La Metallurgia Italiana
International Journal of the Italian Association for Metallurgy

# Mechanical characterization of the ASTM A335 P5 steel and reliability of radiant tubes after long operating time in a petrochemical industry furnace

P. Aliprandi, E. Guglielmino, A. Sili

This paper deals with mechanical characterization of ASTM A335 grade P5 steel specimens, taken from two radiant tubes of the Milazzo Refinery topping furnace, which were put out of service because they underwent unacceptable thickness reductions from 7 to 4 mm. Radiant tubes are designed to guarantee long operation times at the working temperature, therefore periodic inspection are scheduled to verify their reliability and dismount the damaged ones. Chemical composition resulted slightly different in the two considered tubes, even if within the limits of the Standard. Our investigations showed that the tube richer in alloying elements is characterized by a finer microstructure and better tensile and creep properties. The creep test results were compared by means of the Larson-Miller parameter; then the residual life of the two tubes was estimated numerically, by a procedure developed by us to take into account both creep data and progressive wall thickness reduction. By this way we ascertained that many years of residual life can be foreseen at temperatures up to 600°C. It is equal to some years at 700°C, but is reduced drastically to few hundreds of hours at 800°C for the less alloyed tube. We concluded that, in order to guarantee safe operating conditions at least until the subsequent scheduled plant stop, it is strongly advisable to replace the radiant tubes when their thickness is reduced to 4 mm and to monitor regularly that surface temperature is not higher than 600°C.

**KEYWORDS:** RADIANT TUBES, ASTM A335 P5 STEEL, MECHANICAL PROPERTIES, CREEP, RESIDUAL LIFE, TEMPERATURE.

## INTRODUZIONE

The ASTM A335 / ASME SA335 Standard identifies ferritic steels largely utilized in fossil power plants and in petrochemical industry at temperature around 600°C. These steels are characterized by Cr contents up to 9% and Mo not higher than 1%. The ASTM P11 (1.25Cr-0.5 Mo) and P22 (2.25Cr-1Mo) grades are those historically more widespread; nowadays ferritic steels containing higher amounts of Cr and Mo, together with the addition of other microalloying elements, are produced. In [1] the authors follow the historical development of creep resistant steels, showing the good influence of Mo and Cr on creep strength in low alloyed ferritic steel, which was experimented since the 1950s. Their properties are documented in technical literature, where creep data for ASTM A335 steels (only in the as produced conditions) are allowable [2].

The microstructural features after long operating time are of current interest among researchers and some resul-

P. Aliprandi, E. Guglielmino, A. Sili
Dipartimento di Ingegneria - Università di Messina - Messina - Italy

ts concern our investigations: Michel et al. [3] noticed in 10CrMo9-10 steel, after 2.1•$10^5$ hours of service at 530°C, several microstructural deteriorations that give rise to pearlite spheroidization, coarse carbide segregation at grain boundaries and increasing of precipitation inside the ferritic matrix if compared to the initial state. In [4] scanning electron microscope observations on specimens of 20CrMoV5-8 steel, after $10^5$ hours under creep conditions, show precipitate coagulation in the pearlitic areas, that simultaneously increase their size, and transformation of the initial fine precipitation inside the ferritic grains into coagulated precipitates.

Concerning mechanical properties, Masuyama, in a review on progress in heat resistant steels [5], dealt with the effects of Cr: the best creep behavior is experimented with percentages not exceeding 9%, despite higher chromium contents increase steel resistance to hot oxidation. Moreover, the presence of Mo around 1%, together with microalloying elements, such as V and Nb, gives good mechanical strength at high temperature. In particular V and Nb exhibit optimal contents in combined addition, respectively around 0.2% and 0.05%.

Creep strength decreases due to microstructural changes, such as coarsening of precipitate and decreasing in dislocation density. On these drawbacks Kimura et al. [6] highlighted the role of the initial microstructure and the negative effects of its degradation. They found in high Cr steels with tempered martensitic microstructure the importance of its stability at elevated temperature to obtain high creep strength during long-term. Actually the microstructural stability, as reported in [7] for 9-12% Cr steels, depends on the precipitates morphology. Better creep results were obtained in [8] for two different 9% Cr steel with low carbon content, reduced sub-grain growth and very slow coarsening of MX carbonitrides.

