Mr Gordana Bakić, prof. dr Vera Šijački-Žeravčić

ODREĐIVANJE VREMENSKE ČVRSTOĆE POMOĆU MIKROSTRUKTURNIH PARAMETARA NISKOLEGIRANIH ČELIKA IZLOŽENIH PUZANJU

Drugi deo: Određivanje vremena do loma

ESTIMATION OF LONG-TERM STRENGTH BY MICROSTRUCTURAL PARAMETERS OF LOW-ALLOYED STEEL EXPOSED TO CREEP

Second part: Determination of time-to-fracture

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Adresa autora / Author's address:
Mašinski fakultet Univerziteta u Beogradu, Srbija & Crna Gora

Ključne reči

- Niskolegirani čelik
- Puzanje
- Vremenska čvrstoća
- Mikrostruktura

IZVOD

Mikrostrukturni parametri, dobijeni na osnovu kinetičke teorije čvrstoće (model Žurkova) su korišćeni za određivanje vremena do loma materijala izloženog puzanju na visokoj temperaturi. Ulazni parametar, potreban za određivanje preostalog veka pomoću kompjutera, je čvrstoća puzanja za dati radni vek. Kako se čvrstoća puzanja smanjuje sa vremenom u eksploataciji zbog degradacije mikrostrukture, bitno je da se koriste mikrostrukturni parametri da bi se statistički definisale promene čvrstoće puzanja, što, za uzvrat, omogućava da se sledi fizički značaj tih promena. Zbog velikog rasipanja podataka, njihova obrada regresionom analizom fizički značajnih parametara predstavlja problem, koji još uvek nije rešen na zadovoljavajući način. U ovom radu je opisan jedan pristup generalnog rešenja razmatranog problema. Preostali vek, kao osnova za ocenu integriteta, određen je na komponenti, koja je uzeta iz termo elektrane posle određenog vremena eksploatacije pod poznatim radnim uslovima.

UVOD

Prema kinetičkoj teoriji čvrstoće, osnova za modeliranje procesa razaranja puzanjem je jed. (1), koja povezuje vreme do loma sa aktivacionom energijom. Da bi se korigovala dobijena vrednost za čvrstoću puzanja u slučaju niskog nivoa napona i povišenih temperatura, što predstavlja granični uslov za vreme do loma, neophodno je uvođenje funkcije $\tau_0 = \tau_d\varphi(T,\sigma) = 10^{-13}\varphi(T,\sigma)$, koja je obuhvaćena koeficijentom A /1/:

$$\tau_f = A\frac{T^n}{\sigma^m}exp\left(\frac{Uo-\gamma\sigma}{RT}\right) \qquad (1)$$

gde je: τ_f – vreme do loma, U_0 - koeficijent koji odražava tzv. energiju aktivacije procesa razaranja; γ - strukturni parametar sa dimenzijom zapremine atoma, čiji je fizički predstavlja lokalno prenaprezanje koje izaziva razaranje na tom mestu; R - univerzalna gasna konstanta; T - apsolutna temperatura; σ - delujući napon; $AT^n\sigma^{-m}$ je funkcija koja

Keywords

- Low-alloyed steel
- Creep
- Long-term strength
- Microstructure

ABSTRACT

Microstructural parameters, obtained based on kinetic theory of strength (model Zhurkov), are used to estimate the time-to-fracture of a material subjected to high-temperature creep. The input parameter, necessary for the residual life estimation by computer, is the creep resistance for a given service time. Since the creep resistance decreases with time in operation due to microstructure degradation, it is essential to use microstructural parameters in order to statistically define the changes in the creep resistance, which, in turn, enables to follow the physical significance of these changes. Due to a considerable dT scattering, their processing by regression analysis of the physically significant parameters is a problem, that has not been satisfactorily solved yet. The present work describes one approach to general solution of considered problem. The residual life, as the basis for the integrity assessment, has been determined for the component, taken from a power plant after determined service time under known operating conditions.

