Dr. Horia Ştefan MATEIU, Dr. Nicolae FARBAŞ, Dr. Traian FLEŞER, Dr. Romulus PASCU

ISPITIVANJA ZA OCENU OŠTEĆENJA TERMOOTPORNIH ČELIKA ZA IZRADU KOMPONENTI U TERMOELEKTRANAMA

RESEARCHES CONCERNING DAMAGE ASSESSMENT OF HEAT RESISTANT STEELS USED FOR POWER PLANT COMPONENTS

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.17:669.14
Rad primljen / Paper received: 15.09.2003.

Adresa autora / Author's address:
National R&D Institute for Welding and Material Testing (ISIM)
Timişoara – ROMANIA

Ključne reči
- Komponente termoelektrana
- Puzanje
- Zamor
- Termootporni čelik
- Degradacija
- Ocena oštećenja

Keywords
- Power plant components
- Creep
- Fatigue
- Heat resistant steel
- Degradation
- Damage assessment

IZVOD

U radu je predložen način ocene kritičnog stanja degradacije termootpornih čelika za komponentie složenih sistema termoenergetskih postrojenja (parovodi, kotlovi ili parne turbine).

Eksperimentalna istraživanja termootpornih čelika izvedena su ispitivanjima razaranjem i bez razaranja. Ispitivanje razaranjem je izvedeno na bazi toplotnog zamora, sa periodom zadržavanja i bez njega. U drugom slučaju pažnja je posvećena naponu koji je otpušten puzanjem pri maksimalnoj temperaturi u poluciklusu perioda zadržavanja. Predstavljeno je kumulativno oštećenje materijala parovoda izloženog zamoru i puzanju. Ispitivanja bez razaranja posvećena su istraživanju zavisnosti metalografskog parametra A i stanja degradacije materijala, pri čemu je stanje degradacije razmatrano statistički.

ABSTRACT

The paper proposes the method for the assessment of critical degradation state of heat resistant steels for the components of power plant complex systems (steam pipelines, boilers or steam turbines).

The experimental investigations of heat resistant steels were performed by destructive and non-destructive testing. The destructive testing was based on thermal fatigue, with holding time and without it. In the second case the attention was paid to the stress relieved by creep at maximum temperature in the holding time semicycle. The cumulative fatigue -creep damage of a steam pipeline material was presented. The non-destructive testing was devoted to the research of the correlation between metallographic parameter A and the statistically considered material degradation state.

UVOD

Stalni rast tehnoloških parametara (nivo mehaničkog i toplotnog opterećenja, dugotrajni radni režim) različite opreme koja radi pod visokim mehaničkim i toplotnim opterećenjem uslovljen je kako tehničkim (povećanje jediničnog kapaciteta, maksimalna efikasnost, rukovanje, održavanje) tako i ekonomskim zahtevima (smanjenje utroška materijala i ukupna cene opreme).

Osnovna odlika korišćenja komponenti koje su deo termoenergetskih postrojenja (kotlovski bubnjevi, sabirnici, zaporni ventili, cevi generatora pare, kućišta turbina, vratila, vijci, cevi i prirubnica) /1/, /2/ je nestacionarno toplotno i mehaničko opterećenje. To izaziva ciklični karakter elasto-plastične deformacije materijala i procesa degradacije, koji obično nastaju kao posledica dejstva neizotermičkih radnih uslova.

U slučaju parnih kotlova visokog pritiska u postrojenju parne turbine, zbog njegove specifične eksploatacije iskazane dužinom trajanja stabilnog režima, oštećenje puzanjem je veće od oštećenja cikličnim opterećenjem, izazvanog niskocikličnim zamorom.

INTRODUCTION

The continuous increase of the technological parameters (the level of the mechanical and thermal loading, long-term regime) of different equipment operating under high mechanical and thermal loading is imposed by the technical (unit capacity increase, maximum efficiency, handling, maintenance) and by the economic requirements (reduction of material consumption and the total cost of equipment).

Basic feature of the application of the components, which are part of the thermal power plants (boiler drums, collectors, shutt-off valves, steam generator pipes, turbine casings, shafts, bolts, pipes and flanges) /1/, /2/ is the non-stationary thermal and mechanical loading. This gives a cyclic character to the elastic-plastic strain of materials and degradation process, which is usually caused by the effects of non-isothermal service conditions.

In case of a high-pressure steam boiler in the steam turbine plant, due to its specific exploitation, exhibited by the duration of stable regime, creep damage is higher than the damage caused by cyclic loading, induced by low-cycle fatigue.

Do unutrašnjeg sprečavanja toplotnih deformacija dolazi zbog dejstva temperaturnog gradijenta u komponentama velikog poprečnog preseka (vratila, kućišta i lopatice parnih turbina); ove deformacije proizvode elastoplastični niskociklični zamor (na nivou napona tečenja materijala i iznad njega). U drugim slučajevima deformacije komponenata opterećenih u prelaznom režimu (ciklična promena temperature) su potpuno ili delimično blokirane spolja, što takođe izaziva oštećenje niskocikličnim toplotnim zamorom.

Međutim, najoštriji uslovi opterećnja javljaju se u zonama koncentracije napona /3/, i prema /4/ toplotni naponi rastu od $0,25\Delta T$ pri jednoosnom naponskom stanju do $0,63\Delta T$ pri troosnom naponskom stanju, karakterističnom za zone koncentracije napona (ΔT je razlika temperatura u toplotnom ciklusu).

U novije vreme pritisak u parnim kotlovima sa natkritičnim pritiskom povećavan je i do 335 bar, a temperatura do 620°C, zavisno od vrste čelika (temperatura pare na izlazu 580ºC i pritisak na izlazu iz pregrejača od 275 bar) /5/, /6/.

Faktori koji određuju nivo degradacije prethodno navedenih komponenti, izloženih opterećenju visokim pritiskom i temperaturom, su:

1. nestacionarni toplotni i mehanički režim u toku eksploatacije;
2. visoka temperatura;
3. visok temperaturni gradijent;
4. niska frekvencija cikličnog opterećenja i mali broj ciklusa (niskociklični karakter);
5. dugotrajna eksploatacija u stabilnom režimu.

EKSPERIMENTI SA TOPLOTNIM ZAMOROM

Toplotno-mehanički model ponašanja materijala izloženog toplotnom zamoru

Prva ispitivanja toplotnog zamora izveo je 1954. Kofin /7/. On je koristio uređaj koji omogućava potpuno sprečavanje toplotnih deformacija. Za ispitivanje sa različitim amplitudama deformacije bilo je potrebno da se u uređaj za ispitivanje ugradi elastični element (elastična membrana ili luk) /3/, /8/. To je omogućilo delimično sprečavanje toplotne deformacije i zato Manson-Kofinov izraz povezuje početnu deformaciju $\Delta\varepsilon_{in}$ i broj ciklusa do loma N_f.

Ispitivanje niskocikličnog zamora definisano je postupkom ASTM E 606 /9/. Ispitivanje toplotnog zamora posebno je definisano u standardu GOST 25.505-85 /10/. Propisan je poseban postupak za ispitivanje toplotnog zamora pri čemu se navode vrsta epruvete, zahtevani nivo krutosti pri ispitivanju i uslovi ispitivanja.

Slika 1 predstavlja toplotno-ciklični model opterećenja /3/. Ispitivana komponenta 1 (koja predstavlja epruvetu ili deo opreme) mehanički je povezana u seriji sa elastičnim elementom 3. Pretpostavlja se da je ispitivana komponenta 1 izložena ponovljenim ciklusima zagrevanja i hlađenja. Blok 2 (obično ga čine svi nepokretni elementi komponente 1, osim elastičnog elementa 3 i pokretnih delova komponente 1) ima krutost $C_2 = \infty$.

The internal blocking of thermal strains occurs due to the effect of the temperature gradient in the components of large cross sections (shafts, steam turbine casings and blades); these strains induce elastic-plastic low-cycle fatigue loading (at the level of material yield stress and beyond it). In other cases, the strains of the components loaded in transient regime (cyclic variation of the temperature) are totally or partially externally blocked, which also causes a low-cycle thermal fatigue damage.

However, the most severe loading conditions occur in the stress concentration zones /3/, and according to /4/ the thermal stresses increase from $0.25\Delta T$ in the uniaxial stress state to $0.63\Delta T$ in the triaxial stress state, typical for the stress concentration zones (ΔT is a temperature difference in thermal cycle).

Recently, the pressure in the steam boiler with supercritical pressure has been increased up to 335 bar and temperature up to 620°C, depending on the steel quality (the overheater outlet steam temperature of 580°C and the outlet pressure of 275 bar) /5/, /6/.

The factors which determine the degradation level of the above mentioned components, subjected to high pressure and temperature loading, are:

1. non-stationary thermal and mechanical regimes in operation;
2. high temperature;
3. high temperature gradient;
4. low frequency of cyclic loading and small number of cycles (low-cycle character);
5. long-term exploatation in stable regime.

THERMAL FATIGUE EXPERIMENTS

Thermo-mechanical behaviour model of material subjected to thermal fatigue

The first thermal fatigue testing was performed in 1954 by Coffin /7/. He used a device enabling total blocking of thermal strain. For testing with different magnitudes of the strain amplitude it was necessary to introduce an elastic element (elastic membrane or arc) in the test device /3/, /8/. It allowed to obtain a partial blocking of the thermal strain and therefore the Manson-Coffin expression correlates initial strain $\Delta\varepsilon_{in}$ and number of cycles to fracture N_f.

The low-cycle fatigue testing is defined by the ASTM E 606 procedure /9/. The thermal fatigue tests are defined specifically in the standard procedure GOST 25.505-85 /10/. Special procedure is prescribed for the thermal fatigue testing, indicating the specimen type, the required stiffness level for testing and testing conditions.

