ISPITIVANJE CIJEVI PROCESNIH PEĆI METODAMA BEZ RAZARANJA I NJIHOV POPRAVAK ZAVARIVANJEM

REFORMER FURNACE TUBES NON-DESTRUCTIVE TESTING AND REPAIR BY WELDING

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Ključne riječi: cijevi procesne peći, nerazorna ispitivanja, popravak zavarivanjem

Key words: reformer furnace tubes, non-destructive testing (NDT), welding repair

Sažetak: Za izradbu reforming cijevi koristi se centrifugalni lijev materijala HK40,HP modified i mikrolegirane legure. Zbog izloženosti različitim opterećenjima, u materijalu se javljaju raznolika oštećenja kao što su pukotine uslijed puzanja i toplinskog umora. U programima održavanja- nadzoru opreme u radu - nerazorna ispitivanja imaju značajno mjesto u osiguranju rada industrijskih postrojenja. Da bi ispravno odredili stanje cijevi i njihov preostali vijek potrebno je na njima provesti određena ispitivanja. U radu je prikazan pregled metoda bez razaranja (NDT), koje zasebno a posebice u kombinaciji mogu dati vrijedne podatke kod određivanja preostalog vijeka cijevi. Također su prikazani rezultati metalurških ispitivanja cijevi izuzetih iz peći. Ovi podaci mogu biti korisni pri planiranju i izvođenju popravka cijevi zavarivanjem, a što je prikazano u radu.

Abstract: Centrifugally cast materials, namely HK40, HP Modified, and Micro-Alloy materials, are used for tube materials in steam reformer tubes. The material undergoes various stresses resulting in damage which can manifest itself in several ways. Non-destructive testing (NDT) plays an essential role on maintenance program to assure operation of industrial plants. Proper determination of tube condition and its remaining life requires specific in-site examinations. The combination of techniques provides valuable date for the prediction of the remaining life of tubes, what is in article shown. Metallurgical examination of tubes removed from such service has been examined and also in paper shown. All mentioned parameters and results could be useful by tube repair welding planning and performing. Field experiences and findings are discussed in the paper.

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1. INTRODUCTION

The primary reformer in any steam reforming synthesis gas complex is the most expensive and energy-intensive part of the plant equipment items which can cause plant shutdowns. In fact this is furnace packed with banks of tubes packed with catalyst through which the reaction gases pass (figure1). Heat realized by the burners is transferred to the reformer tubes. Considerable thermal stress is placed upon the reformer tubes themselves, making them prone to a variety of problems, and fractures and mechanical failures are common. Furthermore, as pressure to enhance plant efficiency increases, so the focus is on critical equipment items which can cause plant shutdowns. Their lives are limited by creep, driven by combination of internal pressure stress and through-wall thermal stresses generated by operational transients. Creep life exhaustion may be accompanied by progressive grain boundary cavitation-depending on the microstructure of the material and may be exacerbated by micro-structural degradation processes, such as sigmatization. Reformer catalyst tubes are commonly manufactured from high strength, creep and corrosion resistant alloys. They are of relatively thick wall and are usually produced by centrifugal casting.

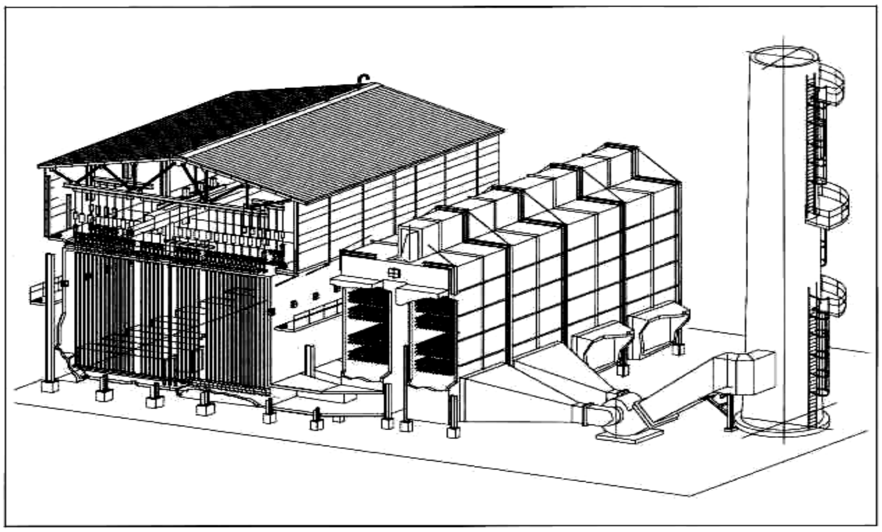

Figure1: Scheme of fertilizer factories primary reformer unit [8]

