Weld Geometry Defect Influence on Boiler Tube Structural Integrity

Conference Paper · January 2006

In Proceedings IIW International Congress “Welding and Joining Technologies for a Sustainable Development and Environment” The 1st South-East European Welding Congress 24–26 May 2006 Timisoara, Romania, (2006), pp.169-179

WELD GEOMETRY DEFECT INFLUENCE ON BOILER TUBE STRUCTURAL INTEGRITY

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ABSTRACT

Damage of boiler tubes is a very serious problem in many utilities worldwide, including even in the most advanced countries. Preserve of boiler tube integrity present major part in maintenance programs centered to achievement of high levels of availability and reliability of thermal power plants. This is due to a very specific and complex interconnection of design and operating characteristics of the boiler unit. Based on the results of numerous boiler tube damages investigation performed on domestic thermal power plants it is concluded that the initiation of different damage mechanism was strongly influenced by tube weld geometry defects. In this paper particular attention was dedicated to this not well documented problem. Structural integrity of the boiler tubes are greatly affected by the weld excessive root penetration (melt-through) on the tube inner surface. This type of weld geometry defect, which occured often on boiler tubing system, present local flow disrupter and also very strong stress riser. In the vicinity and donwnstream of excessive root penetration type disrupter initiation of different damage mechanisms (erosive and corrrosive wear, underdeposit corrosion, stress corrosion, corrosion fatigue) occured due to working fluid nucleate boiling destabilization (eveporator), or due to turbulent flow (superheater and reheater), followed by intensive suspended solids deposition.

KEYWORDS

Weld defect; Geometry defect; Structural integrity; Thermal power plant; Boiler tubes; Fracture mechanism

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1 INTRODUCTION

Weld defects are often unavoidable in such a complex systems like a thermal power plants which may contain more than 50.000 welds. As a result of the rather rigorous codes requirements for pressure vessels number of boiler tube weld failures on contemporary thermal power plant are negligible and usually account for below 5% of boiler failures. Basically, there are two principal reasons for that, one is the improvements in manufacturing and welding technologies in recent years, while the other is pre-service hydrostatic testing, which eliminate critical weld defect before a boiler is put into service.

Boiler tube weld failures can be generaly divided into two distinctive groups:

- "direct" failure - characterized by usually premature tube failures due to weld failure provoked directly by weld defect and
- "indirect" failure - characterized by tube base metal failure, not necessairly premature and often delayed, due to initiation and development of different tube metal corrosion/erosion process and thermal or hydrodynamic perturbation of fluid in the vicinity of defect weld.

The existence of different weld surface discontinuities: undercut, overlap, and improper contour represent a possible stress raisers, therefore fatigue loading during boiler tube service can cause premature "direct" weld crack originate, which could further propagate from these defects during service. Therefore, the proper contour of a weld, many times, can be much more important than the actual weld size, since a slightly undersized weld, free of abrupt surface irregularities, could serve more satisfactorily than a weld of adequate size exhibiting a poor contour.

Despite the fact that all major welding codes allow the existance of welding defects, and at a same time set limitation of the defects severity, it may be concluded that sometimes acceptable boiler tube weld, prone to "direct" failure, could present dominant limiting factor in preservation of tube structural integrity in the specific boiler service condition due to their strong influence on initiation of tube metal "indirect" failures.

The aim of present work is to identify and investigate the currently not well documented, influence of weld geometry (contour) defect on boiler tube structural integrity from the aspect of initiation of different weld and tube metal damage mechanisms in the vicinity of improper weld. In adition several examples of damaged and fractured boiler tubes were analyzed in the aim of emphasizing of complex and different influence of material-weld quality and boiler operating factors on initiation and propagation of particular, often multiple-mode, damage/fracture mechanisms.