INTRODUCTION

According to the kinetic theory of strength, the base for modelling of creep failure process is the Eq. (1), relating the time-to-fracture with the activation energy. In order to correct the obtained value for the creep resistance in case of low stresses and elevated temperatures, which is boundary condition for the time-to-fracture, it has been necessary to introduce the function $\tau_0 = \tau_d\varphi(T,\sigma) = 10^{-13}\varphi(T,\sigma)$, included in the coefficient A /1/

$$\tau_f = A\frac{T^n}{\sigma^m}exp\left(\frac{Uo-\gamma\sigma}{RT}\right) \qquad (1)$$

where τ_f – time to fracture, U_0 – coefficient expressing the activation energy of fracture process; γ - structural parameter with dimension of atomic volume, which physically represents local overstressing initiating the fracture in this position; R - universal gas constant; T - absolute temperature; σ - applied stress; $AT^n\sigma^{-m}$ is a function which koriguje vrednosti τ_0 u oblastima niskog nivoa napona i povišenih temperatura /2/, pa τ_0 dobija oblik

$$\tau_0 = AT^{n}\sigma^{-m} \tag{2}$$

Međutim, ako se, u slučaju složenih legura, koeficijenti U_0 i γ ne koriguju na odgovarajući način, vrednosti dobijene statističkom obradom najčešće nisu u saglasnosti sa onim fizičkim konstantama osnovnog materijala koje odražavaju kinetičku koncepciju procesa razaranja zbog /3/:

- uticaja legirajućih elemenata, parametara mikrostrukture i tipa sekundarnih faza na aktivacione parametre razaranja, kao i uticaja različitih mehanizama puzanja;

- pojave oblasti malih promena, sa statističkog aspekta, u okolini tačke sa minimalnom disperzijom, tako da postoji mogućnost da veći broj rezultata i vrednosti traženih parametara bude validan sa matematičkog aspekta (višeznačnost); u tom slučaju, prema pravilima statistike, optimalno rešenje je ono koje ima minimalnu disperziju.

Metalurški uticaj se uzima u obzir uvođenjem dopunskih koeficijenata u jed. (1), kojima se koriguju vrednosti U_0 i γ, na sledeći način, u zavisnosti od toga da li ih ta korekcija umanjuje ili uvećava:

$$\tau_f = AT^{n}\sigma^{-m}\left(\frac{U_0 \pm \sum\limits_{i=1}^{n}\Delta U_i - (\gamma\sigma \pm \sum\limits_{i=1}^{n}\Delta\gamma_i\sigma)}{RT}\right) \tag{3}$$

gde su ΔU_i i $\Delta\gamma_i$ koeficijenti koji. odražavaju promenu aktivacionih parametara razaranja.

Treba podvuči da određivanje dopunskih koeficijenata statističkom regresionom metodom treba da bude izvedeno tako da definisane vrednosti dobiju potpuno jasan fizički smisao.

U ovom radu je predložen postupak provere stabilnosti modela za određivanje vremena do loma prema kinetičkoj teoriji čvrstoće za jedan toplotno postojani Cr-Mo-V čelik.

RAZVOJ MODELA

Kako podaci o korekcijama veličine aktivacione energije ΔU_i i prednaprezanja $\Delta\gamma_i$ nisu poznati, pogodno je direktno primeniti uticajne parametre preko koeficijenata vrednovanja uticaja svakog od njih. Pretpostavlja se da je zavisnost između korigovanih veličina i koeficijenata vrednovanja svakog uticajnog parametra linearna. Najuticajniji pokazatelji mikrostrukture, koji utiču na parametre razaranja toplotno postojanih Cr-Mo-V čelika sa aspekta kinetike razaranja, prema kinetičkoj teoriji čvrstoće su /2; 4 - 7/:

- sadržaj molibdena i hroma u čvrstom rastvoru u posmatranom trenutku (Cr+Mo, %);
- zapreminski udeo karbidne faze;
- veličina subzrna;
- rastojanje između čestica sekundarne faze.

Zbot toga je razvijeni oblik jed. (3):

corrects the values of τ_0 in the regions of low stress level and elevated temperatures /2/, so that τ_0 takes the form

$$\tau_0 = AT^{n}\sigma^{-m} \tag{2}$$

However, if in the case of complex alloys the coefficients U_0 and γ are not corrected accordingly, the values obtained by statistical processing are often inconsistent with those base material physical constants which reflect the kinetic nature of the fracture for the following reasons /3/:

- the effect of alloying elements, microstructural parameters and secondary phases type on fracture activation parameters, as well as the effect of different creep mechanisms;

- the appearance of region of small changes, from statistical aspect, in the vicinity of a point with a minimum dispersion, thus making it possible to have mathematically valid large number of the results and values for required parameters (multiplicity); in that case, according to the statistical laws, the optimal solution is the one with a minimum dispersion.

