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The Structure for Monitoring the Technical Condition of Furnace Tubes from Refineries and Petrochemical Plants

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Abstract

A quantitative assessment of degradation is needed in order to allow continuous monitoring in operation and maintaining an acceptable level of failure risk for furnaces tubular material in refineries and petrochemical plants. This paper aims to create an assessment program that can estimate the remaining operating life, a program that can allow the correction of estimated values and the replacement of the estimated damage that results from technical periodical inspections.

Key words: *furnace tubes, degradation, assessment program, technical condition, service life*

Introduction

Furnaces tubular coils (practically a set of elements and devices: pipes or tubes, return-bends, elbows, tubular plates, supports, suspensions and other joining shaped elements [1]) are subjected to severe thermal regimes during operation.

High temperatures (350...550 °C in atmospheric and vacuum distillation units, 500...700 °C in thermal cracking plants and 650...850 °C in pyrolysis installations [2]) which causes creep degradation, the intensity of creep phenomenon increasing with temperature above the minimum level of "creep exclusion temperature" corresponding to different types of steel used for manufacturing furnaces coils in refineries and petrochemical plants; relatively high working pressure (due to the action of transmitted fluids inside the tubes), phenomenon that, combined with other loads, that can be permanent or accidental (some of which may be varying stresses), such as mass or thermal stresses and also telluric movements; and the chemically active working environment (which cause internal carburization of steel tubes due to the interaction with the mixture of hydrocarbons flowing inside the pipes and external oxidation of the tubes due to the working atmosphere in the furnace) are the main sources of degradation of tubular materials.

Therefore, the steels used to build the elements of coils must guarantee both yield strength at maximum working temperature and good mechanical behaviour in creep conditions: creep limit and creep rupture strength.

The main brands of such steels, summarized in the table below, can be found in [3] and [4], listed as materials used for elements of equipment operating under pressure at high temperatures.

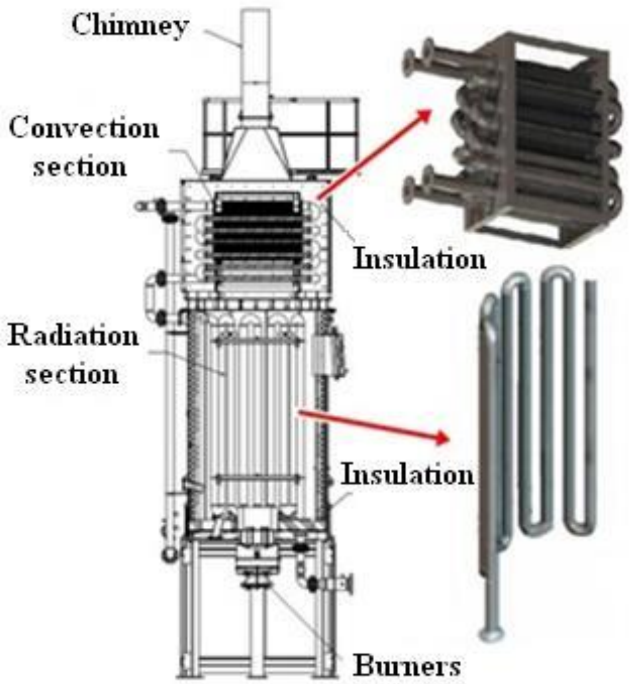

Fig. 1. The coils from the convection and radiation zones of a furnace [2]

Table 1. The main brands of steels used for furnace coils according to EN 10216-2 standard

No.	Steel	Denomination	Heat treatments
1	Carbon Steel	**P195GH**	N
2		**P235GH**	
3		**P265GH**	
4	0,5Mo	**16Mo3**	
5	1,25Cr – 0,5Mo	**10CrMo5-5**	NT, QT
6	2,25Cr – 1Mo	**10CrMo9-10**	
7	5Cr – 0,5Mo	**X11CrMo5**	I
8	9Cr – 1Mo	**X11CrMo9-1**	NT, QT, I
9	9Cr – 1Mo – V	**X10CrMoVNb9-1**	NT, QT
10	12Cr – Mo – V(W)	**X20CrMoV11-1**	
11	Austenitic Stainless Steel	**X5CrNi18-10**	AT
12		**X2CrNiMo17-12-2**	
13		**X6CrNiTi18-10**	
14		**X6CrNiNb18-10**	