2. WELD GEOMETRY DEFECT INFLUENCE ON BOILER TUBE STRUCTURAL INTEGRITY

Evaluation of criticality of different weld defects is well covered by fracture mechanics concept including recent fitness for purpose assessment concept, which offers an effective way of quantifying the significance of defects. In order to do this, three input values are necessary: nominal stress level, defect size and material mechanical properties. However assessing of weld defects using fitness for purpose methods, as well as assessing of the other types of defects in material, is quite complex and not practical for most application including boiler tubes in thermal power plants. The main reasons for limited applicability was strong influence of different boiler tube metal corrosion processes whose cumulative effects on decrease of structural integrity and probability of failure during plant operation was very difficult to estimate. Also, most of the boiler tube failure mechanisms are not strictly mechanical rather it was environmental assisted. Corrosion and erosion processes induced and assisted failures often exert considerable influence on number of forced outages and hence on the loss of thermal power plant availability. However, generally it is difficult to applied theoretical knowledge in practice in the case of environmental degradation of power plant components, because the corrosion and erosion processes of such a very complex systems, which are often highly localized, are in the function of numerous influencing parameters, including the parameters which are very difficult to assume and hence to control. Particularly there are many factors that need to be considered when conducting boiler tubes water/inner side corrosion assessments in multiphase – water/vapor flow condition (evaporator tubes) and also in the case of super heated steam flow condition (super heaters and reheaters tube), although to the lesser degree because of single phase flow.

Most dominant causes for boiler tube corrosion and corrosion assisted failures on domestic thermal power plant are [1,2]:

- Material imperfection (chemical composition, microstructure, mechanical properties)
- Service factors (water treatment system inadequacy, boiler water contamination, improper boiler blowdown technique and condenser leakages)
- Operating parametars excursion (boiler overfiring, disturbance in the flame spreading in the boiler furnace, improper boiler warm-up, water treatment plant or condensate polisher regeneration chemical upset and excursion in boiler water pH)
- Weld defect

Based on the results of numerous boiler tube damages investigation performed on domestic thermal power plants it was concluded that the initiation of different damage mechanism was strongly influenced by tubes weld joint defects. Number of failures directly or indirectly provoked by weld defects was far from negligible.

Weld joint defect is flaw or group of flaws which present interruption of the typical structure of a material, such as a lack of homogeneity in its metallurgical, mechanical, or physical characteristics. Weld joint defects are numerous and frequently divided and classified in to the groups with different terms used in literature. The presence of geometry defects which corresponded with improper contour of a boiler tube weld joints was of particular importance from the aspect of preservation of tube integrity during prolonged service.

Two characteristic weld root geometry defects, which often occurred on boiler tubes butt weld, were excessive root penetration and burthrought cavity (overlap), Table 1. The term "excess penetration" refers to disruption of the weld bead beyond the root of the weld. This disruption usually exists as excess metal on the root side of the weld. Burnthrought cavity represent concavity of the weld metal on the root side of the weld. Since disruptions of this type are, in the case of boiler tube inaccessible for repair, target measure is prevention of their occurance. Although the causes of weld geometry defect originate could be very different, root excess penetration is usually caused by improper welding techniques, poor joint preparation or poor joint alignment.

It was very important to note that defect acceptance criteria's and allowable imperfection level for welding joints in pressure piping welding codes are mainly based on what is considered as achievable rather than what is really necessary for the reliable service. In the case of allowable excessive root penetration (reinforcement) different international codes recommended, as a function of tube diameter or tube wall thickness, max. height values approximately up to 1.6 (3) mm [3-5]. The height and effect of excessive root penetration was usually exerted in the case of tube weld mismatch (misalignment) due to different thickness or different inner diameter of tubes.

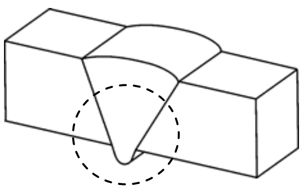
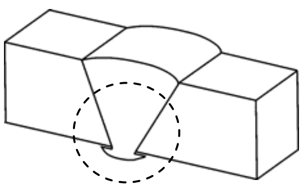
Influence of these two types of weld defect on boiler tubes integrity was very complex and could be indirectly analyzed and also classified into the four groups, according to their effect on:

- Local stress increase in metal
- Fluid boiling/flowing regime
- Local rate of deposit precipitation on tube inner side
- Protective oxide - magnetite layer on tube inner side

None of the mentioned efects can be characterized as a benefitial and consequently during service numerous unfavourable appearance and phenomenon were provoked, Table 1. Taking into account three main influencing factors, responsible for initiation of corrosion: material, environment and thermal/mechanical stresses, it was obvious that both type of weld defects, as a strong local stress riser, represent benefitial location for "direct" – weld failure. Process of protective oxide (magnetite) layer destabilization on boiler tube inner side, essential for inititation of corrosion, can generaly be provoked either by chemical means (corrosion) or by mechanical means (stress) or by synergistic effect of both of them. However, it was noted that corrosion processes on boiler tubes inner side are not taking place even in the case when protective magnetite layer is seriously destabilized and mechanically deteriorated or partially removed in the absence of concentrated corrosive ingredients in the endangered area [6].