The effect of microstructure is considered by introducing the additional coefficients in the Eq. (1), to correct the values of U_0 and γ, depending on the condition whether this correction increases or decreases these values

$$\tau_f = AT^{n}\sigma^{-m}\left(\frac{U_0 \pm \sum\limits_{i=1}^{n}\Delta U_i - (\gamma\sigma \pm \sum\limits_{i=1}^{n}\Delta\gamma_i\sigma)}{RT}\right) \tag{3}$$

where ΔU_i and $\Delta\gamma_i$ are coefficients reflecting the change in the fracture activation parameters.

It should be emphasised that determination of the additional coefficients by statistical regression method should be performed in such a way that the defined values should obtain clear physical meaning.

In this paper the verification procedure to the stability of the time-to-fracture assessment model based on the kinetic theory of strength for thermally stable Cr-Mo-V steel is proposed.

MODEL DEVELOPMENT

Since the data of correction for the activation energy values ΔU_i and prestressing $\Delta\gamma_i$ are not known, it is convenient to apply the affecting parameters directly through determination of the weighted cofficients of each of them. It is assumed that the dependance between the corrected values and weighted coefficients for each affecting parameter is linear. The most important microstructural indicators affecting the fracture parameters of heat resistant Cr-Mo-V steels from the kinetic theory of strength, are /2; 4 - 7/:

- content of Mo and Cr in solid solution at the given moment (Cr+Mo, %);
- volume fraction of carbide phase;
- subgrain size;
- spacing between the secondary phase particles.

Thus, the developed form of Eq. (3) is:

$$\log\tau_f = a + n\log T - m\log\sigma + \frac{b}{T} \pm \left[\lambda_1\frac{b_1}{T} + \lambda_2\frac{b_2}{T}) - (c\frac{\sigma}{T} \pm (\mu_1 c_1\frac{\sigma}{T} + \mu_2 c_2\frac{\sigma}{T})\right] \tag{4}$$

Uvođenjem korekcionih faktora b_1 prelazi u oblik $\lambda_1 b_1$, b_2 oblik $\lambda_1 b_1$, c_1 oblik $\mu_1 c_1$ i c_2 oblik $\mu_2 c_2$. Unošenjem:

$$log\tau_f - n\,log\,T + m\,log\,\sigma - \frac{b}{T} + c\frac{\sigma}{T} = Y$$

jednačina, kod koje može da se primeni metoda najmanjih kvadrata za određivanje nepoznatih koeficijenata regresije, dobija konačni oblik /2/:

$$Y = a + \lambda_1 x_1 + \lambda_2 x_2 + \mu_1 x_1 + \mu_2 x_2 \qquad (6)$$

U prvoj iteraciji je neophodno odrediti sve koeficijente u jedn. (6) koji zavise od postojeće mikrostrukture čelika, čije se vreme do loma određuje.

Određivanjem sadržaja Mo and Cr u čvrstom rastvoru na osnovu rendgenostrukturne analize, zapreminskog udela karbidne faze, rastojanja čestica sekundarne faze i veličine subzrna sa mikrofotografija pripremljenih uzoraka čelika 1Cr1Mo0,25V iz eksploatacije na svetlosnom mikroskopu pri povećanjima 1000X i 2000X, određene su vrednosti strukturnih parametara, tab. 1, a iz njih i vrednosti promenljivih za jedn. (6), date u tab. 2. Sa podacima iz tab. 1. i 2. su određeni koeficijenti regresije u jedn. (6), tab. 3.

Ograničenje modela, predstavljenog jedn. (4), odnosno (6), je u tome da on omogućava zadovoljavajuće rešenje samo pod uslovom da bar dva koeficijenta regresije mogu da se fiksiraju, odnosno da se izbace kao promenljive iz regresione analize /2/. Ovde izvedeni proračuni su pokazali da se najprihvatljiviji rezultati dobijaju ako se fiksiraju koeficijenti koji pokazuju uticaj zapreminskog udela karbidne faze i veličina subzrna kao najmanje osetljivi parametri na vreme eksploatacije.

Involving correction factor, b_1 becomes $\lambda_1 b_1$, b_2 becomes $\lambda_1 b_1$, c_1 becomes $\mu_1 c_1$ and c_2 becomes $\mu_2 c_2$. By inserting:

$$x_1 = \lambda\frac{b_1}{T};\, x_2 = \frac{b_2}{T};\, x_3 = \frac{c_1}{T}\sigma;\, x_4 = \frac{c_2}{T}\sigma \qquad (5)$$

the equation, in which it is possible to apply the least square method for determination of unknown regression coefficients obtains the final form / 2/:

$$Y = a + \lambda_1 x_1 + \lambda_2 x_2 + \mu_1 x_1 + \mu_2 x_2 \qquad (6)$$

In the first iteration it is necessary to determine all coefficients in Eq. (6), dependent on the actual microstructure of steel, for which the time-to-fracture is being determined.

