Edmund Tasak, Aneta Ziewiec

Problems Accompanying Repairs of Chemical Equipment

Abstract: The paper presents problems experienced during repairs of structures operated at high temperature for a long time. Research-related TOFD method-based ultrasonic tests revealed indications implying the presence of unacceptable imperfections in welded joints. Attempted repairs involving the use of welding methods proved ineffective as the welding and heat treatment processes resulted in the formation of cracks. The tests and analysis of the above-named issue revealed that the reason for repair-related problems lay in relaxation cracks triggered by excessively high stresses in the joints and improper parameters of heat treatment to which the steel of the boiler was subjected. The welding technology developed as a result of the study enabled the performance of the proper repair of related equipment and made it possible to re-start the production.

Keywords: welding, steel SA204Gr.B, reheat cracking, boiler repairs

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Introduction

Many structures exposed to high temperature during operation are made in accordance with ASME guidelines. In accordance with the aforesaid standard, one of the steel grades used in the production of boilers operated at temperatures of up to approximately 450°C is steel SA204GR.B. According to commercial information, an equivalent to steel SA204GR.B in accordance with the PN-EN10028-2 standard is steel 16Mo3. However, a comparison of the chemical composition of the steel grades (Table 1) reveals significant differences. The ASTM standard does not provide information about the content of chromium and nickel, whereas in PN-EN 10028-2 the aforesaid content is limited up to maximum of 0.3%. There are also differences as regards the content of molybdenum. In accordance with the ASTM standard, in steel SA204GR.B the content of molybdenum is restricted within the range of 0.41% to 0.64%, whereas in steel 16Mo3 the content of molybdenum is restricted within the range of 0.25% to 0.35% (PN-EN 10028-2). Following suggestions contained in related reference publications, a repair of a boiler made of steel SA204GR.B was performed using welding procedures concerning steel 16Mo3. The aforesaid approach led to the formation of cracks in the HAZ during two repairs and, consequently, resulted in the decommissioning of the boiler. Because of the fact that the second boiler made of the same steel also required a repair, it was necessary to carry out detailed tests aimed to identify reasons for crack formation and develop a technology enabling the successful repair of the boiler.

Prof. Edmund Tasak (Professor PhD (DSc) Habilitated Eng.) – retired Professor at AGH University of Science and Technology; dr inż. Aneta Ziewiec (PhD (DSc) Eng.) – Faculty of Materials Engineering and Industrial Computer Science at AGH University of Science and Technology

Table 1. Chemical composition of the boiler steel

Specimens	Chemical composition, %								
	C	Mn	Si	P	S	Cr	Mo	V	Ni
Specimen 1	0.148	0.698	0.161	0.015	0.025	0.349	0.539	–	0.12
Specimen 2	0.154	0.844	0.304	0.024	0.020	0.495	0.583	0.0244	0.15
SA204Gr.B in accordance with ASTM	<0.2	<0.98	0.13–0.45	0.035	0.035	–	0.41–0.64	–	–
16Mo3 in accordance with PN-EN 10028-2	0.12–0.20	0.4–0.9	<0.35	<0.025	<0.010	<0.30	0.25–0.35	–	<0.30
Specimen 1 – analysis from report [2], Specimen 2 – analysis from report [3]									

Analysis of the welding technology

The TOFD method-based ultrasonic tests of the boiler welds after 40 years of operation revealed numerous indications of imperfections both inside the weld at a depth of approximately 26 mm and a crack on the weld face side in the HAZ. The aforesaid detection was followed by an attempted removal of the indications (cracks) and the welding of the cut-out grooves. The cracks were cut out by milling and grinding. The cut-out grooves were welded using E MoB32H5-PN-EN ISO 3580 electrodes (FOX DMO Kb Böhler). Approximately 24 hours after the welding of the grooves, the HAZ of the girth weld developed a crack. The crack was subjected to grinding and repeated welding. After the repair, visual tests and MT did not reveal the presence of cracks.

Conditions of the Office of Technical Inspection (Urząd Dozoru Technicznego – UDT) no. WUDT-UC-WO-W/02:2005 Annex 3 specify the hold temperature range for steel 16Mo3 between 570°C and 650°C. In the Welding Procedure Specification concerning the joints it was assumed that the temperature of post-weld heat treatment should amount to 600±20°C, whereas the hold time should be 36 minutes. The above-presented post-weld heat treatment parameters were consistent with the Conditions specified by the UDT. The aforesaid parameters were applied during the post-weld inductive heat treatment of the cut-out elements of the girth welds.