Fine stable alloy carbides prevents dislocation movements reducing creep rate, however a degradation of such structures during a long time service results in a reduction of creep life. These phenomena can be affected by the initial thermal treatment, as reported by Gonzales et al. [9], that experimented for the 1%Cr-0.5%Mo steel the beneficial effects of austenitization at 1223 K, followed by air cooling and tempering at 1023 K for 3 hours and cooling in air again.

Michel et al. [10] investigated in a 10CrMo9-10 steel tube the gradual transformation of the initial ferrite – pearlite microstructure: after about $10^5$ hours of service at 530°C, the microstructure is still ferrite-pearlite, but pearlite was spheroidized more. The spheroidizing process is complete after 1.57•$10^5$ h. Then, after 2.6•$10^5$ h, scattered carbides inside the ferritic grains and coarse carbide particles segregated at grain boundaries in the form of net like patterns can be observed.

Anyway the main problem in managing of petrochemical furnaces, besides the verification of any accidental damage, is represented by the evaluation of radiant tubes residual life in order to allow safe operating conditions at least until the next scheduled plant stop, taking into account factors of uncertainty such as the actual temperature. Because its determination by means of pyrometers involves a wide range of error, radiant tubes may undergo working conditions more severe than expected, which can further reduce their life. So it is advisable to evaluate their residual life on the basis of creep test performed on specimens cut from tubes dismounted after long time of service, as performed by us in [11] for radiant tube made of the ASTM 608 HP–Nb alloy.

Therefore many activities, including both internal and external inspection methods, are usually performed to check tubes conditions and identify any local problems of overheating and consequent corrosive phenomena, which are usually detected by in-line ultrasonic measurements [12]. In the case of radiant tubes working at very high temperatures, due to the uncertainty in foreseeing creep deformations, the internal diameters are measured by a laser probe system at every scheduled plant stop [13].

Plant managements are primarily interested in foreseeing the residual life of radiant tubes, which must not fail at least until the subsequent scheduled plant stop. Therefore we investigated mechanical properties of radiant tubes made of ASTM A335 grade P5 steel, which were decommissioned from the topping furnace of the Refinery of Milazzo, after 2.3•$10^5$ hours of service. In [2] the Larson-Miller (LM) diagrams for the ASTM A335 steels are drawn with creep data obtained utilizing specimens made of material in the as produced conditions. In order to take into account the damage due to service, we performed creep test on specimens cut from a tube dismounted from a topping furnace with the aim to draw the relative LM diagram [14]. We developed also a numerical method to calculate the residual life, considering both the indications on creep life coming from the LM diagram and the progressive wall thickness reduction which is measured on radiant tubes. By this way we took into account on one hand the consequences of microstructure features that influence the creep test results and on other

the effects of corrosion phenomena.
In the present paper, the above said investigation was expanded to another radiant tube, decommissioned from the same furnace. This tube revealed small differences in composition compared with the one investigated in [14], even if the alloying elements are within the limits of the ASTM A335 P5 Standard. Thus our primary interest is to compare the results of mechanical characterization of specimens cut from these two radiant tubes, which were dismounted after 230000 hours because unacceptable thickness reductions were locally detected by ultrasonic measurements during a recent scheduled plant stop. Crude oil, flowing inside the tubes at a pressure of 7.5 bar, is heated up to 350°C by the radiant heat provided by gas burners installed on the furnace walls. Although tubes are designed to work over 200000 h around 500°C, some environment conditions, such as bad flames regulation, can give rise to local damages that make necessary tubes decommissioning. Therefore "in situ" inspections, as visual observations of tubes external surface, ultrasonic measurements of tube thickness, metallographic investigation by the "replica method" and Vickers hardness test, are usually performed during every scheduled plant stop with the purpose of identifying the tubes to put out of service.
Our investigation highlighted different mechanical properties and small differences in composition in the two decommissioned tubes. Composition measurements on the specimens cut from the two tubes were performed by X-Ray Fluorescence (XRF) and by hot gas extraction technique as concern carbon content. Tensile and creep test were carried out at various temperatures. Creep test results were analyzed by means of the Larson Miller parameter. A numerical procedure was developed to evaluate the residual life of the two decommissioned tubes, taking into account the stress increment due to the thickness reduction that would take place in the case of further permanence inside the topping furnace. Finally this procedure was applied to simulate the consequence on residual life of accidental overheating, with the aim to ascertain the tubes reliability respect to an increment of temperature and avoid unplanned shutdowns.

