Janusz Adamiec

Cracking of Welded Structures in Power Engineering Systems

Abstract: An increase in demand for electric power necessitates the revamping and construction of systems characterised by increasingly high efficiency. The construction of power units exposed to supercritical and ultra-supercritical parameters requires the use of new technologies and materials. The study presents two examples concerned with the cracking of boiler systems related to the use of a new hybrid welding technology and the use of a new material, i.e. Alloy 59. It was ascertained that the use of state-of-the-art technologies and materials is justified, yet requires the analysis and verification of designs assumptions and operating conditions.

Keywords: power generation systems, membrane walls, hybrid welding, Alloy59

Introduction

The ever-developing civilisation entailing the development of economy increases demand for electric energy. Presently, to secure their development (or even existence), economies need reliable systems enabling the generation and transfer of energy [1,2]. Growing demand for electric energy combined with EU regulations concerning the increased thermal efficiency of power units and the reduced emission of noxious gases into the atmosphere necessitate the revamping of the power generating industry. One of the methods making it possible to meet the aforesaid challenges is an increase in steam parameters and, consequently, in thermal efficiency. However, the obtainment of net efficiency exceeding 50% requires the use of new technologies and materials characterised

by higher high-temperature creep resistance and heat resistance than those used previously [3, 4].

The use of new manufacturing technologies and new materials requires not only the development of a related welding procedure qualification but also allowing for changes in the boiler structure. Failure to adapt the structure of the boiler and its operating conditions to the new technology and materials could lead to serious failures during the construction of the boiler or the operation of the entire system.

The article presents exemplary problems related to the stress corrosion-triggered cracking of tight wall tubes as well as reasons for the irreversible damage to protective layer of the flue gas desulphurisation (FGD) scrubber (in the flue gas wet desulphurisation system).

dr hab. inż. Janusz Adamiec (PhD (DSc) Habilitated Eng.), Professor at Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Katowice

Identification of reasons for the cracking of gas-tight walls

Tight (gas-tight) walls, also referred to as membrane walls, are used in state-of-the-art water-tube boilers, providing the boiler with tightness on the flue gas side and increasing its general efficiency. The making of tight walls involves the joining of such elements as flat bar-tube-flat bar-etc. (approximately 12 tubes), to panels being approximately 25 metres in length. Usually, membrane wall panels are joined using the submerged arc welding process [5].

The Energoinstal company, when joining individual elements of a panel, uses one of the most technologically advanced welding methods, i.e. Laser + MAG hybrid welding [4, 5]. Advantages resulting from the use of the above-named technology include not only an increased welding rate (exceeding 4 m/min) but also the significant extension of production potential. The new welding technology is characterised by a very narrow heat affected zone (below 1 mm), enabling the reduction of the tube wall thickness and leaving a minimum 2 mm of a material not subjected to heat treatment (Fig. 1a). The use of the above-named technology makes it possible to reduce the weight of boiler gas-tight walls by 30%. Another advantage of the hybrid welding technology is the possibility of joining elements having various wall thicknesses, e.g. a tube having a wall thickness of 3 mm and an 8 mm thick flat bar (Fig. 1b). When using a conventional welding method, e.g. submerged arc welding, the making of the aforesaid joint satisfying the requirements of related technical regulations (e.g. PN EN ISO 12952, VGB –R 501 H) is difficult because of the HAZ width and the possible burn-through of the tube. Another advantage of the new welding method includes the possibility of welding tight wall panels characterised by a very low scale, i.e. the width of the flat bar not exceeding 20 mm (Fig. 1c) [5].

