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THE INFLUENCE OF MANUAL METAL ARC MULTIPLE REPAIR WELDING OF LONG OPERATED WATERWALL ON THE STRUCTURE AND HARDNESS OF THE HEAT AFFECTED ZONE OF WELDED JOINTS

Welded installations failures of power plants, which are often result from a high degree of wear, requires suitable repairs. In the case of cracks formed in the weld bead of waterwall, weld bead is removed and new welded joint is prepared. However, it is associated with consecutive thermal cycles, which affect properties of heat affected zone of welded joint. This study presents the influence of multiple manual metal arc welding associated with repair activities of long operated waterwall of boiler steel on properties of repair welded joints. The work contains the results of macro and microscopic metallographic examination as well as the results of hardness measurements.

Keywords: repair welding, waterwall, manual metal arc welding, power engineering, HAZ

1. Introduction

Failures of welded power engineering systems, often resulting from substantial structural wear and tear, require necessary repairs. It would be best to replace old structures with new ones, yet because of technical and economic aspects, such a solution is usually out of question. For this reason, repair welding needs to be applied [1].

Producers of electric energy and institutions responsible for the power sector are primarily focused on maintaining the existence of power engineering installations and systems. Related activities include rational and thorough diagnostic, surveys, repairs and the revamping of installations significantly exceeding an operational time of 100 000 hours (resulting from time creep resistance used in related calculations). The situation is particularly difficult as most of the power units operated in Poland have exceeded the above named time, reaching an operational time of more than 200 000 hours. Decisions concerning the extension of operation above the aforesaid time are made using an assessment method based on the time average of creep resistance for 200 000 hours and on positive results of complex diagnostic tests [2,3]. The properties of structural elements deteriorate due to operational damage. Damaging processes taking place in power engineering systems include creep, thermomechanical fatigue, high-temperature corrosion, erosion and cavitation, dry cracking as well as operational and corrosion-induced cracking. Technical, economic, environmental, legal and, first of all, material and technological factors affect the development of power engineering technologies. High-temperature resistance and service life (referred to as high-temperature creep resistance) of structural elements of pressure facilities depend on the stability of material structure, producibility, structural solutions and technological advancement [2,4].

In the power industry, during operation, structural elements are subjected to locally accumulated effects of heterogeneous and non-stationary temperature fields, mechanical loads, environmental impact as well as changes and heterogeneity of material structure. The foregoing may lead to changes in mechanical properties If elements are exposed to periodical and random overloads, it may occur local plastic strains and failures, which usually are present in areas of stress accumulation caused by mechanical notches, structural notches and by the high gradient of temperature. Structural changes, geometry and residual stresses in welded joints trigger the concentration of stresses, thus reducing fatigue strength [5]. In particular, the heat affected zone (HAZ), as an area having a diversified microstructure, is susceptible to crack initiation [6].

The boiler furnace chamber is, among other things, composed of waterwall used in order to ensure the leaktightness of the boiler and to increase its general efficiency. Waterwalls are made of tubes with flat bars or sections welded to them [7].

The operation of waterwalls leads to various defects generation, including [8]: the distortion of a panel by more than ±50 mm, a crack passing through the thickness and along a flat bar, cracks in welded joints located along flat bar and opening on the tube wall side (Fig. 1), cracks in the base material of tubes, tube material delamination reaching the surface and fragments torn out of the tube wall reducing its thickness. Cracks

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in welded joints located along flat bar and opening on the tube wall side are detected using visual tests and magnetic particle inspection. Such defects are removed by replacing the fragment of a tube containing the crack. Cracks which do not penetrate a tube through and through can be removed by cutting out only a given fragment of the weld and weld it again [8]. In order to remove the entire defect, the part of material cut out of the tube should be sufficiently deep and long. In addition, the ends of craters should be provided with gentle bevels from the bottom to the surface of metal being welded [9]. It is also necessary to take into consideration the possibility of crack formation in the weld, in the same area of a waterwall, entailing repeated repairs. For the reasons enumerated above, the objective of the tests presented in this article was to determine the influence of multiple repair welding on the structure and hardness of repair welded joints of waterwall.