By determination of Mo and Cr content in solid solution by X-ray analysis, volume fraction of carbide phase, spacing between the secondary phase particles and the subgrain size from micrographs of the samples, prepared of 1Cr1Mo0,25V steel from service, using light microscope at magnifications 1000X and 2000X, the values of structural parameters are determined, Table 1, and from them the values of variables in Eq. (6), given in Table 2. With the data from Tables 1 and 2 regression coefficients in Eq. (6) are found, Table 3.

The limitation of the model, presented by Eq. (4), and (6), respectively, is that it provides adequate solution only under condition of fixing at least two regression parameters, that is, by eliminating them as variables from the regression analysis /2/. Here performed calculations have shown that the most acceptable results have been obtained by fixing the coefficients representing the influence of the carbide phase volume fraction and subgrain size, which are the least time-sensitive parameters during service.

Tabela 1: Vrednosti strukturnih parametara za regresionu analizu

Table 1. Values of microstructural parameters for the regression analysis

Red. br.	Cr+Mo u osnovi	Zapreminski udeo karbida	Veličina subzrna		Srednje rastojanje između karbida	
Nr.	Cr+Mo in base	Volume fraction of carbide	Subgrain size		Mean spacing between carbides	
		$f_v = (1.17 r_{sr}/\lambda)^2$	$\overline{d}_{sub}$		λ_{SR}	
	%	%	μm	mm	μm	mm
1.	0.80	47.99	0.60	0.000600	0.52	5.20E-04
2.	0.80	25.63	0.60	0.000600	0.52	5.20E-04
3.	0.68	18.03	0.63	0.000630	0.62	6.20E-04
4.	0.80	14.99	0.70	0.000700	0.68	6.80E-04
5.	0.80	25.63	0.60	0.000600	0.52	5.20E-04
6.	0.68	18.03	0.63	0.000630	0.62	6.20E-04
7.	0.80	14.99	0.70	0.000700	0.68	6.80E-04
8.	0.65	18.62	0.90	0.000900	0.61	6.10E-04
9.	0.77	14.99	0.70	0.000700	0.68	6.80E-04
10.	0.69	13.37	1.10	0.001100	0.72	7.20E-04
11.	0.80	25.63	0.60	0.000600	0.52	5.20E-04
12.	0.80	14.99	0.70	0.000700	0.68	6.80E-04
13.	0.65	18.62	0.90	0.000900	0.61	6.10E-04
14.	0.69	13.37	1.05	0.001050	0.72	7.20E-04
15.	0.58	8.75	1.35	0.001350	0.89	8.90E-04
16.	0.54	8.56	2.10	0.002100	0.90	9.00E-04

Ako su eksperimentalni uslovi nekog ispitivanog čelika takvi da nije moguće pronaći dva parametra sa malom osetljivošću na promenu, odnosno ako ih nije moguće fiksirati, model daje nepouzdana predviđanja /2/.

If the experimental conditions of any tested steel do not allow to find two parameters of low sensitivity to the changes, that is, to fix them, model will produce unreliable predictions /2/.

Tabela 2: Vrednosti promenljivih u linearnoj regresionoj analizi, jed. (6)

Table 2. Values of variables in linear regression analysis, Eq . (6)

Red. br. No.	$Y_i = \log\tau_f - 2\log T + 3\log\sigma - 26058/T + 8.0\sigma/T$	$x_1 = (Cr+Mo)/T$	$x_2 = f_v/T$	$x_3 = \overline{d}_{sub}\,\sigma/T$	$x_4 = \lambda_{sr}\,\sigma/T$
1.	-16.93	0.000943	0.06	7.08E-07	0.10
2.	-17.23	0.000943	0.03	7.08E-07	0.09
3.	-17.04	0.000802	0.02	7.43E-07	0.11
4.	-17.07	0.000943	0.02	8.25E-07	0.11
5.	-17.62	0.000943	0.03	7.08E-07	0.08
6.	-17.44	0.000802	0.02	7.43E-07	0.09
7.	-17.26	0.000943	0.02	8.25E-07	0.10
8.	-17.08	0.000767	0.02	1.06E-06	0.09
9.	-17.46	0.000908	0.02	8.25E-07	0.09
10.	-17.14	0.000814	0.02	1.30E-06	0.10
11.	-18.05	0.000943	0.03	7.08E-07	0.06
12.	-17.69	0.000943	0.02	8.25E-07	0.08
13.	-17.51	0.000767	0.02	1.06E-06	0.07
14.	-17.35	0.000814	0.02	1.24E-06	0.08
15.	-17.31	0.000684	0.01	1.59E-06	0.10
16.	-17.13	0.000637	0.01	2.48E-06	0.11