## MATHERIALS AND METHODS

The radiant tubes investigated by us are made of ASTM A335 P5 steel. For the Standard composition see table 1: it is worth to notice that the Mn, Cr and Mo percentages are within limits which are enough wide to involve variations in mechanical properties. They were produced by hot forging and have length 19.3 m, external diameter 168.275 mm and thickness 7.11 mm. Their external surface is subject to radiant heat supplied by gas burners, in order to heat the crude oil flowing inside them from room temperature up to 350 °C. The internal pressure (7.5 bar) determines hoop stress equal to about 9 MPa.
Mechanical properties at room temperature of the ASTM A335 P5 steel are given in table 2 [15]. The recommended heat treatment consists of normalizing and tempering at 675 °C, anyway at a temperature higher than the operating one [15].

**Tab.1** - Standard composition of the ASTM A335 P5 steel (weight %).

| C max | Mn | P max | S max | Si max | Cr | Mo | Fe |
|---|---|---|---|---|---|---|---|
| 0.15 | 0.30-0.60 | 0.025 | 0.025 | 0.50 | 4.0-6.0 | 0.45-0.65 | Bal. |

**Tab.2** - Mechanical properties at room temperature of the ASTM A335 P5 steel.

| Yield strength (minimum value) (MPa) | Ultimate tensile strength (minimum value) (Mpa) | Elongation (%) |
|---|---|---|
| 205 | 415 | 20-30 |

During a recent plant stop (it is usually scheduled yearly), radiant tubes were subjected "in situ" to visual inspections, ultrasonic measurements of thickness, metallographic observations by replica method on their external surfaces, mechanically prepared and etched by the Vilella's reagent.
The direct contact of tubes with flames depends on an incorrect regulation of the fired heaters operating parameters [16]. Tubes are decommissioned when their external surfaces show burns due to flame impingement. In particular when they show oxidized zones affected by thickness reduction greater than 3 mm, being equal to 4 mm the minimum wall thickness for safe operating according

to the plant managing practice. Therefore the experimental investigations were addressed to ascertain the reliability of a residual thickness equal to 4 mm respect to accidental overheating.
The ultrasonic measurements were performed by a portable meter with standard resolution of 0.01 mm, frequency range 2,25 ÷ 10 MHz and operating temperature -10 ÷ 50°C.
In this work we recalled the investigation performed on a first tube [14], in order to have a comparison with the results obtained by testing the specimens cut from another tube. Both the tubes (in the following indicated as tube A and tube B) come from the central room of the topping furnace, have the same size and were put out of service after 230000 hours.
The specimens cut from the two tubes showed slight difference of chemical composition as reported in the following (see table 3 in the Results section).
Chemical compositions were measured by a X-Ray Fluorescence (XRF) spectrometer equipped with a X-ray generator (Rhodium anode, accelerating voltage and current respectively up to 50 kV and 200 mA) and Silicon drift detector; Carbon content was determined by means of an element analyzer based on the principle of the carrier gas hot extraction (CGHE).
Metallographic preparations were performed "in situ" on tubes selected surfaces, grinding them by abrasive disc, disc with abrasive paper and then disc with velvet cloth and diamond paste; finally cleaning by denatured alcohol and etching by the Vilella's reagent for 5-10 s. Optical microscopy observations were carried out by the replica method, making the replicas by means of a cellulose acetate thin tape and then metallization with gold.
Tensile and creep tests were performed on flat specimens cut from the two dismounted tubes, with gage length equal to 47 mm and cross section 10x3 $mm^2$ according to the ASTM E8 M Standard. We utilized a machine for tensile and creep test which works with temperatures up to 950°C and static loads up to 20 kN. Tensile tests were performed under strain control at rate equal $1.7 \cdot 10^{-3}\ s^{-1}$. Creep test loads were constant and chosen to keep the stationary creep rate not higher than $10^{-5}\ s^{-1}$. Vickers microhardness were measured applying a load of 300 g for 15 s.