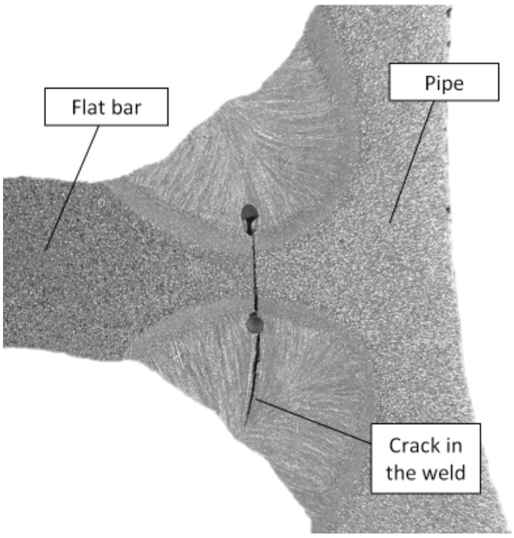

Fig. 1. Crack in a weld of a long operated waterwall

2. Material and methods

The tests, conducted in laboratory conditions, were performed using fragments cut out of a waterwall made of boiler steel grade P265GH. Initially, the tube diameter and wall thickness were 60.3 mm and 6.3 mm respectively, and the flat bar thickness was 6 mm. The waterwall sampled for test specimens had been operated for 180 000 hours in temperature up to 535°C and at a pressure of 24 ata, and required repairing due to low-oxygen corrosion. The operation leads to thickness reduction of the tube and the flat bar, which were 5.9 mm and 4.7 mm respectively. The chemical composition of repaired waterwall determined by spark emission spectrometer is shown in Table 1. The corrosion-affected areas were removed from the specimens using sand blasting. A weld to be repaired was removed using a milling process. During the preparation of the specimens, the use of the milling process made it possible to reduce the effect of variable factors on the size and shape of the area prepared for repair welding (e.g. groove depth) and to reduce material overheating during the removal of the weld using an angle grinder.

A one-time process of repair welding included the removal of the weld and the process of repair welding. A two-time repair process included the removal of the weld, the process of repair welding, the repeated removal of the weld and the repeated process of repair welding. Three, four and five-time repair welding processes were performed in a manner similar to those presented above. It was used welding filler metal which chemical composition was similar to welded elements. The repair joints were welded using the manual metal arc (MMA) process. The welding current and arc voltage (Table 2) were measured using the ArcWeld system developed at the Institute of Welding in Gliwice. The tests assumed the making of a repair weld having dimensions (specified in EN ISO 2553:2014-03 [10]) similar to and not smaller than the dimensions of the weld made initially (removed).

TABLE 1

The chemical composition of repaired waterwall made of boiler steel grade P265GH

Waterwall part	Chemical composition, wt.%											
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	Ti	V
Tube material	0.205	0.303	0.477	0.014	0.028	0.063	0.002	0.022	0.010	0.043	0.002	0.001	0.001
Flat bar material	0.200	0.245	0.476	0.008	0.030	0.179	0.005	0.085	0.020	0.181	0.002	0.001	0.002

TABLE 2

Repair welding parameters

Welding process	Welding position	Welding current [A]	Arc voltage [V]	Travel Speed [cm/min]	Linear energy of welding [kJ/mm]	Efficiency [-]	Heat input [kJ/mm]
MMA	PF	107	31	17	1.187	0.8	0.95

The specimens were cut out of the welds using a Delta AbrasiMet cutting machine manufactured by Buehler. Afterwards, the specimens were included in VaridDur resin made by Buehler. Grinding and polishing processes were performed using a PowerPro 4000 grinder/polisher as well as waterproof abrasive paper and polishing cloth. Microscopic metallographic specimens were prepared using two-stage etching (3 and 2 seconds) in the Nital reagent (2% solution of nitric acid and ethanol). The microscopic metallographic tests were performed using a Nikon ECLIPSE MA200 light microscope provided with the NIS-Elements Advanced Research 4.11 software programme. Vickers hardness tests, following the requirements of EN ISO

6507-1:2007 [11], were performed using a KB50BYZ-FA tester manufactured by KB Prüftechnik GmbH and the KB Hardwin XL software programme.

3. Results and discussion

The microscopic metallographic tests of the repair welded joints revealed the effect of successive thermal cycles (resulting from repeated repair welding) leading to the formation of tempered structure zones in the HAZ and to grain refinement in the fusion zone area. A similar phenomenon takes place during multilayer welding, where successive thermal cycles influence the HAZ microstructure of previously made joints [1]. The identification of the microstructure in the repair joints welded using the MMA process was performed in the weld and in six areas located in the HAZ (Fig. 2).