The Assessment Program for the Technical Condition of Furnace Coil Elements

Scientific literature recommends the use of the following methods in order to evaluate the technical condition after a certain period of operating time for furnace tubular elements:

- metallographic structure analysis of elements of the coil [5 ... 8, 11, 13] in order to observe the structural changes and density of dislocations and the modifications on austenite grain boundaries due to the formation of carbides and voids [7] or the presence of cavities and micro-cracks in the tubular material [8];

- non-destructive inspections [6, 10] - sound waves or radiography inspections of coils to highlight areas with defects [5], liquid penetrant inspection [9, 11] and / or laser profilometry [9];
- geometric measurements for wall thickness [5, 6] and the determination of diameter changes for the pipes (increase of volume occurs due to localized overheating or prolonged exposure in creep range temperatures and the shrinkage of volume is caused by localized corrosion and/or erosion) [5];
- evaluation of mechanical properties by tensile [5] and hardness tests [5, 7, 13] in order to find areas affected by carburizing effects [7];
- use of different assessment methods to help determine the remaining life - determination of structural integrity by evaluating growth of existing microcracks [9] or use of Omega method described in API 579 and the methodology from API 530 (which considers creep as the unique degradation mechanism) - both methods presented in the two standards relying on measurements of characteristics of coil material as the basis for an eventual assessment of remaining life in terms of mechanical stresses at high temperatures [12] and also the use of software programs – for example, TUBELIFE Software to determine the remaining life [6] or finite element simulation for coil degradation [8];
- accelerated creep tests [13];
- visual inspections [5];
- internal pressure tests in order to find areas with cracks [5];
- continuous temperature monitoring of the coils (using infrared technology to identify "hot spots" before they can lead to failure) [5];
- assessment of carburizing effects (using magnets to identify high carbon areas of the coil) [5].

The assessment program for the technical condition of furnace coil elements after a certain operation period, proposed in this paper, also allows the possibility of estimating the remaining service life and monitoring them. As stated, tubular material degradation occurs as a result of action concomitant phenomena that result from the operating conditions. Carburization and oxidation phenomena causes the decrease of the effective thickness of wall tubes, while the creep and fatigue phenomena depend on operating parameters (temperature and working pressure). Degradation depends on the geometrical characteristics of tubular material parameters that continuously change as a result of oxidation, carburization, creep and fatigue phenomena.

The degradation can be estimated after the initial working period, but at every periodic inspection is necessary to evaluate the pipe geometry (outside diameter and wall thickness) in order to compare the actual degradation with the estimated degradation value. If the estimated value is inferior to the value measured after the periodic inspection the pipe can still be functional, otherwise the tubular material should be replaced.

If one of the periodic inspection shows an accelerated degradation, (below the allowable value) then the reduction of working parameters should be taken into account ($t_i<t_{i-1}$ and $p_i <p_{i-1}$) in order to extend the life of the tubular material without the replacement of the pipes.

The schematic representation of the program described above is shown in figure 2. It requires the knowledge of mechanical characteristics at each periodic inspection, so at each step, tests are needed to reveal if there are changes in the properties of the steels. Cumulating the results of these tests with degradation at some point, the remaining service life can be estimated.

In addition, to determine the remaining service life and to assess the level of damage at some point (usually at the point of time for a certain technical inspection) there is an analytical method that follows the procedures described in API 579 and BS 7910 standards that takes into account the effects of creep and fatigue, the comprehensive method being presented in [14].