The first weld defect, excessive root penetration is undesirable because the excess material on the tube inner side can disrupt flow, leading to destabilization of fluid boiling/flowing regime downstream of defect. This phenomenon also provoked local increase in concentration of acid or caustic components in working fluid, intensification of deposit precipitation rate on metal surface, tube metal thermal cycling and finally destruction of magnetite layer leading to localized metal corrosion (boiler water tube) or localized metal corrosion and overheating (boiler steam tube) downstream of the weld with defect. The second weld defect, burnthrought concavity can substantially reduce weld fatigue life or induce tube metal crevice corrosion [7], while excess concavity (weld reinforcement) has been also involved in thermal-fatigue failures of the weld joint.

Table 1 – Summary of weld geometry defect influence on boiler tube structural integrity

Weld geometry defect	Provoked appearance/phenomenon	Boiler tube damage/failure mechanisms	
		"direct" – tube weld failure	"indirect" – tube metal failure
 Excessive root penetration (melt-through)  Burthrought cavity (overlap)	▪ Strong stress raiser ▪ Flow disrupter ▪ Destabilization of fluid boiling/flowing regime downstream of defect ▪ Increase in concentration of corrosive ingredients ▪ Intensive deposit's precipitation ▪ Local tube metal thermal cycling ▪ Protective oxide (magnetite) layer destabilization/ destruction	▪ Fatigue cracking ▪ Corrosion-fatigue cracking ▪ Stress corrosion cracking (SCC) ▪ Hydrogen embrittlement (HE) – cold cracking ▪ Hydrogen induced cracking (HIC)	▪ Underdeposit corrosion: • hydrogen damage • caustic corrosion ▪ Stress corrosion cracking (SCC) ▪ Corrosion-fatigue ▪ Thermal fatigue ▪ Flow-assisted corrosion (FAC) ▪ Crevice corrosion ▪ Erosive wear ▪ Corrosive wear

It may be concluded that initiation of different boiler tube damage and failure mechanisms are possible as a consequence of synergistic effect of mentioned apperances and phenomena. "Direct" – tube weld failure mechanism were predominantly controled by degree of tensile stresses increase on the surface of weld root with excessive penetration or in the zone of root overlap, and also by quantity of hydrogen dissolved in metal during weld process. On the other hand, numerous "indirect" – tube metal failure mechanisms were controled by geometry of weld defects on tube inner side and their consequence on the rate of fluid flowing and boiling destabilization including side effects and also by stability of magnetite layer on tube inner surface.

Summary of weld geometry defects influence on boiler tube structural integrity with characteristic appearance/phenomenon and possible boiler tube failure mechanisms is presented in Table 1. More detailed analysis of particular appearance/phenomenon and provoked failure mechanism are presented in the examples of in service damaged and fractured boiler tubes.

3. EXAMPLES

3.1 Example 1 – boiler water wall tube failures, type: "indirect" failure

During exploitation of one natural circulation boiler of 210 MW fossil fuel power plant, significant failures of evaporator (water wall) tubes were taking place after 73000 service hours. Failure had occurred in furnace zones of maximum heat fluxes, in the area of burners. Water wall tubes (∅60x6 mm) were made of plain carbon steel, St 20 (GOST) and were exposed to working parameters P=15,5MPa, t=350^{o}C. Failure analysis was carried out on a specimen, removed from the failed tube. To determine damage mechanism, main cause of damage, the microstructural state and mechanical characteristics of material, several standard techniques were used [8-9]. Chemical analyses of tube material and hardness measurements were performed in the vicinity of fracture. Tensile test was carried out at room temperature on the samples prepared from the tube fireside in the region near fracture. A metallographic investigation of the damaged zones was carried out on numerous specimens using light microscopy.

”Window” type thick-edge fracture was observed on tube fireside. The outer surface of the specimens exhibited a general corrosion condition. Thick coarse and hard deposit was visible on inner surface of tube fireside, especially downstream of the welded joint. It is also observed that weld joint in the damaged zone have poor weld overlay in the form of excessive root penetration, Figure 1.