Tabela 3. Vrednosti koeficijenata regresije dobijeni rešavanjem jed. (5)

Table 3. Values of regression coefficients obtained by solving Eq. (5)

Koeficijent	Coefficient	a	λ_1	λ_2	μ_1	μ_2
Vrednost	Value	-25,61	$-1{,}349 * 10^3$	12,786	$-2{,}239 * 10^3$	20,57

KVALITATIVNA PROVERA MODELA

Poređenje matematičkog modela (6) i fizičkih zakonomernosti procesa razaranja /1; 2; 8/ predstavlja kvalitativnu proveru članova (λ_1, λ_2, μ_1 i μ_2) u obliku parametarske jednačine, koji su određeni regresionom analizom.

Dobijene vrednosti koficijenata (λ_1, λ_2, μ_1 i μ_2) svojim znakom odgovaraju pretpostavljenoj fizičkoj interpretaciji (sa aspekta umanjenja ili uvećanja aktivacione energije razaranja i koeficijenta prednaprezanja), s jedne strane, a potvrđuju ispravnost pristupa, sa druge strane. Koeficijent a, koji u analizi predstavlja termofluktuacioni period atoma železa (usvojeno je da i atomi ostalih elemenata imaju istu vrednost), ostaje kao jedina nedorečenost On je eksperimentalno određen i iznosi 10^{-13}s, odnosno $2{,}77\text{x}10^{-16}$ h, pa je realna vrednost a oko –15,56 /1/. U modelu a ima vrednost –25,61, što jeste blisko po redu veličine sa literaturno određenom, s tim što postojeća razlika može da ukaže ne samo na neminovne greške u modelu, već i na moguću promenu termofluktuacionog perioda kada je reč o složenom metalurškom sistemu. Greške metode, računske greške kao i greške koje nije moguće odstraniti /8/ postoje u modelu i utiču na njegovu tačnost.

QUALITATIVE VERIFICATION OF THE MODEL

Comparison of mathematical model Eq. (6) and physical laws of fracture mechanisms /1; 2; 8/ represents qualitative verification of the terms (λ_1, λ_2, μ_1 and μ_2) in a form of parametric equation determined by regression analysis.

The sign of obtained values (λ_1, λ_2, μ_1 and μ_2) corresponds to assumed physical interpretation (from the point of view of decreasing or increasing fracture activation energy and prestress coefficient) on one hand, and confirm the validity of the approach on the other hand. The coefficient a, which represents thermal-fluctuating period of iron atom (it is also accepted that the atoms of other elements have the same value), is the only one that remained unexplained. It is experimentally determined as 10^{-13} s, that is $2.77\text{x}10^{-16}$ h, so the real value of a is approximately -15.56 /1/. In the model a has a value of -25.61 which is indeed close to the value from references in order of magnitude; the difference can indicate not only the unavoidable model errors, but also the possible changes of the thermal-fluctuating period when complex metallurgical system is considered. Method errors, calculation errors and the errors that cannot be excluded as well /8/ exist in the model and can affect its accuracy.

Osnovni problem je način na koji bi mogla da se poveća tačnost modela proverom ili promenom polaznih pretpostavki. Variranjem fiksiranih vrednosti za eksponente n i m /1; 2; 4/, koji predstavljaju korekciju perioda oscilovanja atoma za granične uslove pod dejstvom temperature i napona /2/ (u kinetičkoj teoriji čvrstoće nisu u potpunosti jasno definisani, odnosno nije jasno definisana njihova fizička suština), dobijen je niz rezultata koji, u većoj ili manjoj meri, odstupaju od rezultata dobijenih osnovnom postavkom modela. Vrlo je interesantno da se za vrednost $m = 6$ dobija vrednost koeficijenta $a = -19{,}884$, a vremena do loma u mnogo manjoj meri odstupaju od eksperimentalno dobijenih. Rezultati analize za $m = 6$ i sve preostale iste vrednosti dati su u tab. 4.