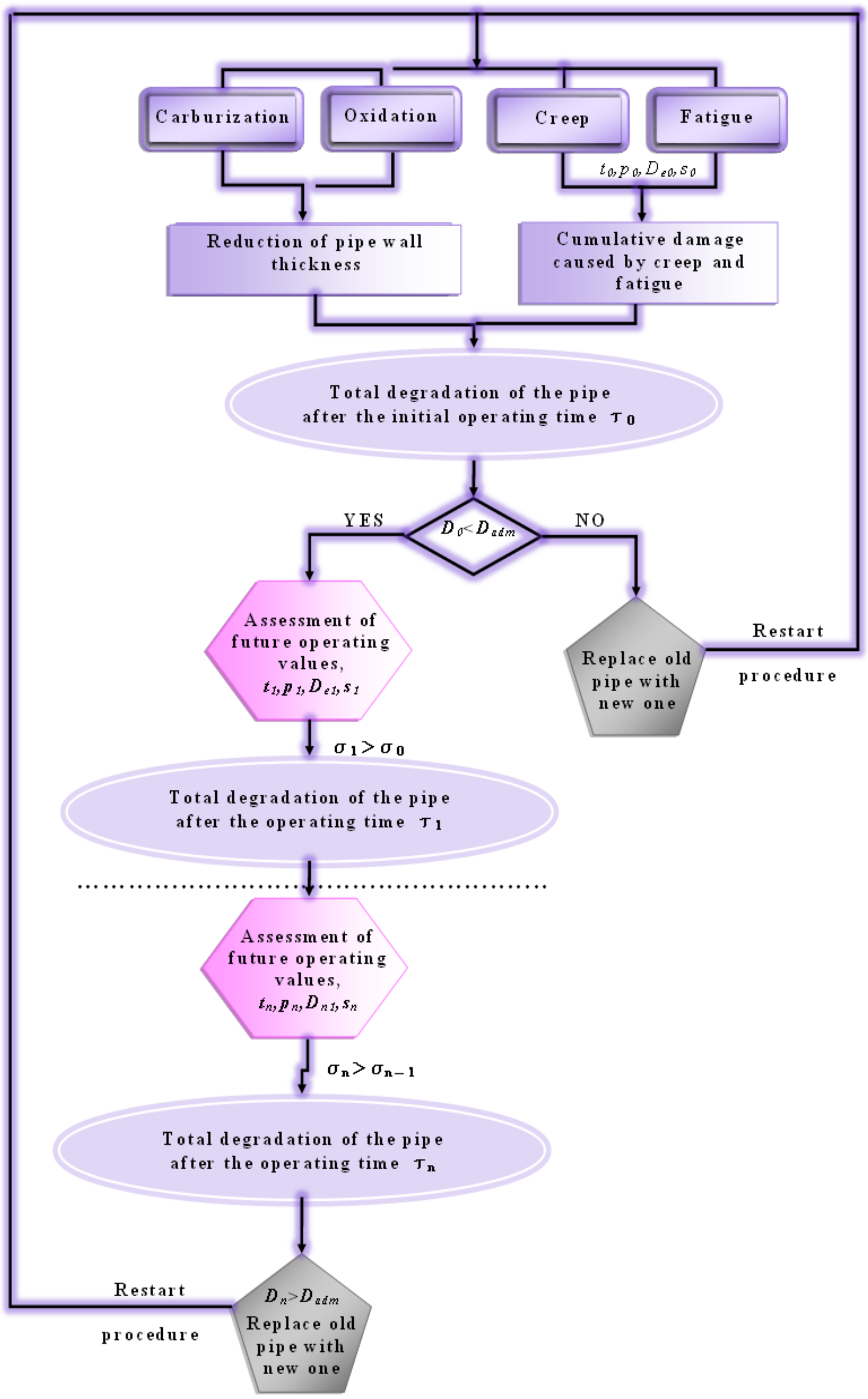

Fig. 2. The assessment program for the technical condition of furnace coil elements

The Main Tests for the Assessment Program

The remaining lifetime of coils cannot be estimated without the knowledge and/or the experimental determination of effective quality characteristics (chemical composition, microstructure, toughness, creep and fatigue characteristics, etc.) both in delivery state and after different operation periods.

To highlight the technical condition of coil elements at every technical inspection samples will be taken from the tubular material in order to get tested and the results obtained must be compared with values from samples subject to the same tests, but from new (unused) tubular material. Since there are straight and curved sections in the elements of the coils, samples from both parts will be tested.