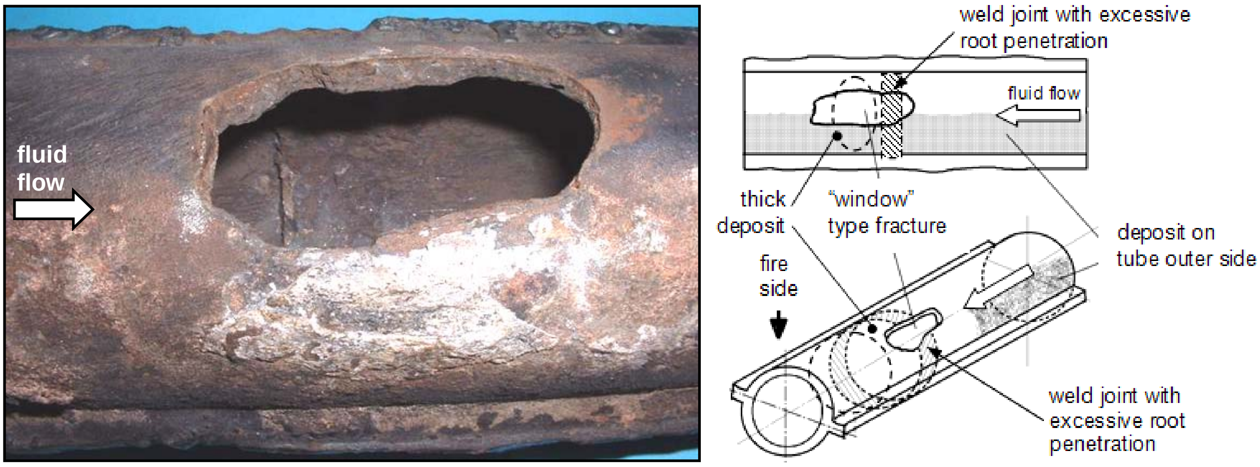


Figure 1 – Macro photo of “window” type fracture with schematic view of the specimen

The results obtained for chemical composition of tube metal are satisfactory. Mechanical characteristics indicated a noticeable embrittlement of material. Yield strength of $R_{0.2}$=403 MPa was significantly higher then minimal designed value, $R_{0.2min}$=216 MPa, and it is close to the minimum value of standard tensile strength of R_m=420 MPa. Tensile strength was R_m=481 MPa while deformation characteristic, expressed by elongation, A_5=13.2%, was much lower than recommended (A_{min}=24%) which is an indication of a significant increase of the material embrittlement. The hardness values in the range of 155-184HV are higher than 145HV that is generally considered as the upper limit for steel St. 20 in normalized state. The obtained hardness level is in agreement with the tensile test results.

Microstructure in the middle of the sample cross sections was ferrite-pearlite, with the presence of completely degradated pearlite. Also, a distinctly banded structure with non-homogenous distribution of very fine elongated MnS inclusion was visible, Figure 2(a). Due to a complete decarburization, the microstructure was pure ferrite, with macro crack along the boundaries and many discontinuous intergranular micro cracks, closer to the inner side, Figure 2(b). Observed decarburization as well as the degradation of pearlite microconstituent indicate that the hydrogen penetration occurred through the tube wall. Many discontinuous, intergranular cracks and fissures are the result of great pressure effect of methane molecules or molecular hydrogen precipitated along the ferrite grain boundaries.

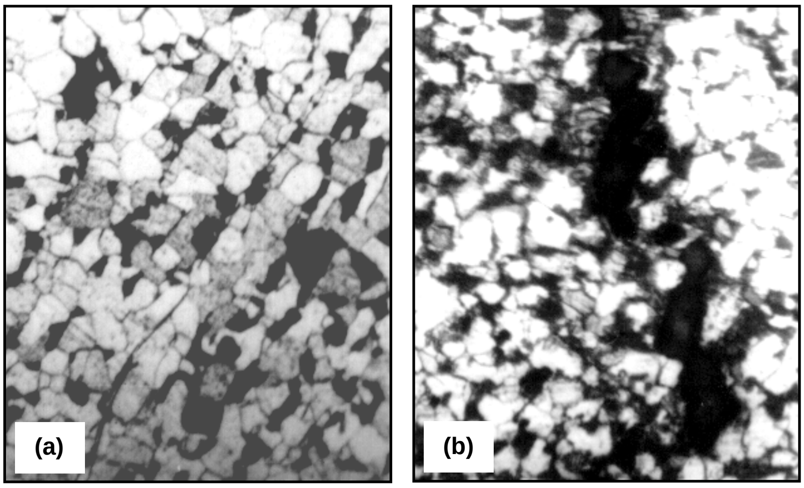


Figure 2 – Microstructure of the investigated samples
(a) Middle section: Ferrite – pearlite, banded structure, MnS inclusions, 200x
(b) Middle section near inner side: Ferrite, decarburization, intergranular cracks, 200x