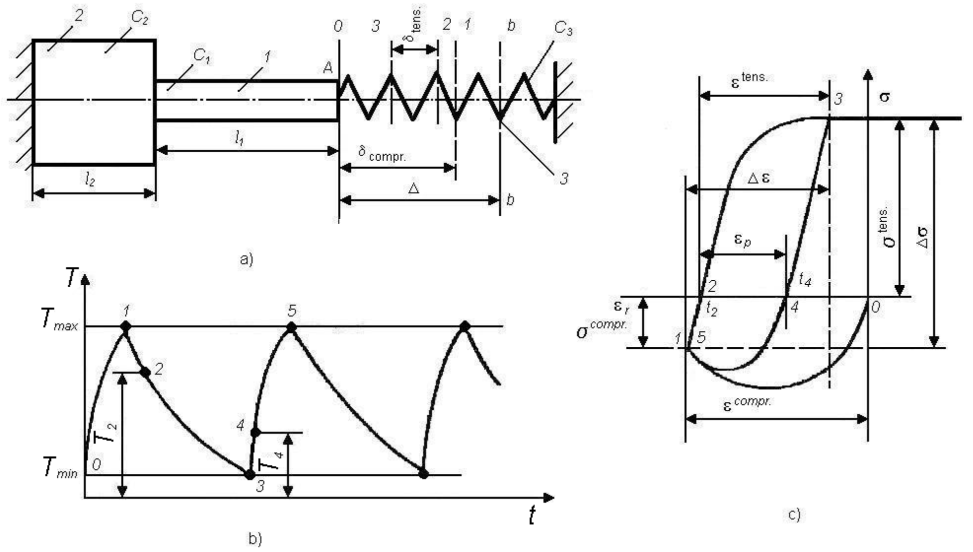
Figure 1 presents the thermal cyclic loading model /3/. The investigated component 1 (representing a specimen or part of the equipment) is mechanically connected in series with an elastic element 3. It is supposed that the investigated component 1 is subjected to heating-cooling repeated cycles. The block 2 (usually formed of all fixed elements of the component 1, except the elastic element 3 and non-fixed parts of component 1) is of stiffness $C_2 = \infty$.

Krutost elastičnog elementa 3 je $C_3 < C_1$.

Ovakav odnos krutosti obezbeđuje razvoj delimične toplotne deformacije u analiziranoj komponenti 1.

The stiffness of the element 3 is $C_3 < C_1$.

These stiffness relation enables the development of a partial thermal strain in the analysed component 1.



Slika 1. Model toplotno-mehaničkog ponašanja analizirane komponente pri toplotnom zamoru /3/ a) elastični element; b) toplotni ciklus; c) histerezisna petlja elasto-plastične deformacije; *(compr. – pritisak; tens. - zatezanje)*

Figure 1. The model of the thermal-mechanical behaviour of the analysed component subjected to thermal fatigue /3/ a) elastic element; b) thermal cycle; c) hysteresis loop of the elastic-plastic strain

Koeficijent blokiranja (ili krutost opterećenja) R je uveden radi kvantitativnog određivanja uticaja ovih faktora toplotne deformacije:

$$R = \Delta\varepsilon_M/\Delta\varepsilon_T \qquad (1)$$

gde je $\Delta\varepsilon_M$ mehanička elastoplastčna deformacija, a $\Delta\varepsilon_T$ je toplotna deformacija.

Uvođenje promenljive krutosti sistema u postupak ispitivanja toplotnog zamora omogućava odvajanje toplotnih od energetskih faktora. Osnovni termo-ciklični parametri za temperaturu i za vreme se mogu na taj način varirati. Krive toplotnog zamora mogu se dobiti pri odgovarajućim uslovima. Poznavanje uticaja osnovnih parametara toplotnih i mehaničkih ciklusa na izdržljivost omogućava istraživanje otpornosti materijala prema toplotnom zamoru.

Šeme ispitivanja toplotnog zamora

Šema sistema za ispitivanje može se izabrati na osnovu prethodno prikazanog modela toplotnog zamora. Postojanje ovog modela omogućava razvoj sistema toplotno-cikličnog opterećenja epruvete i sistema za ispitivanje sa promenljivom krutošću. To omogućava konstantnu razliku temperatura (ΔT = const) za svaki opseg ($\Delta\varepsilon_t$ = constant) konstantne ukupne deformacije.

Slika 2 prikazuje tri načelne šeme za ispitivanje toplotnog zamora. Ispitivanje se sastoji od cikličnog hlađenja i zagrevanja epruvete 1, koja je hvataljkama 2 i 3 pričvršćena za noseći okvir.

The blocking coefficient (or stiffness of loading) R is introduced for the quantitative evaluation of the effect of these thermal strain factors:

$$R = \Delta\varepsilon_M/\Delta\varepsilon_T \qquad (1)$$

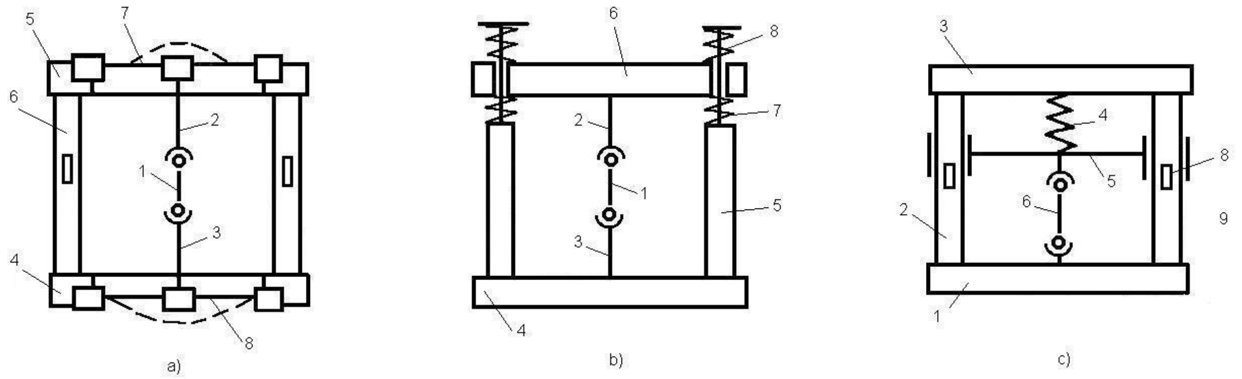
where $\Delta\varepsilon_M$ is mechanical elastic-plastic strain, and $\Delta\varepsilon_T$ is thermal strain.

The introduction of the variable stiffness of the system in the thermal fatigue testing procedure enables the separation of the thermal factors from the mechanical ones. The main thermal cyclic parameters for temperature and time can be varied in this way. The thermal fatigue curves can be obtained under corresponding conditions. The knowledge of the effects of thermal and mechanical cycles main parameters on the durability enables the investigation of material thermal fatigue resistance.

Thermal fatigue testing schemes

The scheme of the testing system can be chosen on the basis of above presented thermal fatigue model. The existence of this model enables the development of thermal cyclic loading systems of the specimen and the testing system with varying stiffness. This enables constant temperature difference (ΔT = constant) for each range ($\Delta\varepsilon_t$ = constant) of constant total strain.

Figure 2 presents three principle schemes for thermal fatigue testing. The testing consists of the cyclic heating-cooling of the specimen 1, fixed with clamping dies 2 and 3 on the supporting frame.



Slika 2. Sheme uređaja za toplotni zamor /3, 11, 12/

Figure 2. Schemes of the devices for thermal fatigue /3, 11, 12/

Noseći okvir može biti izveden od stubova 6 i šipki 4 i 5 promenljive krutosti (sl. 2a), ili od stubova 5 i krutih šipki 4 i 6 i elastičnih lukova 7 i 8 (sl. 2b), ili od stubova 2 i 9 sa krutim šipkama 1 i 3 i od pokretne šipke 5 između epruvete 6 i luka 4, koja može da se pomera po vertikalnim vođicama (sl. 2c).

U prvobitnom uređaju koji je Kofin /7/ napravio 1954. godine potpuno su sprečene slobodne toplotne deformacije epruvete, pa se na taj način one potpuno pretvorene u mehaničke deformacije epruvete.

Radi određivanja raspona aksijalne deformacije, Kofin je koristio katetografsku metodu, koja je prilično netačna i zametna. Crtanje dijagrama histerezisne petlje takođe je prilično netačno.

Novija konstrukcijska rešenja uređaja za ispitivanje toplotnog zamora, koja su posle Kofina razvili Karden /13/, /14/ i Filatov /15/, donela su značajna unapređenja u konstrukciji i rukovanju uređajem tokom ispitivanja. U dva uređaja, koje je predložio Karden epruveta se neposredno zagreva električnom strujom. Drugačije šeme, zasnovane na ovom principu ispitivanja toplotnog zamora, koje su predložili Siniavski /16/, /17/ i drugi /18/, /19/, korišćene su za ispitivanje termootpornih legura.

Postupak transformacije radijalne deformacije u aksijalnu objašnjen je u dodatku ASTM postupka ispitivanja /9/. Averčenko nudi još precizniju metodu /17/. On uzima u razmatranje tačnu vrednost modula elastičnosti *E(T)* i Poasonovog koeficijenta $\mu(T)$, koji zavise od dostignute temperature u svakom trenutku.

Uređaj za ispitivanje toplotnog zamora (ISIM)

Uređaj za ispitivanje toplotnog zamora je projektovan i izrađen u Institutu za zavarivanje i ispitivanje materijala (ISIM) u Temišvaru /20/, /21/, /22/, a programi za upravljanje, prikupljanje podataka (temperatura, sila, deformacija) i njihovu obradu razvijeni su na Katedri za automatizaciju Politehničkog univerziteta u Temišvaru prema algoritmima koji definisao prvi autor. Opšti izgled uređaja razvijenog u ISIM prikazan je na sl. 3, a šeme blok-dijagrama upravljanja i prikupljanja podataka, zajedno sa izgledom histerezisne petlje date su na sl. 4.

