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Fitness-For-Service Assessment of Steel Tubes Operating in Oil Refineries Furnaces

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Abstract

This paper analyses the main degradation mechanisms of pipes used in furnaces from refineries and petrochemical plants and suggests a procedure for determining the cumulative damage of these pipes, given their long use in fluctuating pressure and temperature regimes according to the needs of the technological processes served by the furnaces. It is established that Fitness-For-Service assessments for furnace pipes in refineries and petrochemical plants must be made considering the effects of creep phenomenon, combined with those of cyclic loading (fatigue) and with the action of the fluid that flows through pipes (which can cause superficial carburization on the inside surface of the pipes) and with the working environment inside the furnace (which can cause oxidation and superficial decarburization of the pipes). The proposed methods for examining and checking the pipes during periodic inspections of the furnaces are also indicated together with the ways these results may be used to increase the confidence level of the information provided in the procedure proposed by the authors for continuous monitoring of the pipes in use.

Key words: *steel pipes for refineries furnace, creep, creep – fatigue interaction, Fitness-For-Service assessment*

Introduction

Furnace pipes in petroleum refineries and technological plants for hydrocarbons processing – PRFP are subject to severe thermal regimes during operation. In refineries, the working temperatures of these pipes reach 120...130 °C in desalination installations and can go up to 350...550 °C in atmospheric and vacuum distillation units and may be even higher – 500...700 °C – in thermal cracking plants and 650...850 °C in pyrolysis installations [1]. Furthermore, mechanical stresses of high intensity, variable in time, are generated during operation within PRFP, due to the action of transmitted fluids pressure, mass loads (weight of pipe and transported fluids) and frequent temperature fluctuations. In addition, due to the interaction with transmitted fluids and with the atmosphere inside the furnaces, the PRFP suffer (in their superficial layers or in all their section) significant changes of chemical composition, metallurgical structure and physical and mechanical properties [1, 2].

In time, due to the working conditions, the PRFP undergo a damage process (they have limited durability) and must be replaced periodically. The main degradation phenomenon for PRFP is creep, but fatigue damage (due to cyclic stress) and also damage caused by the interaction with fluids circulating inside the pipes and the atmosphere in furnaces can have substantial effects on the endurance of the pipes.

Depending on the working conditions, the PRFP can be made from plain steels, low, medium or high alloy steels, or from superalloys; generally, (seamless) rolled pipes are used, and also centrifugal cast pipes (austenitic stainless steel Cr – Ni type) are used for some other applications such as pyrolysis furnaces. The main materials used for PRFP are briefly presented and characterized in Table 1 [2, 3].

Table 1. Types of materials used for PRFP

Material	Material designation *	Group of material according to CR ISO 15608	Temperature limit to define the creep range according to:	
			BS 7910	API 579
C – Mn Steel	P195GH … P265GH / N	1.1	330 °C	343 °C
0,5Mo Steel	16Mo3 / N	4.1	420 °C	399 °C
1,25Cr – 0,5Mo Steel	10CrMo5-5 / NT; QT	5.1		427 °C
2,25Cr – 1Mo Steel	10CrMo9-10 / NT; QT	5.2		
5Cr – 0,5Mo Steel	X11CrMo5 / I	5.3		
9Cr – 1Mo Steel	X11CrMo9-1 / I; NT; QT	5.4		
9Cr – 1Mo – V Steel	X10CrMoVNb9-1 / NT; QT	6.4		454 °C
12Cr – Mo – V(W) Steel	X20CrMoV12-1 / NT; QT	6.4		482 °C
Austenitic Stainless Steel	X5CrNi18-10 / AT	8.1	485 °C	510 °C
	X2CrNiMo17-12-2 /AT			538 °C
	X6CrNiTi18-10 / AT			
	X6CrNiNb18-10 / AT			
Incoloy (Fe – Ni – Cr Alloy)	800H Alloy; 800HT Alloy **	–	–	565 °C

* N – normalized; NT – Normalised and tempered; QT – quenched and tempered; I – isothermally annealed; AT – solution annealed (annealed at 1050…1100 °C, held for min. 60 minutes and water quenched);

** Chemical composition: 0.05…0.10 %C; 30…35 %Ni; 19…23 %Cr

Rational use of PRFP involves continuous monitoring of their technical status, by tracking their working regime (temperature t_s and pressure p_s) and by assessing cumulative damage and remaining life, applying the procedures proposed in this paper.