The determination of geometrical characteristics

Measurements of wall thickness and outer diameter of the tubes will be taken in various areas to highlight the degradation effects after certain service periods of time. A decreased wall and/or outside diameter thickness will highlight the effect of oxidation on the outside of the tubes, as a result of prolonged exposure to combustion gases from inside the furnaces, while an increased wall thickness (also with the observation/identification of layer deposition, when possible) will attest the carburizing effect, occurred due to penetration of carbon into the surface of the coils.

Microstructure analysis

The surfaces for metallographic examination will be properly prepared by grinding, polishing and metallographic attack using Nital.

The aim will be the examination with optical microscopes for microstructure samples taken from different areas of tubular material and the examination with SEM and EDX to highlight composition changes in the superficial layers (from both inside and outside of tubes) of samples taken from different areas of tubular material, with examination, photography and interpretation of results obtained.

Microstructural evaluation will be carried out using the recommendations presented in [15].

Determination of chemical composition

Determination of chemical composition by spectrometry method of samples taken from new (unused) tubes and samples from different areas of tubular material which operated certain time periods in order to determine the mass concentrations of the main alloying elements (C, Mn, Si, S, P, Cr Ni, Mo, V) of steels used for the fabrication of coils, will be made on the same samples used for hardness tests. The minimum average of three determinations for each of the tube elements, both on the outside and the inside of the tube, will be made, so that the chemical composition determined should be in accordance with [4]. An increased carbon concentration on the inside of the tubes will attest carburizing effects.

Hardness test

In order to determine the harness of the tubular material minimum three samples of 25x25 mm will be taken from the coil and the average of the determinations will be made for each of the distances, in the thickness of the material, in at least 10 points from the inside to the outside of the sample as the obtained values will be compared with those of an unused, similar steel.

Because of the carburizing process inside the tubes, due to hydrocarbons movement through the coils at high temperatures, which favours the passage of carbon from the environment in the surface of the steel, higher hardness values on the inside of the tubes will attest damage by carburization phenomena.

Flattening test

In order to determine plasticity and toughness loss, flattening test, whose schematic diagram is shown in figure 3, will be used. Pipe section type samples will be taken from the coil for the determination of flattening before cracking.

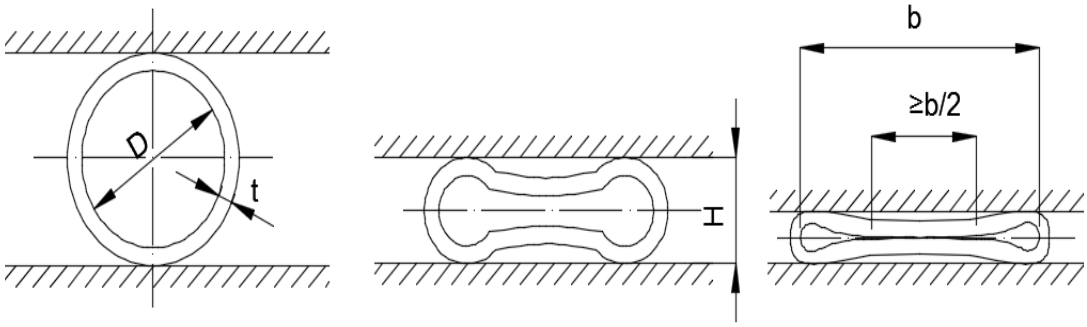

Fig. 3. Schematic representation of flattening test

Tests carried out must be in accordance with [16], as the standard specifies the method for determining the plastic deformation ability by flattening metal tubes with circular cross section. This method can also be used to highlight flaws.