## RESULTS

### Visual inspections and non-destructive measurements by ultrasounds

Burns on the tubes external surfaces, due to flame impingement, were clearly identified by visual inspections inside the furnace chambers (fig. 1a). The exposure to flames caused serious damaging, because wall temperatures exceeding 700°C led to coke deposition from crude oil on the inner surface (fig. 1b), as it is also documented in [17]. This carbon sediment reduced the dissipation of thermal flow coming from the external surfaces, generating further overheating with consequent acceleration of the hot oxidation process. Ultrasonic measurements performed in the zones affected by flame impingement showed thickness reductions greater than 3 mm, which made necessary the tube replacement.

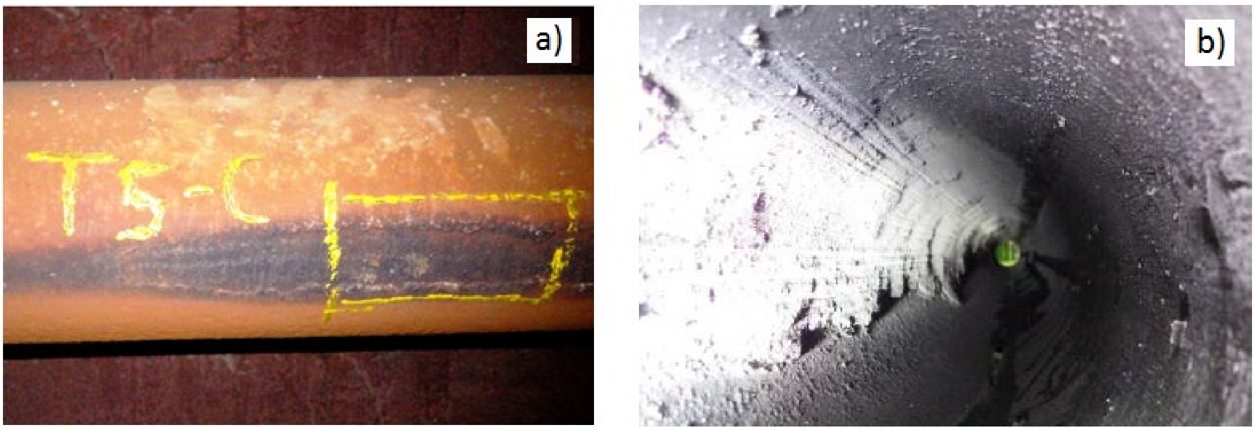


**Fig.1** - External burning (a) and carbon sediment on tube internal surface (b).

### Experimental composition

Results of XRF and hot gas extraction measurements are given in table 3 for both the two tubes.
The compositions are within the composition range of the ASTM A335 P5 Standard and carbon content is lower than the maximum limit equal to 0.15%.

Tube A is more alloyed than tube B. The alloying elements of tube A are about in the middle of the Standard limits; while, in tube B, Mn and Cr are close to the lower limits and Mo is equal to the lower limit. It is well known that Mn and Si are effective in solid solution strengthening (see ref. [18] for a quantitative evaluation). Mo is useful also to enhance creep strength: in particular creep strength increases with the equivalent percentage of Mo up to a peak, that is when (Mo + 0.5W) = 1.5% [5]. As for the role of Cr about mechanical properties, it is a carbides former; but the kinetic of precipitation and stability of Cr-carbides depends on the initial thermal treatment and the subsequent ageing conditions at high temperature [9,10]. Unluckily, after so many years, it is difficult to trace with certainty the conditions of the initial heat treatment.

Tubes are usually stocked by the plant management and utilized when it is necessary, so it is plausible that tubes coming from different producers are put in service at the same time. This consideration can explain also the reason of different compositions measured by us.

**Tab.3** - Experimental values of composition of the two tubes.

| C | Mn | P | S | Si | Cr | Mo | Fe |
|---|---|---|---|---|---|---|---|
| Tube A | | | | | | | |
| 0.12 | 0.49 | 0.04 | 0.02 | 0.33 | 4.9 | 0.48 | Bal. |
| Tube B | | | | | | | |
| 0.11 | 0.36 | 0.05 | 0.07 | 0.27 | 4.3 | 0.45 | Bal. |

**Metallographic observation and Vickers hardness test**

Metallographic observations performed by the replica method pointed out a ferritic microstructure with grain size scattered in a wide range. During service metallic carbides precipitated inside ferritic grains and at their boundaries, as shown by the micrographs of tubes A and B in figure 2; the respective hardness values are 140 and 123 HV. Tube A, with greater hardness, is characterized by finer grains and more distributed carbide precipitation inside ferritic matrix than tube B.