Determination of Pipes Creep Cumulative Damage

Because the working temperatures field [$t_{\min}$; $t_{\max}$] is placed at high temperatures, where creep phenomenon occurs, PRFP are designed for ensuring limited sustainability. The intensity of creep process increases with temperatures above the minimum threshold indicated in Table 1, which represents creep exclusion temperature t_c, below which creep effects are negligible under 200,000 hours of service life. t_c is dependent on the type of metallic material from which PRFP are made of and on their operating period, and is defined as follows [4]:

a) for metallic materials with an elongation percentage (ductility) $A_f \geq 10$ %, at creep rupture (under uniaxial tensile stress), under time – temperature conditions describing the operating regime of PRFP, t_c is the temperature at which a creep strain $\varepsilon_f = 0,2$ % is accumulated throughout the whole working period, at a mechanical load generating mechanical stresses with the maximum intensity equal to the proof strength, $f_{\varepsilon f} = \sigma_{\varepsilon 0,2/t}$ in PRFP walls, which for usual assessments is considered $\sigma_{\varepsilon 0,2/t} = F_p R_{p0,2}/_t$, where $F_p \leq 1$, and for special assessments, when taking into account any existent flaws (metal loss or cracks) - $\sigma_{\varepsilon 0,2/t} = (R_{p0,2/t} + R_{m/t})/2$, $R_{p0,2/t}$, and

$R_{m/t}$ are the yield strength and tensile strength (at temperature $t = t_c$) of the metallic material from which PRFP are made of;

b) for metallic materials with uniaxial creep rupture ductility A_f <10%, according to time – temperature conditions describing the working regime of PRFP, t_c is determined in the same way, but considering an allowable strength, $f_{\varepsilon f}$, associated with a creep strain having a magnitude of 1/50th of the actual rupture ductility.

PRFP behavior (exploited under creep conditions) should be evaluated considering both the history of their exploitation (the operating time before the moment when the analysis is performed), and the future operational needs. The PRFP operational history can be developed (in terms of mechanical loads and working temperatures) based on the documents used to monitor the working regime and operating conditions of the furnace in which they are used, and the future operational requirements may be specified considering the furnaces technological installation production programs; if the operating regime and working conditions of the furnace vary over time, then describing past and future operating conditions of PRFP must be done through a series of loading blocks.

When conducting PRFP behavior assessments, a special attention should be paid to the determination of the state of stress and strain generated during each of the loading block they are subject to, so the method based on stress categories (stress classification) should be applied for their establishment [2, 4].

Knowing the mechanical characteristics of the PRFP material, at the working temperatures corresponding to the loading blocks that define their operating regime, is essential for a relevant evaluation that leads to results with high confidence level. The following characteristics must be known: $R_{p0,2/t}$, $R_{m/t}$, $\sigma_{\varepsilon 0,2/t}$, creep curves $\varepsilon = g(\tau)$ or creep rate curves $v_f = g^{/}(\tau)$, isodeformation curves and creep rupture curves, fracture toughness, etc. It is difficult to determine these characteristics (given that tests are performed at high temperatures, with complicated methodologies and rigorous requirements regarding the testing conditions, the accuracy and validation of results) and, therefore, the available database in this area is incomplete and lacks consistency. For describing the creep behavior of PRFP, complex diagrams containing the $f_{\varepsilon f} = q(\tau)$ curves for different values of the ε_f parameter and creep rupture, as shown in Figure 1, are currently used. These diagrams can be processed to obtain many of the properties required in the evaluation of creep behavior of PRFP (for the temperature at which they were built): creep curves, creep rate curves etc. For a large number of materials (steels and superalloys) used for pressure vessels and furnace pipes construction, [4] contains the characteristic curves of creep behavior (master curves). Creep screening selection curves and creep damage curves of the type shown in Figure 2 are currently used to assess creep damage characteristics of the material used for PRFP.

