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CREEP RESISTING STEELS, NANOPARTICLES, INTERPARTICLES MATRIX STRESSES, MOBILE DISLOCATIONS MOTION AND CREEP RATE

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Development of improved equation for better accuracy of calculation of stationary creep rate of creep resisting steels. Effect of acting stress components in particles disjunction matrix. Effect of increase of number of ferrite lattice vacancies.

Key words: creep resistant steel, carbide nano-particles, particles disjunction matrix, ferrite vacancies, creep equation

INTRODUCTION

The aim of this article is not the analysis of physics of the creep process, the aim is to present the concept of stationary creep of modern creep resisting steel with creep rate governed by component of acting stress in inter-particles ferrite matrix named particles disjunction matrix (pdm). Since, in earlier publications, a great number of works of many authors was quoted, two basic and the reference with the newly derived equation, are cited, only.

The microstructure of creep resisting steels consists of ferrite grains of size 10-20 μm and nanoparticles of carbides and carbonitrides of alloying elements, mostly vanadium, niobium and chromium. The particles precipitate from oversaturated solution of carbon and nitrogen in martensite. The size on particles is in the range 5 to 500 nm and it depends of the ageing temperature and time. After ageing, the number of particles depends of the content of constitutive elements in steel and it is generally of order of magnitude of about 10^{11} cm^{-3}. The distribution of particles affects strongly the creep rate. In Figures 1 and 2, particles are shown in a steel X20 aged 24 h, rsp. 672 h at 800 ^{o}C. The creep rate of the specimen in Figure 1 was $<1 \times 10^{-8}$ and by specimen in Figure 2 $\approx 22 \times 10^{-8}$ s^{-1}, while the difference of average size of particles was ≈10 %. The difference demonstrates that the distribution of particles, especially stringers of particles, influence strongly the creep rate. On the other side, the rate of decomposition of stringers of particles is very high. For this reason, only small average particles size, low coarsening rate and uniform distribution, ensure the low stationary (secondary) creep rate, long time and stable operation of steel tubings in thermoelectric power plants producing electricity from fossil fuels.

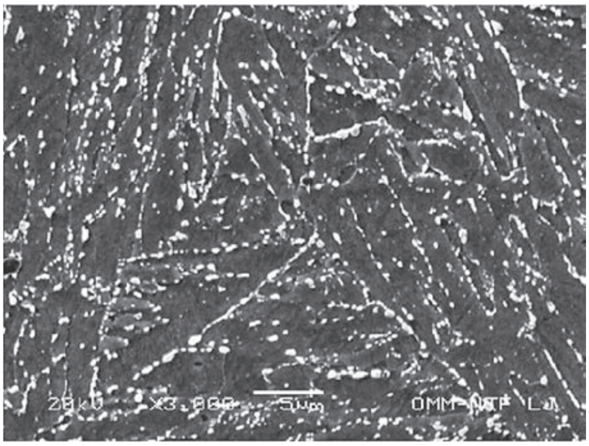

Figure 1 Steel X20, quenched from 1 050 ^{o}C and tempered 24 hours at 800 ^{o}C

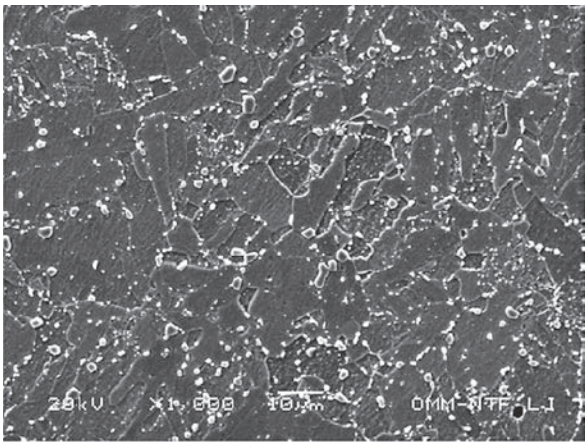

Figure 2 Steel X20, quenched from 1 050 ^{o}C and tempered 672 hours at 800 ^{o}C

The secondary (stationary) creep of steel proceeds with gliding and climbing of mobile dislocations in the ferrite matrix. Particles are polyhedrons and arrest the gliding of dislocation which continues with by-passing of particles with mobile dislocation climb.

