Janusz Adamiec

Properties of Laser Welded Finned Tubes Made of Nickel Alloys

Abstract: The article presents test results concerning properties of finned tubes made of the Inconel 625 nickel alloy in terms of their thermal efficiency, resistance to high-temperature corrosion and electrochemical corrosion resistance. It was ascertained that the use of ribs (fins) as the extension of heat exchange surface increases the thermal efficiency of pipes almost by thrice without compromising high corrosion resistance in flue gas atmosphere and electrochemical corrosion.

Keywords: Nickel alloys, Inconel 625, finned tube, laser welding

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Introduction

The use of heat exchangers made of welded fin tubes, e.g. in gas boiler and waste-heat boilers, as heaters, evaporators and superheaters increases heat exchange by almost 300% in comparison with that provided by smooth tubes [1]. This is particularly important where convective heat-transfer coefficients on two sides of the thermal division wall vary significantly. As a result, gas boilers are characterised by high efficiency and availability reaching 98% [2,3]. The high thermal efficiency and availability of such systems is important taking into consideration EU requirements concerning the prevention of greenhouse effect and the necessity of using renewable sources of energy.

There are several technologies of making fin tubes (Fig. 1). The latest technology developed by Energoinstal SA utilises laser welding (Fig. 2). The process, performed at a welding rate of up to 250 rev/min (for tubes made of unalloyed and low-carbon steels), enables the obtainment of proper tube-fin joints with full penetration along the entire length of the weld. The analysis

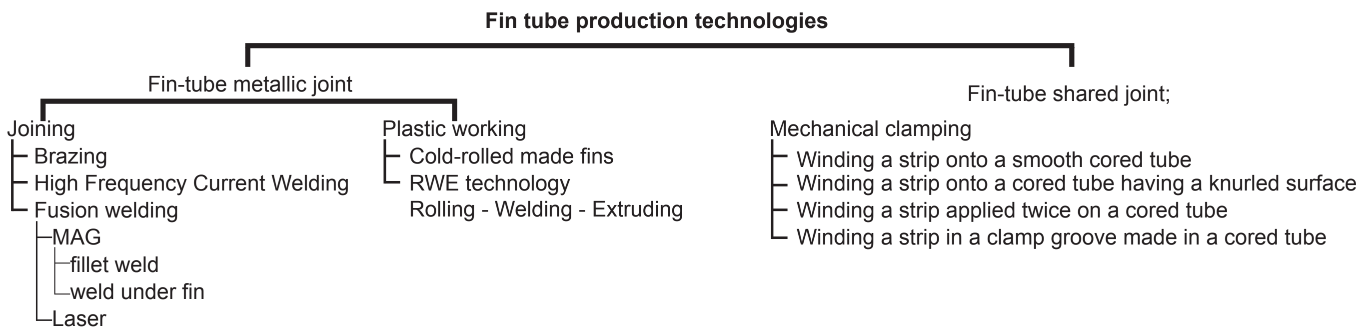

Fig. 1. Division of fin tube production technologies [4]

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

of presently used design solutions of modern waste-heat boilers and gas boilers revealed that the production of fin tubes usually involves pipes having diameters between 31.8 mm and 63.5 mm made of unalloyed steels (e.g. P235 or P355) and creep-resistant steels 16Mo3, 13CrMo4.5 and 10CrMo9.10 according to PN-EN 10216-2.

The analysis of design assumptions concerning units of supercritical parameters indicates that the application scope of classical steels used in power generation systems finishes at an operating temperature of 650°C (because of reduced creep resistance and oxidation resistance). It is recommended that heat exchangers operating in ultrasupercritical conditions be made of nickel superalloys. The development of gas turbine technology enables an increase in efficiency from approximately 38% to 58%-60% and an increase in the temperature of flue gases from 1250°C to 1400°C. The above-presented conditions require the use of nickel alloys in the production of fin tubes.