Plant productivity can be directly controlled by the reliability of the steam reformer. Reformer tubes in particular will fail and require replacement. Predicting and extending reformer tube life can have a direct impact on the plant's reliability and bottom line, whether by reducing unplanned outages or allowing longer runs in between shutdowns. A design life of 100,000 operating hours has been the normal time-based criteria for considering retirement of tubes. Non-destructive testing (NDT) plays an essential role on maintenance programs to assure operation of industrial plants. At a cost of several thousands of dollars per tube and a re-tubing cost of a several millions dollars a significant amount of capital can be inadvertently applied if tubes are retired either too early or too late.

The disadvantages in removing tubes from service on a sampling basis to determine tube integrity include:

- Catalyst removal
- Early retirement of serviceable tubes
- Late removal of non-serviceable tubes, impacting turnaround critical path duration if it is found that all the tubes need to be renewed

- Maintenance costs.

The advantage of removing tube(s) from service to determine condition includes:
- True metallurgical condition of that particular tube is known.

2. REFORMER TUBES MATERIALS

Reformer catalyst tubes are commonly manufactured from high strength, creep and corrosion resistant alloys. They are of relatively thick wall and are usually produced by centrifugal casting.

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Tube design is traditionally based on pressure stresses, conservative outside wall temperatures and factored lower bound material rupture lives, according to API-calculation formula.

The characteristics of these alloys at temperatures up to 1000 °C are mainly:
- Creep resistance
- Oxidation resistance
- Ductility at high temperature
- Thermal fatigue resistance
- Weldability after aging.

The range of high temperature alloys needed by the petrochemical industry for fired heaters often cause confusion since the majority is not included in international specifications and design codes such as ASTM and ASME. Furthermore, the alloys are often known by their proprietary name. In fact there is a small family of alloys available for selections for fired heater tubes. Originally, in the 1960's two cast alloys became important, designated in ASTM and ASME as HK-25%Cr20%Ni0,4%C and HP-25%Cr35%Ni0,4%C. During the 1970's HK was improved with additional nickel and small additions of niobium. The obsolete HP grade was reintroduced with various additions of niobium and tungsten to give the now well-known HP modified range. The latest development is the additional of small amounts of titanium and zirconium to the HP modified alloys. This micro alloys currently offer the highest creep strength giving thinner tube walls and greater furnace efficiency [1].

3. NDT METHODS APPLICATION

The actual technique used is heavily dependent upon the following:
- Costs
- Individual plant preferences (limited knowledge of technologies)
- Historical experiences at the specific location
- Turnaround duration
- Availability of analyzed data from reformer tube testing
- Knowledge of the different NDT technologies (strengths and weaknesses)
- Availability of specialist services.

To reduce the occurrences of furnace tube removal for condition-based assessment and to improve overall reliability of tube life, the use of NDT techniques on a regular basis during reformer furnace turnarounds is beneficial. The condition of a reformer tube is inferred from the response of a NDT sensor to a change in material properties. As such, there are certain limits on detectability, sizing and characterization of flaws that are heavily dependent on the overall test system characteristics, comprised of the environment, instrumentation, sensor, material under test and, of course, the operator.

The combination of techniques provides valuable date for the prediction of the remaining life of tubes. Reformer tube condition can currently be inferred in-situ by qualitative NDT assessment using the following techniques [6]:

3.1. Profilometry-diametrical growth

The principal rationale behind this technique is that, as creep damage occurs, the tube bulge (normally at burner locations).

Each material type has its own nominal value of diameter change where creep is considered to have occurred. The following rules of thumb have been reported by various operators over the years.