The basic problem is how to develop a mean to improve the model accuracy by verifying or changing the initial assumptions. By varying the initial values for n and m /1; 2; 4/, which represent correction of the atom oscillation period for boundary conditions under influence of temperature and stress conditions /2/ (in the kinetic theory of strength these are not completely clearly defined i.e., their physical significance is not clear), a number of results is obtained which, more or less, deviate from the results obtained from the basic model. It is very interesting that for value $m = 6$ the value of coefficient $a = -19.884$, while the time-to-fracture deviates to considerably extend less from the one experimentally obtained. The result of analysis for $m = 6$ and all other values are shown in Table 4.

Tabela 4. Vreme do loma za m=6 (a =-19,884)

Table 4. Time-to-fracture for m=6 (a =-19.884)

Uzorak	Vremenska čvrstoća, σ_v (eksperimentalna)	Temperatura	Vreme do loma, τ_{fi} (eksperimentalno)	Vreme do loma, τ_{fi} (proračunato)
Sample	Creep rupture stress, σ_v (experimental)	Temperature	Time-to-fracture, τ_{fi} (experimental)	Time-to-fracture, τ_{fi} (calculated)
	MPa	K	h	h
1.	170	848	9525	12108
2.	150	848	9525	3890
3.	150	848	14570	17136
4.	137	848	21850	19133
5.	125	848	9525	9702
6.	125	848	14570	20694
7.	125	848	21850	20886
8.	125	848	33180	16138
9.	113	848	21850	28058
10.	113	848	46158	47649
11.	100	848	9525	14968
12.	100	848	21850	32297
13.	100	848	33180	24956
14.	100	848	48158	33433
15.	100	848	53000	94226
16.	100	848	80040	77476

Ova pretpostavka ($m = 6$) ima i svoje moguće fizičko objašnjenje: eksperimentalno je dokazano da se vrednosti eksponenata puzanja, za stepeni zakon puzanja, za niskougljenične niskolegirane Cr-Mo-V čelike, nalaze u opsegu 3 – 8 /9; 10/, u zavisnosti od veličine delujućeg napona i mehanizma puzanja.

Nepouzdanost modela je moguće smanjiti primenom dopunskih statističkih kriterijuma, kakav je npr. interval poverenja, odnosno njegova usvojena širina rasipanja, za predviđanje vremena do loma po jednačinama regresije u zadatim tačkama. Činjenica da širina intervala poverenja zavisi kako od srednjeg kvadratnog odstupanja jednačine regresije od eksperimentalno određenih tačaka, tako i od korelisanosti ulaznih prametara (x_i), ovaj pristup čini pogodnim za dopunski kriterijum verifikovanja stabilnosti modela.

This assumption ($m = 6$) has a possible physical explanation: it has been shown experimentally that the values of creep coefficient for the step-like creep law for low-carbon low-alloyed Cr-Mo-V steels are found to be in the range of 3 – 8, /9; 10/, depending on the acting stress and creep mechanism.

The unreliability of the model can be reduced by applying additional statistical criteria, such as, for instance, confindence interval, i.e. its accepted scatter band, for predicting the time-to-fracture according to the regression equations in given points. The fact that the confidence interval width depends on both mean square deviation of the regression equation from the experimentally determined points and the correlated initial parameters (x_i) makes this approach suitable for an additional criterium for verification of the model stability.

PROVERA OSETLJIVOSTI MODELA NA ULAZNE VELIČINE

Jedan od osnovnih pokazatelja važenja modela je njegova osetljivost na ulazne veličine. Stabilan model ne treba da daje veća odstupanja na male promene ulaznih veličina (reda veličine greške merenja temperature ili napona). U tab. 5 – 7 date su izračunate vrednosti vremena do loma za dobijenu grešku merenja temperature ili napona ili obe veličine, a dobijeno odstupanje je greška reda veličine greške modela.

S druge strane, potrebno je istaći da koeficijenti regresije zadržavaju znak i malo odstupaju, najviše do 5%, u odnosu na polazni model bez uvršćene greške merenja, što govori o stabilnosti modela.

ZAKLJUČAK

Na osnovu kinetičke teorije čvrstoće razvijen je regresioni model za određivanje vremena do loma niskougljeničnih niskolegiranih Cr-Mo-V čelika u uslovima puzanja. Na osnovu dostupnih podataka iz literature, izabrani su osnovni parametri i uneti u model da bi se opisala kinetika promena strukture materijala izloženog uslovima puzanja. Svaki od ovih parametara, kojima se koriguju aktivaciona energija razaranja i koeficijent prednaprezanja osnovne faze složene legure, ima svoju fizičku interpretaciju, što omogućava njihovo eksperimentalno određivanje. Ovim modelom je još jednom potvrđena kinetička priroda čvrstoće čvrstih tela, s obzirom da dobijene vrednosti koeficijenata regresije, kao i njihov predznak, odgovaraju fizičkom smislu pojave koju opisuju.