The procedure of cumulative damage determination for PRFP subjected to multiple loading blocks (numbered $i = 1 \ldots n$) has the following steps [2, 4]:

a) circumferential stress in PRFP wall, $\sigma_{\theta i}$, is set for each of the loading block using the formula (conservative): $\sigma_{\theta i} = p_i(0.5D_e/s)$;

b) knowing the characteristic parameters ($\sigma_{\theta i}$ – stress and t_i – temperature) for each of the loading block ($i = 1 \ldots n$), the damage rates, $D_{c,i}$, can be determined using the creep damage curves for the steel the furnace pipes are made of (see Fig. 2);

c) knowing the characteristic parameters ($D_{c,i}$ – damage rate and τ_i – the duration of the loading block) the total damage for each of the loading block can be determined using the formula: $D_{cu,i} = \tau_i \, D_{c,i}$;

d) PRFP cumulative damage can be calculated: $D_{cu} = \sum_{i=1}^{n} D_{cu.i}$; PRFP creep behavior is appropriate (their durability has not been affected), if the following condition is met: $D_{cu} \le D_{cu,A}$. $D_{cu,A}$ is the allowed value for PRFP cumulative damage, $D_{cu,A}$ = 0.25 ... 0.80 <1 (proposed values in [2, 4]).

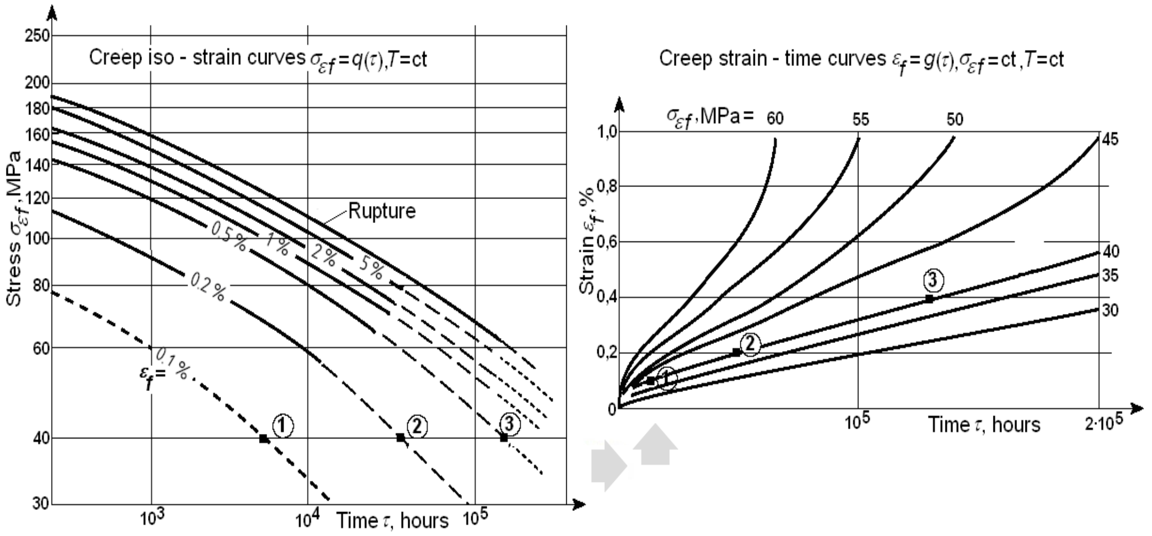

Fig. 1. Creep iso – strain curves for a PRFP steel

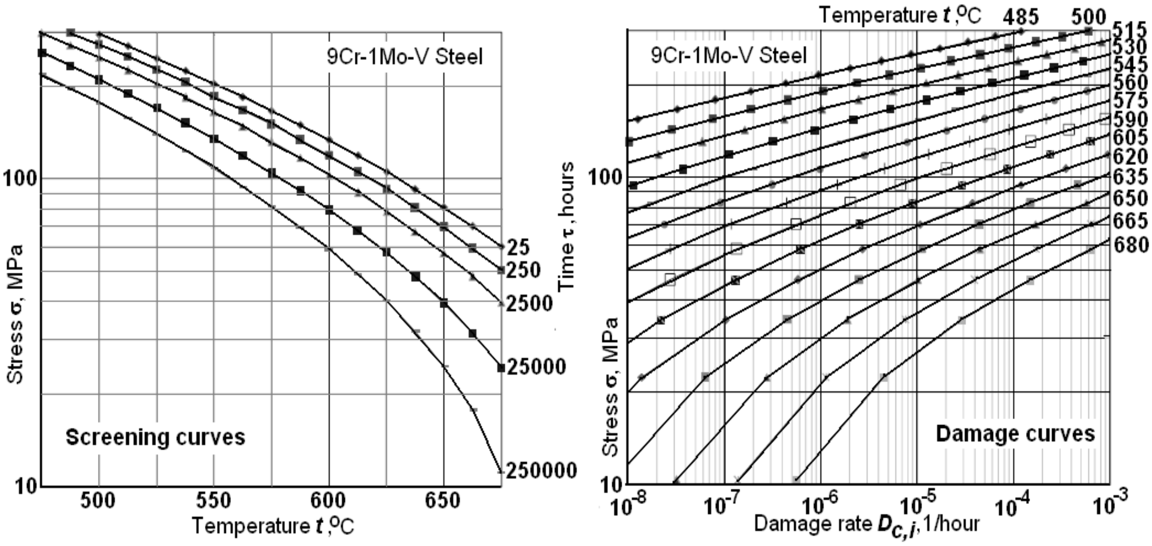

Fig. 2. Creep screening curves and creep damage curves for a PRFP steel