Only through the application of other techniques is possible the true condition of the tube determined, have been developed. Yet, recent findings show that in some cases, significant growth may be apparent, but the tube may show the absence of internal damage. Using diametrical growth (O.D. and I.D.) may provide a very general indication of tube condition; however, using diametrical growth as a stand alone method for measuring creep damage, or lack of damage as the case may lead to a significant false call on the actual condition of the tube. The issue is further complicated by the fact that no tolerance is given by the manufacturer for tube O.D. measurement; and the tube I.D., while machined, can vary greatly over the length of the tube segment. In fact, the machining process may produce a given I.D. dimension, but because of the variation in the machining process, the tube may see a significant reduction in wall thickness on one side of the tube while having an abundance of material on the other side. After testing each tube profilometry result will be evaluate and assignee a damage grade per tube determined on the worst section of tube. These grades are assigned based on comparison of each tube to the NDT responses obtained from samples subjected to metallography confirmation. Final evaluation tube grading and dimensions are then transferred automatically to life assessment software. In recent times is measuring accuracy improved by applied laser scanning automated technique.

3.2. Wall thickness measurement

As creep damage occurs, an apparent decrease in wall thickness is evident. Due to the difference in O.D. measurements of the tube segments caused by manufacturing variations, it is preferable if baseline data can be obtained on the tubes when initially installed so accurate trends may be developed.

3.3. Replication

Replication is useful for in-site assessment of reformer tube outside surfaces, to detect overheating that causes microstructural changes. Replication is a "spot" type assessment and is normally used as a supplemental technique. Only the advanced stages of creep damage, i.e. macro-cracking, can be assessed utilizing in-site replication.

3.4. Radiography

Random radiographic examination is normally used as a supplementary technique to confirm the presence of severe cases of final creep damage (macro-cracking). It is reasonable to expect to locate such damage when it has extended 50% in the thru-wall direction, when the tubes are filled with catalyst and isotopes are used instead of an X-ray tube. Although using an X-ray tube provides an improved quality image, it is not normally employed, because of practical conditions on site.

3.5. Eddy current

The technique relies on changes in electric circuit conditions; the circuit being the instrumentation, cables, sensing coil, and the item under test. As the mechanical properties of the test materials change, a change in overall circuit impedance occurs, which is displayed on an oscilloscope. By monitoring these changes, it can be inferred that creep damage is present, based on observation of the signal parameters in comparison to similar changes that occurred on known creep-damaged materials. The basic principles of the technique can be found in Reference [2]. The depth of penetration of eddy currents is primarily influenced by frequency, conductivity, and relative permeability.

Eddy Current coil design is important to obtain adequate sensitivity and signal to noise ratio. Some tubes, such as HP-40 and similar materials that have a high percentage of nickel, require the use of magnetically shielded or biased coils to reduce the effects of material permeability variations. This improves the signal to noise ratio so a reliable test result is obtained, allowing adequate discrimination of creep damage from general material property characteristics. Referring to varying degrees of damage within a reformer tube, the eddy current operator evaluates these changes in signal response.

Other factors that the operator considers are:

- Varying lift-off, influencing the signal response, scale and welds being typical examples
- Overheating that causes chromium migration, scale formation, and a significant eddy current response in terms of phase and amplitude changes
- Variations in material permeability
- Noticeable change in the O.D. or I.D. dimension (for instanceHK-40…2-3% andHP-45…5-7 %).

The advantages of eddy current inspection technique are the followings:

- No requirement for cleaning the tubes
- No need to remove catalyst
- No variation due to coarse grains
- No coupling medium (water) is required
- No limitation due to defect orientation
- 120° on each fire side are tested
- Eddy current penetration into tube wall up to 25 mm
- 200-250 inspected tubes per normal work shift (0,3 m/sec)
- High repeatability of the results.

The inspection is performed with a pneumatic tube crawler with speed of 0,3 m/sec. This translates into an estimated 250 tubes inspected per normal work shift (Fig. 2). Increment of tube diameter is an indicator of creep relaxation presence. Then, as the laser scanner is inspecting and moving vertically, two perpendicular tube diameters are measured along the tube.