VERIFICATION OF THE MODEL SENSITIVITY TO INPUT VALUES

One of the basic indicators of model validity is its sensitivity to the input values. Stable model should not produce large deviations for input values small changes (order of magnitude of an error in measurement of temperature or stress). In Tables 5-7 the calculated values for the time-to-fracture for the error obtained by measurement of temperature or stress or both values are given, and the obtained deviation is of the same order of magnitude as the error in the model.

On the other hand, it should be pointed out that the sign of regression coefficients remains unchanged and deviates little up to 5%, in comparison with the initial model not not included the measurement error, thus confirming the model stability.

CONCLUSION

The regression model for determination of the time-to-fracture of low-carbon low-alloy Cr-Mo-V steels under creep conditions, based on the kinetic theory of strength has been developed. From the available literature data, a selection of the essential parameters has been made and introduced in the model to describe the kinetics of structural changes in the material subjected to creep conditions. Each of these parameters, used for correction of the fracture activation energy and prestress coefficient of basic phase of a complex alloy, has its physical interpretation, enabling their experimental determination. This model confirms the kinetic nature of the strength of solids once again, since the values obtained for the regression coefficients as well as their sign correspond to the phenomenon physical meaning.

Tabela 5. Vreme do loma za ulazne podatke sa greškom merenja u temperaturi

Table 5. Time-to-fracture for input data with error in temperature measurements

Uzorak	Vremenska čvrstoća, σ_v (eksperimentalna)	Temperatura*	Vreme do loma, τ_{fi} (eksperimentalno)	Vreme do loma, τ_{fi} (proračunato)	Vreme do loma, τ_{fi} za grešku merenja u T
Sample	Creep rupture stress, σ_v (experimental)	Temperature*	Time-to-fracture, τ_{fi} (experimental)	Time-to-fracture, τ_{fi} (calculated)	Time-to-fracture, τ_{fi} for measurement error in T
	MPa	K	h	h	h
1.	170	846	9525	12108	9710
2.	150	845	9525	3889	7001
3.	150	847	14570	17136	20738
4.	137	851	21850	19133	15857
5.	125	845	9525	9702	12543
6.	125	849	14570	20695	19222
7.	125	845.3	21850	20886	24785
8.	125	850.1	33180	16138	15876
9.	113	851	21850	28058	19266
10.	113	845	46158	47649	48924
11.	100	848	9525	14968	12223
12.	100	849	21850	32297	22862
13.	100	846	33180	24955	26274
14.	100	847	48158	33432	50502
15.	100	849.2	53000	94226	67656
16.	100	846.9	80040	77476	82742

Tabela 6. Vreme do loma za ulazne podatke sa greškom u određivanju σ_v*

Table 6. Time-to-fracture for input data with error in measurening σ_v *

Uzorak	Vremenska čvrstoća, σ_v* (eksperimentalna)	Temperatura	Vreme do loma, τ_{fi} (eksperimentalno)	Vreme do loma, τ_{fi} (proračunato)	Vreme do loma, τ_{fi} za grešku merenja u σ_v
Sample	Creep rupture stress, σ_v* (experimental)	Temperature	Time-to-fracture, τ_{fi} (experimental)	Time-to-fracture, τ_{fi} (calculated)	Time-to-fracture, τ_{fi} for measurement error in σ_v
	MPa	K	h	h	h
1.	171	848	9525	12109	10699
2.	150	848	9525	3890	6099
3.	151	848	14570	17137	16523
4.	136	848	21850	19133	19630
5.	127	848	9525	9702	10093
6.	125	848	14570	20695	19842
7.	124	848	21850	20886	20917
8.	125	848	33180	16138	19980
9.	113	848	21850	28058	24394
10.	113	848	46158	47649	45112
11.	99	848	9525	14968.	15160
12.	101	848	21850	32297	24704
13.	102	848	33180	24956	23469
14.	100	848	48158	33433	34054
15.	100	848	53000	94225	85737
16.	98	848	80040	77476	82672

