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EVALUATION OF HIGH TEMPERATURE CORROSION RESISTANCE OF FINNED TUBES MADE OF AUSTENITIC STEEL AND NICKEL ALLOYS

The purpose of the paper was to evaluate the resistance to high temperature corrosion of laser welded joints of finned tubes made of austenitic steel (304,304H) and nickel alloys (Inconel 600, Inconel 625). The scope of the paper covered the performance of corrosion resistance tests in the atmosphere of simulated exhaust gases of the following chemical composition: 0.2% HCl, 0.08% SO_2, 9.0% O_2 and N_2 in the temperature of 800^{o}C for 1000 hours. One found out that both tubes made of austenitic steel and those made of nickel alloy displayed good resistance to corrosion and could be applied in the energy industry.

Keywords: finned tubes, laser welding, high temperature corrosion, austenitic steel, nickel alloys

1. Introduction

An increased demand for electricity as well as requirements of the EU directives, including 2001/77/EC, 2001/80/EEC, 1997/97/23/EEC, result in the necessity to modernize the European energy sector, and thus to undertake measures in the scope of design, manufacture and operation of electrical power equipment. One of the design solutions applied to the power boilers are finned tubes, which, depending on the thermal parameters (pressure, temperature), the working medium and the flue gases, may serve as heaters, economizers or superheaters.

The manufacture of finned tubes with the laser welding technology is highly efficient (10 times faster) and energy efficient (power demand is 10 times less), compared with the technology of welding of finned tubes with MAG methods. The laser welding technology also enables one to increase production of boilers elements by 40% [1,2].

The materials commonly used in finned tubes are unalloyed steels (e.g. P235) and low-alloy steels of the C-Mo, C-CrMo type, which due to their decreased resistance to creep and to oxidation cannot be used in boilers with supercritical parameters (steam temperature 565-620°C and pressure 30 MPa) and ultra supercritical parameters (steam temperature 650-720°C and pressure 35 MPa) with a net efficiency of 45-50% [3]. Therefore it is necessary to use other materials, e.g. austenitic steel or nickel alloy, that can be applied in boilers with supercritical and ultra supercritical parameters.

Finned tubes considerably increase the heat exchange surface, increasing thus the thermal efficiency of the heat exchanger (2.5 times higher than the efficiency of smooth tubes and 1.5 times higher than the efficiency of Favier tubes). The analysis of the literature data shows that the key factor determining the thermal efficiency of finned tubes is the continuity of the weld (the tube – fin joint) and the degree of the weld fusion. Discontinuity of the weld over a 50% length of the fin results in the reduction of the thermal efficiency by nearly 20% [4,5]. A lack of weld penetration or incomplete weld penetration also determines the resistance of the joint to high temperature corrosion in the atmosphere of exhaust gases. In the literature there are no data available on the resistance to high temperature corrosion of finned tubes used in the hear exchangers intended for the power industry. Therefore it is necessary to conduct research on the resistance to high temperature corrosion of joints in the laser welded finned tubes made of materials with a large potential for application in the units with supercritical and ultra supercritical parameters, i.e. austenitic steel and nickel alloys.

2. Research material

Laser welded finned tubes made of austenitic steel: 304 and 304H and nickel alloys: Inconel 600 and Inconel 625 were used to conduct the research. The finned tubes for the research were made using an automatic laser welding station developed by the company Energoinstal SA (Fig. 1a,b). The station is made up of a TRUDISK 8002 laser disc of the Trumph company, with a system dividing the laser beam into two welding stations equipped with systems turning and feeding the tubes during the welding process, as well as an automatic painting system. A triaxial system with a flexible adjustment in each axis enables one to

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a) b) c)

Fig. 1. Laser welding station for the welding of finned tubes, developed in the company Energoinstal SA: a) general diagram of the welding system [19], b) laser welding of the tubes, c) finned tube

precisely adjust the position of the laser head, to automatically tack the strip before the beginning of the welding process and to automatically cut the strip with the laser beam after the end of the welding process. A tube induction heating system allows one to fully adjust and control the preheating temperature.

The technological parameters of the laser welding process are shown in Table 1. An argon shield with a flow rate of 5 l/min was used as a shield of the welding area. One prepared finned tubes with a diameter of 48.3×2.77 mm, with a continuous fin of the width of 1 mm and height of 15 mm. The distance between the fins was 6.25 mm. A example of the finned tube was shown in Fig. 1c.

