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CREEP RESISTANCE OF MICROSTRUCTURE OF WELDS OF CREEP RESISTANT STEELS

ODPORNOST PROTI LEZENJU PRI MIKROSTRUKTURI ZVAROV JEKEL, ODPORNIH PROTI LEZENJU

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Welds are essential parts of tube systems in high temperature power works producing electrical energy and have a heterogeneus microstructure due to the welding gradient of temperature and cooling rate. A short summary is given of findings related to the creep resistance of welds of creep resistant steels. In the majority of references it was found that creep resistance was lower for the intercritical part of heat affected zone (HAZ). The effect of potential changes of intercritical microstructure on creep rate at exploitation is discussed.

Key words: creep resistant steel,welds, creep rate, HAZ, intercritical zone

Zvari so bistvena komponenta cevnih sistemov v termoelektrarnah, njihova mikrostruktura pa je heterogena zaradi gradienta temperature in ohlajanja pri varjenju. Pripravljen je bil kratek pregled ugotovitev v zvezi z odpornostjo različnih delov cone toplotnega vpliva varjenja (TVC) proti lezenju v dosegljivih virih. Večina virov navaja, da je odpornost najnižja v področju, kjer je bilo med varjenjem jeklo segreto v interkritično področje CTV. Analizirane so mogoče spremembe interkritične mikrostrukture in od njih odvisne spremembe hitrosti lezenja.

Ključne besede: jeklo odporno proti lezenju, zvari, hitrost lezenja, TVC, interkritična cona

1 INTRODUCTION

Welds are an essential parts of steels tube systems in thermal power works. The heating cycle of welding, the temperature gradient and cooling rate give to the weld part of tubes, the heat affected zone (HAZ) a heterogeneous microstructure of products of transformation of austenite at cooling. This microstructure depends on the temperature at welding and the cooling rate. It consists of a slightly affected microstructure of basic steel, the products of transformation of cooling from intercritical range, the range of temperature of stability ferrite + austenite and the transformation at cooling of austenite from a temperature up to melting point on the boundary to the deposed metal. Also the HAZ microstructure may be affected by the cooling rate and influenced additionally by reheating at deposition of following welding passes. The heating time is short, however, the local temperature is sufficient for inducing changes of grains size and may even change the quantity and distribution of carbide particles hindering the movement of dislocations and affecting the creep rate. For this reason, the creep resistance of welds of creep resistant steels has received considerable attention. In this work, an abbreviated review of the most significant findings in accessible references is given. Conclusions are proposed with accent on more reliable findings and some so far insufficiently clear facts are mentioned, also. The effect of possible changes of microstructure in intercritical zone on creep rate is examined, also.

2 REVIEW

For a 21Cr steel it was established that the weld metal had a greater creep rate than the base metal due to agglomerate of carbide particles facilitating the cavitation.[1] The creep activation energy of 337.5 kJ/mol was deduced, a value in acceptable agreement with the creep activation energy for α-iron.[2] For the steels 9Cr1Mo and 2.25Cr1Mo, the dissimilar weld joint showed lower creep strength than base steels and the creep deformation was for both steels concentrated in the intercritical (ICZ, $\alpha+\gamma$ range) zone of HAZ.[3] Creep cavities were generated mostly at grain boundaries in ICZ, their number increased with creep deformation that was self-accelerating.[4] Also, it was established that at creep tests at 650 °C and 675 °C, the change of hardness was small for ICZ and great for weld metal, coarse grained HAZ and base metal. Creep failure of welds occurred with IV type cracking in ICZ with the highest generation of voids. HAZ modelling showed for ICZ the higher equivalent stress and strain.[5]

The higher ICZ susceptibility to cracking in welds of a 1.25Cr0.5Mo steel in service may be due to the heterogeneous distribution of precipitates. Close to 90 % of voids are found at grains of size lower than 10 µm. However, 200 to 300 voids per mm^2 did not shorten significantly the steel rupture time.[6] Calculation showed that ICZ has a higher equivalent strain and high hydrostatic pressure and than the base material submits ICZ to a strong constraint.[7] The distribution of voids and equivalent stress were similar for all HAZ zones, thus independent on microstructure. Also, it is suggested that hydrostatic pressure may accelerate the coalescence of voids to cracks.[7] The greater crack susceptibility of ICZ may be due to a heterogeneous distribution of precipitates and the greater change of particles morphology during creep.[8]