Ultrasonic tests performed after heat treatment revealed the presence of 13 discontinuities failing to meet acceptance level 1 in accordance with PN-EN ISO 15626:2014-01E. The depth of indications (from the weld face surface) determined using the ultrasonic method was restricted within the range of 7 mm to 14 mm. An exemplary crack observed under the face of the girth weld is illustrated in Figure 1.

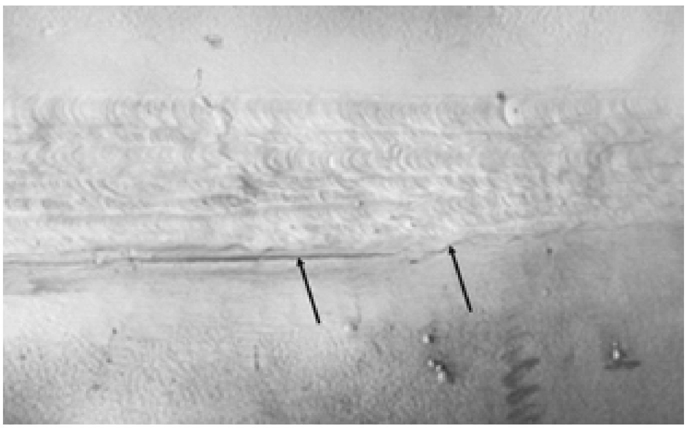

Fig. 1. Girth weld with visible crack from the edge of the weld under the weld face (MT)

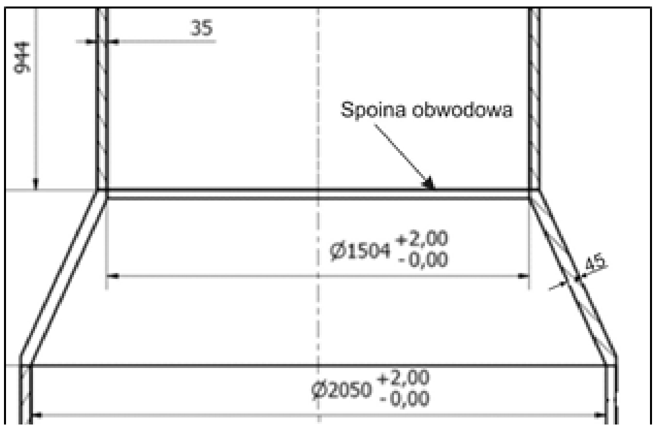

Fig. 2. Fragment of the upper part of the boiler shell with the girth weld (marked) containing the highest number of cracks

Reasons for crack formation during the repair of the boiler

The analysis of the results of the ultrasonic tests performed before the repair revealed that most of the indications (cracks) were detected in the girth weld joining a 35 mm thick cylindrical element with a 45 mm thick conical element. The fragment of the boiler shell containing the weld subjected to analysis is presented in Figure 2.

The specimen cut out of the joint were subjected to tests [1, 2, 3, 4] revealing that the material satisfied related requirements of the standards in relation to properties and structure. The material did not contain traces of degradation resulting from operational exposure to hydrogen atmosphere at higher temperature. As a result, there were no contraindications as to the further use of the material. Reports [1 and 3] contain photographic documentation confirming that cracking in the heat affected zone was of annealing (relaxation) nature. The cracks (and their nature) are presented in Figures 3 and 4.

Analysis of the chemical composition of the steels

The analyses of the chemical composition of 2 specimens cut out of the boiler shell (the results of which are presented Table 1) revealed that the contents of chromium and molybdenum in steel SA204Gr.B were higher than those specified in the PN-EN 10028-2 in relation to steel 16Mo3. For this reason, design engineers should not be advised that steel 16Mo3 is equivalent to steel SA204Gr.B. The higher contents of chromium and molybdenum in steel SA-204Gr.B significantly affect its weldability and, consequently, susceptibility to cracking during welding and post-weld heat treatment. The susceptibility of steels to reheat cracking is estimated using computational parameter ΔG.

$$\Delta G=\%Cr+3{,}3\%Mo+8{,}1\%V-2$$

If ΔG<0, given steel is not susceptible to reheat cracking, whereas if ΔG>0, the steel is susceptible to cracking.