The authors' method for applying the procedure described above, is explained based on a case study: creep behavior evaluation of 9Cr-1Mo-V steel PRFP of a coking plant from a petroleum refinery; PRFP have the following parameters: the outside diameter, D_e = 102 mm, and wall thickness, s = 8 mm, and were subjected to multiple loading blocks (p_i – pressure, t_i – temperature, τ_i – time) listed in Table 2.

Table 2. Parameters of the loading blocks used in the PRFP case study

Pressure p_i, MPa	Temperature t_i, °C	Time τ_i, ore
5.0	590	960
3.2	500	2400
5.0	530	4800
3.5	490	3600
5.5	650	2400
2.2	485	1200
4.8	560	9600
3.6	500	9600
4.5	670	4800
3.5	485	4850
Total service time τ, hours		**44210**

Table 3. Creep behaviour assessment results for the PRFP case study

Stress $\sigma_{\theta i}$, MPa	Damage rate $D_{c,i}$, ore $^{-1}$	Total damage $D_{cu,i} = \tau_i D_{c,i}$
31.9	$4.33278\cdot10^{-09}$	$4.159469\cdot10^{-06}$
20.4	$2.8302\cdot10^{-14}$	$6.792514\cdot10^{-11}$
31.9	$6.12875\cdot10^{-12}$	$2.941799\cdot10^{-08}$
22.3	$1.38741\cdot10^{-14}$	$4.994679\cdot10^{-11}$
35.1	$1.82465\cdot10^{-06}$	$4.379153\cdot10^{-03}$
14.0	$1.31101\cdot10^{-15}$	$1.573207\cdot10^{-12}$
30.6	$1.32864\cdot10^{-10}$	$1.275491\cdot10^{-06}$
23.0	$4.69942\cdot10^{-14}$	$4.511444\cdot10^{-10}$
28.7	$5.87784\cdot10^{-06}$	$2.821361\cdot10^{-02}$
22.3	$8.02074\cdot10^{-15}$	$3.890061\cdot10^{-11}$
Cumulative damage D_{cu}		**0.032598231**

