 0.3 sec (storage digital multimeter Sanwa PC-520M) and the load sensitivity 0.5 H. After registration the load was converted into deforming strength according to the ratio $\sigma = P(1+\varepsilon)/S$ (S is initial cross-section of a sample, ε is relative elongation of a sample). For uniform movement of the rod in the fracturing machine the relative deformation was defined as following $\varepsilon = \upsilon_{rod} \cdot t/L$ ($\upsilon_{rod} = 5$ μm·sec^{-1} – velocity of a rod movement, L – initial length of the active region of a sample)with error ±0.1%.

During the deformation, the samples of steel T91 were exposed to electron irradiation according to the method explained before [7]. Consider only parameters and time structure of the electron beam. The electron beam with energy *E*=0.8 MeV and electron flux density through the sample $(1.9\ldots4.0)\cdot10^{16}$ m^{-2}·s^{-1}(irradiation power ~3 W) from the 'Resonance' linac [7] directed on the active region of the sample. Electrons had uniform distribution on area ~5…6 mm². Microbunches of electrons with duration τ_{mb}= $4\cdot10^{-11}$ sfed the beam with frequency $3\cdot10^{9}$ GHz in a bunch with duration $\tau_b = (1.8\ldots2)\cdot10^{-6}$ s. The bunch repetition rate $1/T_0$ was 25 Hz.

During the deformation the sample was mounted in a heater that allowed its heating in the range 313-673 K. The temperature variation of the sample due to external or by electron irradiation heating was measured using Cu-Constantan thermocouple. The accuracy of the temperature measurements ΔT was ±1 K.

To achieve the temperature below 273 K the sample was placed in a cryostat in a liquid nitrogen steam and was heating up so that the temperature may be varied in the range 193…273 K.

Experimental results

The effect of high-energy electron beam on plastic flow of Al at room temperature in the cycle-change deformation mode (with period ~50…100 s) under electron irradiation (φ≠0) or its absence (φ=0) (continuous [8] and differential irradiation mode [6]) was considered before.

There was shown in the paper [8] that electron beam effects on decreasing of deforming strength σ and increasing of a sample elongation ε. Such variations on the deforming diagram σ(ε) of the metal may indicate the genesis of less strength structural state under high energy electron flux.

Figure 1 shows curves of deformed strengthening σ(ε) (σ is deforming strength, ε is relative elongation) of the steel T91 samples under electron irradiation (2, 4 - φ≠0) and on its absence (1, 3 - φ=0).

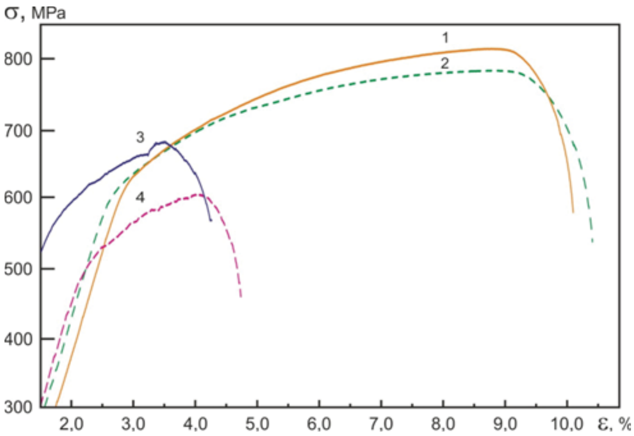

Fig. 1. Deformation curve for reactor steel T91 (EUROFER) without irradiation (1, 3) and at $\varphi = 4.0\cdot10^{16}$ m^{-2}·s^{-1} (2); $1.9\cdot10^{16}$ m^{-2}·s^{-1} (4) at RT (1, 2) and at 553 K (3, 4).

Due to continuous mode of electron irradiation, the deforming strength value is decreased in the total range of deformations starting from yield stress and up to the sample breakdown, and the plasticity resource of the metal is increased.

Mean free path of 0.8 MeV electrons in the steel is ~2.0 mm (Fig. 2). Therefore, electrons of the irradiating beam penetrated through the steel.