Analysis of boiler operation showed that there was no significant deviations from the fluid nominal working parameters, water pH value and the amount of disolved impurity content during the operation prior to damage occurrence. Disturbance in the flame spreading in the furnace which usually lead to overheating of certain zones of evaporator were not observed. The same applies to the hydrodynamic disturbance and thermal-hydrodynamic instabilities. The microstructure analyses confirmed the absence of overheating.

The effect of hydrodynamic perturbation and destabilization of nucleate boiling of two-phase mixture in steam-drum boiler water wall tubes on the initiation of the hydrogen damage is well documented [10-13] including the in-situ obtained results. Water wall tubes of boiler with natural and driven flow of two-phase fluids may be considered as protected from overheating and magnetite layer destruction as long as the inner wall surface maintains a stabile subcooled – or nucleate – boiling.

Visually observed joint with excessive root penetration (max. height 1.2mm) act as local flow disrupter which caused flow destabilization in boundary layer: local turbulence and pressure drop, Figure 3-1 [10]. Departure from boiler fluid flow and boiling regime conditions adjacent to the tube wall can be provoked locally by many different factors at lower heat fluxes than critical heat flux. Figure 3 is a schematic representation of how this process occured in this particular case. This type of hydrodynamic perturbation in boundary layer initiated flow-assisted corrosion mechanism and local dissolution of protective metal oxide-magnetite layer. The local flow disrupter also cause the stabile nucleate boiling process to be disrupted and a dry spot, in the form of local steam blanket or bubble, is formed on tube inner side downstream of the weld joint, Figure 3-2. This local area is intermittently dried and then rinsed, and it may be at a slightly higher temperature than the surronding area which is cooled by the flowing water. Intermittent formation of the dry patches at the tube inner surface provokes the periodical changes of the heat transfer coefficient and the wall temperature oscillations. This, and also fluid turbulence and pressure drop caused the increase in the concentrations of acid/base suspended solids within the boundary layer magnetite-fluid This process will cause dissolved or suspended solids to begin to be deposited just downstream of the flow disruption and on the hot side of the tube, Figure 3-3. In thick porous deposit, process of wick boiling of fluid further increased the concetration of acid components within the boundary layer defective magnetite-porous deposit due to hydrolysis of salts and tube metal thermal cycling. In deposit area, local pH value drops significantly due to concetration of acidic contaminant. At the sites of local destruction of magnetite resulting from the flow-assisted corrosion, thermal cycling and its chemical decomposition during reaction with the hydrolysis products [12], hydrogen is formed during steam-water corrosion of metal. The so-formed hydrogen easily diffused into the tube surface layer causing the hydrogen attack according to a well defined mechanism [8, 10-15].

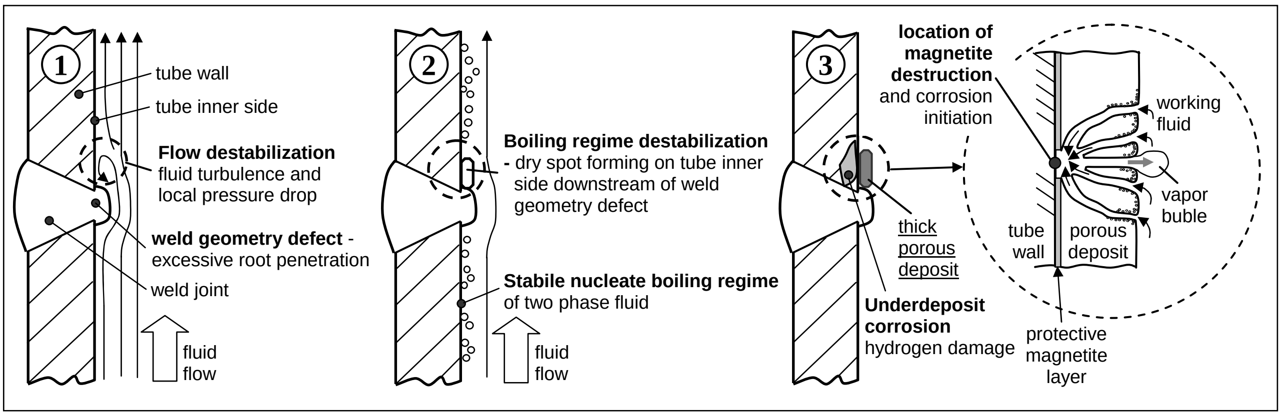


Figure 3 – Hydrogen damage mechanism of boiler water wall tube in the vicinity of weld with excessive root penetration