The grain boundaries sliding hinders the generation of cavities at accelerated creep rate tests.[9] For this reason, the density of cavities could not be an absolute parameter of creep damage effect in ICZ. From strain rate measurements the rupture life can be predicted with reasonable accuracy.[9] The most effective factors reducing the creep rupture strength of welds of steel P 91 are the finer austenite grains that accelerate the growth rate of subgrains from martensite laths and the softer martensite matrix that both increase the rate of softening and creep cavitation.[10]

The intrinsically higher ICZ creep rate is due to the effect of stress triaxiality.[11] Stress relief cracking could occur in coarse grained HAZ because of sulphur and phosphorus segregations.[12] In the investigation of the effect of triaxiality on creep with notched specimens, it was found that the equivalent stress played a major role in the multiaxial rupture life of a 1.25Cr0.5Mo steel.[13] For a similar steel, it was deduced that multiaxial stress could play a key role in the type IV failure of welds and that this failure may be caused by grain boundaries sliding of fine grains produced by the partial transformation at welding.[14] With small punch tests it was found that the creep rupture time of HAZ was by low stress levels shorter than for the base and deposited metal[15]. Also, it was assumed that a film like carbide phase at grain boundaries and coarsening of $M_{23}C_6$ particles may affect the creep rupture strength of HAZ.[15]

For the 9Cr1MoVNbN and 12Cr2MoWVTiB steels the creep damage was greater for undermatched than for equal and overmatched welds and for overmatched welds the failure tendency was higher than for equal matched welds.[16] After normalising at 1050 °C and tempering at 780 °C, the creep rupture strength for HAZ was equal as for the parent steel[17]. For proper understanding and modelling of creep behaviour of welds, it is necessary to know the individual creep strength of different weld regions and the effect of stress multiaxiality that is changed permanently because of creep and relaxation.[18]

The creep rupture strength of cross weld joints is usually about 20 % to 30 % lower than that of the base steel.[19] Also, it was found that in steel P 91 the particles spacing of secondary phases was higher in HAZ than in base steel. Creep strength is for welds identical to that of the base steels up to 575 °C and the creep resistance may be influenced by post-weld heat treatment.[20] Creep fracture occurs in ICZ and the density of creep voids is greater in the interior of the specimen section, where also the multiaxial stress is larger.[21]

The creep strength of the 9 Ce to 12 Cr steels was improved and the formation of small grains in ICZ suppressed with addition of 0.1 % B because of the grain strengthening effect of this element[22]. In[23] the effect of boron addition is confirmed and is established that no coarsening of carbide particles occurred by 10 000 h creep test at 650 °C. Also, the cross weld stress of boron steel is up to 10 000 h of creep time higher for the weld than for the base steel. The stress concentration in the softened zone of ICZ explains it creep propensity only if the smaller grain size is considered, also.[24]

Up to 575 °C the weld creep strength is in the scatter band of ±20 % of the base steel, while, at higher temperature the weld creep strength is below this range.[25] In HAZ the recovery is faster because of the faster deterioration of laths structure and the decrease of dislocation density that facilitate a faster creep deformation.[26] With small punch tests the localization of creep fracture in ICZ was confirmed especially by small load and a simple relation was established between the punch load and the equivalent stress.[27] Creep damage from preliminary uniaxial tests shortens the time to rupture by small punch test.[28]

The following conclusions and remarks are derived from this review:

- in welds of creep resistant steels the creep resistance of the HAZ intercritical zone (ICZ) is the lowest and the creep rate increased appropriately;
- creep failure occurs with coalescence of grain boundary voids to type IV cracks;
- in operation, creep relaxation occurs that affects the equivalent stress and the creep resistance;
- boron presence in steel increases the creep resistance of the ICZ zone of HAZ;
- reliable weld creep modelling should be based on the effect of operation time and temperature on creep rate for individual constituents of HAZ and on stress multiaxiality;
- data on the accurate creep rate of typical HAZ microstructure constituents are insufficient;
- plastic deformation increases the number of defects in metal lattice and accelerates diffusion and related processes, also diffusion and creep. It is not clear how these processes can be accelerated by stressing without plastic deformation.