Considering that tensile and creep testing is the primary focus of our work in order to ascertain the reliability of tubes, metallographic investigation was limited to optical microscopy, without elaborating a more in-depth carbides characterization. Anyhow our observations match with those reported in literature: in addition to the aforementioned work of Michel et al. [10], Ferreira Lima et al. [19] followed in 2.25%Cr-1%Mo steel specimens the progressive cementite spheroidization and precipitation coarsening at temperature equal to 600°C and ageing time from 100 to 2000 h.

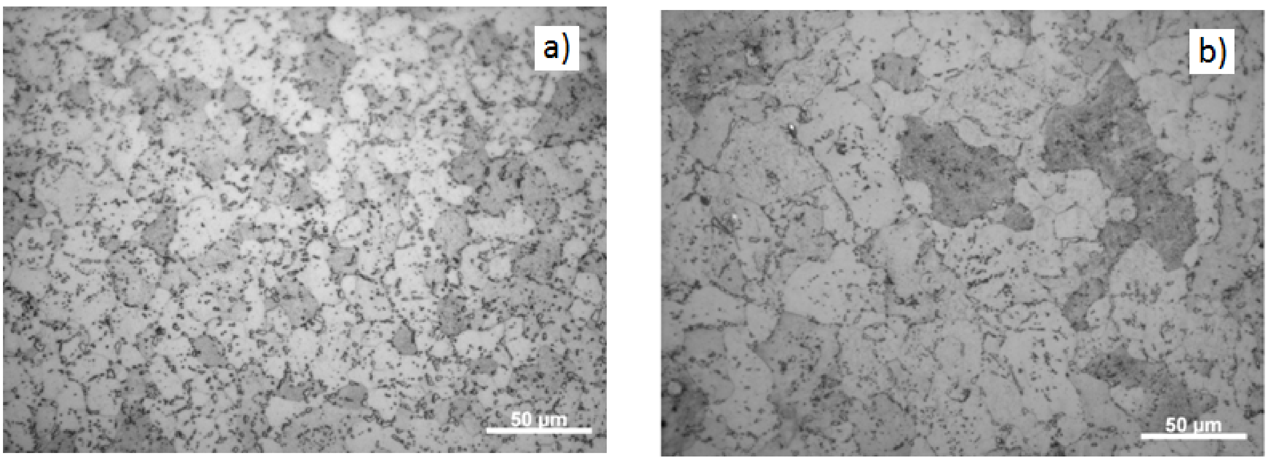


**Fig.2** - Optical micrographs of the external surface: a) tube A, b) tube B.

**Tensile test**

Stress-strain curves show higher mechanical strength and lower ductility for specimens A than for specimens B (fig. 3a). At room temperature, yield strength and ultimate tensile strength of the two tube are above the minimum values prescribed by the ASTM Standard (table 2).

As temperature increases, mechanical strength decreases progressively and more significantly above 600°C: in particular at 650°C yield and ultimate tensile strength are about one third of the respective values at room temperature, while ductility grows by about 50% (fig. 3b).