3.2 Example 2 – boiler super heater tube failures, type: "indirect" and "direct" failures

Frequent appearance of super heater tubes fractures forced circulation once-through tower-type boiler provoked numerous forced outages of domestic 350 MW thermal power plant. Participation of number of outages induced by boiler super heater failures in the total number of plant outages during period of four years service was very significant and approximately 30%. Due to frequent fractures of super heater tubes occurring at the similar location in the area near the tube bends and the ensuing reduction of the plant availability as well as substation financial losses, there was an urgent need to resolve the problem. Second stage super heater tubes (∅30x5 mm) were made of 1Cr0.5Mo steel (13CrMo44 DIN) and were exposed to operating parameters P=2,14MPa, t=404^{o}C.

Standard experimental procedures which include visual investigation, tensile test, hardness test, chemical analysis and microstructural characterization was performed on damaged tube samples removed from the input section of superheater through the width of boiler from the area in the vicinity of tube bend (near furnace wall) [15]. The view of the tube inner side in the vicinity of weld joint of different tube samples (N^{o} 1-3) is presented on Figure 4(a)-(c)

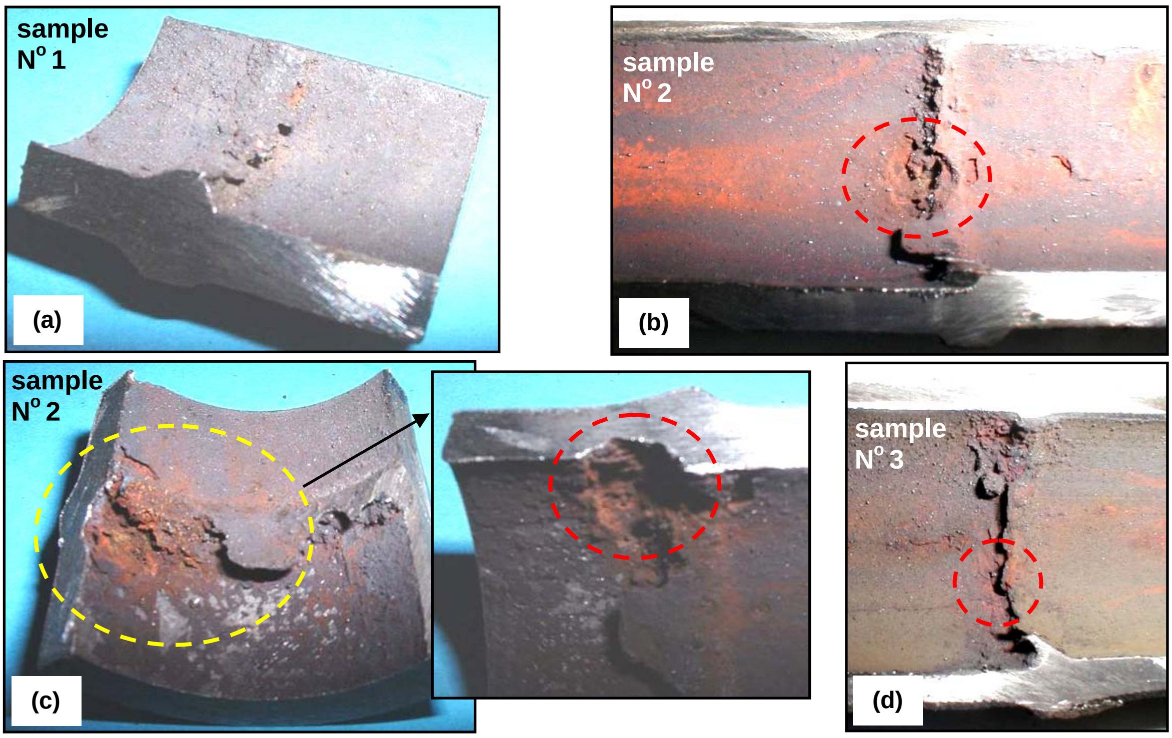


Figure 4(a)-(c) – Macro photo of tube weld defects, "direct" and "indirect" damages