The supporting frame can be formed of columns 6 and bars 4 and 5 with variable stiffness (Fig. 2a), or of column 5, the rigid bars 4 and 6 and the elastic arcs 7 and 8 (Fig. 2b), or of columns 2 and 9 with rigid bars 1 and 3 and the bar 5 between specimen 6 and arc 4, mobile on the column guides (Fig. 2c).

The original device made by Coffin in 1954 /7/ completely eliminated the specimen free thermal strain, so that they were totally converted in mechanical strains in the testing specimen.

For the determination of the axial strain range, Coffin used the cathetographic method, which is rather inaccurate and complex. The recording of the hysteresis loop is also rather inaccurate.

After Coffin's, new design versions of thermal fatigue testing device were developed by Carden /13/, /14/ and Filatow /15/, which brought important improvements in the design and the handling of the device during testing. The two devices suggested by Carden used heating system with the electric current, conducted through the specimen. Other schemes, based on this principle for thermal fatigue testing, proposed by Siniawskii /16/, /17/ and the others /18/, /19/, were used for investigation of heat resistant alloys.

The procedure of the diametral strain conversion in the axial strain is explained in the annex of the ASTM testing procedure /9/. Averchenko presented a still more accurate method /17/. He took into consideration the exact value of the elasticity module *E(T)* and also the Poisson's ratio $\mu(T)$, depending on the attained temperature in each moment.

The device for thermal fatigue testing (ISIM)

The device for thermal fatigue testing was designed and produced in the Institute for welding and material testing (ISIM) in Timisoara /20/, /21/, /22/, and the control, data acquisition (temperature, force, strain) and processing programmes were developed by the Automation Department of the Politehnica University in Timişoara, according to the algorithm defined by the first author. General view of the device developed in ISIM is presented in Fig. 3, and the schemes for control block and for data acquisition, together with the hysteresis loop view, are given in Fig. 4.

Uređaj je opremljen sa pet zamenljivih lukova različite krutosti, od 60 do 300 kN/mm, što omogućava primenu pet različitih nivoa amplitude ukupne (ili plastične) deformacije za epruvete iste veličine. Na uređaju mogu da se ispituju epruvete od cilindrične cevi ili kalibrisanog cilindričnog preseka (sl. 5) cikličnim opterećenjem napona pritiska u poluciklusu zagrevanja i napona istezanja u poluciklusu hlađenja. Veličina nazivnog poprečnog preseka epruvete je $\phi 13/\phi 12$, sa krajevima za pričvršćivanje navojem M16.

Slika 3. Opšti izgled uređaja za ispitivanje toplotnog zamora ISIM /20/, /21/

Figure 3. The general view of the thermal fatigue testing device ISIM /20/, /21/

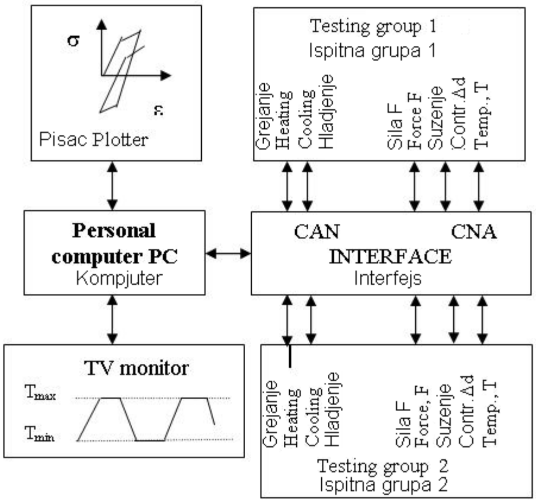
Kao posledica ciklične promene temperature i delimičnog sprečavanja pomeranja krajeva epruvete javljaju se deformacije i naponi koji prelaze napon tečenja materijala (elasto-plastična oblast).

Uređaj može da ispituje dve nezavisne grupe. Svaka ispitna grupa dobija signal za poluciklus zagrevanja od softvera na računaru tipa 586 pomoću analogno-numeričkog pretvarača (CAN) interfejsa tiristorskog sistema za podešavanje snage elementa za zagrevanje.

Zagrevanje se postiže zračenjem halogene sijalice snage 1 kW. Upotrebom nekih CAN kanala interfejsa upravlja se sistemom razvoda u dovodu gasa, što omogućava pristup vazduha (ili pristup inertnog gasa) kalibrisanom delu epruvete. Komanda za vreme zadržavanja temperature (T_{max}, T_{min}, respektivno) izdaje se softverom za podešavanje elementa za zagrevanje.

Kada se radijalni pretvarač koristi za prevođenje radijalne u aksijalnu deformaciju koriste se preporučeni postupci ASTM E 606 /9/, kao i oni iz rada /17/. Prednost poslednjeg je u tome što računa sa promenom modula elastičnosti E i Puasonovog koeficijenta ν sa temperaturom. Radijalni pretvarač je takođe razvijen u ISIM (sl. 6) za ispitivanja toplotnog zamora i neizotermnog niskocikličnog zamora. Elementi koji su u kontaktu sa zagrejanom epruvetom izrađeni su od kvarcnih šipki, a kao osetljivi element korišćen je induktivni pokretni pretvarač, koji je povezan sa mostom za pojačanje.

The device is provided with five replaceable arcs of different stiffness, ranging from 60 to 300 kN/mm, which enables the application of five different amplitudes of total (or plastic) strain for the specimens of the same size. The device can be used for the specimens of cilindrical pipes or those of calibrated cylindrical section by applying cyclic loading of compression stress in the heating semicycle and tensile stress in cooling semicycle. The specimen nominal cross section is $\phi 13/\phi 12$, ending with M16 thread for fixing.



Slika 4. Blok-dijagram upravljanja instalacijom za ispitivanje toplotnog zamora /20/, /21/

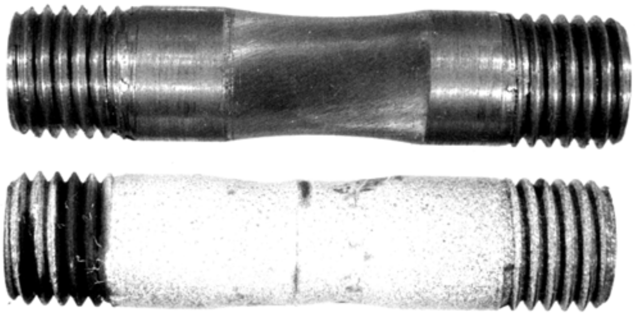
Figure 4. Control block scheme of the thermal fatigue testing installation /20/, /21/

As a consequence of the cyclic variation of temperature and of partial blocking of the specimen ends displacements, the stresses and deformations appear which exceed the material yield stress (the elastic-plastic region).

The device can test two independent groups. Each testing group receives the signal for the heating semicycle from the software of the 586 type computer by analog-numerical converter (CAN) interfaced to thyristors power adjusting system of the heating element.

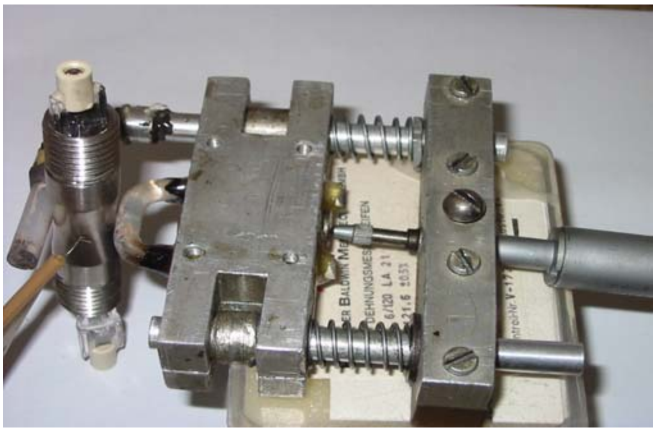
The heating is achieved by the radiation from an 1kW halogen lamp. By means of some interface CAN channels system gas distribution coil is controlled, which allows the air access (or the access of an inert gas) to the calibrated section of the specimen. The signal to hold the temperature (T_{max}, T_{min}, respectively) time is given through the software for adjustment of the heating element.

When the radial converter is used for conversion of radial into axial strain the procedures recommended in the ASTM E 606 /9/ are used, but also the procedure given in Ref. /17/. The last one has the advantage that it takes into account variation of the elasticity modulus E and of the Poisson's ratio ν with the temperature. The radial converter is also developed at ISIM (Fig. 6) for thermal fatigue testing and non-isothermal low-cycle fatigue. The elements in contact with the heated specimen are made of quartz bars, and an inductive mobile converter is used as a sensitive element, connected with an amplification bridge.



Slice 5. Epruveta na početku ispitivanja toplotnog zamora i polomljena epruveta posle ispitivanja

Figure 5. Initial shape of specimen for the thermal fatigue testing and cracked specimen after testing



Slika 6. Pretvarač radijalne deformacije u aksijalnu u kontaktu sa epruvetom

Figure 6. The radial strain converter for conversion radial into axial strain in contact with the specimen

Eksperimentalna istraživanja toplotnog zamora

Ispitivanje toplotnog zamora izvedeno je na kompjuterizovanom uređaju IIOT – 2, projektovanom i izrađenom u ISIM /20/. Korišćeni su standardni postupci ispitivanja ASTM E606 /9/ i GOST 25.505-85 /10/. Temperatura, napon i radijalna deformacija ostvareni u eksperimentima odgovarali su zahtevima standardnih ispitivanja (maksimalna greška manja od 1% za temperaturu i manja od 2% za napon i deformaciju). Cilindrične epruvete (sl. 5) su imale spoljnji prečnik 13 mm i unutrašnji prečnik 12 mm. Tačnost dimenzija epruveta ispunjavala je zahteve standardnog postupka ispitivanja. Hemijski sastav ispitivanih čelika dat je u tabeli 1.