Technology of the Laser Welding of Fin Tubes Made of Nickel Alloy

The analysis of the technical documentation concerning waste-heat boilers and gas-vapour boilers manufactured by Energoinstal SA as well as the results of the tests performed within project PBS1/A5/13/2012 *Technology of the Laser Welding of Fin Tubes Made of Austenitic Steels and Nickel Alloys Intended for Operation in Boilers of Supercritical and Ultrasupercritical Parameters* led to the conclusion that one of the materials having the greatest application potential in the production of fin tubes was the Ni-Cr-Mo nickel alloy known as Inconel 625. It was assumed that tubes (ϕ 48.3×3.6 mm) provided with 1 mm wide and 15 mm high fins made of Inconel 625 (Fig. 3a) would be subjected to laser welding using an automated station at Centrum Innowacyjnych Technologii Laserowych Energoinstal SA (Centre for Innovative Laser Technologies) (Fig. 1b, 3b). The laser welding tests enabled the adjustment of laser welding parameters (welding rate of 70 rev/min and beam power restricted within the range of 2.4 kW to 2.8 kW) ensuring the obtainment of joints satisfying the requirements of quality level B according to PN-EN ISO 13919 [6].

The visual and structural tests did not reveal any welding imperfections. Welds were

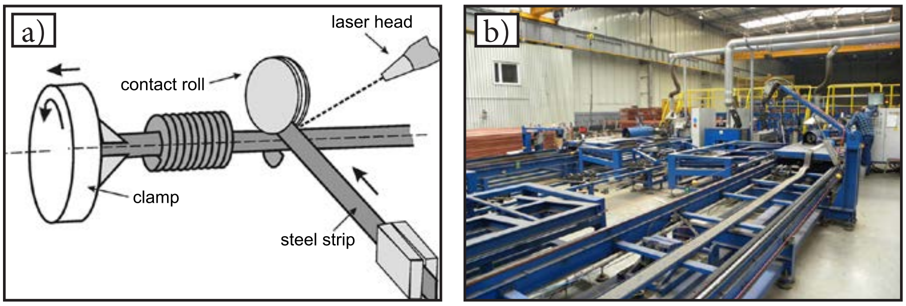

Fig. 2. Laser welding of fin tubes: a) schematic diagram of the welding station, b) automated line for the welding of fin tubes at the Centre for Innovative Laser Technologies (CITL) Energoinstal SA [5]

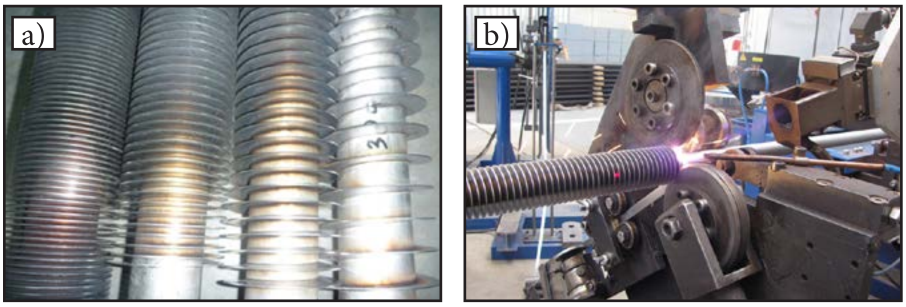

Fig. 3. Fin tubes made of alloy Inconel 625 at Energoinstal SA (a), laser welding of tubes (b) [2]

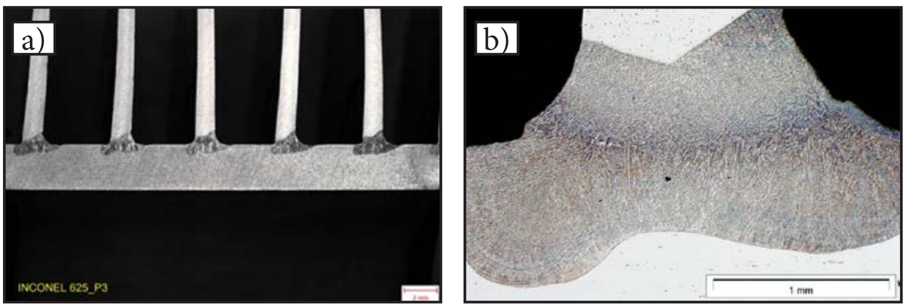

Fig. 4. Structure of the laser-welded fin tube made of alloy Inconel 625: a) macrostructure b) microstructure of the tube-fin joint