Creep crack depth measured by eddy current technique is rated in percentage of sound wall lost to the crack (i.e. 30%, 40 %, 50% etc.). The crack normally begins approximately one third from the wall-thickness inside diameter, growing first toward the ID and then the OD. Combination both results provide optimum information on the tube condition and remaining life expectancy.

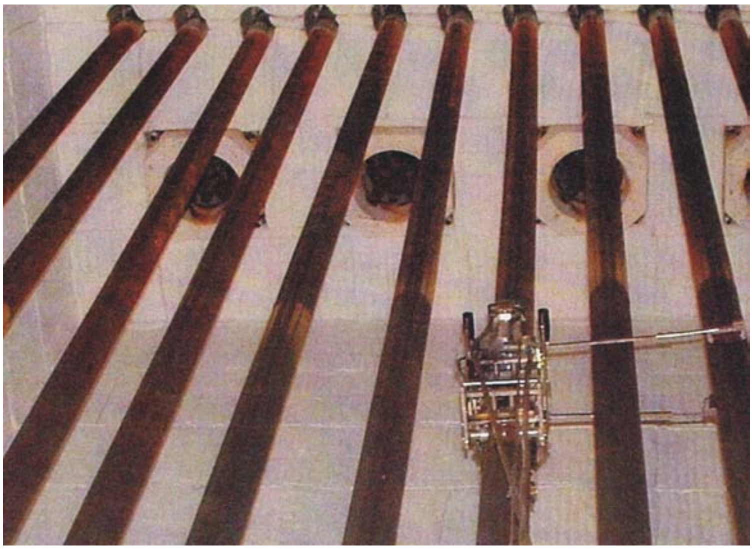

Figure 2: MP-automatic climbing device for eddy current crack depth and laser outside diameter (OD) measuring (profilometry) during in-service inspection of reformer tubes [12]

3.6. Ultrasonic (UT)

If the relationships between ultrasonic parameters and material are known, it will be possible to determine the state of the material by measuring the ultrasonic variables. When the material exhibits creep damage, due to the presence of cavities, the attenuation changes from its standard value; studying these changes the damage can be characterised (transmission ultrasonic attenuation technique). Due to the surface state of reformer tubes, non-contact techniques should be applied. Since no water spilling (or any other liquid) is allowed into the furnace, the design is based in a local immersion technique, using compression wave probes. The method consists on a pair of probes arranged in pitch and catch fixture. The transmitter sends a pulse, which travels following a chord in the tube and is picked up by the receiver (see Fig. 3a). When the UT beam go through the water and cross the steel, the probe angle is diffracted (see Fig. 3b). Even, mode conversion is produced (unless in the case of normal incidence), generating shear and longitudinal waves.

The shear wave front has some limitations to be transmitted in this type of materials that the best probe arrangement (based on the distance between emitter and receiver probes and in the tilt angle) consists of doing the longitudinal wave cross the tubes along the middle thickness structure (Fig. 3b).

The primary disadvantage of this technique is the influence of tube surface condition, which can vary from smooth, dimpled, tightly-adhering scale, to loose scale, or a combination of them all, that affects the ultrasonic signal and gives the impression of creep damage. Careful evaluation of a suitable ultrasonic technique is required to demonstrate its suitability for the examination of cast materials. Using an incorrect ultrasonic attenuation technique as a stand alone assessment tool in this case could lead to a significant false call.

Acquisition of NDT data is accomplished by the use of a powered carrier mechanism that traverses the length of a tube. The following NDT sensors can be loaded onto a carrier mechanism for simultaneous data collection [4]:

- Ultrasonic (attenuation, scattering and wall thickness)
- Eddy Current
- Profilometry.

It takes about one hour to set up such a system on-site and two to four minutes per tube for data collection and to assign a provisional condition status. The NDT specialists evaluate each tube and assign a damage grade per tube determined on the worst section of tube. These grades are assigned based on comparison of each tube to the NDT responses obtained from samples subjected to metallography confirmation.