In relation to the chemical composition of specimen 1, ΔG=0.27%. In turn, relation to the chemical composition of specimen 2, ΔG=0.62%. Finally, as regards the maximum chemical composition of steel 16Mo3 specified in PN-EN 10028-2, ΔG<0 and amounts to - 0.54%. According to the calculations, steel 16Mo3 (even characterised by the maximum content of the chemical elements specified in PN-EN 10028-2) is not susceptible to reheat cracking. However, steel SA204Gr.B (used in the boiler) is susceptible to reheat cracking during heat treatment.

In addition to the chemical composition, welding stresses were the primary factor responsible for cracking during heat treatment. Most of the stresses were located at the edge of the interface between the weld and the base material.

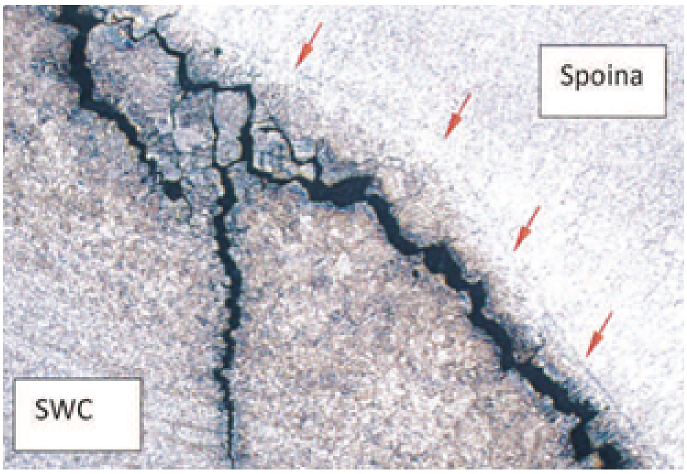

Fig. 3. Annealing crack formed in the coarse-grained area of the HAZ; fusions lines are marked with arrows [1]

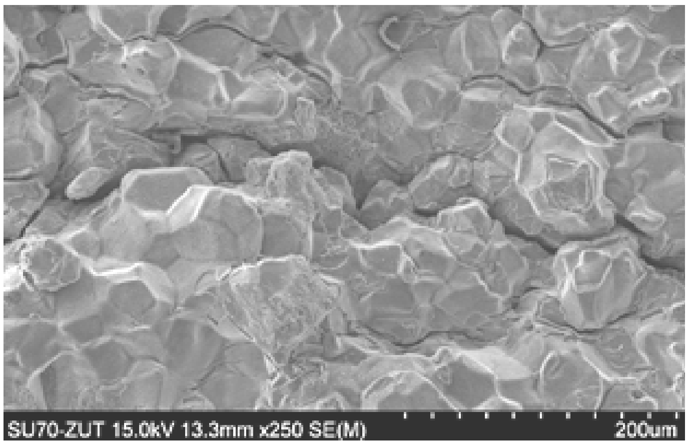

Fig. 4. Intercrystalline nature of reheat cracking [3]

Because of the fact that the chemical composition of a given steel grade is specified and cannot be modified, the only way enabling the reduction of cracking during heat treatment is by decreasing the level of welding stresses. This aim can be achieved by applying appropriate post-weld heat treatment. As regards steels susceptible to reheat cracking, stress relief annealing should be performed in two stages. Up to a temperature of approximately 550°C, welded joints should be heated slowly and held at the temperature for a time necessary for the partial relaxation of stresses. Usually, this time is twice as long as the time calculated from dependence t = 2 min/mm of the weld thickness. At the second stage, in order to obtain appropriate structure and continue the process of stress relaxation, the weld should be heated up to a stress relief annealing temperature restricted within the range of 680°C to 700°C. If only possible (to prevent cold cracking), post-weld heat treatment should be performed directly from the temperature of welding. A typical diagram of the stress relief annealing cycle following the welding of steel Cr-Mo or Cr-Mo-V is presented in Figure 5. The gradual heating to stress relief temperature involving a "stop" at a temperature of approximately 550°C was necessary to initially reduce the level of welding stresses and, consequently, minimise susceptibility to cracking during further heating up to the proper stress relief annealing temperature.