characterised by proper shapes and fins were characterised by full penetration (Fig. 4a). It was revealed that the fusion line contained crystals accumulating in the direction of heat discharge, forming the crystal contact line in the axis (Fig. 4b). The structural tests were supplemented by the microanalysis (EDS) of the chemical composition in the fusion line. The test results revealed the uniform distribution of elements in the entire joint (Fig. 5).

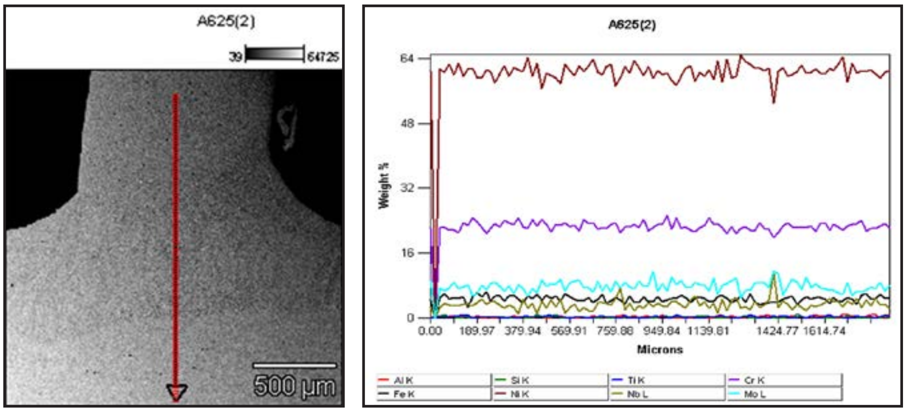

Fig. 5. Results of the chemical composition microanalysis (EDS) involving the cross-section of the joint – linear distribution

The tests confirmed that the joints satisfied the requirements of quality level B according to PN EN ISO 13919. The test results can be the basis for the qualification of the technology of the laser welding of fin tubes made of nickel alloys according to PN EN ISO 15614-11.

Effect of a Welding Technology on the Thermal Efficiency of Fin Tubes

The tests concerning the thermal efficiency of laser welded fin tubes made of alloy Inconel 625 were performed using a test rig schematically presented in Figure 6. The adopted thermal efficiency of a fin tube was the ratio of heat flux flowing in a fin tube to that flowing in a smooth tube. The test rig enabled the performance of test both with the natural and imposed convection of heat. The heat exchanger used in the tests was a two-phase thermosiphon in which condensate flowed to the evaporator in counter-flow to steam flowing to the condenser. The working liquid used in the tests was water enabling the performance of measurements within the temperature range of 100°C to 220°C under a pressure of 1-25 bar.

The assessment of the thermal efficiency of laser welded fin tubes made of alloy Inconel 625 related to the number of fins (heat exchange area) required the making of tubes with different pitches between fins, i.e. 5 mm (designation P18, 200 fins/running metre), 6.7 mm (designation P17, 150 fins/running metre), 10 mm (designation P16, 100 fins/running metre), and 20 mm (designation 15, 50 fins/running metre) (Fig. 3a). The test results were referred to the heat flux flowing in a smooth tube (specimen designation – smooth tube) in the same conditions (temperature, pressure). The tests were performed for the temperature of the medium in the tube (steam) within the range of 100°C to 170°C. Figure 7 presents the results concerning the measured flux of heat emitted from steam (in a tested tube segment having a length of 800 mm) to air in stabilised thermal conditions of the test rig.