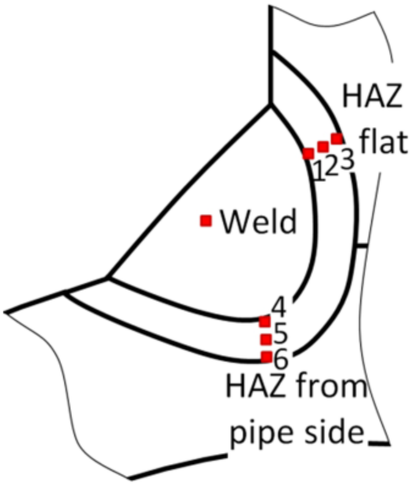

Fig. 2. Microstructure observation areas

The HAZ macrostructure of the MMA welded repair joints was diversified in terms of phase composition. In most of the joints, areas 1 and 4 of the HAZ (near the fusion line) contained bainite as well as granular and acicular ferrite. Some joints contained significantly more ferrite. This phenomenon could be ascribed to the irregular overlapping of thermal cycles entailing grain refinement and phase transformations. In most of the joints, areas 2 and 5 contained granular ferrite, bainite and acicular ferrite. The HAZ areas located farthest from the fusion line (areas 3 and 6) contained mainly granular ferrite mixed with pearlite and, in some cases, with very small amounts of bainite. The repair welds contained mainly acicular ferrite with some granular ferrite and bainite.

Fig. 3 presents the weld and HAZ diversity of the second repair weld. The area was formed as a result of the repair welding process, which was manifested by the sequence of HAZ areas starting from the weld, i.e. medium-grained (refinement area), coarse-grained, medium-grained and fine-grained. It was also observed that the HAZ, at an equal distance from the fusion line, contained zones of various structures and variously sized grains (Fig. 4). This could be attributed to various and multiple thermal cycles affecting the above named areas, which, in turn, resulted from different dimensions and shapes of successive repair welds. The areas which underwent grain refinement were characterised by lower hardness. As a result, the joints were characterised by irregular hardness distribution in overlapping heat affected zones formed in the successive repair welding processes.

The above named phenomenon concerning the presence of variously structured zones having variously sized grains and located at the same distance from the fusion line can also be observed in multilayer welding processes, where successive thermal cycles affect not only the structure and properties of individual runs (layers) of welds, but also influence the properties of the HAZ of the joint. The formation of the zones containing tempered microstructure reduced hardness and improved plastic properties [1,12,13].

The grain refinement in the HAZ near the fusion line, presented in Fig. 3, decreased the HAZ hardness in this area (measurement points 12-15 in Fig. 5). In spite of the coarse-