The Energoinstal SA company made gas-tight walls of a water-tube boiler having an assumed thermal power of 115 MW. According to related documentation, the above-named walls were composed of tubes having a diameter of 76.1 mm and a wall thickness of 4 mm made of steel P265GH TC1 and a 6 mm thick flat bar made of steel P265 (two-sided welded joints were characterised by full penetration). The welding of the tube with the flat bar was performed using a hybrid (Laser+MAG) welding method, qualified and approved by a related notified body. During the start-up and the initial operation of the boiler, the tube surface (of the walls) revealed the presence of cracks. The analysis concerning the reasons for the formation of the cracks was performed by the Institute of Materials Engineering at the Faculty of Materials Engineering of the Silesian University of Technology (Instytut Inżynierii Materiałowej Politechniki Śląskiej, Wydział Inżynierii Materiałowej i Metalurgii). The tests involved specimens cut out of damaged fragments of the tight wall (Fig. 2).
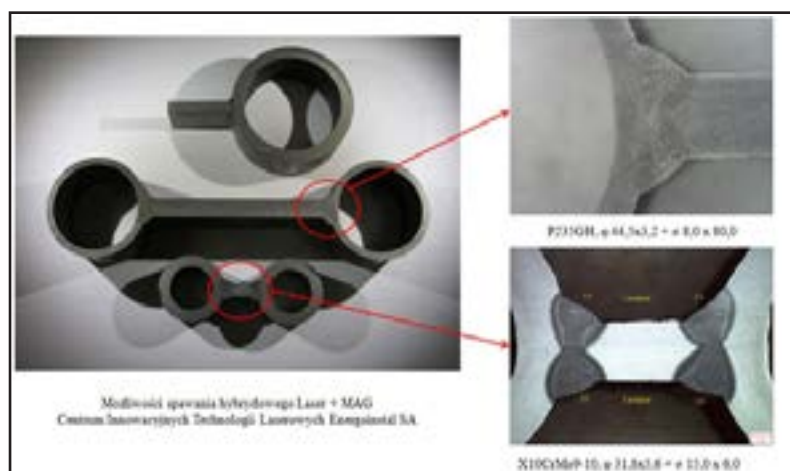
Structural tests involved the preparation of metallographic specimens subjected to etching in 5% Nital for 10 seconds. The initial observations of the structure were performed using a stereoscopic microscope (SM) and magnification of up to 50x. Exemplary results of the observations are presented in Figure 3a. Observations involving magnification of up to 500x were performed

Fig. 1. New possibilities in the welding of tight wall panels using the Laser + MAG hybrid method [5]

using a light microscope (LM) and the bright field technique (Fig. 3b). The metallographic tests were supplemented by observations involving the use of a scanning electron microscope (SEM) and the secondary electron technique SE (magnification restricted within the range of 50x to 1000x (Fig. 3 c-d).

The tests along with the analysis of their results revealed that the two-sided welded joint of a gastight wall (tube-flat bar) made using the MAG + Laser hybrid welding method was proper, free from welding imperfections and satisfied the requirements of quality level B according to EN ISO 13919 (Fig. 2).

The joint structure was typical of hybrid welding. The joint was composed of three characteristic zones, i.e. the base material having the ferritic-pearlitic structure characterised by the band-like morphology, ferritic-bainitic heat affected zone characterised by morphology consistent with the welding thermal cycle (HAZ width below 1 mm) and the weld having the ferritic-bainitic structure in the columnar arrangement of primary austenite grains (Fig. 2).