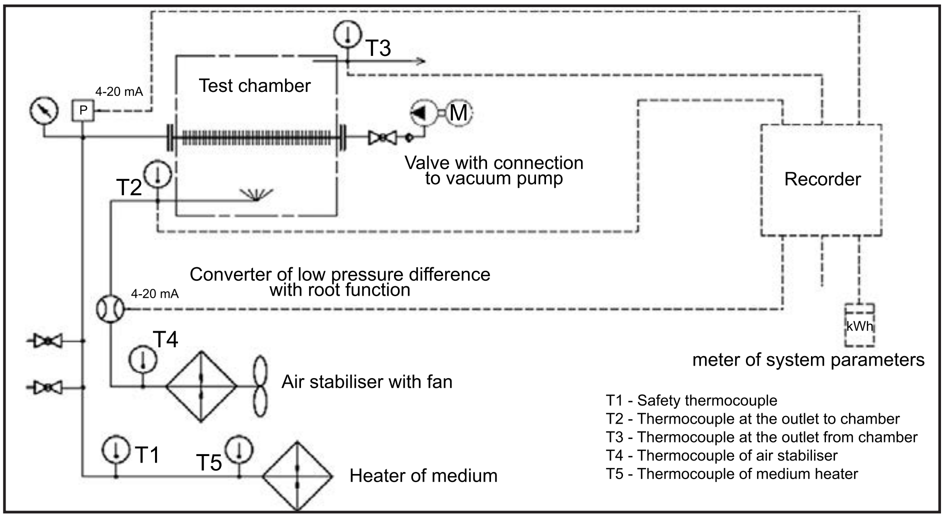

Fig. 6. Schematic diagram of the test rig for measuring the thermal efficiency of fin tubes

The above-presented tests were supplemented by the assessment of the effect of weld discontinuity (lack of penetration) on the heat exchange efficiency of a fin tube. The tests were performed using fin tubes with a fin pitch of 7 mm (140 fins/running metre). The tests involved the simulation of the lack of penetration (in tubes) over 25% of the joint fragment (designation P11), 50% (designation P12) and 75% (designation 13). The tube designated as P10 was characterised by the full penetration along the entire length of the joint. Figure 8 presents the heat flux emitted by steam through the fin tube to air compared with the flux of heat emitted in the same thermal conditions by a smooth tube.

The analysis of the measured heat flux in the experimental conditions revealed that the use of a fin in order to extend the area of heat exchange in fin tubes increased the heat flux, i.e. at a temperature of 100°C from approximately 0.2 kW in terms of smooth tubes to over 0.5 kW in cases of fin tubes. At a temperature of 170°C, the heat flux grew by more than twice (from 0.35 kW as regards smooth tubes to nearly 1.1 kW in relation to fin tubes) (specimens P15-P18) (Fig. 7). The comparison of heat flux transmitted by laser welded fin tubes in relation to fins per a running metre revealed that the increase in the area of heat exchange was accompanied by the increase in the heat flux flowing in the fin tube (Fig. 7). The highest efficiency was obtained in the tube having a pitch of 5mm (200 fins/running metre).

The tests of heat flux transmitted by fin tubes having diversified weld discontinuity (specimens P10-P13) confronted with smooth tubes revealed that the metallic contact of a fin with a tube (without penetration) was sufficient to provide the thermal efficiency of fin tubes amounting to 200-250% if compared with that provided by smooth tubes (Fig. 8). The loss of the above named contact resulted in the reduction of fin tube thermal efficiency to that of smooth tubes. Therefore, because of corrosion phenomena taking place during the operation of heat exchangers, it is necessary to use tubes with full penetration along the entire length of the weld.