For this case study (and other similar ones), the authors have developed an EXCEL software, which can perform all the above steps and can quickly provide the value of the cumulative damage, D_{cu}. The use of this software requires the knowledge of the damage curves analytical expressions; for example, referring to the case study, the analysis of the experimental data that led to the drawing of the damage curves for 9Cr 1Mo-V steel (see Figure 2) revealed that their analytical expression is:

$$\lg D_{c,i} = a(t) + b(t)\sqrt{\sigma_{\theta i}}\,, \tag{1}$$

$a(t)$ and $b(t)$ having the values shown in Figure 3.

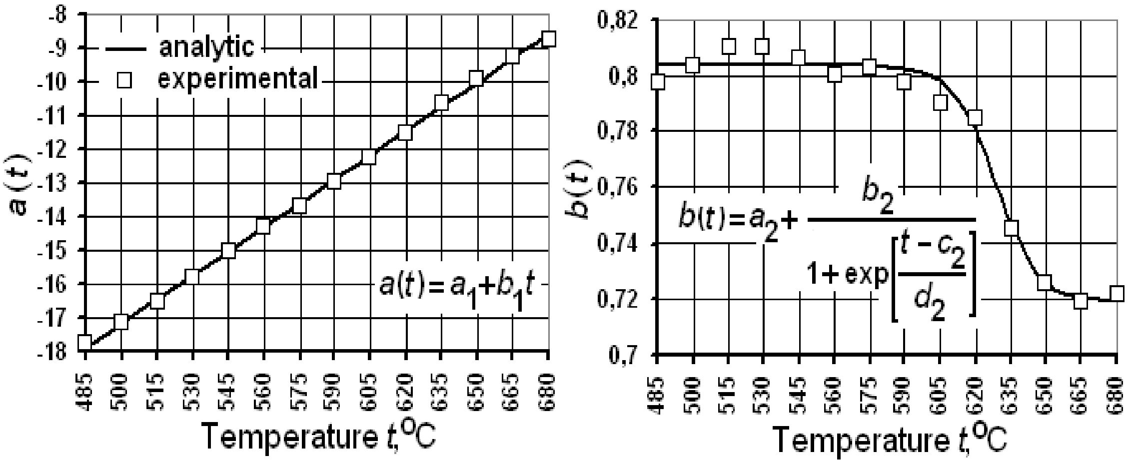

Fig. 3. $a(t)$ and $b(t)$ values for the damage curves of an 9Cr-1Mo-V steel: a_1 = -40,9776945; b_1 = 0,04759809; a_2 = 0,71914445; b_2 = 0,0846554; c_2 = 628,473693; d_2 = 8,9802850

The results obtained for the case study are summarized in Table 3. The following comments can be made:

a) The procedure used for the case study can be applied to both design (considering the multiple loading blocks provided for further use) and (as seen above) evaluation of the technical condition of the existing PRFP (that has been subjected to multiple loading blocks);

b) When using the procedure, it must be taken into account that, in terms of creep PRFP damage, the temperature increase has a damage intensification effect significantly higher than the increase of working periods. For example, if the working temperature for the first 5 loading blocks of the case study considered before increases by 50 °C (while the durations are maintained), then the cumulative damage grows up to $D_{cu} = 0.347827141$. The same effect can be achieved by increasing approximately 85 times the duration of the first 5 loading blocks (if temperatures in Table 2 are the same for these loading blocks);

c) Using the $D_{cu} \leq D_{cu,A} < 1$ criterion (instead of $D_{cu} \leq 1$ criterion) for the evaluation has two reasons: creep damage curves in [2] are based on a small amount of experimental results; during PRFP exploitation complementary damage phenomena, such as fatigue, carburizing or sigma-phase embrittlement (not taken into account when building creep damage curves), may occur.