Experimental investigations of thermal fatigue

The thermal fatigue testing had been performed on the computer controlled testing device IIOT – 2, designed and produced by ISIM /20/. Standard testing procedures from ASTM E606 /9/ and GOST 25.505-85 /10/ were used. The temperature, stress and radial strain achieved in experiments corresponded to the standard testing requirements (maximum error less than 1% for temperature and less than 2% for stress and strain). The cylindrical specimens had outer diameter 13 mm and inner diameter 12 mm. Specimens dimension accuracy met the requirements of the standard testing procedure. Chemical composition of tested steels is given in Table 1.

Tabela 1. Hemijski sastav čelika koji su ispitivani toplotnim zamorom

Table 1. Chemical composition of the thermal fatigue tested steels

Čelik Steel	Hemijski sastav (prema standardu), % Chemical composition (according to standard), %									
	C	Mn	Si	P	S	Ni	Cr	Mo	V	ostalo - rest
12H1MF (GOST 1050)	0.08-0.15	0.4-0.7	0.17-0.37	≤0.03	≤0.025	≤0.25	0.9-1.2	0.25-0.35	0.15-0.30	0.015-0.035 Al
14CrMo4 (STAS 2883-80)	max. 0.19	0.35-0.84	0.13-0.37	max. 0.045	max 0.045	-	0.68-1.04	0.38-0.62	-	-

Ruski čelik 12 H1MF korišćen je u energanama za elemente parnih kotlova i za parovode u CET - Bukurešt. Rumunski čelik 14 CrMo 4 obično se koristi za elemente parnih kotlova i u hemijskim postrojenjima za transport procesnog gasa. Češki čelik 15.128.5 upotrebljen je za izradu parovoda u CET. U tabeli 2 su date mehaničke karakteristike ispitivanih čelika.

Za svaki čelik ispitano je termičkim zamorom najmanje 12 epruveta, na 4 nivoa raspona ukupne deformacije $\Delta\varepsilon_t$, do pojave prsline dužine 1-2 mm na 3 uzorka pri razlici temperatura ΔT. Nivo raspona deformacije $\Delta\varepsilon_t$ ostvaren je pogodnim izborom opsega temperatura, debljine zida epruvete i krutosti luka, koji je serijski povezan sa epruvetom.

The Russian steel 12 H1MF was used in power plants for steam boiler components and for the steam pipelines in CET- Bucureşti. The Romanian steel 14 CrMo 4 is usually used for the steam boiler components and in chemical plants for process gas transport. The Czeck steel 15.128.5 was used for the steam pipelines in CET. Mechanical properties of tested steels are given in Table 2.

For each steel minimum 12 specimens were tested by thermal fatigue, at 4 range levels of total strain $\Delta\varepsilon_t$, up to the occurrence of 1-2 mm long crack on 3 samples at temperature range ΔT. The strain range level $\Delta\varepsilon_t$ was achieved by convenient choice of temperature range, specimen wall thickness and arc stiffness, in series linked to the specimen.

Tabela 2. Mehaničke karakteristike ispitivanih čelika

Table 2. Mechanical characteristics of the investigated steels

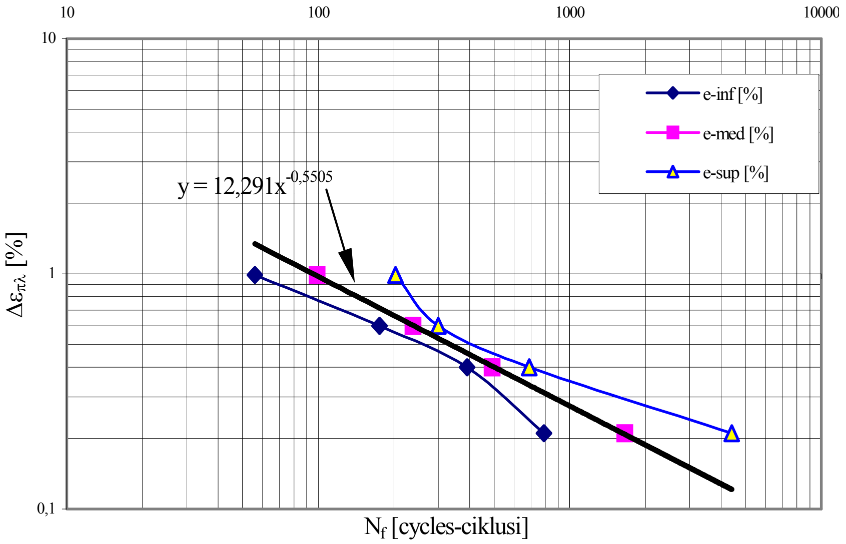
	Napon tečenja Yield stress	Zatezna čvrstoća Ultimate tensile strength	Izduženje pri lomu Elongation at fracture	Udarna žilavost Impact toughness
Čelik Steel	$R_{p0,2}$, min.	R_m	A_5, min.	KV, +20°C, min.
	MPa	MPa	%	J
12 H1MF (GOST 1050)	340	470-690	21	31
14 CrMo 4 (STAS 2883-80)	275	440-590	19	31
15.128.5 (CSN 41.5128)	365	490-690	18	KCU3=min. 50 J/cm2

“Testerasto” ispitivanje (zagrevanje-hlađenje) toplotnim zamorom ruskog čelika 12 H1MF za parovode u elektranama izvedeno je u opsegu od 60º do 540ºC, bez perioda zadržavanja, što znači da je opterećenje čist zamor. Period zagrevanja trajao je oko 30 s, a period hlađenja oko 340 s, a rezultujući ciklus je bio niskociklični zamor. Slika 7 prikazuje krivu toplotnog zamora (zavisnost raspona plastičnih deformacija od broja ciklusa do inicijacije prsline, $2\Delta\varepsilon_t$ - N_f, u dvostrukim logaritamskim koordinatama). Jednačina toplotnog zamora za čelik 12 H1MF (osnovni metal) ima oblik:

$$2\Delta\varepsilon_{ap} = 12{,}291 N_f^{\,-0{,}5505} \qquad (2)$$

The saw-tooth thermal fatigue testing (heating-cooling) of Russian steel 12 H1MF for steam pipelines in power plants was performed in the range from 60º to 540ºC, without holding time, which means that a pure fatigue loading was applied. The duration of the heating period was about 30 s, and the cooling one about 340 s, the resulting cycle being low-cycle fatigue. Figure 7 presents the thermal fatigue curve (dependance of the plastic strain range on the number of cycles up to the crack initiation, $2\Delta\varepsilon_t$ - N_f, in double logarithmic coordinates). The thermal fatigue equation for the steel 12 H1MF (parent metal) has the form:

$$2\Delta\varepsilon_{ap} = 12.291 N_f^{\,-0.5505} \qquad (2)$$



Slika 7. Manson-Kofinov izraz sa granicama rasipanja za čelik 12 H1MF, ispitan toplotnim zamorom u opsegu 60º do 540ºC /23/

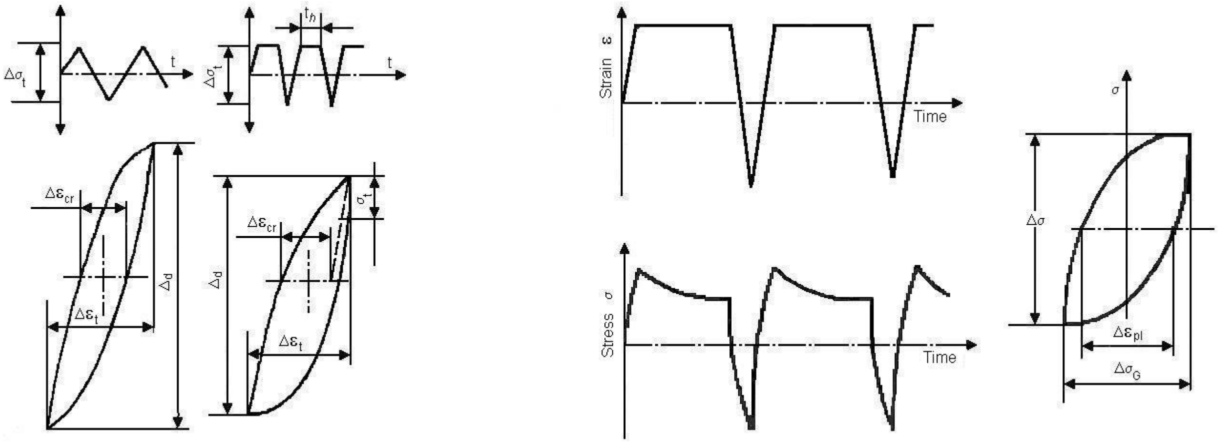
Figure 7. The Manson-Coffin equation with scatter bands for steel 12 H1MF, thermal fatigue testing in the range 60º to 540ºC /23/

Za čelik 12 H1MF izvedena su i ispitivanja toplotnim zamorom, sa vremenom zadržavanja od 360 s na maksimalnoj temperaturi ciklusa (540°C); u tom delu dolazi do otpuštanja napona puzanjem (zamor i puzanje), što se vidi na sl. 8.

Slika 9 prikazuje dijagrame toplotnog zamora (za verovatnoću loma od 50%) u dvostrukim logaritamskim koordinatama raspona plastične deformacije $2\Delta\varepsilon_{ap}$ u zavisnosti od vremena do loma usled zamora (vreme t_f) i od vremena do loma usled zamora i puzanja (vreme t_{f+c}). Može se uočiti da se broj ciklusa do loma se smanjuje, iako se ukupno vreme do loma povećava sa povećanjem vremena zadržavanja.