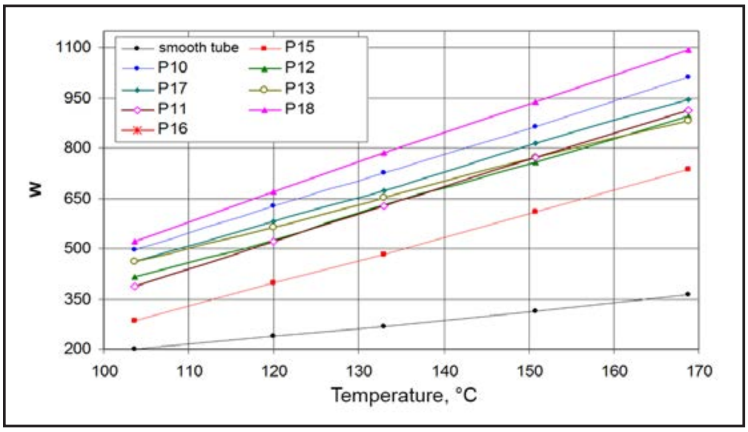

Fig. 7. Measured heat flux emitted by steam through test tubes to air

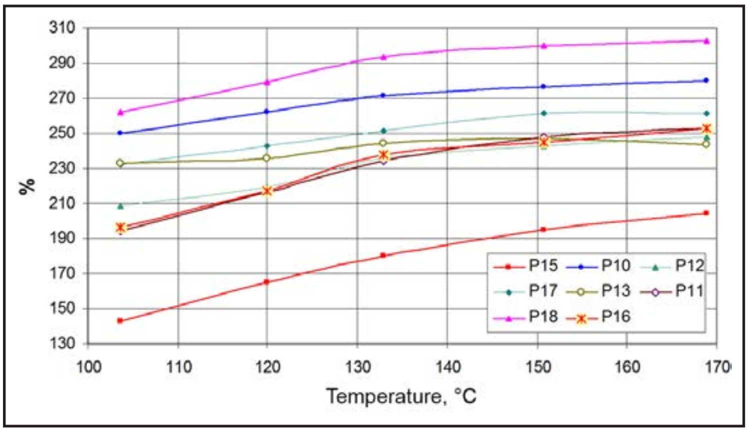

Fig. 8. Relative heat flux emitted by steam through test tubes to air compared to heat flux emitted through smooth tube

High-Temperature Corrosion of Fin Tube Made of Alloy Inconel 625

The scheme of a test rig used when investigating resistance to high-temperature corrosion in simulated operation conditions is presented in Figure 9. The measure representing the resistance of fin tubes to high-temperature corrosion was the change in the specimen weight after the tests.

The tests involved specimen cut out of laser welded tube-fin joints made of alloy Inconel 625 and, for comparison, specimens made of alloy Inconel 600. The specimen width contained three fins. The specimens were placed in test crucibles with Al_2O_3

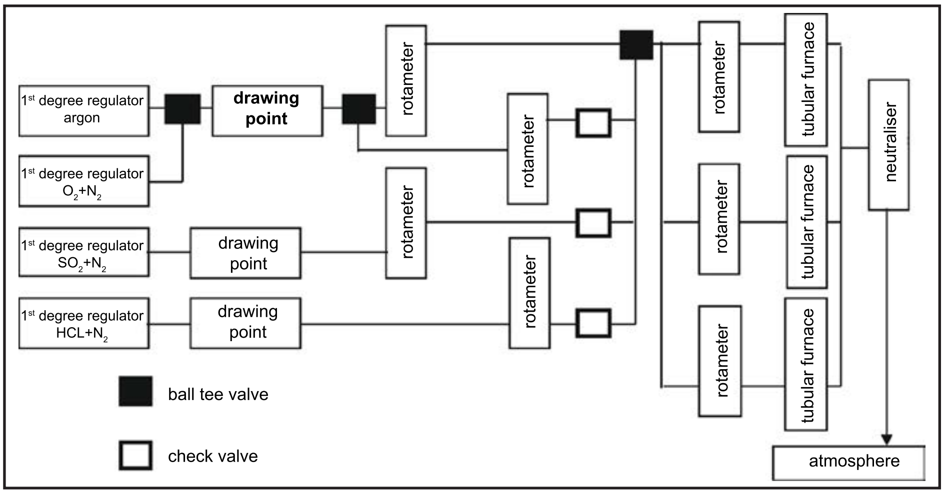

Fig. 9. Scheme of the test rig for investigating high-temperature corrosion of fin tubes

and, next, fixed in the test chamber of a tubular furnace. The mixture of test gases containing N_2 + 9% O_2 + 0.08% SO_2 + 0,2% HCl corresponded to the typical composition of flue gas in waste-heat boilers used in the systems for the cold drying of coke (CDQ). The tests concerning the resistance of welded joints to high-temperature corrosion were performed at a temperature of 800°C for 1000 hours with measurements of the growing weight of corrosion products performed every 250 hours. Each of the specimens was subjected to three (averaged) measurements. The standard deviation from the mean value was below 1%. Exemplary curves demonstrating changes in the weight of specimens in time are presented in Figure 10.