Tabela 7. Vreme do loma sa greškom u određivanju T i σ_v

Table 7. Time-to-fracture with error in measurement of T and σ_v

Uzorak	Vremenska čvrstoća, σ_v * (eksperimentalna)	Temperatura*	Vreme do loma, τ_{fi} (eksperimentalno)	Vreme do loma, τ_{fi} (proračunato)	Vreme do loma, τ_{fi} za grešku merenja u T i σ_v
Sample	Creep rupture stress, σ_v * (experimental)	Temperature*	Time-to-fracture, τ_{fi} (experimental)	Time-to-fracture τ_{fi}, (calculated)	Time-to-fracture, τ_{fi} for measurement error in T and σ_v
	MPa	K	h	h	h
1.	171	846	9525	12108	10212.91
2.	150	845	9525	3889	6580.74
3.	151	847	14570	17137	18436.52
4.	136	851	21850	19133	16076.56
5.	127	845	9525	9701	10834.41
6.	125	849	14570	20694	18828.19
7.	124	845.3	21850	20886	25949.81
8.	125	850.1	33180	16138	16245.84
9.	113	851	21850	28058	19624.14
10.	113	845	46158	47649	51348.22
11.	99	848	9525	14968	12873.52
12.	101	849	21850	32297	22946.84
13.	102	846	33180	24956	25693.29
14.	100	847	48158	33433	53989
15.	100	849.2	53000	94226	79306
16.	98	846.9	80040	77476	74635

Model je dokazao stabilnost jer odstupanja u ulaznim veličinama (temperatura, napon) nisu uzrokovala velika odstupanja u vrednosti vremena do loma. Odstupanja u vrednostima vremena do loma dobijenim postavljenim modelom od realnih vrednosti potiču od:

- Grešaka u određivanju strukturnih parametara; vrlo je teško precizno odrediti svaki od strukturnih parametara u materijalu, pre svega zbog različitih vrsta nehomogenosti u materijalu; greška merenja može se svesti na minimum usrednjavanjem velikog broja merenja.
- Mogućih grešaka u usvajanju korekcija za granične uslove; provera sprovedena za vrednost eksponenta napona $m = 6$, kojim se koriguje vreme do loma za područje niskih nivoa napona i povišenih temperatura, ukazuje na mogućnost povezivanja stepenog zakona puzanja i vremena do loma dobijenog ovim modelom, s obzirom da daje veću tačnost za koeficijent termofluktuacionog perioda atoma.
- Mogućih grešaka nastalih usled toga što nije utvrđena korelacija pojedinih strukturnih parametara, pa je time njihov uticaj ili uveličan ili umanjen.
- Mogućih grešaka usled toga što su strukturni parametri određivani na površini metala.

Dalji razvoj ovog modela treba usmeriti na uopštavanje date jednačine za što veći broj toplotno postojanih čelika i na detaljna istraživanja koja treba sprovesti radi otklanjanja što većeg broja grešaka.

Nepouzdanost modela može da se umanji primenom dopunskih statističkih kriterijuma, kakav je npr. interval poverenja, odnosno njegova širina, za predviđanje vremena do loma po jednačinama regresije u zadatim tačkama. Širina intervala poverenja zavisi kako od srednjeg kvadratnog odstupanja jednačine regresije od eksperimentalno određenih tačaka, tako i od korelisanosti ulaznih prametara (x_i), što ovaj pristup čini pogodnim za dopunski kriterijum dobijanja pouzdanosti modela.

The model has exhibited its stability, since the deviations in the input values (temperature, stress) have not caused appreciable deviation in the time-to-fracture. Deviations in the time-to-fracture values obtained from proposed model from the real values are due to:

- Errors in determination of structural parameters; it is very difficult to determine precisely each of the structural parameters of material, primarily due to different types of inhomogeneities in the material; measurement errors can be minimized by averaging large number of measurements.
- Possible errors caused by adoption of corrections for the boundary conditions; verification of the exponent value $m = 6$, used to adjust the time-to-fracture in the range of low stress levels and elevated temperatures, indicates that this model allows to correlate the power law dependence of creep and time-to-fracture, since it provides a more accurate estimate of the atom thermo-fluctuation period coefficient.
- Possible errors due to non-established correlation between individual structural parameters, which, in turn, increases or decreases their effect.
- Possible errors caused by determination of the structural parameters at the metal surface.

Further development of this model should be directed to generalisation the above described equation for a large number of heat-resistant steels and detailed investigations, to be performed to eliminate as many errors as possible.

Unreliability of the model can be reduced by introducing additional statistical criteria, such as, e.g. confidence interval, i.e., its scatter band, for predicting the time-to-fracture at given points by using regression equations. Since the confidence interval depends on the regression equation mean square deviations from the experimentally determined points, as well as on the correlated input parameters (x_i), this approach becomes very convenient for further improvement of the model reliability.

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