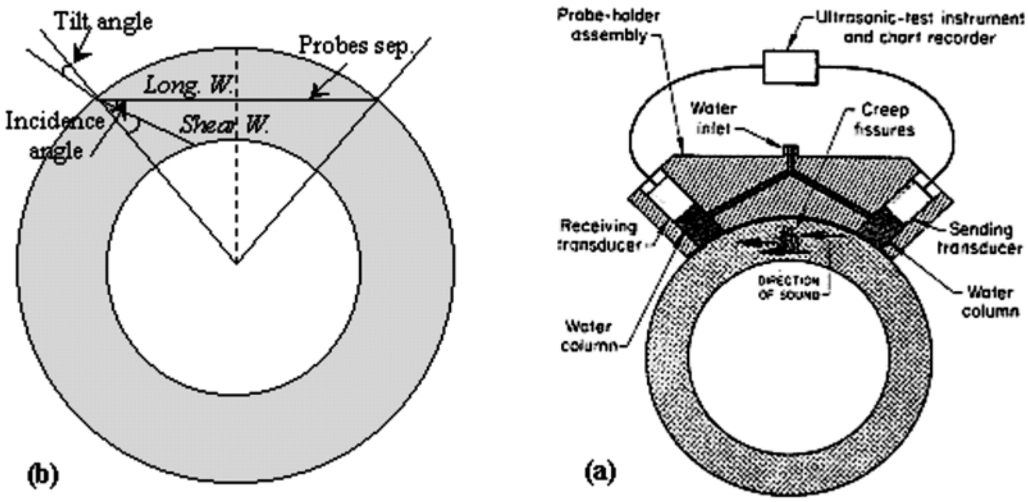

Fig 3: Scheme of ultrasonic method for detection of creep damage: a) inspection device for in-service inspection; b) fundamentals of the UT technique for reformer tubes inspection [3]

4. METALLOGRAPHIC ANALYSIS OF CREEP DAMAGED MATERIAL

However, the condition of the sample tube may or may not be a representative of the total number of tubes in the furnace. For an operating facility to change from a time-based to condition-based philosophy requires confidence in the methods and techniques used to determine tube condition. Extracting tubes at a turnaround close to the end of their design life and subjecting them to metallurgical investigation would appear to be fairly well accepted practice. Some facilities have also embraced the use of certain NDT techniques to trend changes in tubes. Exactly, this tubes structures anisotropy acts a lot of difficulties at NDT. For reformer tubes ratio between columnar and equiaxed grains in structure of min. 50%/50% is recommended. From the metallographic point of view, the state of the material is classified in several stages. Table 1 reproduces a possible classification method based on the presence of carbides, voids and cracks, from level 1 (undamaged material) to level 6 (highly damaged material).

On Fig. 4 progress of failure of furnace tubes regarding on thermal creep degradation and oxidation on high temperatures is presented. Depending on work hours, the presences of different degradations stages (i.e. third stage creep damages or fissured material) are noticed.

Table 1: Creep damage level classification

Level	Micrographic observation
1	Only coalesced carbides
2	Creep voids
3	Aligned creep voids
4	Few cracks
5	Cracks <50% thickness
6	Cracks >50% thickness