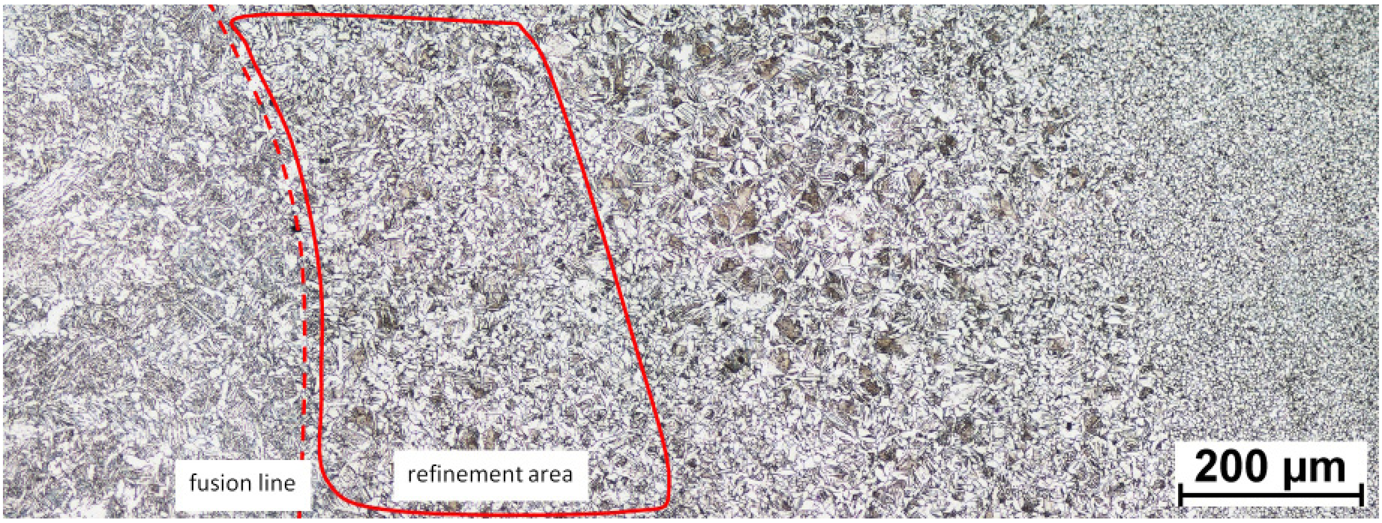

Fig. 3. HAZ areas, the second repair weld, the weld on the left, mag. 200×

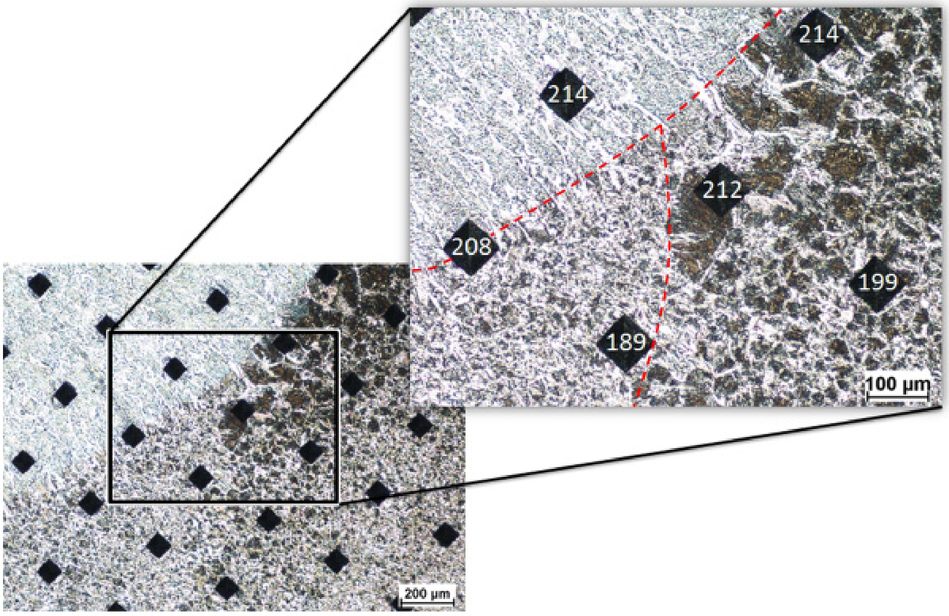

Fig. 4. Diversification of the HAZ microstructure and hardness (HV1) at the same distance from the fusion line (coarse-grained HAZ on the right, fine-grained HAZ on the left, the weld at the top), the first repair weld, mag. 50× and 100×

grained structure, the difference in hardness over the entire HAZ width was small and amounted to ±5%, which could be ascribed to two consecutive repair welding thermal cycles. The decrease in hardness, resulting from the formation of areas having tempered microstructure (located in the HAZ), present in production multiple-pass welding [1,12,13] can also take place during repair welding.

The MMA welded repair joints contained areas mainly composed of ferrite, similar to those present in the HAZ along the fusion line (Fig. 6). The areas dominated by ferrite also took the form of a zone characterised by coarse alloyed ferrite visible in Fig. 7.

The hardness of the area dominated by fine-grained acicular ferrite (Fig. 6) amounted to approximately 186 HV0.1 (measurement point 5 in Fig. 8). The hardness of the adjacent areas, i.e. the weld and the HAZ, grew rapidly (even by 21%). The high gradient of hardness led to the formation of a structural notch. A rapid decrease in hardness on the interphase surface was observed between the base material and the overlay weld during tests concerning the surfacing of boiler tubes [14].

The results concerning the measurements of microhardness HV0.01 of the zone characterised by coarse alloyed ferrite (Fig. 7) are presented in Fig. 9. In spite of the diversified HAZ structure, the values of microhardness were similar over the