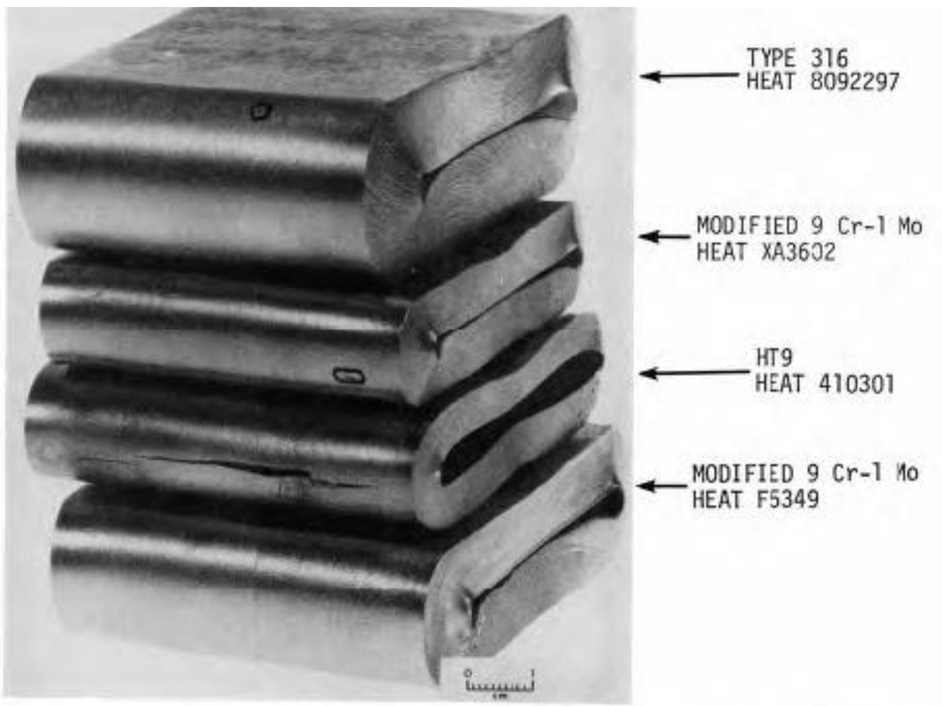

Fig. 4. Flattening test behaviour of different steels used for the fabrication of furnace tubes [17]

Rings type samples taken from new (unused) tubes will flatten complete as their inside surfaces will come in contact with each other when the maximum pushing force is reached.

If rings taken from tubes with different operating periods of time will not produce a complete flattening, the test will reveal that exploitation at high temperatures in an environment that favours carburizing makes tubes degrade considerably, becoming fragile and break when the maximum pushing force at relative low radial movement is reached.

Figures 5 and 6 show the behaviour of samples taken from tubes with various service times at high temperatures.

Fig. 5. Images of samples tested for flattening (from bottom to top), taken from tubes that operated 3000 hours at 482 ^{0}C, 538 ^{0}C, 593 ^{0}C, 649 ^{0}C, and 704 ^{0}C, respectively [17]

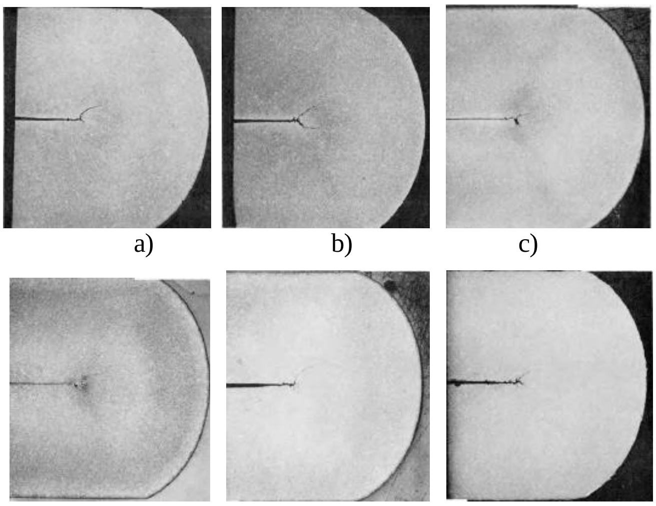

Fig. 6. Cross-sections of 9cr-1Mo steel samples with different operating periods of time at different temperatures subjected to flattening tests: a) non-aged; b), c), d), e), f) 3000 hours at 482 ^{0}C, 538 ^{0}C, 593 ^{0}C, 649 ^{0}C, and 704 ^{0}C, respectively [17]

For conclusive test results obtained after flattening tests the recommendations of [17] will be followed.

Tensile test

Tests aim to determine mechanical characteristics in accordance with [18], at room temperature and to verify the compliance with [19]. At least three samples from the tubes will be taken, in order to build the stress-strain curve and to determine the following features: the yield stress, $R_{p0,2}$, ultimate tensile stress, R_m, percentage elongation after fracture, A and the necking coefficient, Z .