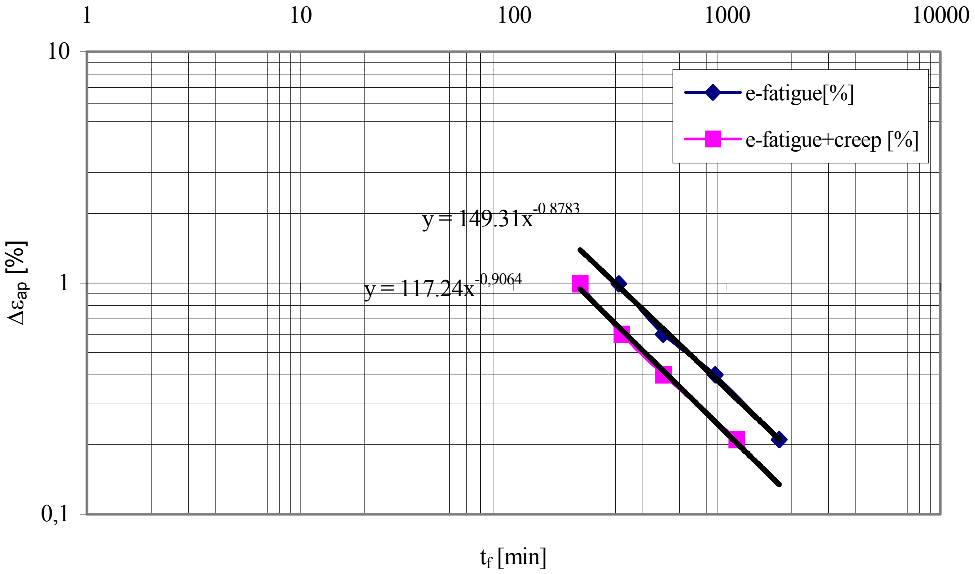
For the steel 12 H1MF thermal fatigue testing was also performed, with holding time 360 s at cycle maximum temperature (540°C); in this part the stress relief by creep occurs (fatigue and creep), as illustrated in Fig. 8.

Figure 9 presents the thermal fatigue diagrams (for the fracture probability of 50%) in double logarithmic coordinates of the plastic strain range $2\Delta\varepsilon_{ap}$ as a function of the time up to the fatigue fracture (time t_f) and that of fatigue-creep fracture (time t_{f+c}). It can be noticed that although the total duration time up to the fracture increases when the duration of holding time increases, the cycle numbers up to the fracture decreases.



Slika 8. Shematski oblici čistog toplotno-zamornog ciklusa i toplotno-zamornog ciklusa sa periodom zadržavanja na maksimalnoj temperaturi. Na desnoj strani može se videti otpuštanje napona usled puzanja.

Figure 8. Schematic forms of the pure thermal fatigue cycle and of the thermal fatigue cycle with holding time at maximum temperature. On the right side the stress relieving under creep can be seen.



Slika 9. Dijagram toplotnog zamora u koordinatama $2\Delta\varepsilon_{ap} - (t_f/t_{f+c})$ /24/ *(fatigue – zamor; creep - puzanje)*

Figure 9. The thermal fatigue diagram in coordinates $22\Delta\varepsilon_{ap} - (t_f/t_{f+c})$ /24/

Slika 10 prikazuje razliku između krive čistog toplotnog zamora i krive zamor-puzanje raspona plastične deformacije $2\Delta\varepsilon_{ap}$ u zavisnosti od broja ciklusa do loma N_f. Kriva zamor-puzanje je pomerena ulevo i nadole u odnosu na krivu čistog zamora.

Čelik 14CrMo4 je ispitan mnogo detaljnije na puzanje i na toplotni zamor bez perioda zadržavanja i sa periodom zadržavanja pri maksimalnoj temeperaturi ciklusa. Parametar *A* je takođe određen iz prekinutih ispitivanja.

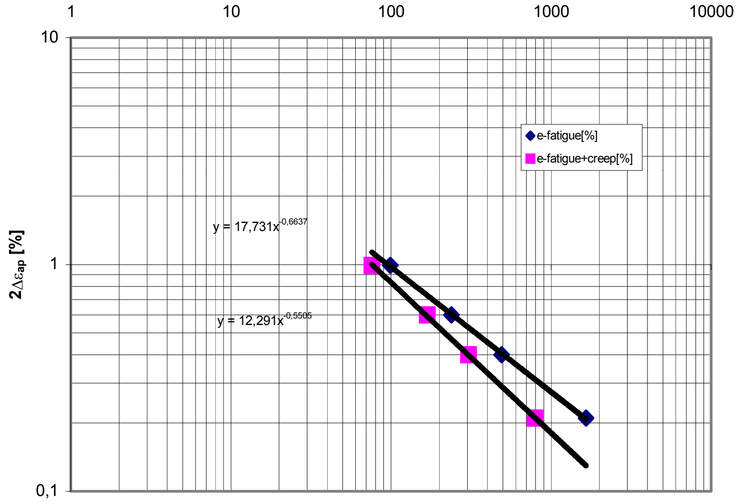
Ispitivanja dugotrajne otpornosti prema puzanju izvedena su na mašini za ispitivanje puzanjem WPM (Nemačka), na 20 uzoraka od čelika 14 CrMo 4. Rezultati, dati u obliku dijagrama dugotrajne otpornosti prema puzanju na sl. 11, za ekstrapolaciju radnog veka na osnovu 30000 časova pri temperaturama od 570°C, 535°C i 500°C su:

Figure 10 presents the difference between the pure thermal fatigue and fatigue-creep curves of the plastic strain range $2\Delta\varepsilon_{ap}$ as a function of the cycle number up to the fatigue fracture N_f. The fatigue-creep curve is shifted to the left and downward against the pure fatigue curve.

The 14 CrMo 4 steel was tested in detail on creep and also on thermal fatigue testing without and with holding times at the cycle maximum temperature. Parameter *A* had also been determined from the interrupted testing.

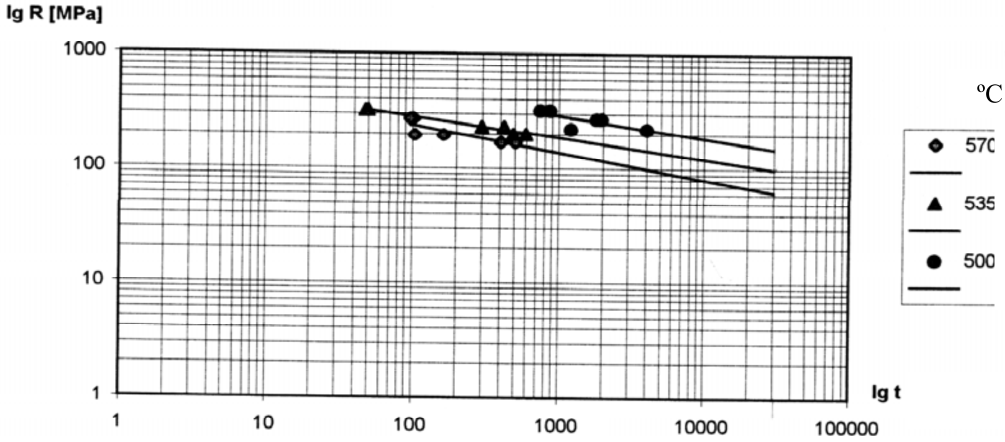
The testing for determining the long-term creep resistance was performed on a creep testing machine WPM (Germany), on 20 samples of the 14 CrMo 4 steel. The results, presented in the long-term creep resistance diagram in Fig. 11 for the service life extrapolation based on 30000 hours on temperatures of 570°C, 535°C and 500°C are:

$$R^{570}_{r/30.000} = 62\ MPa; \quad R^{535}_{r/30.000} = 99\ MPa; \quad R^{500}_{r/30.000} = 149\ MPa$$



Slika 10. Uticaj vremena zadržavanja na krivu toplotnog zamora /23/ *(fatigue – zamor; creep - puzanje)*

Figure 10. The influence of the holding time on the thermal fatigue curve /23/



Slika 11. Krive puzanja za uzorak materijala parovoda od čelika 14 CrMo 4, posle više od 110.000 časova rada /23/

Figure 11. Creep curves for the material sampled from a steam pipeline of 14 CrMo 4 steel, after over 110,000 hours in service /23/

Da bi se isključio uticaj puzanja na otpornost prema toplotnom zamoru, izvedena su i ispitivanja toplotnog zamora sa periodom zadržavanja na maksimalnoj temperaturi ciklusa, uvedenim u čist zamor posle otpuštanja napona puzanjem.

Ispitivanja toplotnog zamora na uzorku čelika 14 CrMo4 izvedena su u opsegu temperatura 60º do 535ºC, bez perioda zadržavanja i sa periodom zadržavanja pri maksimalnoj temperauri ciklusa. Vreme poluciklusa zagrevanja bilo je 30 s, a vreme poluciklusa hlađenja 325 s, pri periodu zadržavanja od 600 s i 3600 s. Kriva čistog toplotnog zamora za čelik 14 CrMo 4 prikazana je na sl. 12, a na sl. 13 prikazane su, radi poređenja, krive za režim toplotnog zamora bez perioda zadržavanja i sa periodima zadržavanja od 600 s i od 3600 s, respektivno.

Slika 14 daje radi poređenja krive srednje verovatnoće (P = 50%) ispitivanja toplotnog zamora u neizotermskom režimu izvedenog u ISIM i krive ispitivanja zamora u izotermskom režimu istog 13 CrMo 44 čelika na temperaturi 540°C. Jednačina Manson-Kofina za krivu toplotnog zamora bez perioda zadržavanja je:

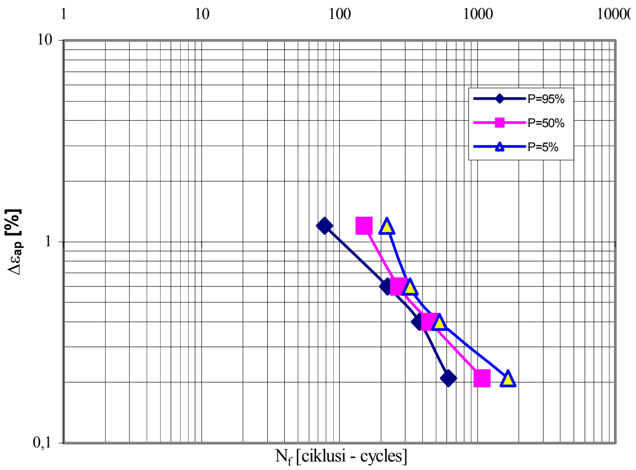
$$\Delta\varepsilon_t = 85{,}064 N_f^{-0{,}8679} \tag{3}$$

To exclude the effect of creep on the thermal fatigue resistance, thermal fatigue testing was also carried out with holding time at the maximum cycle temperature, applied in pure fatigue after the stress relieving by creep.