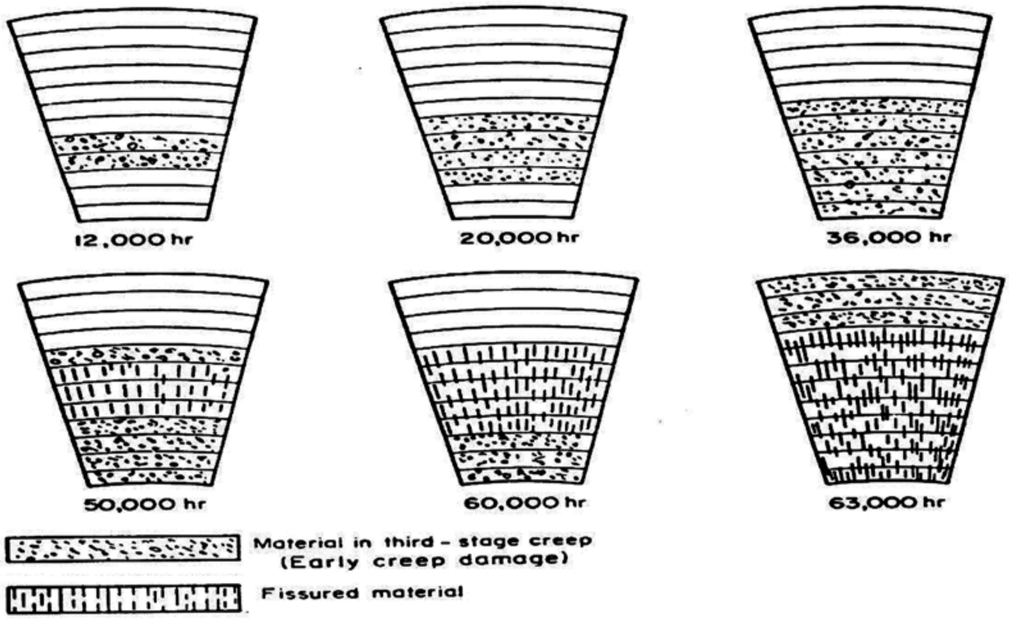

Figure 4: Presentation of progressive failures flow of furnace tubes [5]

Metallographic analysis of damages tubes was performed on one example with eddy current registered cracks. The evaluated damages are metallographic confirmed (Figures 7, 8, 9, 10).

The microstructure of reformer tubes (ASTM A297 HK40) is developed by "Glyceregia" etching (HNO3 + HCl + glycerol).

Macrostructure is developed by etching in Adler's reagent. Structure is characteristic for centrifugally cast process, i.e. The 2/3 of outer side of tube thickness consists of columnar grains. The following 1/3 of thickness has equiaxed grains (Fig. 5 and Fig. 6).

After 50.000 work hours of tubes on temperature in range of 1100-1150 K , the structures with macro-fissures (Figures 7, 8) and disperged Cr-carbides with inter-metallic phase (σ-phase) (Figures 9,10) are shown [9, 11].

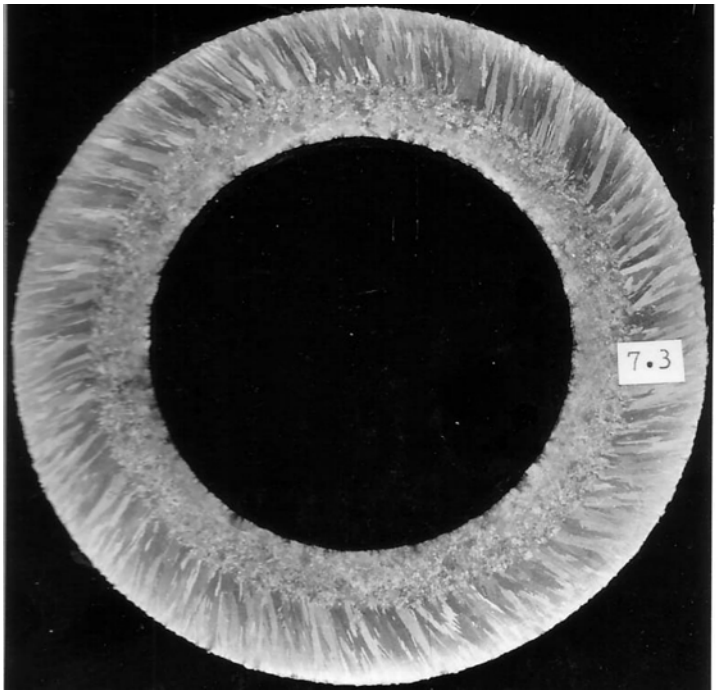

Figure 5: Macrostructure of centrifugally cast tube, 1: 1 Figure 6: Macrostructure, 5:1