Pipe Damage Due to Creep-Fatigue Interaction

If the fluctuations of the temperature t_i and pressure p_i are high, the mechanical loads the PRFP are subjected to can get the characteristics of variable loads, and the damage effects due to creep phenomenon may be overlapped by the damage effects of the fatigue phenomenon. For this situation, [2, 4] recommends to apply the following procedure for the PRFP cumulative damage determination:

a) the cumulated creep damage, $D_{cu,C}$, is determined by applying the procedure described above and using the formula:

$$D_{cu,C} = \sum_{i=1}^{n} D_{cu.i} = \sum_{i=1}^{n} \tau_i D_{c,i} \; ; \qquad (2)$$

b) se definesc, prelucrând blocurile de solicitare considerate la stabilirea $D_{cu,C}$, blocurile de solicitare variabilă (ciclică) ale PRFP, fiecare bloc fiind alcătuit dintr-un număr N_j de cicluri ($j = 1...m$, m fiind numărul total al blocurilor de solicitare ciclică), iar fiecare ciclu având un nivel constant al variației tensiunilor circumferențiale $\Delta\sigma_{\theta j}$, şi al temperaturii t_j şi o durată τ_j; evident:
b) the PRFP variable (cyclic) loading blocks are defined, by means of processing the multiple loading blocks considered for $D_{cu,C}$ determination; each loading block consists of a number of cycles N_j (j = 1 ... m, m being the total number of cyclic loading blocks) and each cycle has a constant level of circumferential stresses variation, $\Delta\sigma_{\theta j}$, and of temperature, t_j, and a time frame, τ_j. It is obvious that:

$$\sum_{i=1}^{n} \tau_i = \sum_{j=1}^{m} N_j \tau_j \; ; \qquad (3)$$

completing this step can raise major difficulties, because the possible PRFP load cycles must be defined and numbered correctly, applying the procedures defined for these issues and taking into account the fact that both pressure and temperature variations can confer the status of variable loads to the mechanical loads of in service PRFP;

c) fatigue damage curves for the PRFP material are used; they are determined for the characteristic conditions of each variable loading block – $j = 1...m$. The fatigue durability of PRFP is then calculated considering they are loaded under typical conditions for each of the variable loading block; the calculated durability values (number of load cycles to failure) is noted $N_{F,j}$, $j= 1...m$.

d) the cumulative fatigue damage, $D_{cu,F}$, is determined using the formula:

$$D_{cu,F} = \sum_{j=1}^{m} \frac{N_j}{N_{Fj}} \; ; \qquad (4)$$

e) a diagram used for the interpretation of the results is built with the coordinates $D_{cu,C}$ and $D_{cu,F}$; on this diagram a domain is drawn defining the accepted damage caused by the combined action of creep and fatigue. The authors have proposed the alternatives shown in Figure 4 for the diagram, considering that this solution is better than the one proposed in [2] (even though it is contrary to the previous recommendation, not to consider for the cumulative damage, D_{cu}, allowable values $D_{cu,A} = 1$).