The macro and microstructural tests of the joint did not reveal the presence of welding imperfections such as cracks, incomplete fusions or other forms of discontinuity in the joint area. The detected cracks of the tube were located outside the zone of structural transformations triggered by the hybrid welding process (approximately 3.2 mm away from the end of the weld and 2.3 mm away from the end of the heat affected zone), in the zone of the material containing the granular ferritic-pearlitic structure and were not connected with the welding of the tube-flat bar joint (Fig. 3a,b).
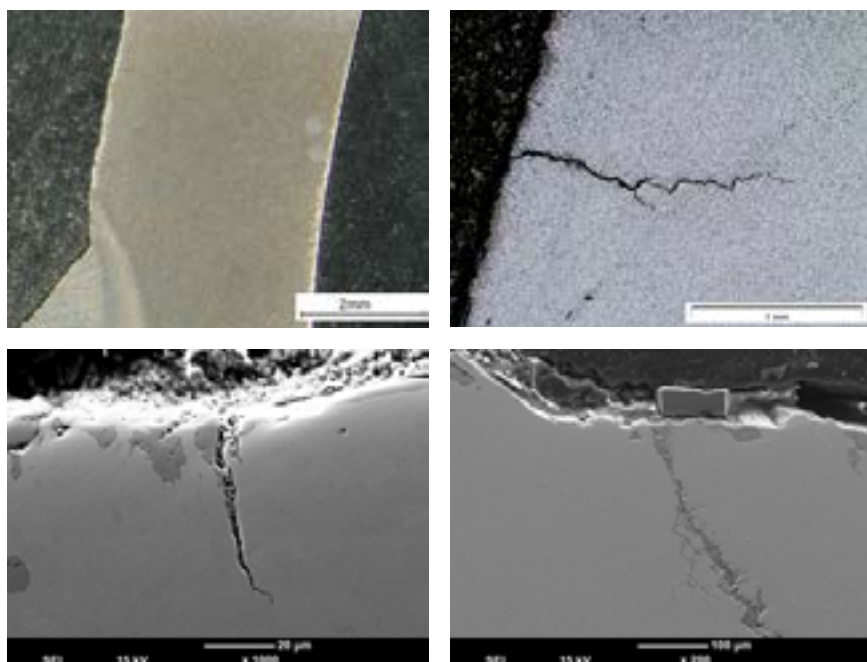

Fig. 2. Specimen sampling area

Fig. 3. Structure of the tube-flat bar joint in the area of the detected crack a) crack areas with corrosion pits and the crack on the side exposed to flue gas (SM), b) crack in the material of the tube exposed to flue gas (LM), c) crack on the surface of the tube with corrosion products and corrosion pits (SEM), d) crack initiated on the surface with the visible small scrap-induced cracks (SEM)

The crack was triggered by stress corrosion, i.e. the process in which an element is damaged beyond repair as a result of the simultaneous effect of static tensile stresses and the corrosive atmosphere. Usually, a crack is initiated in corrosion pits on the tube surface on the side exposed to flue gas and propagates along grain boundaries in the form of the primary crack and scrap-induced cracks (Fig. 3c, d). The above-presented manner of cracking is characteristic of stress corrosion affecting ferritic-pearlitic steels. Usually, the process of corrosion is very fast, with cracks propagating perpendicularly to the axis of tensile stresses [10].

Cracking of the layer protecting the FGD scrubber

Materials used when making the plating of FGD scrubbers are selected in relation to corrosive factors, operating conditions, system structure and general economic aspects. Typically, steels used in the above-named process include austenitic steels (317LMN, 904L) and duplex steels (e.g. 2205, 2507) as well as (less frequently) nickel superalloys (e.g. Inconel 625, Alloy C-276, Alloy 59), used in the most severe conditions (Fig. 4) [6, 7]. The interaction of chlorides, acids, temperature and a flue gas desulphurisation technology are decisive for the aggressiveness of corrosive media (e.g. fluid in the sprinkler and in the absorber or purified gas condensate).

In the flue gas wet desulphurisation system, the passes were plated with 2 mm thick sheets made of Alloy 59 (nickel alloy). The plates having dimensions of 3000 mm x 1000 mm were bonded with the base (steel S235) using a 1.5 mm high TIG girth fillet weld (argon-shielded TIG welding performed using a tungsten electrode). The sheets were additionally tacked using uniformly arranged (in two rows) plug welds. A covering sheet was welded onto each joint in order to separate welds bonding the sheets of the pass housing made of steel S235 and the sheets of the plating made of Alloy 59 (because of the increased content of iron in the weld following the stirring of the materials being joined). The assumed temperature of flue gas in passes amounted to 170°C. The horizontal surface of the passes plated with the sheets made of Alloy 59 was cyclically sprinkled with water to remove desulphurisation product deposits (Ca(SO4)•2H2O, CaSO4, CaCO3 and Ca(OH)2). The periodic check of the system revealed numerous cracks both in the girth and plug fillet welds (Fig. 5a).