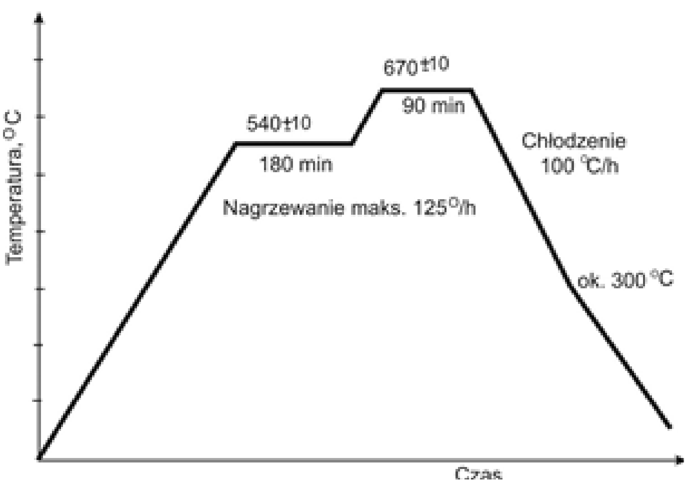

Fig. 5. Schematic diagram of heat treatment after the welding of 45 mm thick steel SA204Gr.B (Cr-Mo) susceptible to reheat cracking

UT-based analysis of the location of cracks inside the weld

The report from CLDT-based ultrasonic tests [5] presents the location of imperfections around the perimeter as well as the length of the imperfections and their depth below the surface. The analysis was concerned with 11 cracks (indications) located, on average, 26.5 mm away below the surface. The relatively regular location of indications (cracks) around the perimeter is presented in Figure 6. The difference between the beginnings of indications was the multiple of a distance restricted within the range of 250 mm to 350 mm (i.e. the approximate distance between successive tack welds). The comparison revealed that the indications (cracks) were formed on the tack welds. The analysis of the weld macrostructure (Fig. 7) made it possible to determine the depth at which the root of the tack weld was situated and the manner in which beads were made. As the weld root was approximately 26 mm from the weld face, there was nearly ideal correlation between the location of the indications (cracks) and the position of the first (tack) back weld.

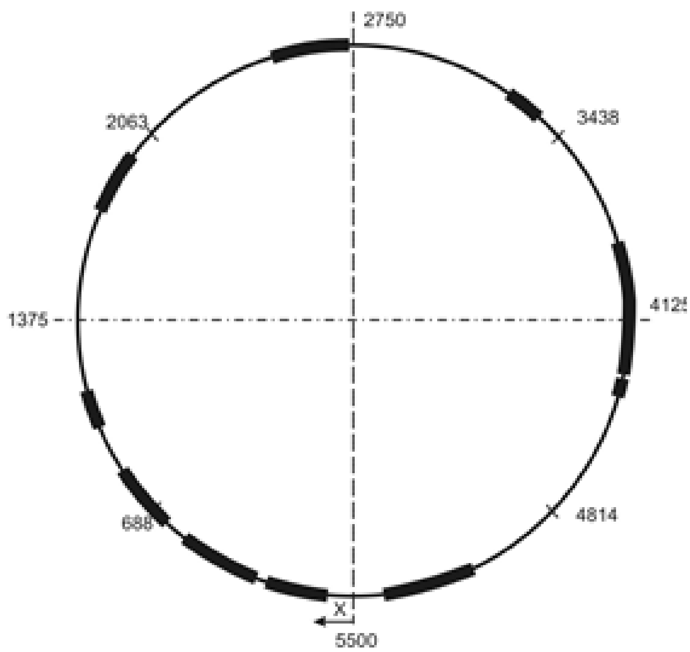

Fig. 6. Schematic diagram of the location of indications (cracks) and their length in the weld at a depth of approximately 26 mm

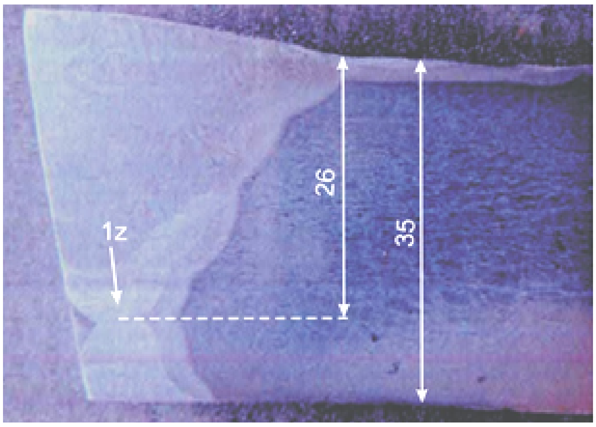

Fig. 7. Macrostructure of the weld fragment; 1z – first (tack) weld in the root; the macrostructure of the weld was obtained from report [2]