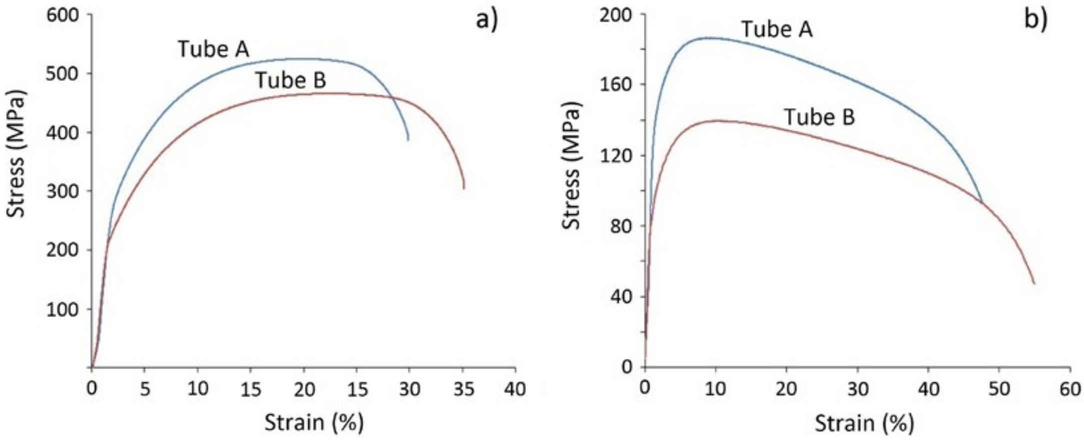


**Fig.3** - Stress-strain curves: a) room temperature, b) T=650°C.

### Creep test

Also for creep behavior the specimens coming from tube A are characterized by greater performances than those from tube B. Figure 4a shows the strain-time curves obtained at temperature T = 650 ° C and applied load **σ** = 70MPa: rupture time is equal to 78 h and 58 h, respectively for tube A and B. Residual life in the operating condition can be extrapolated by means of the experimental points on the LM diagram in figure 4b, where **σ** (Mpa) is the testing load and LMP = T(C + log t) the Larson-Miller parameter (LMP), with T (K) test temperature, t (h) rupture time and C a characteristic constant, assumed equal to 20 for the ASTM A335 P5 steel [20].

The following considerations can be deduced:

- due to damaging phenomena occurred during service, the experimental points of the two dismounted tubes are below the dashed line in figure 4b, characteristic of the ASTM A335 P5 creep behavior [20];
- the position of the experimental data of tube A indicates a better creep behavior than tube B.

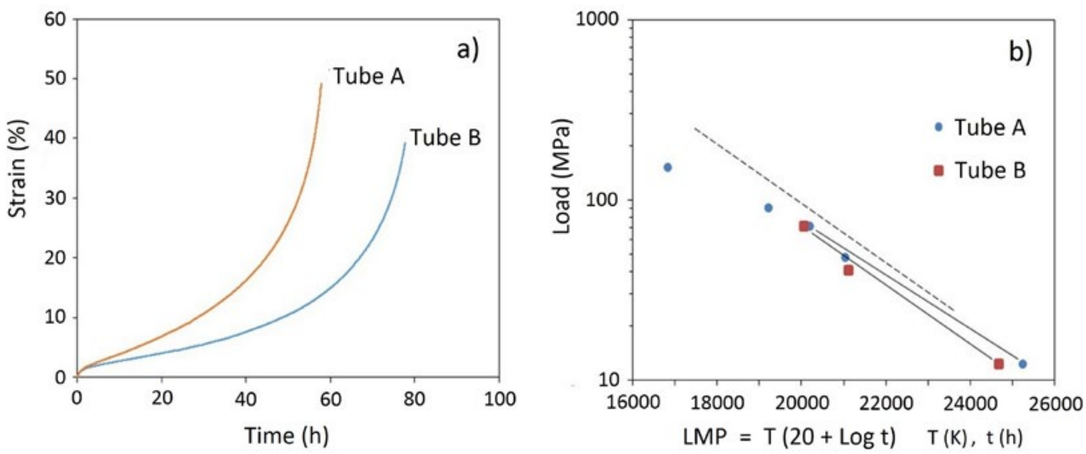


**Fig.4** - Creep curves in comparison obtained at 650°C and 70 MPa (a) and experimental points on the Larson-Miller diagram (b).

## DISCUSSION

In the case that tubes A and B remain in service, in order to calculate their residual life, we took into account the two combined effects of creep behavior (that is shown by the LM diagram) and corrosion phenomena (that cause significant thickness reduction after long operating time).

According to a management practice, the two tubes were decommissioned after 230000 hours of service because they underwent a thickness reduction from 7 to 4 mm; so it is reasonable to assume a corrosion rate of 3 mm in 230000 h; therefore the hoop stress ($\sigma_t$) grows over time (t) as the wall thickness is reduced progressively starting from the value $b_o$:

$$\sigma_t = \frac{p \cdot R_m}{b_0 - \Delta b} = \frac{p \cdot R_m}{b_0 - \frac{3}{230000} \cdot t} \quad 1)$$

Being p=0.75 MPa the internal pressure, $R_m$=84.1 mm the average radius, $b_0$=4 mm the tube thickness at the beginning of the simulation and Δb the wall thickness reduction after the time t.