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DEVELOPMENT OF THE CONCEPT

Based on theoretical analysis of a dislocation line advancing through a field of obstacles (particles) by locally climbing over them, Ashby [1] derived the creep equation:

$$\dot{\varepsilon} = (\frac{2\pi DGb}{\vartheta KT})(\frac{\sigma}{G}) \quad (1)$$

With: $\dot{\varepsilon}$ - creep rate s^{-1}, *D*-diffusion rate, *G*-shear modulus, *b*-Burgers vector, s-acting stress, ϑ-volume of diffusing atom, *k*-Boltzmann constant and *T*-temperature K.

The calculated and experimental creep rates differed for orders of magnitude and some years later, Hornbogen [2] modified Equation (1) with inclusion of a new parameter, particles spacing deduced as $\lambda = 2d / \pi f^{1/3}$.

$$\dot{\varepsilon} = \frac{b^2 D\sigma\lambda\rho^2}{kTG} \quad (2)$$

With: *d*-average size and *f*-volume of steel particles.

The difference of experimental and creep rate calculated from Equation (2) was still too high, for this reason, a number of semi-empirical creep rate equations was suggested fitting acceptably to experimental values by creep test temperature. In these equations, the basic parameters of the microstructure of creep resistant steels, particles size and spacing, were substituted with different parameters, *f*: acting (creep) stress exponents n = 3 to n = 16, the rationalisation of creep stress s with shear modulus, yield stress, tensile strength, a threshold stress below which no creep was observed, a back stress effect and energy barrier concept. The majority of proposed equations had the form:

$$\dot{\varepsilon} = A(\frac{DGb}{kT})(\frac{\sigma - \sigma_{th}}{G})^n \text{ and } \dot{\varepsilon} = A(\frac{\sigma}{\sigma_{ts}})^n e^{-\frac{Q}{RT}} \quad (3)$$

In all equations, the interaction creep stress-particles in inter-particles matrix and the effect of number of vacancies in ferrite lattice were omitted, although basic parameters of the creep process of creep resisting steels. In Figure 3 the section of two particles is shown with conjunction matrix of decreasing and disjunction matrix of increasing spacing of two neighbour particles is depicted. In conjunction matrix, the creep stress is transferred from ferrite to particle and in disjunction matrix it is transferred back to ferrite.

In Figure 4 the creep specimen cut out from a 4,2 mm tube wall is depicted with particles of different shape and ferrite grains dislocations gliding planes. The angles of acting stress, particles faces and ferrite plane

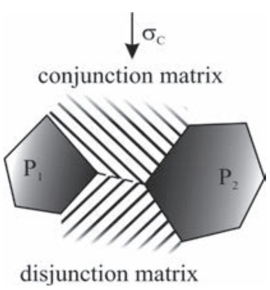

Figure 3 Section of particles and ferrite conjunction and disjunction matrix

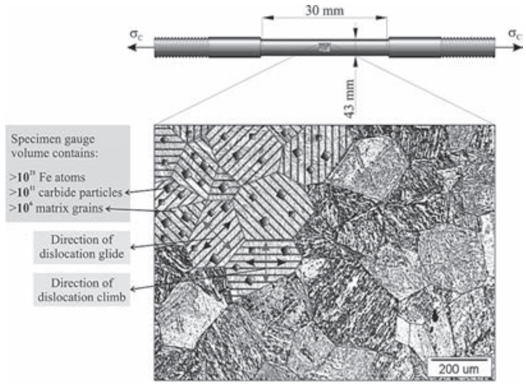

Figure 4 Creep specimen and imaginary specimen section with ferrite grains, shape of particles and ferrite gliding planes

of dislocations gliding may be very different. In Figure 5, the edge of particle section is shown with angles determining the transfer of particle stressing in directions of mobile dislocation gliding and climbing directions of the ferrite matrix.