The metallographic tests of the test welded joints were performed using metallographic specimens subjected to electrolytic etching in Lucas reagent. Macrostructural observations were conducted using a stereoscopic microscope and a magnification of up to 50x (Fig. 5b,c). The microstructural tests were performed using a scanning electron microscope (SEM) and the electron backscatter diffraction technique (Fig. 5d).

Fig. 4. Materials recommended for the making of the plating of scrubber flue gas passes in relation to the work environment [8]
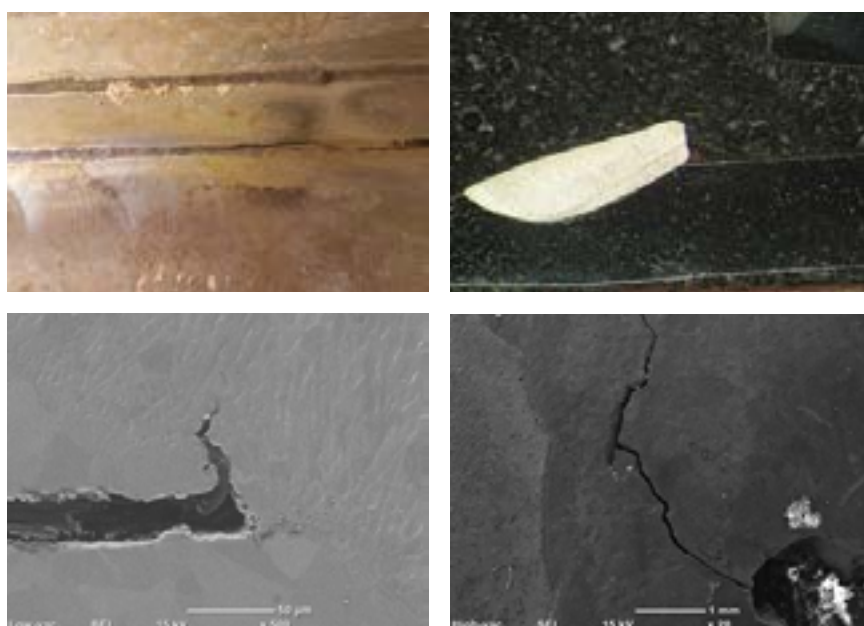

Fig. 5. Cracks on the surface of the protective layer made of Alloy 59: a) longitudinal crack of the girth weld, b) macrostructure of the damaged joint (SM), c) fatigue crack in the sheet-base joint area, d) low-cycle fatigue crack initiated on the notch in the weld

The visual tests of the damaged joint revealed that the crack was located in the weld axis (Fig. 5a). The location of the crack and its rectilinear trajectory indicated that the crack was induced by low-cycle fatigue triggered by stresses and strains of the joint during its operation (Fig. 5b). The protective sheet made of Alloy 59 was heated by flue gas to a temperature restricted within the range of 170°C to 190°C and, next, cooled by water from the sprinkler several times per hour. The stiffening of the plating structure by means of longitudinal girth joints (2 mm thick sheet made of Alloy 59 and 8 mm plate made of steel S235JR), Alloy 59+Alloy 59 lap joints and plug welds led to cyclic stresses and strains of the entire plating and, consequently, to the cracking of the welded joints (Fig. 5c). The fatigue nature of the cracks is demonstrated by their specific trajectory (characterised by changing directions) (Fig. 5d).