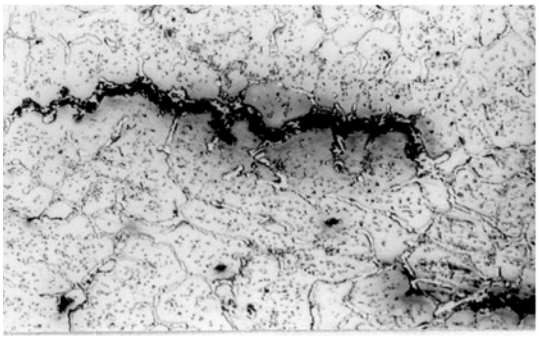

Figure 7. Microstructure of cracked tube, 100:1

Figure8. Macro-fissure, 250:1

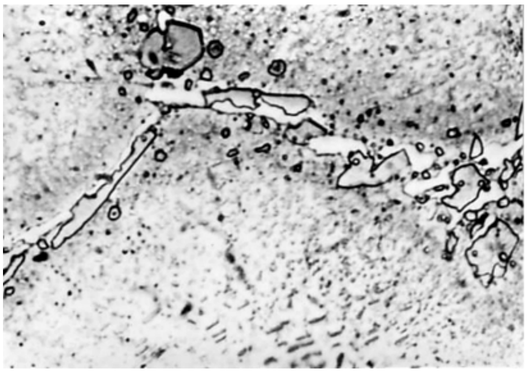

Figure9. Microstructure of sigmatization; 500:1

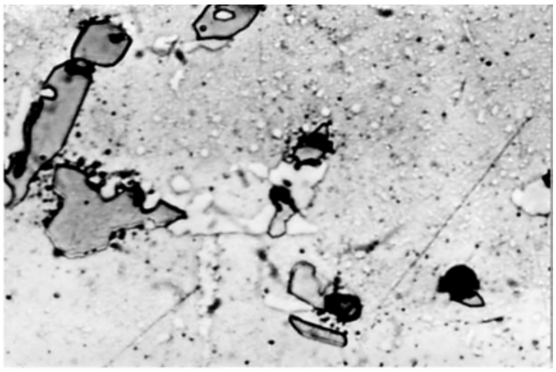

Figure10. σ-phase with disperged Cr-carbides, 1000:1

5. REFORMER TUBES REPAIR BY WELDING

In making an properly furnace tubes repair welds, some factors have great influence:

1) Tube wall soundness of aged reformer tubes determine the extent of stress rupture damage, oxidation and carburization
2) Effect of solution annealing in restoring ductility
3) Effect of filler metal selection on stress-rupture properties
4) Weld joint design and joint preparation
5) Effect of the welding process
6) Effect of welding techniques and sequences.

Ad 1) Castings that have been in service are often oxidized or have metallurgically altered surface layers. All surface oxidized must be removed by grinding or machining prior to welding to prevent defects. Carburised layer must be removed prior to repair welding by grinding or machining at least 10 mm back from the edge of the weld. The layer is magnetic while the unaffected matrix is nonmagnetic. A magnetic inspection with a permeability meter or a spring-supported magnet can give an indication of remaining life of the tube and if repair welding can be attempted.

Ad 2) Alloys such as HK-40 and others have good as-cast ductility, but after exposure to furnace operating temperatures, there is dramatic loss in room temperature ductility as shown in Table 2.

Table 2: Typical room temperature mechanical properties of HP+Nb as cast and after elevated temperature [7]

Casted tube HP+Nb alloy	**Rm, MPa**	**Re, MPa**	**A5, %**	**Kv, J**
As-cast alloy	480	240	20	14
Exposed at 870 °C for 1000 hours	520	280	4	4

HK-40 and others i.e. 25/35 Nb castings that have been in high temperature service, require a solution anneal prior to repair welding or heat affected zone cracks are expected. A minimum solution anneal would be two hours at 1050 ° C.

Ad 3) The product forms include covered electrodes for SMAW and bare filler metal for gas metal arc (GMA) as well as GTA welding. The producing foundry may be source of welding products and should be contacted, particularly for special cast alloy modifications. The bare filler metals are usually more available from foundries than SMA electrodes. A common misconception is that a weld made with a comparable composition welding product has the same stress rupture strength as the cast alloy. In reality the welds may be considerably weaker than the castings. Some general guidelines about high temperature weld properties of a comparable composition are:

GTA and GMA welds have substantially better stress rupture strength than SMA welds, or accurately:

- SMA welds often have strengths 60 % or less than comparable composition castings,
- GMA welds are about 80% as strong as the castings,
- GTA welds are with least 90% of the alloy strength may be obtained.