In particles disjunction matrix (pdm), the glide stress (σ_g) depends of the angles of directions creep stress -dislocations glide - stress transfer particle face. These angles are different in single matrix and pdm's, consequently, in single pdm's, creep stress glide and climb components are different. Ferrite grains and particles are polyhedrons with many faces. The angles particles face-matrix may be very different, for this reason, acting transfer stress components in pdm in dislocations glide and climb directions are different, as well.

By stationary creep, the integrity of the crept multi grains-multi particles specimen free of pores and cracks is attained by virtually equal creep rate in the whole creep specimen. Thus, the creep rate is virtually equal in all ferrite grains and pdm's. Then, is logical to conclude, that the specimen creep rate is governed by the gliding stress component of acting stress in the particles disjunction matrices with the lowest gliding stress, rsp. acting stress component in gliding direction.

By angle acting stress-dislocation glide direction α > 90°, mobile dislocations glide (slip) in creep direction with respect of the particle stress transfer face. According to the triangles similarity in Figure 5, in pdm the

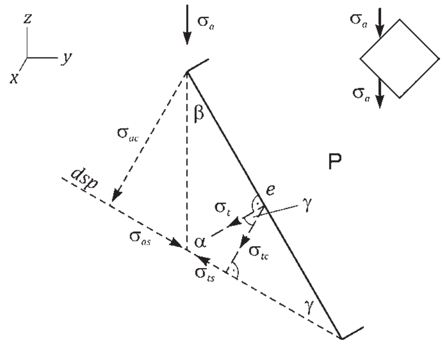

Figure 5 Acting stress components and angles α, β and γ in pdm of the edge (e) of the section of the particle; dsp-dislocation slip plane, climb and slip components of creep stress (σ_{ac}, σ_{as}), climb and slip components of transfer stress (σ_{tc}, σ_{ts})

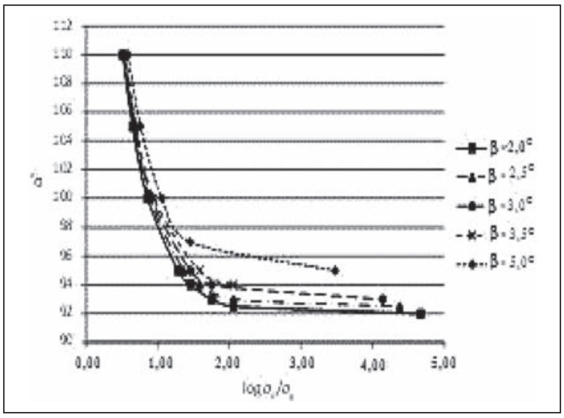

Figure 6 Dependence of log (σ_a/σ_g) and angle a by different angles b

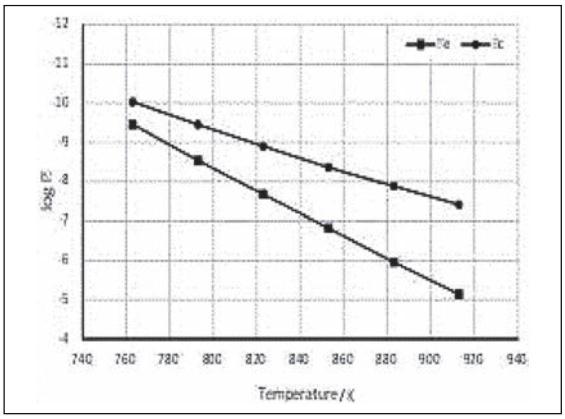

Figure 7 Increase of the experimental creep rate $\dot{\varepsilon}$ and the creep rate calculated using Equation (2) for in temperature range 763-913 K

particles transfer stress components in glide and in climb direction are:

$$\sigma_{as} = \sigma_a \cos(180–\alpha),\ \sigma_t = \sigma_a \sin\beta \text{ and}$$
$$\sigma_{ts} = \sigma_t \cos(90–\gamma),\ \sigma_a \sin\beta \cos\gamma \quad (4)$$