Eventually, if the owned equipment allows, tensile mechanical properties at elevated temperature (T_{max} = 600 ° C): R_m, A and Z shall be determined with at least three cylindrical samples taken from the tubes.

Impact test

Determination of impact energy, *KV* using the impact test at room temperature, in accordance with [20] on tube samples.

Fatigue test

Determination of fatigue resistance using rotating bending fatigue test at room temperature, with fatigue limit corresponding to the maximum rupture stress for the number of cycles equal or superior to 10^6 cycles [21], on tube samples will be made.

If the owned equipment allows the determination the fatigue resistance at higher temperatures, T> 20 °C (T_{max} = 800 °C) than samples taken from the same tubes as for room temperature rotating bending fatigue test will be also tested in order to determine fatigue resistance at elevated temperatures. Scientific literature [22], also recommends other mechanical tests that can be done in order to establish the technical conditions of furnaces tubes:

Ring expanding test

The test will be made complying the guidelines from [23], which reqiure the passage of a mandrel with a 1:5 taper, at a maximum speed of 30 mm/s through multiple rings with lengths between 10 and 16 mm, cutted from the tubes, placed as shown in Figure 7.

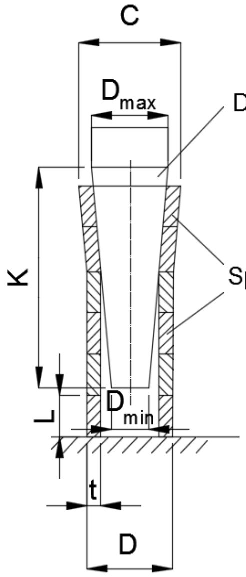

Fig. 7. Schematic representation of Ring expanding test

Ring tensile test

According to [24], this test involves placing a ring with a length of about 15 mm, cutted from the tubes, between two bolts with diameters of at least three times bigger than the wall thickness of the ring and the pulling in the vertical direction until this sample breakes. Welded zones (if existant) should be positioned so that the welded joint forms a right angle with the pullin direction, as shown in figure 8. The pulling speed of this test will not exceed 5 mm/s.

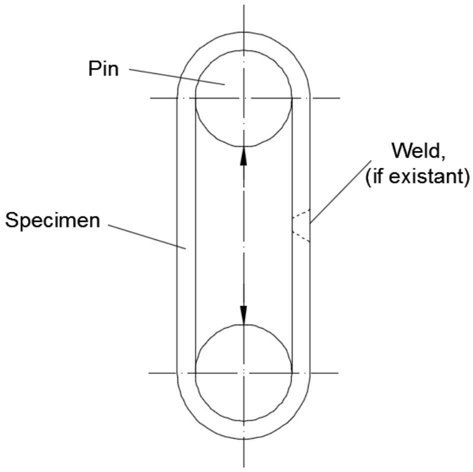

Fig. 8. Schematic representation of Ring tensile test

Drift expanding test

The test is regulated by [25] and involves pushing a mandrel at speeds that don't exceed 50 mm/s, in a ring with length, *L* and diameter, *D*, until the outer diameter reaches a prescribed value, *C*. After the test, the samples will be examined for defects with normal visual acuity. The test result shall be declared satisfactory if the prescribed value, *C* was reached without any defects on tested samples. The schematic representation of the test and the geometric charachteristics of the mandrel depending on the lenght of the samples can be found in Figure 9 and in table 2, respectively.

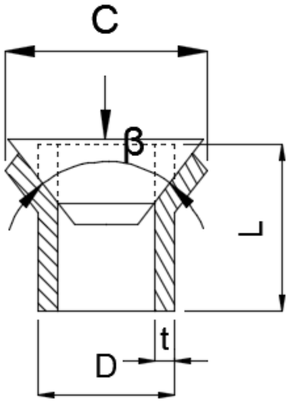

Fig. 9. Schematic representation of Drift expanding test

Table 2. Geometric characteristics of drift expanding test

Material	Length of specimen, L* [mm]	Taper angle, β
Steel	≤2D	30^0
	≤1,5D	45^0, 45^0, 120^0

*L≥50 mms

Flanging test

The test is performed as described in [26] and involves using the device shown in figure 10. It involves the curving of a tube sample with a certain length, *L* = 1,5*D*, until the outer diameter reaches the prescribed values for both the outer diameter, *C* and the radius, *r*, at speeds that must not exceed 50 mm/min. The test result shall be declared satisfactory if no visible cracks appear on the samples tested, while minor defects at the edges can be considered negligible.