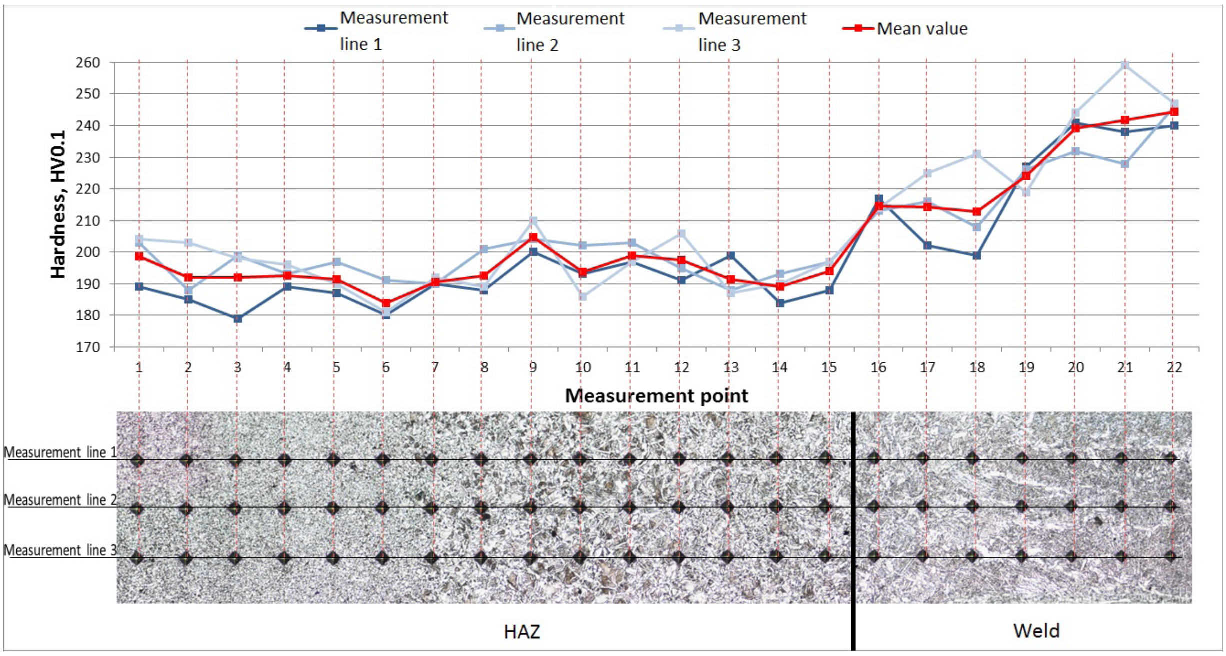

Fig. 5. Microhardness distribution in the HAZ and in the weld of the second MMA welded repair joint, the weld on the right

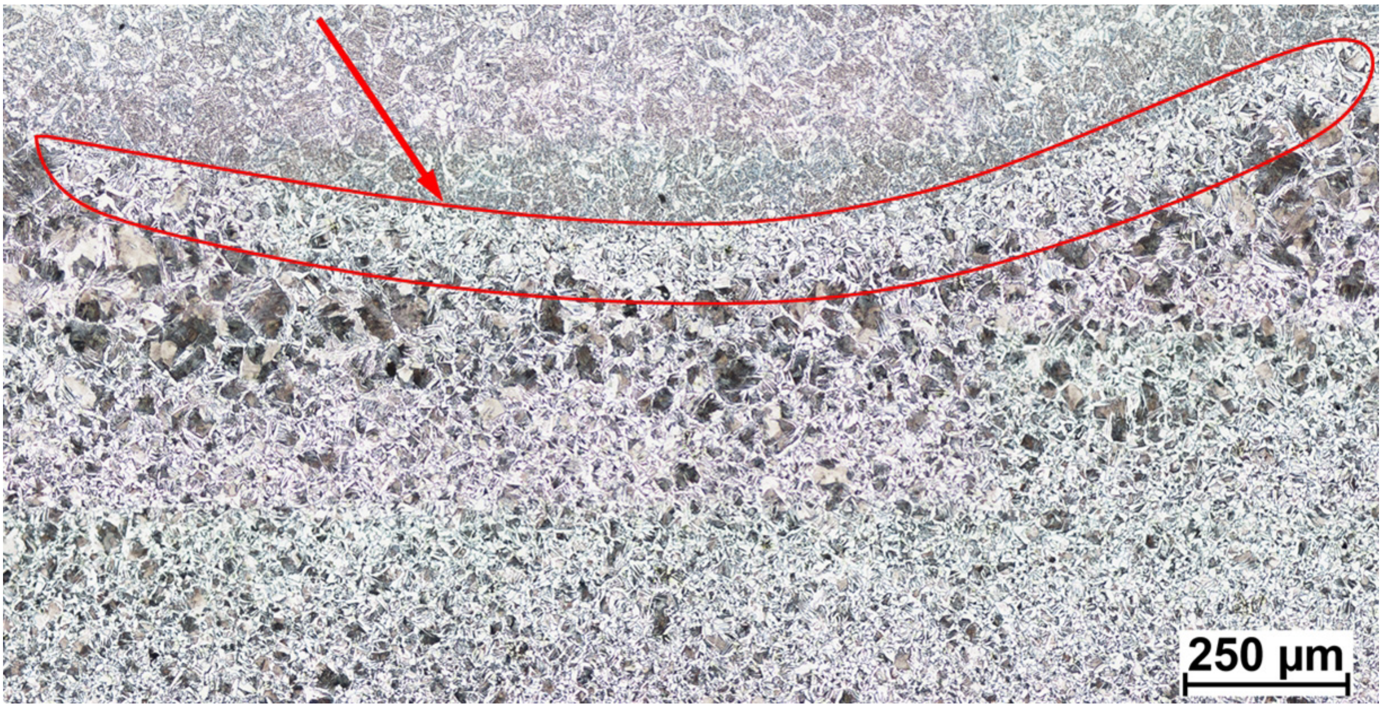

Fig. 6. Area dominated by ferrite along the fusion line in the fifth MMA welded repair joint, mag. 200×