In Figure 6, the angle $\alpha = [180 – (\beta + \gamma)]$ is versus log (s_c/s_g) is depicted for different angle b = 180 °– (α+g). The glide stress σ_g decreases by decrease of angle α and by α = 92 ° and β = 2-3 °, it tends as asymptote to α ° = σ_a = log $(\sigma_g/\sigma_c)^4$ and the gliding stress σ_g = 4,03 MPa, while, the pdm climb component is $\sigma_c \approx$ 168 MPa and the ratio glide/climb stress is σ_g/σ_c = 0,0238.

In Figure 7 are depicted the experimental creep rate and the creep rate calculated using Equation (2) in temperature range 550-640 °C (823-913 K). At all testing temperatures, the calculated creep rate is lower and that the difference calculated-experimental rate decreases by decreasing temperature. It is reasonable to assume that in Equation (2) a creep ~~a~~ parameter is omitted. Lattice vacancies make possible the climb of mobile dislocations and faster experimental than calculated creep rate suggests that by creep of matrix with particles, the parameter D in the earlier quoted creep equations did not consider the effect of the difference of pdm glide and climb stress. By self-diffusion in ferrite, iron atoms may jump in 6 directions, however, in the pdm, the very great climb component of acting stress may induce more frequent climbs in creep direction.

Figure 8 shows that the difference of calculated and experimental creep rate grows parallel with the number of ferrite vacancies. The logical conclusion is that in Equation (2), a parameter representing the number of lattice vacancies at creep tests temperature should be included.

The analysis of experimental and calculated creep rates justified the improvement of Equation (2) improved with the parameter related to the effect of number of vacancies in ferrite lattice at creep temperature k_{vT} and the specimen creep volume (λ-d). The parameter k_{vT} was deduced from the curves in Figure 8. The creep equation including both proposed parameters is [3]:

$$\dot{\varepsilon} = k_{vT}\left(\frac{b^2 D(\lambda - d)\sigma^2}{kTG}\right)$$

and k_{vT} = 0,001 + log (0,022 · ΔT)
and $\Delta T = T – 741$ (8)

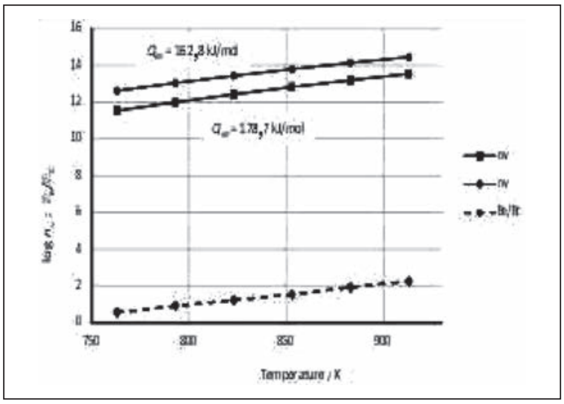

Figure 8 Ratio of experimental and the calculated creep rate and number of vacancies in ferrite lattice versus creep temperature

The difference of experimental creep rate and that calculated using Equation (8) was up to 1 %.

CONCLUSION

In the new derived creep equation, the effect of stress transfer particle-matrix in particles disjunction matrix, rsp, the number of ferrite vacancies on the climb velocity of mobile dislocations and of the specimen creep volume are included. It represents a valuable improvement in the understanding of the creep rate of ferrite matrix with a great number of nano-particles.

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Note: The responsible translator for English language is Franc Vodopivec, Ljubljana, Slovenia