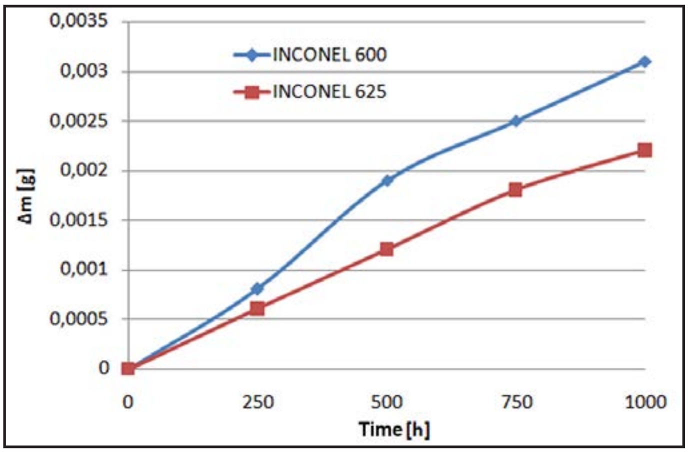

Fig. 10. Change in the weight of laser welded fin tube specimens (with the weld under the fin) made of Inconel 600 and Inconel 625

The analysis of the changes in the weight of laser welded fin tube specimens made of nickel alloys revealed that the specimens were characterised by high resistance to high-temperature corrosion in the atmosphere of flue gas typical of systems used for the dry quenching of coke. The progress of corrosion was close to the linear function, i.e. the increasing time of temperature effect and that of corrosion gas effect was accompanied by an increase in the weight of corrosion products (Fig. 10). It was ascertained that the rate of corrosion was similar in relation to all of the test specimens and amounted to approximately 0.0002 g/100 h (Fig. 10).

The linear nature of corrosion process and the determined dependence of the change in the fin thickness in time made it possible to determine the service life of a fin tube defined as the time during which the metallic joint between the tube and the fin was maintained and provided the proper exchange of heat [4]. The measurements concerning changes in the width of the fin in the function of time revealed that a properly made joint connecting the tube and the flat bar having a width of 1 mm in high-temperature corrosion conditions in the flue gas composed of N_2 + 9% O_2 + 0.08% SO_2 + 0,2 % HCl (typical flue gas of waste-heat boilers in the CDQ system) was characterised by a service life of 10 years. Each welding imperfection such as the reduced weld face, the lack of full penetration as well as the presence of cracks and porosity, leading to the decrease in the weld cross-section, could shorten the service life of the fin tube [4].

The tests concerning the resistance of tube-fin welded joints to high-temperature corrosion were supplemented by metallographic tests. An exemplary specimen after corrosion tests (1000 h) is presented in Figure 11a. The identification of corrosion products required the performance of the microanalysis (EDS) of chemical composition and the identification (XRD) of phase composition. The test results are presented in Figures 11b and 11 c respectively.

The visual assessment of the specimens after the tests concerning high-temperature corrosion resistance revealed a homogenous layer of corrosion products on the surface (Fig. 11a). The layer of corrosion products on the fin tube surface slightly reduced the exchange of heat between flue gas and water or steam inside the tube, yet it protected against high-temperature corrosion. The results of the microanalysis (EDS) of the chemical composition of the corrosion products confirmed the higher contents of chromium and oxygen, which, in turn, confirmed the presence of the layer passivating chromium oxides (Fig. 11c). The phase analysis (XRD) of powdered corrosion products performed using a JEOL JDX-7S X-ray diffractometer confirmed the presence of Cr_2O_3 in the layer of corrosion products (Fig. 11b). This was favourable due to the fact that the layer of Cr_2O_3 was continuous, adhered to the base well and reconstructed quickly in the conditions of high-temperature corrosion providing protection against the above named type of corrosion.