The thermal fatigue testing on the material sampled from the 14 CrMo 4 steel had been performed in the range from 60º to 535ºC, without holding time and with holding time at the cycle maximum temperature. The time of the heating semicycle was 30 s, the time of the cooling one was 325 s and the holding time was 600 s and 3600 s. The pure thermal fatigue curve for the 14 CrMo 4 steel is presented in Fig. 12, and the comparison between the thermal fatigue regime curves without holding time and with holding time of 600 s and 3600 s, respectively, is presented in Fig. 13.

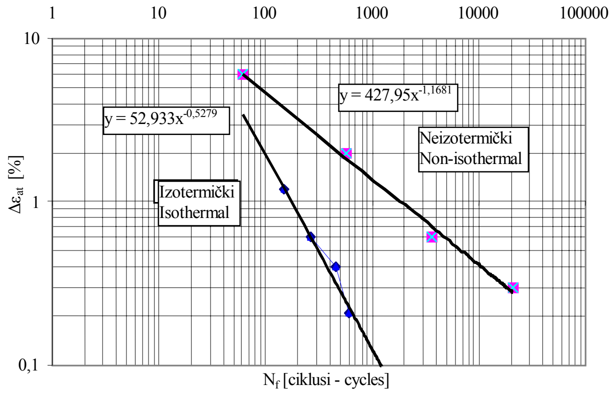
Figure 14 presents a comparison of the mean probability curves (P = 50%) for the thermal fatigue testing (non-isothermal regime) performed in ISIM with the fatigue testing curve in isothermal regime of the same 13 CrMo 44 steel at the temperature 540°C. The Manson-Coffin equation for the thermal fatigue curve without holding time is:

$$\Delta\varepsilon_t = 85.064 N_f^{-0.8679} \tag{3}$$



Slika 12. Kriva toplotnog zamora čelika 14 CrMo 4 u koordinatama raspon ukupne deformacije $\Delta\varepsilon_t$ – broj ciklusa do loma N_f u opsegu temperatura 60° do 535°C /23/

Figure 12. The thermal fatigue curve for 14 CrMo 4 steel in coordinates the total strain range $\Delta\varepsilon_t$ – number of cycles up to fracture N_f in the temperature range 60° to 535°C /23/



Slika 14. Poređenje izotermskog i neizotermskog režima niskocikličnog zamora čelika 13 CrMo 44

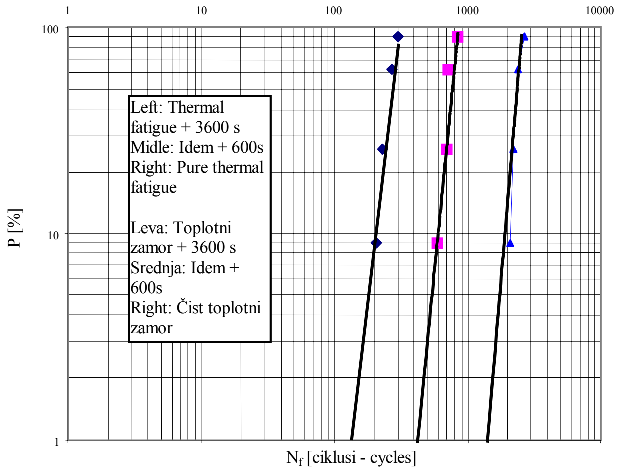
Figure 14. Comparison of the isothermal and non-isothermal regime of low-cycle fatigue of 13 CrMo 44 steel

Krive puzanja (eksperimentalna i prema standardu CSN 41.5128) /23/ date su radi poređenja na sl. 15. Prikazani su eksperimentalni rezultati za dugotrajnu otpornost prema puzanju, ekstrapolirani za 40000 i 50000 časova rada prema metodama Larson-Miler, Šerbi-Dorn i Menson-Halford, zajedno sa vrednostima određenim standardom za ovaj čelik za 100000 časova rada.

Nađeno je da za temperature iznad 535°C ekstrapolirane vrednosti za sve tri metode premašuju vrednosti koje predviđa standard materijala, iako su podaci o puzanju ekstrapolirani kao promenljivi čak i za 50000 časova.

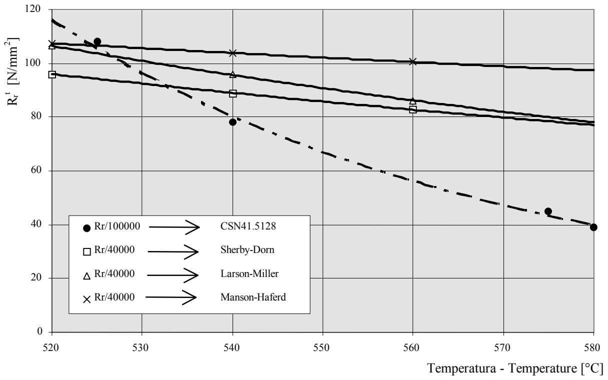
Ispitivanja materijala toplotnim zamorom izvedena su pri režimu toplotnog opterećenja između 60° i 535°C, bez perioda zadržavanja pri maksimalnoj ispitnoj temperaturi. Kriva toplotnog zamora u čistom zamornom režimu (bez perioda zadržavanja) prikazana je na sl. 16, a Menson-Kofinov izraz za čelik 15.128.5 u koordinatama raspona ukupne deformacije $\Delta\varepsilon_t$ i dvostrukog broja poluciklusa do loma $2N_f$ ima sledeći oblik:

$$\Delta\varepsilon_t = -1{,}0246(2N_f)^{-0{,}386} \qquad (4)$$



Slika 13. Linije verovatnoće loma u zavisnosti od broja ciklusa do loma za čisto toplotni zamor u režimu sa periodom zadržavanja pri maksimalnoj temperturi (600 s i 3600 s) /23/

Figure 13. The fracture probability lines depending on the number of cycles to fracture for pure thermal fatigue with the holding time regime at the maximum temperature (600 s and 3600 s) /23/



Slika 15. Eksperimentalne krive puzanja i krive puzanja predviđene standardom CSN 41.5128 /23/

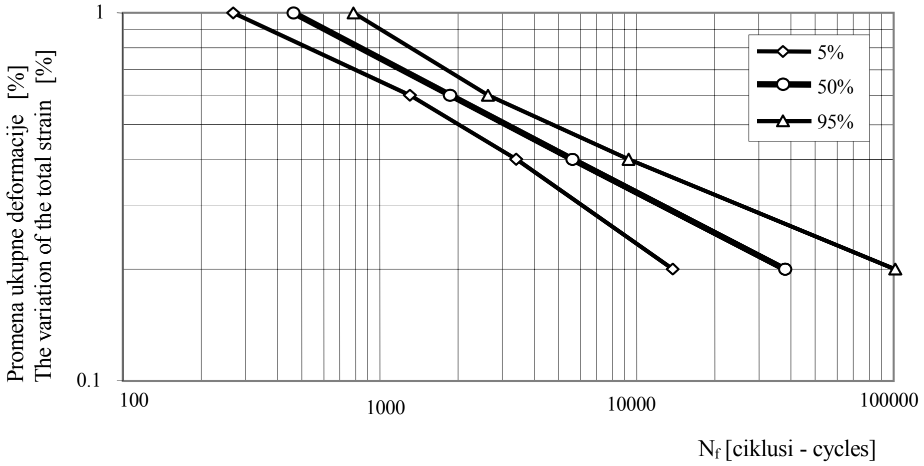
Figure 15. Experimental creep curves and the creep curves prescribed by the CSN standard 41.5128 /23/

The creep curves (experimental and according to CSN standard 41.5128) /23/ are given for comparison in Fig. 15. The experimental results for the long-term resistance are presented, extrapolated at 40000 hours and at 50000 hours after the Larson-Miller, Sherby-Dorn and Manson-Halford methods, together with the values defined by the standard for this steel for 100000 hours of operation.

It was found that, for temperatures over 535°C the extrapolated values for all the three methods exceeded those prescribed in the material standard, although the creep data were extrapolated as variable, even for 50000 hours.

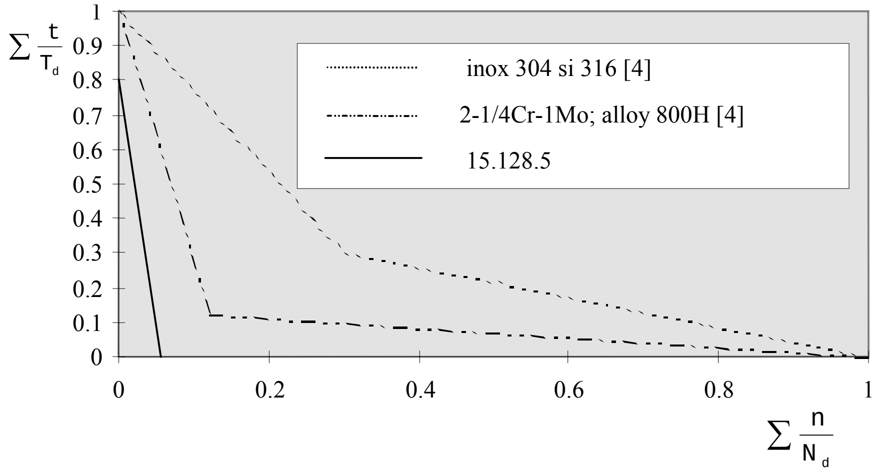
Testing of the material had been performed by thermal fatigue in the thermal loading regime between 60° and 535°C without holding time at maximum testing temperature. The thermal fatigue curve in the pure fatigue regime (without holding time) is presented in Fig. 16, and the Manson-Coffin expression for the 15.128.5 steel in coordinates of total strain range $\Delta\varepsilon_t$ and the double semicycles number up to fracture $2N_f$ has the following form:

$$\Delta\varepsilon_t = -1.0246(2N_f)^{-0.386} \qquad (4)$$



Slika 16. Kriva toplotnog zamora čelika 15.128.5 /23/

Figure 16. The thermal fatigue curve of the 15.128.5 steel /23/



Slika 17. Linearni zbirni dijagram nivoa degradacije od puzanja i zamora za uzorak materijala parovoda od čelika 15.128.5 /24/

Figure 17. The linear summing up diagram of the creep and fatigue degradation levels for the material sampled from the steam pipeline produced of 15.128.5 /24/

Ako se računa sa zajedničkim dejstvom zamora i puzanja, zbir nivoa degradacije dobijen sabiranjem dva nivoa je 0,8546, dakle manji 1, vrednosti koja odgovara linearnom zbiru degradacije. Slika 17 predstavlja dijagrame kumulativne degradacije zamor-puzanje za austenitne nerđajuće čelike kvaliteta 304 i 316, niskolegirani čelik 2-1/4Cr-1Mo i leguru 800H NiFeCr kvaliteta, uzete iz lit. /24/.