As a result of the formation of the fatigue cracks in the welds of protective sheets, water, desulphurisation products and flue gas entered beneath the sheets. The stirring of the material in the welds bonding the sheets made of Alloy 59 and steel S235JR led to their decreased corrosion resistance. In addition to low-cycle fatigue, factors quickening damage (beyond repair) to the plating on the pass floor included surface pitting corrosion (Fig. 6a) and uniform corrosion (Fig. 6b).

The metallographic tests were supplemented by the microanalysis of the chemical composition performed using a Hitachi S3400N scanning electron microscope (SEM) provided with the system enabling the performance of the EDS-based microanalysis of the chemical composition. Exemplary linear distributions of elements in the joint are presented in Figure 7.

The analysis of the linear distribution of primary alloying elements (Fe, Ni, Cr) confirmed the stirring of Alloy 59 and steel S235JR in the welded joint, resulting in the decreased corrosion resistance of the joint in comparison with that of Alloy 59 alone (Fig. 7).
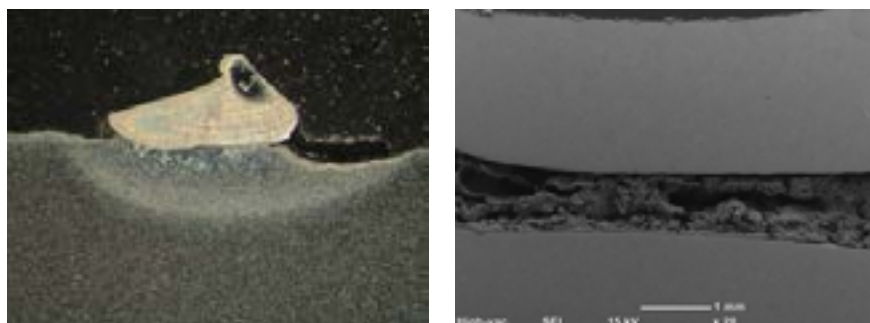

Fig. 6. Corrosion of the elements of the flue gas pass of the FGD scrubber: a) corrosion pits in the heat affected zone of the weld, b) products of corrosion and flue gas desulphurisation under the protective sheets and covers made of Alloy 59
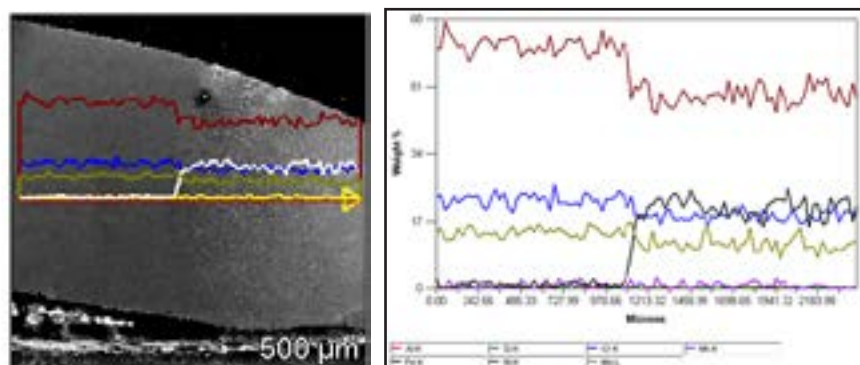

Fig. 7. Results of the linear microanalysis of the chemical composition (Al, Si, Cr, Fe, Ni and Mo) of the joint made of Alloy 59 and steel S235JR

Summary

Important components in the boiler-related part of state-of-the-art power units include tubular elements of heat exchangers (primarily superheaters), thick-walled live steam pipes, finned tubes and membrane tight walls [9]. The construction of state-of-the-art power unit structures characterised by an efficiency of above 50% involves the use of innovative fabrication technologies as well as materials characterised by high-temperature creep resistance and heat resistance. The use of the above-named technologies or new materials should be preceded by the precise analysis of design and structural assumptions. The study of cases presented in the article unequivocally indicates that

it is not possible to implement changes in the manufacturing process or materials without the thorough analysis of the entire power unit structure and changes in operating conditions triggered by technological and material-related changes.