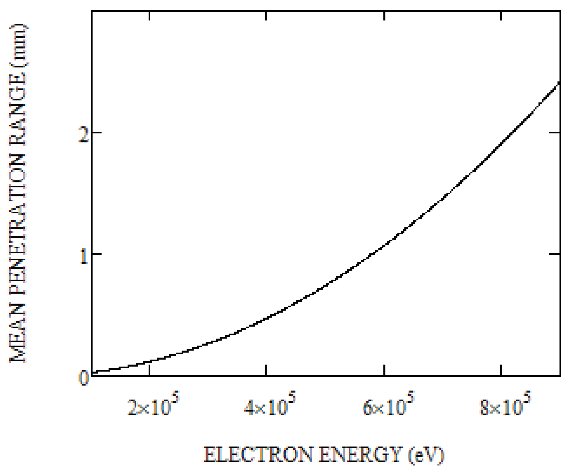

Fig. 2. Calculated mean free electron path vs irradiation energy for iron.

The steel samples were tension deformed at different temperatures: in liquid nitrogen steam, at room temperature and at increased temperature 350-600°K evaluated by external heater. Figure 3 shows the obtained dependences of yield stress (Fig. 3 a), ultimate strength (Fig. 3 b) and the plasticity resource (Fig. 3 c). With the temperature increasing all samples both annealed and non-annealed have decreased yield stress, the ultimate strength decreased in 1.5 times and the relative elongation decreased in 2.5 times.

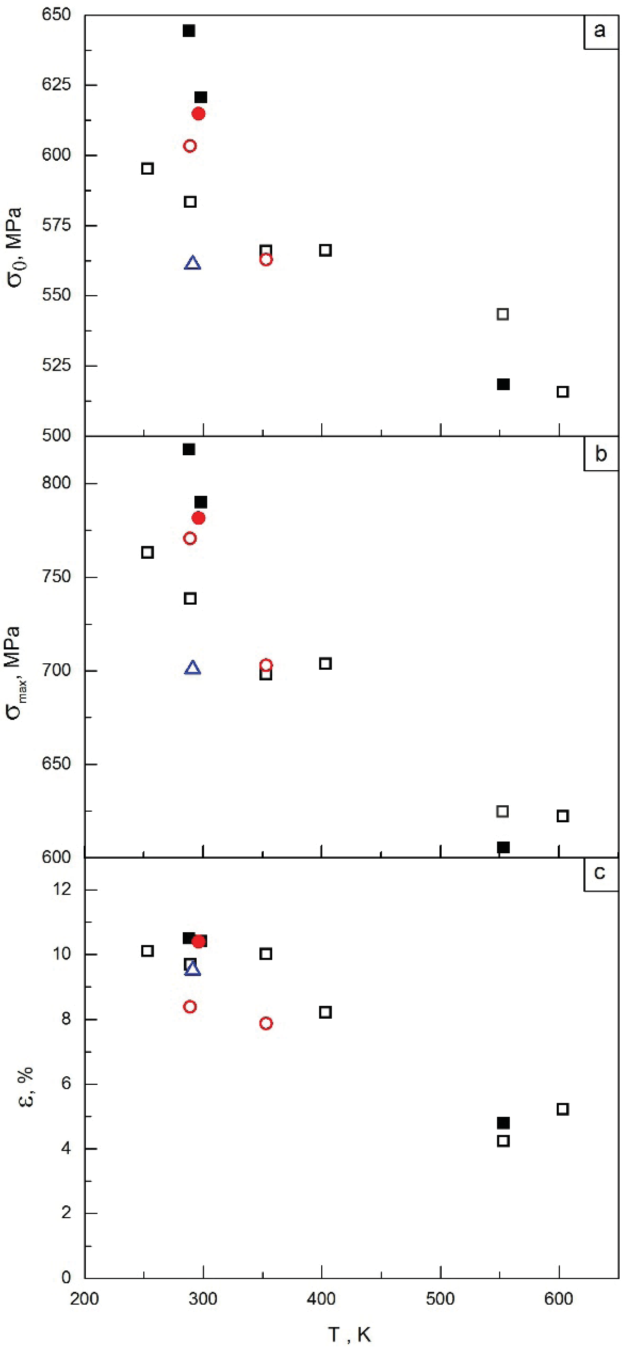

Fig. 3. Strength and plastic performances of the steel T91 samples: yield stress σ_0(a), ultimate strength σ_{max}(b) and plasticity resource ε_{pl}(c); hollow symbols – non-annealed samples, solid symbols - annealed samples.
□ - annealed samples, deformation velocity $5{\cdot}10^{-5}$cm/s;
△ - annealed sample, deformation velocity $5{\cdot}10^{-6}$cm/s;
○ - non-annealed samples, deformation velocity $5{\cdot}10^{-5}$cm/s.