At the beginning t=0, Δb=0, then the hoop stress $\sigma_0$ results:

$$\sigma_0 = \frac{p \cdot R_m}{b_0} \quad 2)$$

During the time t the tube wall is subjected to increasing hoop stress, starting from the value $\sigma_0$ (eq. 2) and growing up to $\sigma_t$ (eq. 1). However, it is reasonable, as a first approximation, to assume for the hoop stress the mean value ($\sigma_a$), constant during all the interval of time t:

$$\sigma_a = \frac{\sigma_t + \sigma_0}{2} \quad 3)$$

Catastrophic failure of tube takes place when $\sigma_a$ equals the creep rupture stress. It can be expressed by interpolating linearly the experimental data in figure 4b, respectively for tube A and B.

Tube A:

$$\sigma_a = 302 - 0.0115\ LMP = 302 - 0.0115 \cdot T \cdot (20 + \log t) \quad 4)$$

Tube B:

$$\sigma_a = 323 - 0.0126\ LMP = 323 - 0.0126 \cdot T \cdot (20 + \log t) \quad 5)$$

Rupture time t, i.e. tubes residual life, can be calculated numerically by equating equations 3 and 4 for tube A; equations 3 and 5 for tube B.
In order to ascertain the reliability of a residual thickness equal to 4 mm respect to accidental overheating, rupture time t has been calculated assuming different values of T for tube A (eq. 4) and tube B (eq. 5).
Results show that residual life is around 200000 hours (23 years) at 600°C, it is reduced at 700°C maintaining values reasonably high for both tubes, but it drastically decreases with temperature increasing: at 800°C (a value that might be reached in the case of accidental flame impingement) residual life is abundantly less than one year for tube A and even lower for tube B. Therefore it is strongly advisable to replace the radiant tubes when their thickness is reduced to 4 mm.

**Tab.4** - Residual life (t) of radiant tubes with thickness $b_o$=4mm, for different temperatures (T).

| | | **Tube A** | **Tube B** |
|---|---|---|---|
| T (°C) | T (K) | t (h) | t (h) |
| 600 | 873 | 206000 | 200000 |
| 700 | 973 | 95000 | 60000 |
| 800 | 1073 | 1800 | 600 |
| 900 | 1173 | 18 | 6 |

## CONCLUSIONS

In petrochemical plants radiant tubes are very critical components, being exposed to severe conditions that make necessary to schedule periodic inspections. Our investigations allowed to evaluate the mechanical properties of two radiant tubes made of ASTM 335 P5 steel, which were dismounted from a topping furnace after 230000 hours of service, due to the presence of burns on their external surface and to wall thickness reductions, that were considered unacceptable according to a plant managing practice.
Even if within the limits of the Standard, the two tubes have slight differences in composition which can be reasonably ascribed to different suppliers. Our investigations showed that the tube richer in alloying elements is characterized by a finer microstructure and better tensile and creep properties. Creep test results were utilized to plot the Larson-Miller curves for the two tubes, which are useful to foresee creep life. By means of a numerical procedure, developed to take into account the two combined effects of creep behavior and thickness reduction due to corrosion phenomena, we ascertained that many years of residual life are still available for the two tubes at temperature equal to 600°C. However residual life is reduced drastically above 700°C: mostly for the less alloyed tube, it becomes equals to few hundreds of hours at 800°C. Therefore, under a conservative approach, radiant tubes have to be decommissioned when their wall thickness reaches a value that is unable to guarantee, for a reasonable increment of temperature, conditions of safe working at least until the subsequent scheduled plant shutdown. In the examined case, it is strongly advisable to replace the radiant tubes when their thickness is reduced to 4 mm and to monitor regularly, during operation, that their surface temperature is not higher than 600°C.

## ACKNOWLEDGEMENTS

The authors are grateful to the Refinery of Milazzo for funding this research.