The difference in rupture strength between a cast alloy and comparable composition welds increases with increasing temperature.

An alternate to the use of a comparable composition is one of the nickel alloy welding products. Suggested types, based on service temperatures, are shown in Table 3.

Table3. Nickel alloy filler metal selection [7]

Welding process	T service < 870° C	Tservice ≥ 870° C
SMA (AWS A5.11)	ENiCrFe-2	ENiCrMo-3
GMA and GTA (AWS A5.14)	ERNiCr- 3	ERNiCrMo-3 or ERNiCr-3

One caution regarding on the higher nickel alloy welds over 50 % nickel is they should not be used in sulfur containing environments over 820° C**.** The presence of sulfur in both the feedstock and fuel oil should be checked before using the nickel alloy products.

Ad 4) The weld joint end preparation is made by grinding or machining. The bevel angles and root radius vary the welding process and whether it is a one or two side weld. In either case, it is good practice to provider a wider and more open joint than used in carbon or low alloy steel to allow the more sluggish weld metal. All repair welding should be done in the flat position, what include producing higher quality welds and allows higher deposition rates. Since the stress rupture strength of welds is often lower than casting, where practically welds should be located in areas of lower stress and away from corners or notches. This rule is normally followed in new fabrications but may be overlooked in retrofiting. Welds should blend with the castings and abrupt thickness changes should be avoided. Differences in heating and cooling rates between thick and thin sections can contribute to thermal fatigue failures.

Ad 5) The GMA process is widely used in fabricating new furnace components but is less used in field work. In the field, it is most common to make the root pass by GTAW and complete the joint by either SMAW or GTAW.

Ad 6) Buttering the face of bevel on a low ductility casting reduces the chance of cracking in the heat affected zone, particularly when a nickel alloy filler can be used. The weld metal has higher ductility and is deposited under minimum restraint conditions. One or more layers are deposited and the bevel remachined. The buttered weld layer is better able to absorb deformation when the butt weld solidifies. This technique may make the difference between success and failure when solution annealing is impossible. Preheat is usually not used. However, if the section size is over 20 mm in thickness, the alloy may be preheated to 100…200 °C. Usually no post weld heat treatment is required. Cooling between passes to 120 °C on resolution annealed castings, and 60° C on used castings not solution annealed, is suggested. The underpass temperature guide would take precedence over preheat.

The alloys are susceptible to crater cracking and care must be taken to fill the weld crater before breaking the arc. All slag is removed between passes and from the finished weld with hammer and/or stainless steel wire brushes. Residual slag is very corrosive to the alloy at high temperatures.

Peeninig of welds is controversial. A major problem with peening is that it is difficult to specify the amount of peening. However, it can be a powerful aid in reducing weld stresses and may make the difference in whether low ductility castings can or cannot be repaired. When performed, it must be done after each bead while the bead is still hot. A guide to an adequate force is that needed to give the weld bead a shot blast appearance. Only the fill passes should be peened, never the root.

Repair welding of high temperature reformer tubes can often add years of life if proper procedures are followed.

6. CONCLUSIONS

Tube condition cannot be determined by one stand-alone technique, as the degree of damage within a particular tube may not lend itself to that specific NDT technique. The reliability of NDT evaluation of reformer furnace tube condition can be improved by combining a variety of advanced NDT techniques that individually monitor differing physical parameters. The advantages and disadvantages of each technique, when compared against each other, reduces the occurrence of false calls, improves tube condition assessment and can increase overall furnace reliability.

Metallographic analysis of damages tubes was performed on one example with eddy current registered cracks. The evaluated damages are metallographic confirmed.

Regarding on others parts of the process furnace, creep-fatigue of pig-tails can be significant operations problem and instances of thermo-mechanical fatigue of outlet manifolds, creep cracking of manifold and riser welds and support problems are known and consequently must be also subject of consideration.

In making an properly furnace tubes repair welds many factors have great influence. In spite of mentioned, if proper procedures are followed, repair welding of high temperature reformer tubes can often add years of life.

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