Let's treat the effect of high energy electrons on the steel T91 samples at different temperatures. As one can see from the Fig. 3 the decreasing of the yield stress, the ultimate strength and the relative elongation is observed for the temperature increasing. Comparing annealed and non-annealed sample for the temperature 553°K it is observed the decreasing of the ultimate strength (Fig. 3 b) but the increasing of the plasticity resource on 13 % (Fig. 3 c) at the same time.

The electron irradiation effect on the sample heating up was studied next. At room temperature without external heater, the sample temperature rises on 7°C under electron irradiation that is compared with environment temperature. It means that electron irradiation effects on the sample heating negligibly due to the sample thickness is smaller than the free electron path. It permits to exclude a temperature component action on dislocation movement in a crystal lattice. In the context of this fact, it should be interesting to consider the effect of both the temperature corresponding to the values the steel T91 is under in nuclear reactors and continuous mode electron irradiation of the sample during its tension deformation.

Because of nuclear reactors are featured by high temperature and irradiation it was necessary to test the steel samples both under external heating up and electron irradiation. The samples were exposed to continues electron irradiation in presence and absence of the external heater.

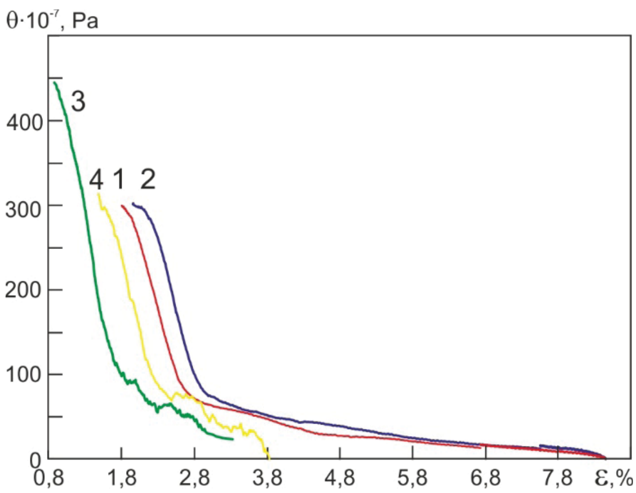

Fig. 4. Deformation strengthening ratio of the steel T91 vs relative elongation ratio in coordinates θ(ε) (1, 3–φ=0; 2, 4 –φ≠0; 1, 2 – deformation at 553 K; 3, 4 - deformation at 291 K).

As one can see from the Fig. 4 there is the difference in 1 and 2 deformation phases for equal temperatures (room and increased values) while the ratio is equal in fact in the deformation phase 3. Comparing irradiated and

Table 1.

The chemical composition of the alloy

Alloy	Mass fraction of element, %																
	C	N	Al	Si	P	S	Ti	V	Cr	Mn	Ni	Cu	As	Nb	Mo	Sn	W
T91	0.10	0.0442	0.015	0.22	0.021	0.0004	0.003	0.21	8.99	0.38	0.11	0.06	0.008	0.06	0.89	0.004	0.01

non-irradiated steel T91 samples while their deformation under exposition to high-energy electron beam there is no the difference in the deformation strengthening ratio. This means that electron irradiation does not effect on the steel deformation. The deformation the strengthening ratio is decreased on $100{\cdot}10^{-7}$ Pa in case of the temperature values similar to nuclear reactor environment. This shows both the sample softening and increasing of its plasticity under electron flux effect on crystal lattice.

Conclusion

The strength performances depending on temperature have been obtained. The yield stress, the ultimate strength and the plasticity resource is decreased for the temperature increasing.

There is the increasing of the plasticity resource and decreasing of the ultimate strength simultaneously while the samples are deformed under electron irradiation at equal temperature values. These points to the effect of electron flux on dislocation structure of the steel T91.

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