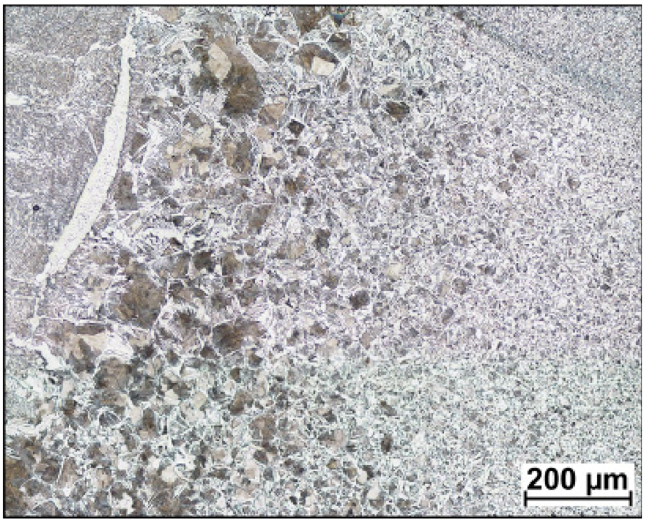

Fig. 7. Zone characterised by coarse alloyed ferrite along the fusion line in the second repair joint, mag. 200×

entire HAZ width. The microhardness of the weld and that of the zone characterised by coarse alloyed ferrite (251 HV0.01) did not differ significantly.

It should be aware of the possibility of the presence of the soft decarbonised zone, which do not affect plastic properties and strength determined in the strength tests. Dependences known in mechanics and describing a plasticising stress in the complex state of stresses apply to the aforesaid soft zone. The presence of the decarbonised zone significantly decreases creep resistance, fatigue strength and, in particular, thermal fatigue and can cause failures of power engineering facilities [15].

The grain refinement in the HAZ near the fusion line and the resultant hardness decrease (Fig. 4) led to the irregular hardness distribution in the HAZ. The HAZ of the joint near the fusion line was characterised by lower hardness values than those present further from the weld (the red arrow in Fig. 10). The successive repair welding processes affected hardness in the individual HAZ areas (Fig. 11), yet that influence did not result from the number of repair welding processes but from the manner in which the weld was made in the joint.

Standard EN ISO 15614-1:2008 [16] states that for group 1 steels (according to ISO/TR 15608:2013 [17]), including steel P265GH used in the tests, the maximum allowed hardness value without heat treatment should amount up to 380 HV10. The hardness measurements did not reveal any areas characterised by hardness exceeding the maximum allowed hardness referred to in the above named standard.

4. Conclusions

The tests justified the formulation of the following concluding remarks:

1. When adjusting the parameters of repair welding, it is necessary to take into consideration differences (if any) in the dimensions of welds subjected to repair (removal) and the groove created as a result of cutting out a given weld.
2. Multiple repair welding is responsible for the diversification of the HAZ microstructure in terms of phases and grain sizes. Similar to multilayer welding, repair welding may lead to the formation of zones (located at the same distance from the fusion line) characterised by various structures and grain sizes (due to the effect of successive welding thermal cycles).
3. Because of the high gradient of hardness, MMA welded repair joints may contain structural notches.