## REFERENCES

[1] Mayer K.H., Masuyama F. The development of creep-resistant steel. In Creep-resistant steels, edited by Fujio Abe, Torsten-Ulf Kern and R. Viswanathan, Woodhead publishing limited, Cambridge 2008

[2] Prager M, Osage DA, Panzarella CH, Brown RG. Development of a material databook for API STD 530. Proceedings of the ASME 2014 Pressure Vessels & Piping Conference PVP2014, July 20-24, 2014, Anaheim, California, USA

[3] Michel J, Buršák M, Vojtko M. Microstructure and mechanical properties degradation of CrMo creep resistant steel operating under creep conditions. Materials Engineering - Materiálové inžinierstvo. 2011; 18: 57-62

[4] Zielinski A, Golanski G, Stroka M, Dobrzanski J. Estimation of long-term creep strength in austenitic power plant steels. J. of Materials Science and Technology. 2016; 32, 8: 780-785

[5] Masuyama F. History of power plants and progress in heat resistant steels, ISIJ International. 2001; 41, 6: 612–625

[6] Kimura K, Toda Y, Kushima H, Sawada K. Creep strength of high chromium steel with ferrite matrix. International Journal of Pressure Vessels and Piping. 2010; 87: 282-288

[7] Wei Yan, Wei Wang, Yi-Yin Shan, Ke Yang. Microstructural stability of 9-12%Cr ferrite/martensite heat-resistant steels. Front Mater Sci. 2013; 7, 1: 1-27

[8] Prat O, Garcia J, Rojas D, Sauthoff G, Inden G. The role of Laves phase on microstructure evolution and creep strength of novel 9%Cr heat resistant steels. Intermetallics. 2013; 32: 362-372

[9] González G, Molina R, Delavalle M, Moro L, Variation of creep resistance in ferritic steels by a heat treatment. Procedia Materials Science. 2015; 9: 412 – 418

[10] Michel J, Bursak M., Mamuzic I. Degradation of mechanical properties of CrMo creep resistant steel operating under conditions of creep. Metallurgija. 2012; 52,1: 79-82

[11] Bonaccorsi L, Guglielmino E, Pino R, Servetto C, Sili A. Damage analysis in Fe-Cr-Ni centrifugally cast alloy tubes for reforming furnaces. Engineering Failure Analysis. 2014; 36: 65-74

[12] Widrig JR. The challenge of inspection and assessment of critical piping systems in chemical plants. Inspection Engineering Journal. 2013; 20, 4: 13-16

[13] Guglielmino E, Pino R, Sili A, Servetto C. Creep damage of high alloyed reformer tubes, Handbook of Materials Failure Analysis With Case Studies from the Chemical, Concrete and Power Industries, edited by A. S. Hamdy Makhlouf e M. Aliofkhazraei. Amsterdam: Elsevier; 2016. 69-91

[14] Aliprandi P, Guglielmino E, Sili A. Damage assessment of topping furnaces radiant tubes and creep behaviour of ASTM A335 P5 steel. Materials at High Temperatures. 2020; 37: 81-88

[15] Designation: A335/A335M – 15a. Standard specification for seamless ferritic alloy-steel pipe for high-temperature service. October 2015

[16] Adili T, Rostamnezhad Z, Chaibakhsh A, Jamali A. Flame Failures and Recovery in Industrial Furnaces: A Neural Network Steady-State Model for the Firing Rate Setpoint Rearrangement. International Journal of Chemical Engineering. 2018: 1-15

[17] Mazaheri M, Djavanroodi F, Nikbin KM. Creep life assessment of an overheated 9Cr-1Mo steel tube. International Journal of Pressure Vessels and Piping. 2010; 87: 746-752

[18] Kostryzhev A, Singh N, Chen L, Killmore C, Pereloma E. Comparative effect of Mo and Cr on microstructure and mechanical Properties in NbV-microalloyed bainitic steels. Metals. 2018, 8, 134: 1-19

[19] Ferreira Lima W, Rigueira G., Cunha Furtado H., Barreto Lisboa M., Henrique de Almeida L. Microstructure evolution and creep properties of 2.25Cr-1Mo ferrite-pearlite and ferrite-bainite steels after exposure to elevated temperatures. Materials Research. 2017; 20(2): 418-422

[20] API Standard 530. Calculation of heater-tube thickness in petroleum refineries. 7th ed. April 2015