3 EFFECT OF CHANGES OF INTERCRITICAL HAZ MICROSTRUCTURE ON CREEP RESISTENCE

In creep resistant steels the creep rate depends on spacing of particles, mostly of carbides of chromium, vanadium, niobium and other metals added in the steel. Two theoretical equations were developed for the dependence of creep rate and particles spacing λ:[29,30]

$$\dot{\varepsilon} = (b^2 / k_B TG) \lambda \sigma^2 D \tag{1}$$

and in the detachment concept of dislocations overcoming of non coherent precipitates[31,32]

$$\dot{\varepsilon} = (6\lambda\rho/k_B TG) \cdot \exp(-E/k_B T) \qquad (2)$$

With $\dot{\varepsilon}$ – creep rate, b – Burgers vector, k_B – Boltzmann constant, T – temperature in K, G – shear modulus, σ – acting stress, D – diffusion coefficient, ρ – density of mobile dislocations and E – creep activation energy.

By constant volume share of carbides f, the particles spacing and carbide particles size d are related with:[30]

$$\lambda = 4d/\pi f^{1/3} \qquad (3)$$

By constant volume share of carbide, the creep rate increases with particles spacing which, by constant volume share of carbide, depends of particles size, thus of particles coarsening rate, also. This rate depends on volume diffusion rate of the main metal bound in carbide phase, fi.: chromium in $M_{23}C_6$ and vanadium and niobium in MC carbides.

For the coarsening of $M_{23}C_6$ carbide particles the experimental coarsening rate was determined[33,34]

$$\Delta d^3_{\text{ce,1073K}} = k_{\text{ce,1073K}} t = 1.48 \cdot 10^{-26} t \qquad (4)$$

The Lifshitz-Slyouzov-Wagner[35] (LSW) equation for coarsening of particles is:

$$\Delta d^3 = 8 S\gamma \Omega D t / 9 k_B T \qquad (5)$$

With Δd^3 – increase of particles size in time t, S – equilibrium content of carbide constituting metal in solution in the matrix, γ – carbide particle-matrix interface energy, Ω – volume of diffusing atoms, k_B – Boltzmann constant, D – diffusion coefficient and T – temperature in K.

Introducing the parameters for the steel X20 the coarsening kinetics for $M_{23}C_6$ particles in steel X20 tempered at 1073 K the relation was deduced:[34]

$$\Delta d^3_{\text{ce,1073K}} = 1.31 \cdot 10^{-26} t \qquad (6)$$

This relation is in acceptable agreement with the experimental equation (4).

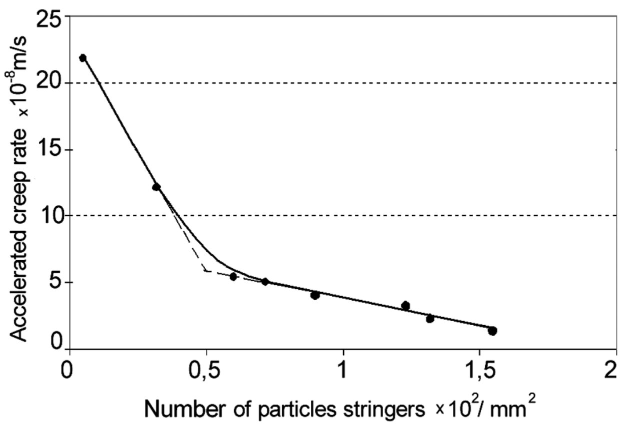

Figure 1: Dependence of accelerated creep rate on the number of stringers of carbide particles in martensite in 0.18C11.5Cr1.08 Mo0.29V steel.[36]

Slika 1: Odvisnost med hitrostjo pospešenega lezenja in številom nizov martenzitnih izločkov v jeklu 0.18C11.5Cr1.08 Mo0.29V[36]

As shown in **Figure 1**, by equal particle size the creep rate depends strongly on the share of particles in stringers[37].

The number of stringers per unity of surface decreases with tempering time several times more rapidly that particles coarsening. The explanation is the faster growth of particles at grain and subgrain boundaries[38,39,40] very probably because the boundary diffusion is faster then volume diffusion. The kinetics of decrease of the number of stringers of particles the relation was deduced:

$$n_t = n_t - k_n t^x = 1.78 \cdot 10^8 - 0.706 \cdot 10^2 t \qquad (7)$$

with n_t – density of stringers at the time t, n_i – density of stringers at t = 0, k_n – rate of decrease of stringers density (m^{-2} s^{-1}) and t – tempering time (s).