Resistance of Welded Joints Made of Alloy Inconel 625 to Electrochemical Corrosion

The assessment of electrochemical corrosion resistance related to laser welded tube-flat bar joints made of nickel alloy Inconel 625 was based on measurements of polarisation resistance current using the DC method. The polarisation tests in DC conditions were performed using a Solartron 1287 potentiostat. The tests were conducted in a 3.5% NaCl solution using a measurement system composed of the above-presented computer-controlled potentiostat and the CorrWare 3 software programme. The active areas of the test specimens amounted to 0.2-1 cm^2. The solution volume-active area ratio amounted to 100. The reference electrode was a NEK calomel electrode, whereas the auxiliary electrode was a platinum wire.

The measurements started with the recording of the open circuit potential (E_{OCP}) lasting 45 minutes. The subsequent stage involved the potentiodynamic recording of polarisation current during the change in potential at a rate of 20 mV/min from a potential by 300 mV more cathodic than E_{OCP} to reaching breakthrough potential E_b (not exceeding a value of 1.5 V_{NEK}). The density of corrosion current i_{kor} was determined on the basis of measurements of polarisation resistance R_p within the range of ±50 mV in relation to E_{OCP} using the Stern-Geary method. In the above-presented manner, the values of corrosion potential E_{kor}, density of corrosion current i_{kor} and polarisation resistance R_p were determined.

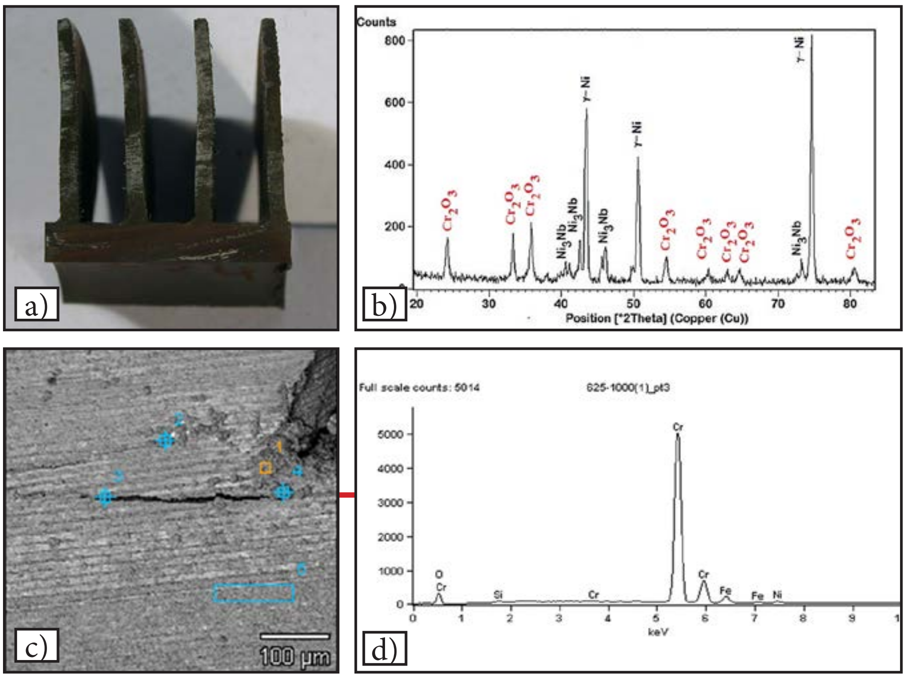

Fig. 11. Test results related to the laser-welded tube-fin joint made of alloy Inconel 625 after the assessment of resistance to high-temperature corrosion in the atmosphere of flue gas for 1000 hours at a temperature of 800oC: a) specimen surface, b) XRD-based phase analysis results of corrosion products, c) EDS-based microanalysis results related to the chemical composition on the specimen surface