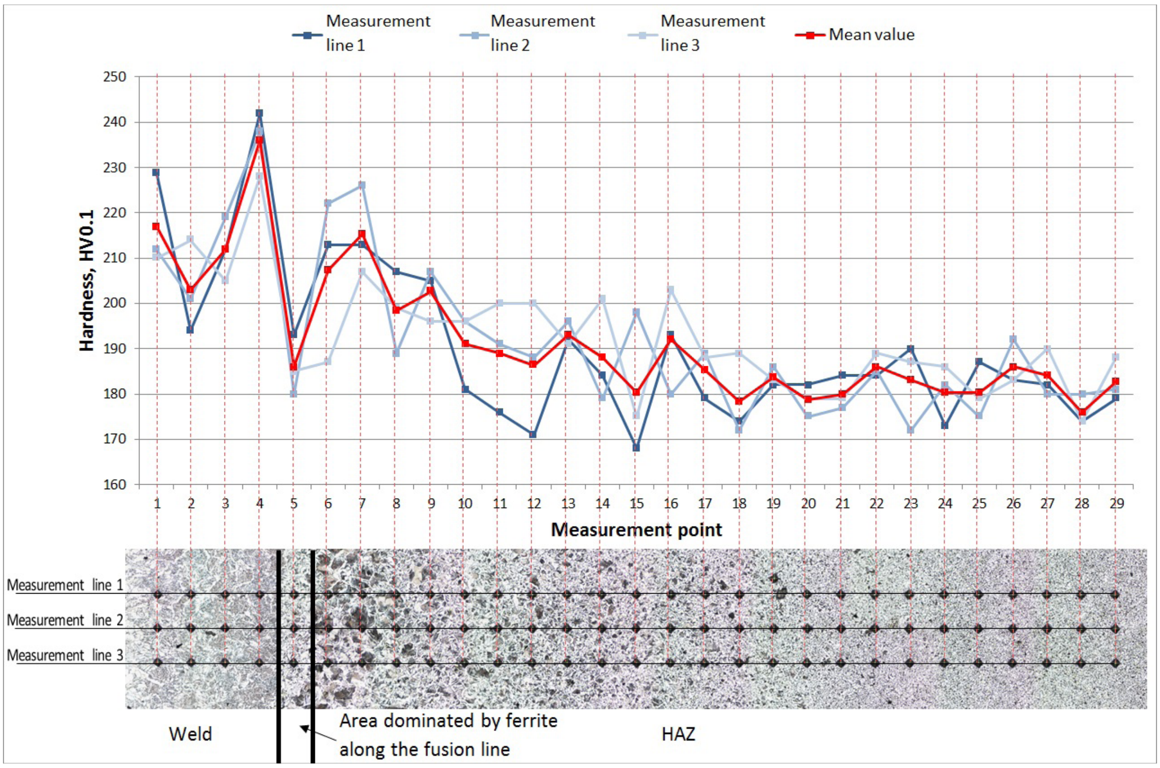

Fig. 8. Microhardness distribution in the HAZ and in the weld of the fifth MMA welded repair joint, the weld on the left

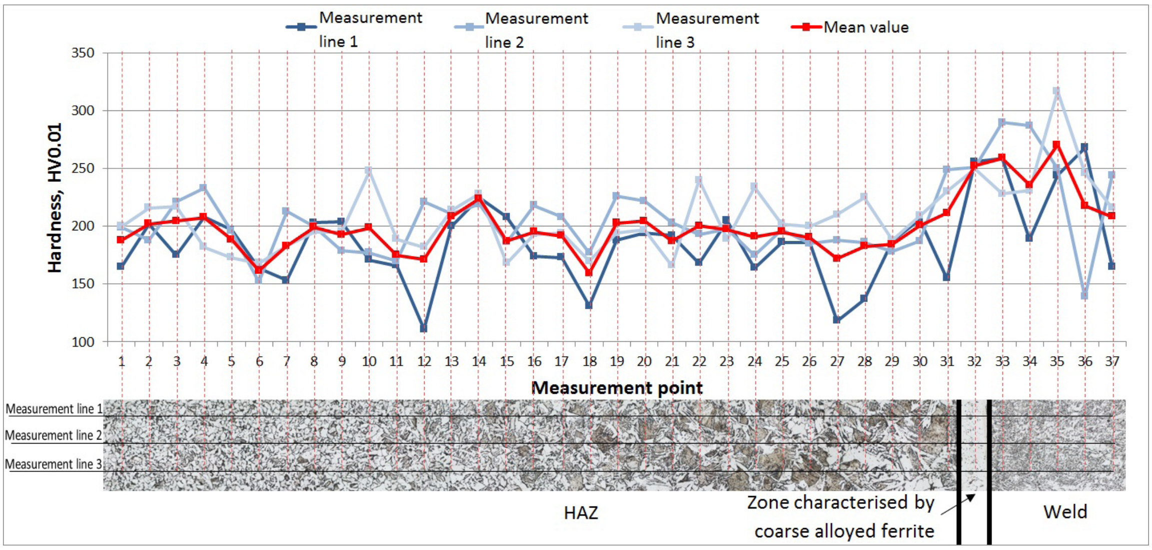

Fig. 9. Microhardness distribution in the HAZ and in the weld of the second MMA welded repair joint, the weld on the right