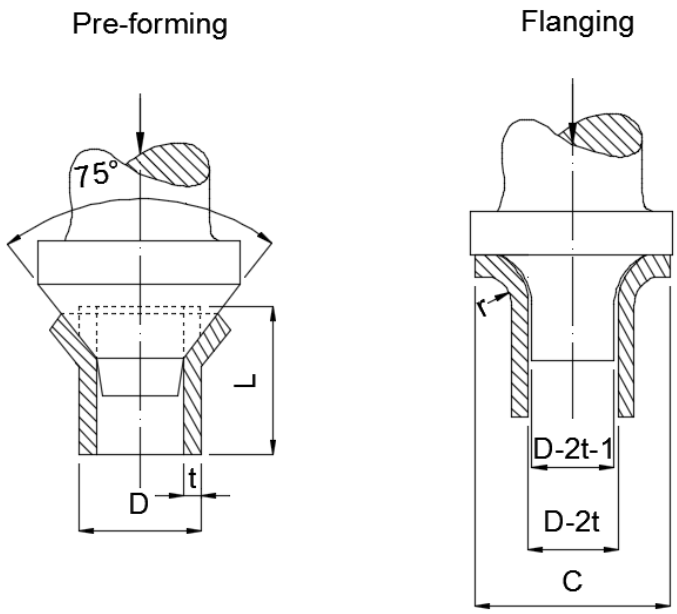

Fig. 10. Schematic representation of Flanging test

Bend test

According to [27] the test implies bending a sample, having the width, *b* and thickness, *a*, taken from the tubes using the device shown in figure 11, until reaching the prescribed angle, α, or until the sample fails. The test result shall be declared satisfactory if the angle α, will reach the prescribed value before breaking. If at the end of the test the sample will return to the initial form, the test will be repeated.

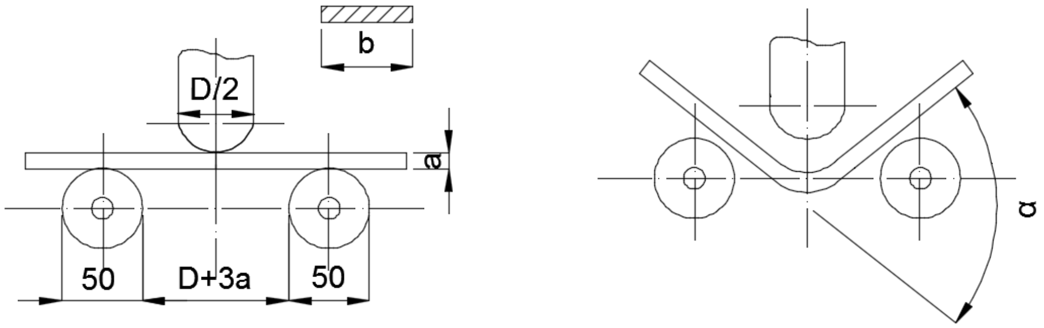

Fig. 11. Schematic representation of Bend test

According to [4] for elements made from ferritic stainless steels the following two kinds of tests will be performed:

A. Required/Mandatory tests, that include:

1. Determination of chemical composition with the verification of the obtained values by checking so that the chemical composition determined should be in accordance with the values prescribed by the standard;

2. Tensile tests at room temperature;

3. One of the following tests:
   a) Flattening test for elements with $D< 600$ mm and the ratio $t/D\leq 0.15$, but with $t\leq 40$ mm;
   b) Ring tensile test for elements with $D> 150$ mm and $t\leq 40$ mm;
where: D is the external diameter of the pipe; t is the wall thickness of the pipe.