Slika 18 prikazuje tri uzorka čelika 12 H1MF koji je ispitan toplotnim zamorom do pojave prsline, a sl. 19, 20 i 21 prikazuju trag transkristalne prsline usled toplotnog zamora, čije su površine napadnute oksidom.

METALOGRAFSKA ANALIZA

U okviru evropskog projekta SPRINT 249 korišćena je kvantitativna metoda ocene šupljina od puzanja na bazi parametra *A*, za osnovni metal, metal šava i krupnozrno područje zone uticaja toplote. Merenje tvrdoće i replike uzete na licu mesta su primenjeni za ocenu degradacije puzanjem vatrootpornih čelika.

In the case of the simultaneous creep-fatigue action, the degradation level sum calculated by summing the two levels is 0.8546, i.e. less than 1, corresponding to the linear sum of the degradations. Figure 17 presents the cumulative creep-fatigue degradation diagrams for austenitic stainless steels 304 and 316 quality, low alloy steel 2-1/4Cr-1Mo and the alloy 800H NiFeCr quality taken from Ref. /24/.

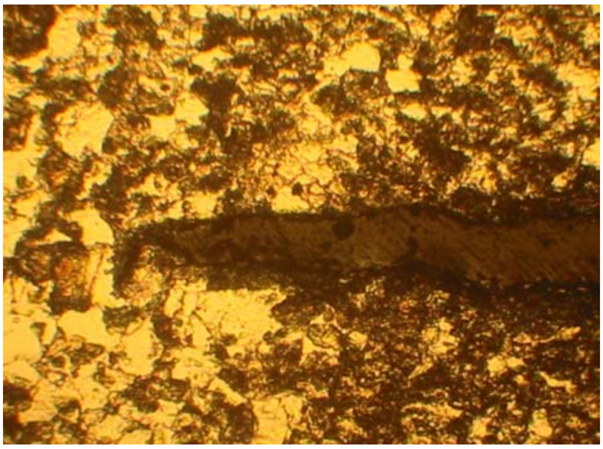
Figure 18 presents three specimens of 12H1MF steel tested by thermal fatigue up to cracking, and Figs. 19, 20 and 21 present the path of transcrystalline crack due to thermal fatigue with surfaces affected by the oxide.

METALLOGRAPHIC ANALYSIS

Within the European project SPRINT 249 the quantitative method of assesment of the creep induced cavities was used, based on *A* parameter, for base metal, weld metal and coarse grain region of the heat-affected-zone. Hardness measurement and in-situ replicas were applied for the creep degradation evaluation of the heat resistant steels.

Slika 18. Epruvete polomljene pri ispitivanju toplotnim zamorom

Figure 18. Specimens fractured in thermal fatigue testing



Slika 20. Trag transkristalne prsline usled toplotnog zamora na uzorku osnovnog metala MB-1. Na slici se vidi vrh prsline

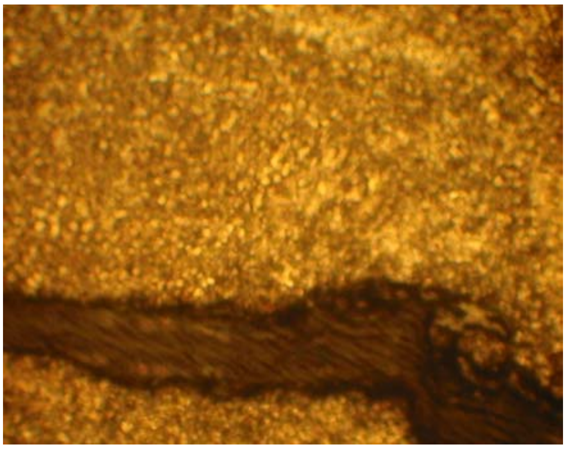
Figure 20. The transcrystalline path of the thermal fatigue crack in the base metal MB-1 specimen. The crack tip is visible

Ako je broj degradiranih granica zrna N_D i broj nedegradiranih granica zrna N_U, njihov odnos predstavlja parameter A; na taj način on predstavlja udeo granica zrna sa šupljinama:

$$A = N_D/(N_U + N_D) \qquad (5)$$

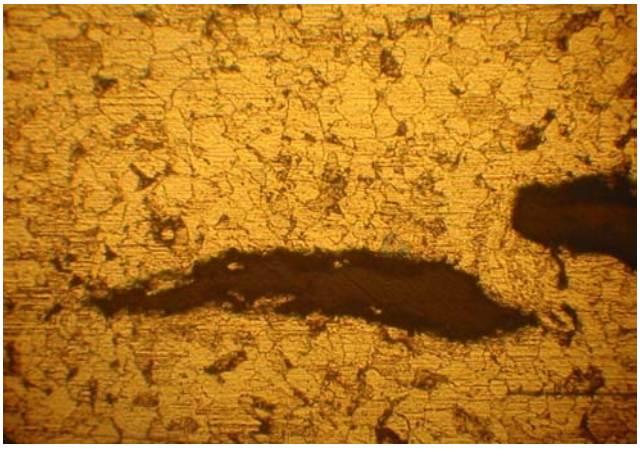
Metalografska ispitivanja šupljina na granicama zrna za određivanje parametra A /25/, predstavljenog na sl. 22, izvedena su optičkim mikroskopom sa zelenom monohromatskom svetlošću, objektivom 40x i okularom 10x ili 12,5x sa uvećanjem od 400x do 500x na liniji paralelnoj pravcu maksimalnog napona.

Tabela 3 predstavlja vrednosti odeđene u programu SPRINT SP 249 za faktor $(1 - L_F)/L_F$, koji povezuje preostali vek sa nivoom degradacije, gde je L_f utrošeni radni vek. Preostali radni vek može se oceniti u zavisnosti od vremena do pojave prsline ili do konačnog loma, uzimajući u obzir da li je degradacija ravnomerno raspoređena po preseku ili je ona lokalna. Na osnovu ocenjene vrednosti parametra A može se izračunati preostala plastičnost (deformacija) ε_r u prisustvu prsline.



Slika 19. Transkristalni trag prsline od toplotnog zamora u epruveti iz metala šava

Figure 19. The transcrystalline path of the thermal fatigue crack in the specimen from weld metal



Slika 21. Trag transkristalne prsline usled toplotnog zamora na uzorku osnovnog metala MB-3. Vidi se cik-cak oblik prsline

Figure 21.The transcrystalline path of the thermal fatigue crack in the base metal MB-3 specimen. Zig-zag crack shape is visible

If the degraded grain boundaries number is N_D and the non-degraded boundaries number N_U, their ratio represents parameter A; in this way it presents the fraction of the grain boundaries affected by cavities:

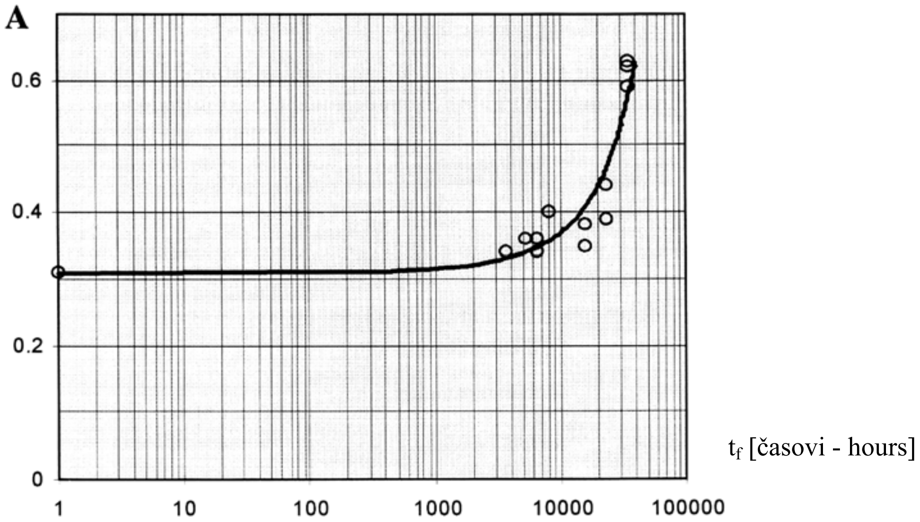
$$A = N_D/(N_U + N_D) \qquad (5)$$

Metallographic testing of cavities on the grain boundary for determination of A parameter /25/, presented in Fig. 22, was perormed by an optical microscope with green monochromatic light, the objective 40x and ocular 10x or 12.5x, with magnification 400x to 500x. (Fig. 22) on the line parallel to the maximum stress direction.

Table 3 presents the values determined in the SPRINT SP 249 programme for the factor $(1 - L_F)/L_F$, which links the remaining life with the degradation level, where L_f stands for consumed service life. The remainingl life can be assessed based on the time necessary for crack initiation or to the final fracture, taking into account if the degradation is uniformly distributed in the section or it is local. From the assessed value of the A parameter. the residual ductility (strain) ε_r in the presence of a crack can be calculated.