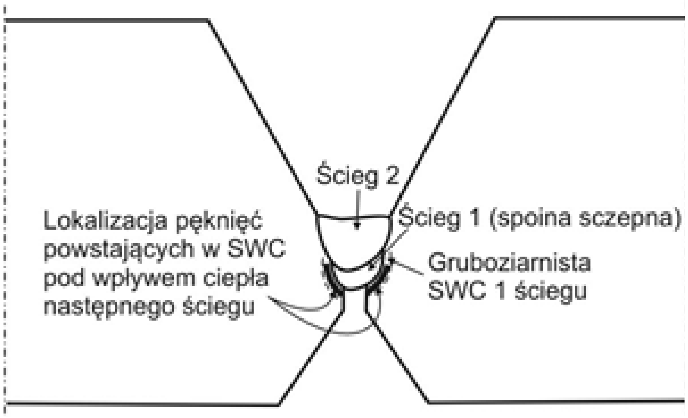

Fig. 8. Mechanism of relaxation crack formation when making the first runs in the root on the tack weld

Hypothetical mechanism of crack formation in the weld

The analysis of the data related to the location and the size of indications (cracks) made it possible to identify the mechanism responsible for the formation of cracks in the weld root as early as during the making of the boiler. The mechanism of crack formation in the weld root is presented in Figure 9. The edges of the truncated cone and of the upper shell were subjected to non-uniform X-shaped preparation. Distances between successive tack welds made around the perimeter were restricted within the range of 250 mm to 350 mm. The heat affected zone of the tack welds near the fusion line contained the martensitic structure formed during post-weld cooling. Significant thicknesses (weight) of the elements subjected to welding combined with the small area of the tack welds generated very high tensile stresses in the area of the tack welds (Fig. 9).

During the making of the first runs around the perimeter, the tack welds were not entirely melted and a heat input accompanying the welding process heated the coarse-grained HAZ up to a temperature of approximately 600°C, i.e. the temperature triggering intensive reheat cracking in the coarse-grained HAZ area. Because of the small dimensions of the weld and HAZ, the dimensions of the cracks were small as well (up to a few millimetres). The size of the cracks was comparable with the mean size of the indications (cracks) amounting to 2.7 mm [7]. The cracks were of annealing nature and, because of the fact that their formation was affected by the heat of the second run, are referred to as "subclad" cracks [8]. The small cracks formed when making the first girth run did not increase during the further part of the welding process and the filing of the weld groove. The further "growth" of the cracks was prevented by the transformation of the stresses in the back weld area from tensile into compressive (Fig. 10).

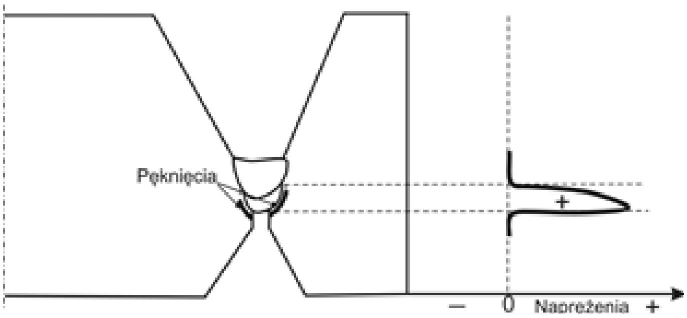

Fig. 9. Schematic diagram of hypothetical stresses after the making of the tack welds

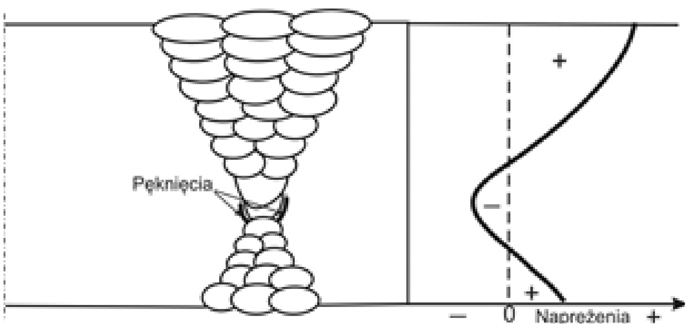

Fig. 10. Schematic diagram of stresses across the joint thickness of the making of the entire weld

Initially high tensile stresses in the zone of the first run were reduced by the shrinkage of the runs on the weld face side and the weld root side. As a result, the weld face area and the inside surface of the boiler contained significant tensile stresses, whereas the area of the tack welds and the first girth run contained compressive stresses. The aforesaid state of stresses did not translate into the further development of the existing cracks during the operation of the boiler.