On tube butt welds of specimens different defects were observed:

- Weld joint with excessive weld reinforcement with max. height up to 1.8mm and excessive root penetration with max. height up to 2.0mm and also deposit precipitated downstream of the defect on samples N^o 1 and 2, Figure 4(a) and 4(b)
- Weld joints with multiple defects: excessive root penetration and mismatch (misalignment) on samples N^o 2 and 3, Figure 4(b)-(d)
- Corrosion damages of tube metal and on weld joint downstream and in the vicinity of defective welds on sample N^o 2 and 3, marked with red circle dashed lines on Figure 4(b)-(d)
- Burnthrough resulting in "icicles" on the weld root on sample N^o 3, Figure 4(d)

Observed butt joints were resistance welded during boiler erection. In the aim of detailed investigation of damages microstructural samples from the transversal and longitudinal section were analysed, Figure 5(a)-(c).

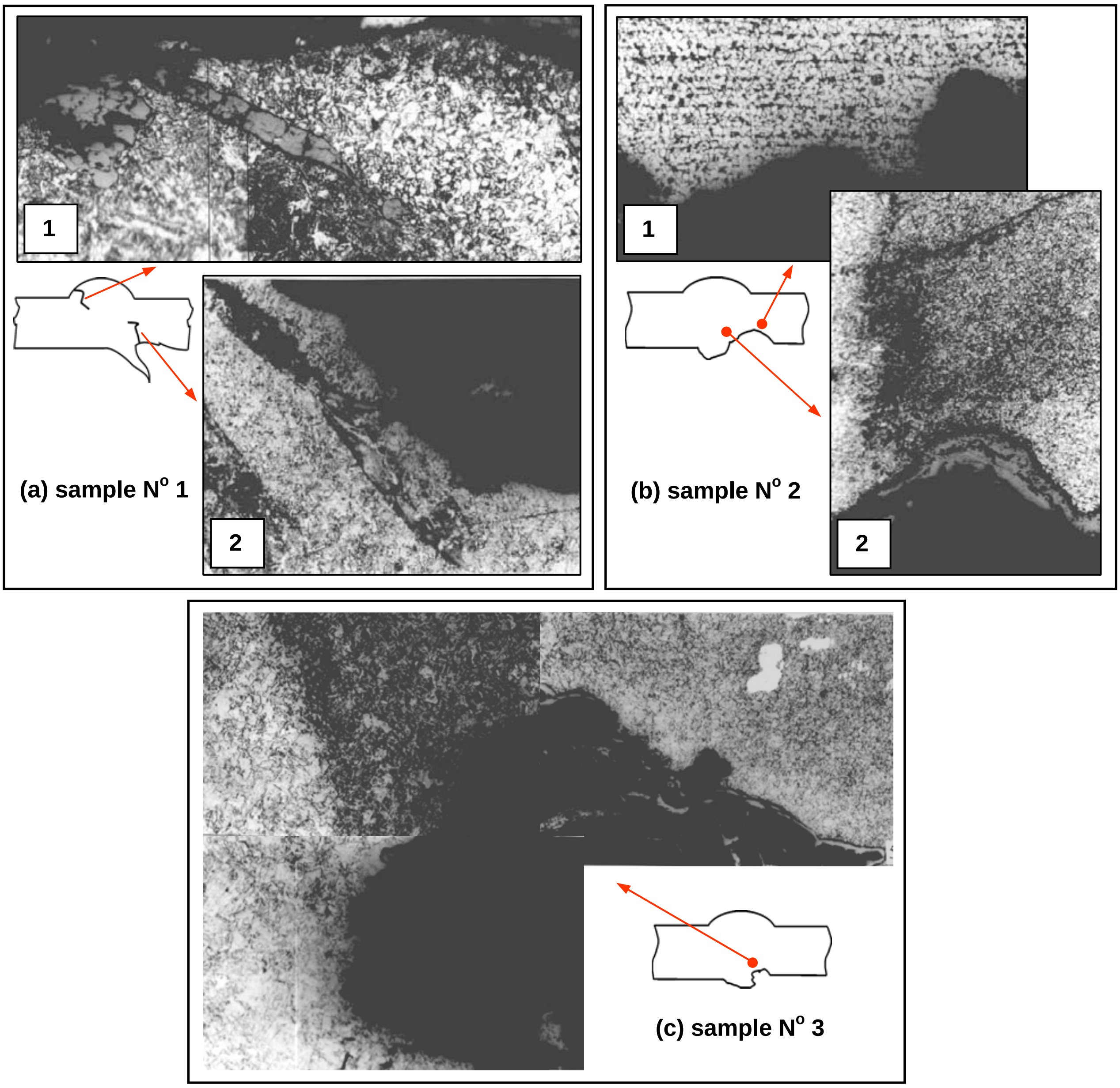


Figure 5 – Microstructure of the investigated samples
(a) 1 – Weld metal: Fatigue crack, 200x; 2 – Weld metal: Corrosion-fatigue crack, 50x
(b) 1 – Base metal: Corrosion pits, 50x; 2 – Weld metal: Corrosion pit, deposit, crack, 100x
(c) Weld fusion zone: Large corrosion pit, deposit, 50x

According to the proposed clasificition of failures due to weld defect on "direct" and "indirect" also the observed damages may be characterized as "direct" – weld damage and "indirect" – base metal damage in the vicinity of imperfect weld.
Following types of damages originated on the weld face and also on the weld root were detected:

- "Direct" failures and damages
  1) Weld metal fatigue cracks and corrosion-fatigue cracks on the face of weld with excessive reinforcement, Figure 5(a)-1 and in the area of excessive root penetration, Figure 5(a)-2
  2) Underdeposit corrosion pits in the weld metal of improper weld with multiple root defects: excessive root penetration and mismatch (misalignment), Figure 5(b)-2
  3) Corrosion – fatigue cracks at the bottom of large corrosion pits filled with porous deposits in the weld base metal, Figure 5(b)-2 and in the weld fusion zone, Figure 5(c)
- "Indirect" damages
  1) Area with numerous linked corrosion pits in the base metal downstream of boot weld with multiple root defects: excessive penetration and mismatch (misalignment), Figure 5(b)-1

Corrosion damages observed on tube samples inner side in the area of welded joint are the result of the following multiple - mode corrosion mechanisms predominantly initiated and controled by numerous weld geometry defects:

- Oxygen corrosion during boiler lay-out, idle periods and operation
- Underdeposit corrosion