4. Alternatively, one of the following tests:
   a) Drift expanding test for tubes with $D\leq 150$ mm and $t\leq 10$ mm;
   b) Ring expanding test on tubes with $D\leq 114.3$ mm and $t\leq 12.5$ mm;

5. Impact tests on tubes made of one of the following steels: 14MoV6-3, 25CrMo4, 20CrMoV13-5-5, 15NiCuMoNb5-6-4, X10CrMoVNb9-1, X20CrMoV11-1;

6. Leak tightness test;

7. Dimensional Inspection/Measurement of the main geometrical features;

8. Visual inspections;

9. Examination by NDT in order to detect longitudinal imperfections;

10. Alloy steel type identification.

B. Optional tests:

1. Determination of chemical composition with the verification of the obtained values by checking to see if that the differences obtained are within the approved limits prescribed by the standard;

2. Tensile testing at elevated temperature;

3. Impact testing for the steels not listed on A5;

4. Impact testing at low temperatures (-10 ^{0}C) for non-alloy steels;

5. The measurement of the wall thickness;

6. Examination by NDT in order to detect transverse imperfections;

7. Examination by NDT in order to detect laminar imperfections.

For samples made from austenitic steels according to [4] ferritic stainless steels, will perform two types of tests:

A. The tests required / mandatory:

1. Determination of chemical composition with the verification of the obtained values by checking so that the chemical composition determined should be in accordance with the values prescribed by the standard;

2. Tensile testing at room temperature;

3. One of the following tests:
   a) Flattening test;
   b) Ring tensile test;
   c) Drift expanding test;
   d) Ring expanding test;

4. Leak tightness test;

5. Dimensional Inspection/Measurement of the main geometrical features;

6. Visual inspections;

7. Examination by NDT in order to detect longitudinal imperfections for tubes with $D > 101.6$ mm or $t > 5.6$ mm;

8. Alloy steel type identification.

B. Optional tests:

1. Determination of chemical composition with the verification of the obtained values by checking to see if that the differences obtained are within the approved limits prescribed by the standard;

2. Tensile testing at elevated temperature;

3. Impact test at room temperature;

4. Impact test at low temperatures;

5. Intercrystalline corrosion identification tests;

6. Wall thickness measurements;

7. Examination by NDT in order to detect imperfections in the longitudinal $D \leq 101.6$ mm pieces with and $t \leq 5.6$ mm;

8. Examination by NDT in order to detect transverse imperfections;

9. Examination by NDT in order to detect laminar imperfections for tubes with $t > 40$ mm.

Conclusions

During operation, the tubular material is subjected over prolonged periods of time to severe working conditions such as temperatures in creep range, relatively high pressure due to circulating fluids inside the tubes and active chemical environment that can produce carburization and/or oxidation at the surface of the tubes.

Furnace coils elements require a quantitative assessment for degradation that can provide the continuous monitoring of the technical state of coil elements in order to maintain an acceptable failure risk level. Carburization and oxidation phenomena cause the actual decrease of wall thickness as degradation depends on geometrical characteristics, so the decrease of the effective wall thickness and chemical composition changes decrease the toughness of steels used for the manufacturing of tubular material, considerably reducing the service life of the coils.

It is necessary that at every periodical inspection to assess the remaining service life of furnace coils by keeping a precise record of working parameters, creating a map of coils elements and specifying the technical condition and service life of each component of it, and to make the necessary tests that can provide sufficient information for a precise estimation of the remaining service life. Therefore, the assessment program for the technical condition of furnace coil elements that allows the correction of previous estimated values and the replacement of the damage rate that results from periodic technical revisions was created and discussed in this paper.

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Structura de monitorizare a stării tehnice a tubulaturilor cuptoarelor din rafinării și instalații petrochimice

Rezumat

O evaluare cantitativă a degradării este necesară pentru a putea permite monitorizarea în exploatare şi menţinerea la un nivel acceptabil a riscului de cedare a materialului tubular al cuptoarelor din rafinării şi instalaţii petrochimice. Se urmăreşte crearea unui program de evaluare a stării tubulaturii care să poată estima durata de viaţă remanentă şi care să permită corectarea valorilor estimate şi înlocuirea valorii degradărilor cu cele determinate în urma reviziilor tehnice periodice.