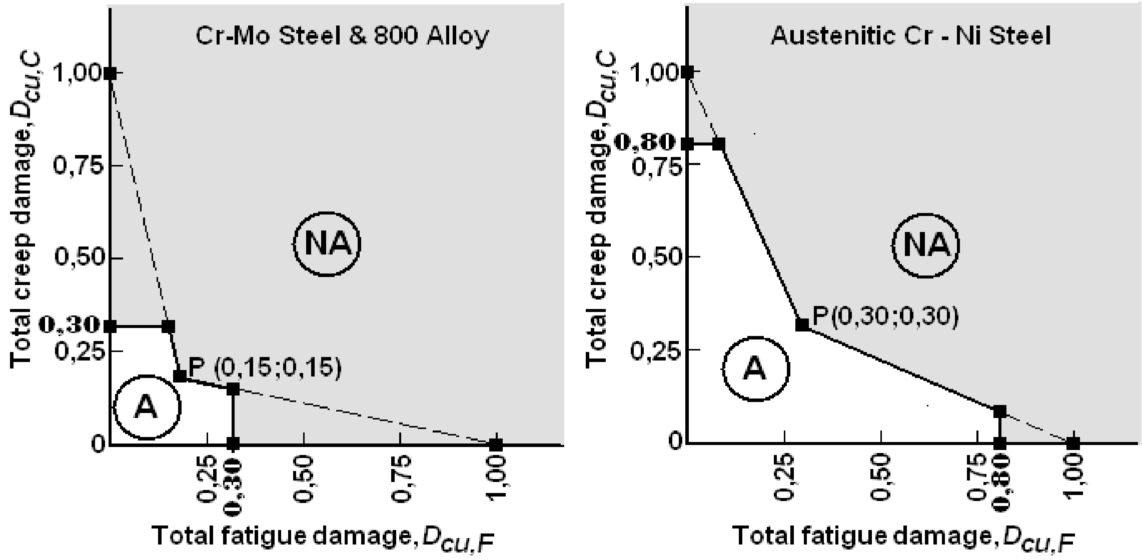

Fig. 4. PRFP damage assessment diagram for combined creep and fatigue action: A – acceptation area, NA – non-acceptation area

f) the point with ($D_{cu,F}$; $D_{cu,C}$) coordinates is placed on the diagram, and, depending on the area where it is located, the PRFP remaining life can be determined. If the point is located in the NA area, then the replacement of the pipes must be performed, while if the point is located in A area, PRFP can continue to be used safely.

Conclusions

The analyzed issues and the case study performed led to the following conclusions:

a) Continuous creep damage monitoring of furnace pipes from oil refineries and technological plants – PRFP by applying the procedure recommended in this paper is an efficient way to avoid their failure during exploitation and to ensure a proper functioning of the furnaces.

b) If the nature of the mechanical stresses that PRFP are subject to requires it, the combined effect of creep and fatigue must be taken into account, using the procedure described in the paper, when establishing the damage during exploitation; defining the variable loadings at which PRFP are subjected to is a difficult problem that requires a closer look in a future paper.

c) The results of applying the procedures presented in this paper, for the determination and estimation of the PRFP damage and of the remaining lifetime, should be corrected and adjusted periodically, based on the analysis of the actual technical condition of the pipes, each time the technical revision is performed; this measure is absolutely necessary, because beside the destructive effects of creep and fatigue, side effects may overlap, such as the modification of the chemical composition, structure and properties of the PRFP, due to the action of the fluids circulating inside the pipes and to the atmosphere within the furnaces.

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Evaluarea de tip FFS pentru țevile din otel ale cuptoarelor din rafinării

Rezumat

In lucrare sunt analizate principalele mecanisme de degradare a țevilor cuptoarelor din rafinării si instalații petrochimice şi se propune o procedură de determinare a degradării cumulate a acestor țevi, în condițiile utilizării lor timp îndelungat, la regimuri de presiune şi temperatură fluctuante în funcție de necesitățile proceselor tehnologice pe care le deservesc cuptoarele. Se stabileşte că evaluările de tip Fitness-For-Service pentru țevile cuptoarelor din rafinarii si instalații petrochimice trebuie efectuate considerând efectele fenomenului de fluaj, combinate cu cele produse de solicitările variabile (oboseală) şi de actiunea fluidului vehiculat prin țevi (care poate determina carburarea superficială a țevilor) şi a atmosferei din incinta cuptoarelor (care poate produce oxidarea şi decarburarea superficială a țevilor). Sunt precizate, de asemenea, metodele propuse pentru examinarea şi verificarea stării țevilor cu ocazia reviziilor periodice ale cuptoarelor şi modalitățile în care rezultatele unor astfel de examinări şi încercări pot fi utilizate pentru a creşte nivelul de încredere al informațiilor furnizate prin aplicarea procedurii propuse de autori pentru monitorizarea continuă a țevilor în cursul utilizării.