- Corrosion-fatigue

Breakdown or cracking of the magnetite necessary for initiation of oxygen attack is largely due to mechanical and thermal stress induced in the vicinity of weld root with excessive penetration which act as a strong local stress riser. Oxygen pit also act as stress concentration sites, thereby fostering the develoment of corrosion-fatigue cracks during boiler operation.

4. CONCLUSIONS

- Boiler tube butt weld damages and failures provoked by weld geometry (contour) defect can be divided in to the two groups: "direct" type – failure in the weld metal or heat affected zone and "indirect" type – failure in the base metal in vicinity of defective weld.
- Acceptable boiler tube butt weld geometry defects, which are not especially prone to "direct" type of failures, may provoked different boiler tube "indirect" type failures during prolonged boiler service, particularly in the case of significant operating parameters excursion.
- As a result of presence of boiler tube butt weld geometry defects multiple unfavourable appearances and phenomena linked with fluid hydrodynamic, heat and mass transfer between fluid and metal, metal stress state and metal protective oxide layer state were provoked in the vicinity of improper weld.
- "Indirect" type of failures are usually delayed and mainly stimulated by local breakdown or cracking of the protective magnetite layer in the vicinity of improper weld and consequently alleviated initiation and propagation of numerous corrosion damage mechanism on the unprotected tube metal inner surface.

Weld defects are causing a increasing number of boiler tube failures, particularly in the older domestic thermal power plant. These types of defects usually date from time of plant erection, and are distributed randomly throughout the boiler tubing system. Thus, it should be expect increase in trend of "indirect" type boiler tube failures due to "hidden" faults of weld jonts. Contemporary thermal power plants have not shown many premature "direct" type failures of original welds and it is hoped that better non destructive testing undertaken during their construction may have prevented many faulty welds from being placed in service [17]. However, structural integrity of the boiler tubes are greatly affected by delayed "indirect" type of failures. This type of failures is dependent on many simultaneous parameters and is therefore accompanied by apparent unpredictability. A comprehensive analysis as a starting point for preventive measures is of the utmost importance both for plant reliability provide and for economical reasons.

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