For this reason, the 40 year-long operation of the boiler did not lead to a failure, which could be triggered by reheat "subclad" cracks formed in the root run (during the making of the boiler).

The cracks were not revealed during the inspection of the boiler as they were very small and the resolving power of the diagnostic equipment used at that time was insufficient to detect them. Presently used ultrasonic tests would detect such cracks and recognise them as unacceptable. The microcracks detected inside the weld did not reduce the fatigue service life of the boiler.

One indication (crack) was located at the edge of the weld (on the weld face side) and had a depth of 14.2 mm. The crack came to the surface and was probably formed during the post-weld heat treatment of the boiler. The crack was not detected during the non-destructive tests following the making of the boiler as in the 1980s such tests were only performed after the making of the weld. At that time nobody supposed that joints could crack during heat treatment as the mechanism of reheat cracking was not known then. Because no crack was detected after the completion of the welding process, the joint was classified as meeting related requirements. The crack was formed during post-weld heat treatment. Because repeated non-destructive tests were not required, the boiler was commissioned and put into service.

The first widely available data concerning the mechanism of reheat cracking were published in 1979 [6]. During the making of the boiler in 1978 the problem of reheat cracking was not commonly known nor were the methods of preventing this phenomenon.

Concluding remarks

The welding imperfections located inside the weld at a depth of approximately 26 mm and detected during the non-destructive tests were not triggered by operation but were formed in the heat affected zone (HAZ) of the tack welds during the making of the first girth run, at the boiler fabrication stage. The presence of the imperfections and the state of imperfection-related stresses (compressive stresses) did not reduce the fatigue service life of the boiler.

The crack located at the edge of the weld on the weld face side was not detected during the non-destructive tests performed after the making of the boiler because in the 1980s such tests were only performed after welding. Heat treatment was not followed by non-destructive tests as nobody supposed that welded joints might develop cracks during post-weld heat treatment and the issue of reheat (relaxation) cracking was not known then. As the crack was not detected after welding, the joint was recognised as satisfying the requirements effective at that time.

The boiler was made of steel grade SA-204Gr.B in accordance with the ASTM standard. A commonly recommended equivalent to the aforesaid steel was steel 16Mo3 in accordance with European standards. However, the chemical compositions of the above-named steels differed significantly. The ASTM standard did not provide information about the content of chromium and specified the content of molybdenum as restricted within the range of 0.41% to 0.64%. The PN-EN 10028-2 standard specified that in steel 16Mo3 the content of chromium amounted to not more than 0.3% whereas the content of molybdenum was restricted within the range of 0.25% to 0.35%. The contractor commissioned with the repair of the boiler, assuming the replaceability of the above-named steels used a heat treatment technique consistent with guidelines specified by the Office of Technical Inspection (Urząd Dozoru Technicznego - UDT). The temperature of stress relief annealing amounted to 600 20°C and was within the stress relief annealing temperature range specified in conditions provided by the UDT. The cycle of heat treatment was a single-stage process. Steel SA204Gr.B, containing between 0.35% and 0.49% chromium and between 0.54% and 0.58% molybdenum, was susceptible to reheat cracking as the cracking susceptibility parameter   G>0. In turn, in the chemical composition of steel 16Mo3 specified in standard PN-EN 10028-2   G<0 and amounted to - 0.54%. As a result, steel 16Mo3 is not susceptible to reheat cracking. The parameters of heat treatment affecting steel 16Mo3 were selected properly, whereas those used in the heat treatment of steel SA204Gr.B (the steel used to make the boiler) was not proper.

The direct reasons for the occurrence of reheat cracking during the post-weld heat treatment of the boiler subjected to repair included the presence of significant welding stresses in the weld on the weld face side, the improper (i.e. single-stage) cycle of heat treatment and overly low post-weld annealing temperature (600°C).

During the repair, the chemical composition of the boiler steel necessitated the use of a special welding technology involving the peening of runs and aimed to initially reduce stresses present in the weld. Post–weld heat treatment should be performed in two stages. The first stage of annealing should be carried out at temperature below that marking susceptibility to cracking (approximately 550°C). Annealing at the aforesaid temperature is accompanied by the relaxation of stresses. The proper annealing temperature amounting to approximately 680°C is responsible for the further relaxation of stresses (to a low level) and enables the obtainment of desired plastic and mechanical properties.

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