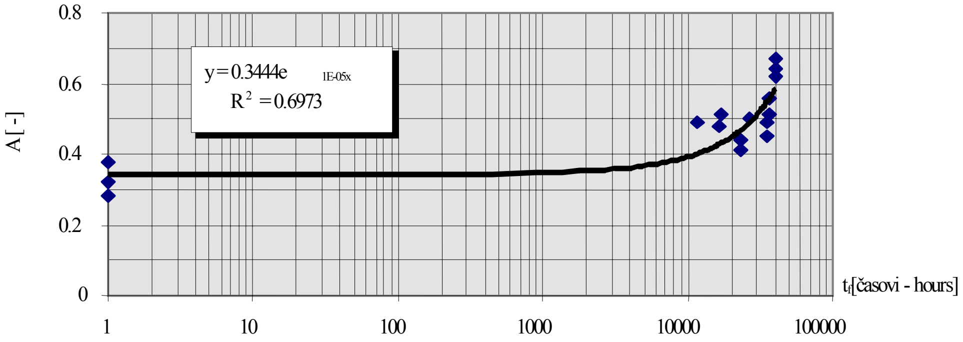
Eksperimentalno je ocenjena veličina parametra *A*, na osnovu ispitivanja puzanjem do loma i prekinutih ispitivanja epruveta. Cilj je bio da se razdvoji trag degradacije u polaznom stanju materijala (pre ispitivanja) i u stanju posle konačnog loma. Dobijena zavisnost traga degradacije puzanjem za čelik 13 CrMo 44 prikazana je na sl. 22, a za čelik 15.128.5 na sl. 23. Vrenost parametra *A* za početno stanje je oko 0,31, a za konačno stanje (pri lomu) je utvrđeno da je oko 0,7.

Experimental assessment of the *A* parameter value was made, based on the creep testing up to fracture and on interrupted testing of specimens. The aim was to compare the degradation path in the initial material state (before the testing) and in the final fracture state. Obtained dependance of creep degradation path for the 13 CrMo 44 steel is presented in Fig. 22, and for the 15.128.5 steel in Fig. 23. Parameter *A* value for initial state is about 0.31, and for final state (at fracture) is found to be about 0.7.



Slika 22. Vrednosti parametra *A* u zavisnosti od vremena ekstrapolacije posle ispitivanja uzoraka puzanjem do loma i prekinutog ispitivanja uzoraka. Dodatno vreme ekstrapolirano na 40.000 časova. Čelik 13 CrMo 44

Figure 22. The values of the parameter *A* depending on the extrapolation after the creep testing of the specimen fracture and specimens interrupted testing. The additional life extrapolated to 40,000 hours. Steel 13 CrMo 44



Slika 22. Vrednosti parametra *A* u zavisnosti od vremena ekstrapolacije posle ispitivanja uzoraka puzanjem do loma i prekinutog ispitivanja uzoraka. Dodatno vreme ekstrapolirano na 40.000 časova. Čelik 15.128.5

Figure 22. The values of the parameter *A* depending on the extrapolation after the creep testing of the specimen fracture and specimens interrupted testing. The additional life extrapolated to 40,000 hours. Steel 15.128.5

Tabela 3. Nivoi degradacije od puzanja u zavisnosti od vrednosti parametra *A*

Table 3. Creep degradation levels depending on the *A* parameter values

Nivo degradacije Degradation level	Parametar *A*, max *A* parameter, max	Udeo utrošenog veka L_F Consumed life ratio L_F	Faktor preostalog veka $(1 - L_F)/L_F$ Factor of remaining life $(1 - L_F)/L_F$	
			minimum	maximum
1	0	0,00…0,12	7,33	Nepoznat (unknown)
2	0,12	0,04…0,36	1,17	24,0
3	0,3	0,30…0,50	1,0	2,33
4	0,48	0,45…0,84	0,19	1,33
5	0,6	0,72…1,00	0 = prekid (giving up)	0,39

ZAKLJUČCI

Dobijeni rezultati su pokazali da:

a) Ispitivanje toplotnim zamorom čelika koji se koriste u Rumuniji omogućava ocenu kumulativne degradacije od zamora i puzanja i karakteristika puzanja prema ASME.

b) Ukupni stepen degradacije zmorom čelika za parovode je do 6 %, a ostatatak (94%) je posledica pojave puzanja;

c) Dijagram korelacije parametra *A* za puzanje omogućava ocenu degradacije do konačnog stanja; on je primenljiv u zoni koncentracije napona i na zavarenim spojevima gde se deformacija od puzanja ne može direktno meriti.

CONCLUSIONS

The obtained results have shown that:

a) Thermal fatigue testing made on steels used in Romania allow an assessment of the creep-fatigue cumulative degradation and the creep characteristics according to ASME.

b) Total fatigue damaging rate of the steels for steamlines is up to 6 %, the rest (94%) is due to the creep occurence;

c) The creep *A* parameter correlation diagram allows to assess the degradation up to the final stage; it is applicable in the stress concentration region and for welded joints where creep deformations can not be measured directly.

LITERATURA – REFERENCES

1. Dobrzanski, L.A., et al.: “The evaluation of the extent of damage as the base for forecasting of the residual life of pressure loaded power installation elements” in Proceedings of 1st Workshop on Influence of Local Stress and Strain Concentrators on the Reliability and Safety of Structures, Program COPERNICUS No CIPA CT94 0194, 10-12 April, 1995, Miskolc-Taploca, Hungary, p. 175.

2. Kautz, H.R.: “Întreținerea centralelor cu combustibil fosil – un obiectiv complex de planificare” in Proceedings 2nd Conference DVS-ASR “Asigurarea calității în domeniul sudurii”,1994, p. 117.

3. Dulinev, R.A., a.o: “Termiceskaia ustalost metallow” (in Russian), Maşinostroienie, Moskwa, 1980, 200.

4. Kussmaul, A.: “Schadenbuch” 1993, MPA, Stuttgart, p. 201.

5. Schroder., H.Cr.: “General observations regarding the assessement, testing and inspection of older power plants” in Special Print VGB Kraftwerks Technik, 1998, vol 78, no 9, p. 28.

6. Hausemann, R.U.: “New materials for critical components in coal-fired steam generators in power plants with increased steam parameters” in Proceed of 3rd Aachen Welding Colloquium, 1995.

7. Coffin, L.F., a.o.: “A study of the effects of cyclic thermal stresses on a ductile metal” Trans. ASME 1954, vol 76, p. 931.

8. Taira, S., et al.: “Teoria procnosti materiallov na visokih temperaturah”, (in Russian), Moskva, Metal., 1986, p. 280.

9. ASTM E 606 “Constant amplitude low-cycle fatigue testing”.

10.GOST 25.505-85 – “Metod ispîtanii na maloțiklovnih ustalosti pri termomehaniceskom nagrujenii”, Moskwa, 1985.

11.Egorov, V.I., et al.: “Ob usloviah deformirovania pri ispîtanii trubciatnîh obrazțov na termiceskuiu ustalosti”, (in Russian), in Zavodsk. Laborat., 1971, vol 37, no 8, p. 881.

12.Siniavskii, D.P.: “O vlianii parametrov nagrujenia na zakonomernosti formoizmenia jaroprocinovo splava usloviah țiklicheskovo izmenenia temperaturî”, (in Russian), in Probl. Proc., 1975, no 12, p. 47.

13.Carden, A.E., a.o.: “Thermal fatigue. An analysis of conventional experimental method” in Proc. ASTM 1963, vol 63, p. 735.

14.Carden, A.E., a.o.: “Thermal fatigue. An analysis of conventional experimental method” in Proc. ASTM 1963, vol 63, p. 735.

15.Carden, A.E., a.o.: “ Thermal fatigue of nickel-base alloy” in Trans ASME 1965, ser 8, vol 87, no 1, p. 237.

16.Filatow,V.M., a.o.: “O nakoplenii povrejdenii pri termiceskoi ustalosti” in Procnosti pri deformații i razruşenie pri maloțiklovoi nagrujenii”, (in Russian), Moskwa, 1967, p. 119.

17.Mahutow, N.A., a.o.: “Procnosti konstrukții pri maloțiklovom nagrujenii”, (in Russian), Moskwa, 1988.

18.Avercenko, E.A., a.o.: “Sopostavlenie deformirovanie i razruşenie pri nezavisimom temperaturno-mehaniceskom nagrujenii pri metodika Coffin”,(in Russian), Zavodsk. Laborat.,1986,nov, p. 60.

19.Majumdar, S., a.o.: “A procedure of strain controll low-cycle fatigue testing at elevated temperature” – in Journ. of testing and evaluation, 1981, vol 9, no 1, p 35.

20.Marchand, N., a.o.: “A computerized test system for thermal-mechanical fatigue crack growth” in Journ. of testing and evaluation, 1996, vol 24, no 6, p 303.

21.Mateiu, H., ş.a.: “Corelarea stării de degradare a oțelului 14CrMo4 realizată al încercările de fluaj şi oboseală termică cu cea relevată prin metoda metalografică” BID-ISIM,1997, nr.2, p.4.

22.Mateiu, H., ş.a.: “Influence of holding time at maximum temperature on thermal fatigue of 14CrMo4 steel” Proceed. Internat. Sympos. Welding 96, Beograd, 1996, p. 284.

23.Mateiu, H, a.o.: „Perfecționarea şi Deu, modele experimentale a sistemelor de măsurare, achiziție şi prelucrare a datelor experimentale” – Contract ISIM nr. 242/B11/1995.

24.Mateiu, H.: „Fenomenul de degradare la solicitări termomecanice” – Teza de doctorat, Timisoara, 2002.

25.ASME Code. Case N-47: Design analysis of components in elevated temperature service”.

26.Brear, J.M., a.o.: “Metallographic tehniques for condition assessement and life prediction in SP 249 guidelines” – in MPA Seminar, oct. 1994, paper 2.