The further recording of the polarisation curve in the anodic range after reaching the potential of pitting corrosion served the assessment of phenomena related to pitting corrosion. The susceptibility to corrosion was assessed on the basis of passive layer breakthrough potential E_b and the difference of potentials $\Delta E_1 = E_b - E_{kor}$. The value of potential accompanying the rapid increase in current density (>25μA/cm²) was recognised as the breakthrough potential E_b. In order to identify the products of corrosion, the structure of the surface of specimens after the polarisation tests was observed using a scanning electron microscope. The results of electrochemical tests concerning the joints made of alloy Inconel 625 are presented in Table 1, whereas the polarisation curves related to the weld are presented in Figure 12. The tests revealed the very high electrochemical corrosion resistance of the laser welded joint made of alloy Inconel 625; both the weld and the base material were characterised by low corrosion rates and relatively high breakthrough potential (>500 mV) guaranteeing high resistance to pitting corrosion.

The analysis of the surfaces of the specimens containing the joint made of alloy Inconel 625 did not reveal corrosion on grain boundaries, thus confirming that the joint was resistant to intercrystalline corrosion. However, the analysis also revealed numerous pits on the entire surface area of the weld; the HAZ and the base material contained few uniformly arranged pits (Fig. 12b).

Table 1. Results of potentiodynamic tests concerning the joint made of alloy Inconel 625

Specimen	E_{OCP} [mV]	E_{kor} [mV]	R_p [kΩ*cm²]	i_{kor} [μA/cm²]	V_V [mm/year]	E_b [mV]
weld material						
625_sp	-115	-191	1639	0.164	0.0019	273
625_1sp	100	-165	4995	0.052	0.0006	856
625_2sp	-83	-108	11.17	2.328	0.0274	821
base material						
625_mr	-165	-269	2614	0.0948	0.0011	377
625_1mr	-148	-216	4819	0.054	0.0006	636
625_2mr	-276	-299	3302	0.078	0.0009	620

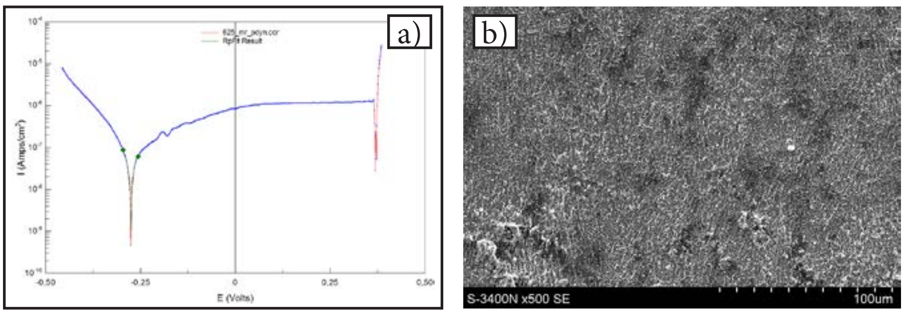

Fig. 12. Polarisation curve with the Stern-Geary adjustment in the cathodic-anodic range related to the weld specimen made of alloy Inconel 625 (a), surface structure after tests concerning resistance electrochemical corrosion in the 3.5% NaCl solution (b)

Conclusions

The tests led to the following conclusions:
– laser welding of fin tubes made of nickel alloy Inconel 625 enables the obtainment of continuous joints characterised by proper structure and satisfying the requirements of quality level B according to PN EN ISO 13919; the technology can be qualified in accordance with PN EN ISO 15614-11,
– extension of the area of tubes made of alloy Inconel 625 (making fins – 200 pieces/running metre) increases their efficiency by nearly 300% in comparison with smooth tubes. Because of operating conditions, it is necessary to undertake efforts aimed to make a joint with full penetration along the entire length of the joint,
– laser welded fin tubes made of alloy Inconel 625 are resistant to high-temperature corrosion in flue gas atmosphere (N_2 + 9% O_2 + 0.08% SO_2 + 0.2% HCl), typical of the QCD systems at a temperature of up to 800°C. Within 1000 hours, high-temperature corrosion proceeds in

a linear manner at a rate of 0.0002 g/1000 h, which confirms the very high chemical corrosion resistance of fin tubes made of nickel alloys,
- laser welded joints of fin tubes are resistant to electrochemical and pitting corrosion in the base material.

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