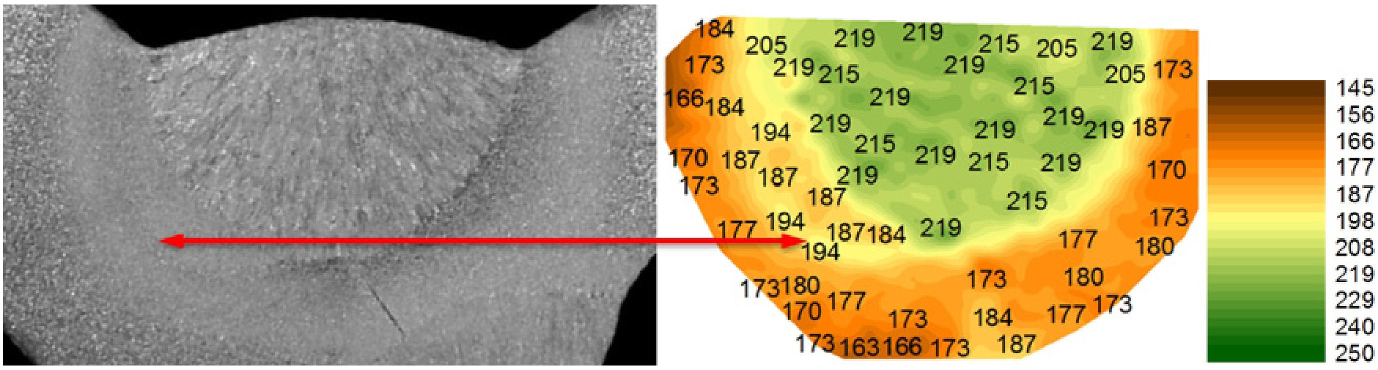

Fig. 10. Macroscopic photograph (left) and the map of hardness HV1 (right) of the first MMA welded repair joint

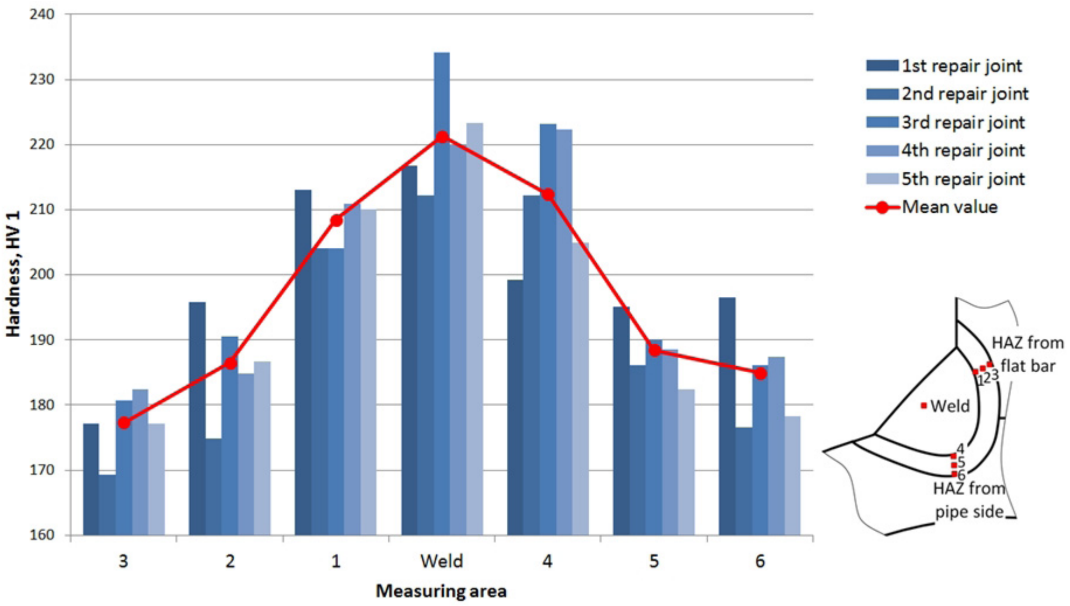

Fig. 11. Values of hardness in the weld and in the individual HAZ areas of the successive MMA welded repair joints; measurement areas according to diagram on the right

4. Joints subjected to multiple repair do not contain dangerous zones characterised by very high hardness. However, it is necessary to take into consideration the irregularity of the field of hardness in the HAZ, resulting from the refinement of grains near the fusion line and structural notches (if any) formed in the above named areas.
5. In the test joints, the zone characterised by coarse alloyed ferrite along the fusion line did not constitute the source of a low hardness-related structural notch. However, areas dominated by fine-grained acicular ferrite near the fusion line could be characterised by lower hardness than the hardness of the adjacent HAZ and that of the weld.

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