The analysis of the cracking of membrane walls welded using a new hybrid technology (Laser + MAG) revealed that detected cracks in the tube were located outside the zone of hybrid welding-induced structural changes, in the zone of granular ferritic-pearlitic structure and were not related to the welding of the tube–flat-bar joint (Fig. 3a, b). The crack was triggered by stress corrosion.

The rupture of the welded joints of the plates protecting the flue gas passes of the scrubber made of new Alloy 59 occurred as a result of low-cycle fatigue triggered by the stiffening of the plating of the flue gas pass by the longitudinal joints of Alloy 59 and steel S235JR as well as of lap joints and plug joints, which, in the conditions of the cyclic cooling of the plating by the sprinkler resulted in the generation of stresses and strains. At the first stage of the process, the rupture resulted from the longitudinal cracking of Alloy 59+Alloy 59 welds induced by low cyclic stresses and thermal strains (Fig. 5a, d). The above-named cracks were responsible for the depressurisation of the pass plating allowing aggressive media, containing sulphur, HCL and HF entered underneath the strips (Fig. 5b, c), leading to the faster (corrosion-triggered) damage to the welds joining Alloy 59 with steel S235JR at the second stage of the process (Fig. 6a, b).

The analysis of the above-presented cases demonstrated that in terms of welded structures it was necessary to take into consideration all aspects of the system, i.e. not only technological or material-related but also structural ones. In the elements subjected to the tests, the primary reason for cracking was not the application of the new technology or the use of the new material, but the implementation of the aforesaid innovations without previous analysis and changes in design design/structural assumptions.

References

[1] Reports by European Parliament, Power Engineering and Environment, 10.2010

[2] Adamiec J.: Pękanie spawanych ścian szczelnych podczas eksploatacji. Przegląd Spawalnictwa, 2018, no. 4, pp. 34-38.

[3] Wojs K. et al.: Aktualne kierunki rozwoju energetyki. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2012.

[4] Adamiec J., Gawrysiuk W., Więcek M.: Nowe możliwości spawania hybrydowego laser + MAG paneli ścian szczelnych. [w] Hernas A., Pasternak J.[red.]: Powerwelding 2013 - praca zbiorowa. Gliwice 2013, pp. 37-48.

[5] Gawrysiuk W., Więcek M., Adamiec J.: Spawanie hybrydowe (laser + MAG) paneli ścian szczelnych kotłów ze stali 7Cr-MoVTiB 10-10. [w] Hernas A., Pasternak J.[red.]: Powerwelding 2013 - praca zbiorowa. Gliwice 2013, pp. 245-256

[6] Kamela A., Adamiec J.: Ocena odporności na korozję wysokotemperaturową złączy spawanych ze stopu Alloy 59. [w] Górka J.[red.]: Sympozjum Katedr i Zakładów Spawalnictwa, Brenna, 12-13 June 2018, Gliwice, Komisja Odlewnictwa PAN. Oddział Katowice, 2018, pp. 69-74.

[7] Kamela A., Adamiec J.: Odporność na korozję wżerową napoin ze stopu Alloy 59 w syntetycznym roztworze FGD. Przegląd Spawalnictwa, 2018, no. 5, pp. 46-50

[8] Vangeli P, Torsner E., Beckers B., Carinci G.: Stale nierdzewne do skruberów w IOS – I część, http://nowa-energia.com.pl/2009/09/04/stale-nierdzewne-do-skruberow-w-ios-%E2%80%93-i-czesc/, accessed on 20.08.2018

[9] Adamiec J.: Technologie wytwarzania rur ożebrowanych stosowanych w energetyce. Wydawnictwo Politechniki Śląskiej,

Gliwice 2017.
[10] Dobosiewicz J.: Korozja naprężeniowa rurek skraplaczy, Energetyka no. 10, 1995, pp. 461-462