After approximately 350 h of tempering at 800 °C the stringers density was diminished below the critical value of about 0.60 · 10^8 m^{-2}, the creep rate increased by approximately 8.5 times,[37] while a much lower increase would be attained from the increase of particles spacing if the rate was calculated using equation (1) and the particle spacing calculated using equation (3) based on the experimentally assessed average particles size. These findings suggest that the creep resistance of the intercritical part of HAZ depends to a significant extent of the number if stringers of carbide particles and their stability.

Investigations of the coarsening of carbide particles in a 12Cr steel have shown[41] that in specimens crept for up to 16 000 h at 650 °C by the stress of 80 MPa the coarsening rate of MX particles was 3.73 times greater that in grip part of tested specimens.[34]

Parts of HAZ are heated to a different temperature and a different microstructure is obtained. In some parts of HAZ the temperature is theoretically sufficient for significant change to steel creep resistance, however, because of the short heating time only partial solution of carbide particles is achieved with the greatest solution for VC, lower for NbC and the lowest for $M_{23}C_6$. Accordingly, it is logical to conclude that, especially the particles distribution in parts of HAZ, heated to the theoretical temperature of complete solution of VC and NbC particles and the HAZ part heated at higher temperature, but to low for a sufficient solution of $M_{23}C_6$ particles, the creep rate is higher mostly because of the diminished effect of particles in stringers.

Equations (1) and (2) show that creep rate increases with the density of mobile dislocations which is related to the creep stress (σ), Burgers vector (b) and shear modulus (G)[42] and the constant α = 0.4.

$$\rho = (\sigma/\alpha MGb)^2 \qquad (8)$$

For accelerated creep rate tests by σ = 170 MPa, G_{853K} = 57.6 · 10^3 MPa [32], M = 3, b = 2.5 · 10^{-10} nm, the dislocation density of ρ = 0.978 · 10^{14} m^{-2} is obtained.[37]

Let us examine how processes of transformation of austenite to martensite and ferrite transformation in HAZ may affect the mobile dislocation density. These dislocation are generated by plastic deformation. Accordingly, no significant effect could be expected from the generation of elastic stresses by austenite to martensite transformation and their relaxation. By transformation of the mixture of austenite and ferrite, thus by cooling from intercritical temperature, these elastic stresses could relax with slight plastic deformation of ferrite and its mobile dislocation density slightly increased. Thus, the density of mobile dislocations could be slightly increased in parts of HAZ with incomplete ferrite to austenite transformation at heating. Carbide stringers consist for a greater part of $M_{23}C_6$ particles. These particles grow faster because of boundary diffusion[39,40] and the rate of decrease of the density of stringers is much greater than for the average coarsening rate in stringers and the rate of stringers decmposition. For this reason, it is expected that by heating at welding the creep resistance is diminished much less by increase of particles spacing than by the decrease of stringers density and it is logical to conclude that the increased creep rate for the intercritical part of HAZ is due mostly to the decrease of the effect of stringers of carbide particles on creep. After heating at higher temperature, a great part of carbide particles is dissolved in austenite and stringers form again at grain and subgrain boundaries of martensite and their effect on creep rate is restored. This interpretation of processes in HAZ, rsp. at temperature of ferrite + austenite range, would be for the creep resistant steel X20 the logical explanation for two experimental findings: 1) compared to as delivered steel X20, the accelerated creep rate at 580 °C and stress of 170 MPa the creep rate was increased for about one order of magnitude after cooling from $\alpha+\gamma$ range, while it was slightly decreased after cooling from the temperature of total carbide particles solution in austenite and 2) the difference of creep rate was decreased after longer tempering.[43]

4 CONCLUSION

On the base of the review of findings in references, of the analysis of the effects of change of carbide particles size and distribution, it is concluded that the decrease of creep rate for the intercritical part of HAZ of creep resistant steels is due to a wide extent to the decrease of the effect of particles in stringers on the creep process. This conclusion is supported by so far unpublished experimental results on the effect of annealing temperature on accelerated creep rate for the steel X20.

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