TABLE 1

Welding parameters of finned tubes applied in the testing

Material	Beam power [kW]	Rotational speed [n/min]	Linear speed [m/s]	Feed [mm]	Number of fins [1/m]
304	3.2	50	0.083	5.8	160
304H	2.8	40	0.067	5.8	160
IN600	2.4	28	0.08	5.8	160
IN625	2.4	28	0.08	5.8	160

3. Experiment

The research on the resistance of the tubes to high temperature corrosion was performed at the Institute of Materials Science of the Silesian University of Technology in Katowice. Samples of the tube – fin joints made of austenitic steel and nickel alloys were cut out for the purpose of the research. The width of the sample covered four fins, whereas the weight was within the range of 15 g – 16 g. In order to evaluate the resistance to high temperature corrosion, one treated the finned tubes with a mixture of gases (0.2%HCl + 0.08%SO_2 + 9.0%O_2 + N_2) in the temperature of 800°C. The chemical composition of the mixture of gases was similar to the atmosphere in power boilers. The experiment was divided into three stages:

- heating of the furnace charge in the argon atmosphere to a specified temperature (800°C) in order to prevent oxidation of the samples,
- exposure of the samples to corrosive atmosphere with a given concentration of gases in a given temperature and a flow of the mixture of gases that ensures a one-off exchange of the atmosphere in the period of four hours,
- cooling of the furnace charge in the argon atmosphere to the temperature of 20°C.

The research on the corrosion resistance was conducted within the time of up to 1000 hours, with the measures of the increase in the weight of corrosion products taken every 250 hours. Three measurements of weights were performed for each sample and the measurements were averaged. The standard deviation was below 1%. Examples of curves that illustrate a change of the weight in time were presented in Fig. 2.

The tests of resistance to high temperature corrosion were complemented by metallographic examinations. Examples of samples after the corrosion tests and the surface of the joint observed with a scanning electron microscope were presented in Fig. 3. In order to identify the corrosion products, one performed a microanalysis of the EDS chemical composition and identified the phase composition, using an X-ray diffraction method (Fig. 4-5).

4. Results and discussion

Based on the curves of changes of the austenitic steel weight in the function of time one can state that the weight of the corrosion products increases with the increase in time of the exposure to temperature and corrosive environment. After 250, 500 and 750 hours of the test, a gain in the weight of the sample made of 304 steel was significantly higher, when compared to the sample made of 304H steel (Fig. 2). However after 1000 hours of the test, the gain in weight in the case of both samples was at similar level and it didn't exceed 0.017 g, (below 0.13% of the initial weight of the sample).

The analysis of changes in the weight of samples of finned tubes made of laser welded nickel alloys carried out during the performance of a test for the resistance to high temperature corrosion in the simulated exhaust gases atmosphere shows that these samples are characterised by high resistance to high temperature corrosion in the atmosphere of exhaust gases typical for the coke dry quenching systems. The course of the corrosion process is similar to a linear function, i.e. with the increase in time of the exposure to temperature and corrosive environment,

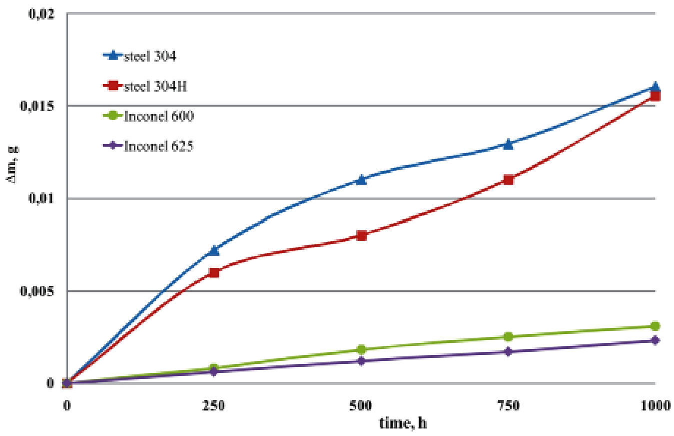

Fig. 2. Change in the weight of samples of finned tubes made of 304 and 304H steel

the weight of corrosion products increases (Fig. 2). In the case of nickel alloys the gain in weight was more than 8 times lower than the gain in weight of the austenitic steels, which confirms their better resistance to corrosion.

One observed a homogeneous layer of corrosion products on the surface of all samples (Fig. 3). This layer slightly restricts the heat exchange between the exhaust gases and water or water vapour inside the tube, however it protects the tube against further corrosion progress. Results of the microanalysis of chemical composition of products of gas corrosion of finned tubes made of 304 and 304H steel indicate that these products are rich in chromium, iron and oxygen (Fig. 4a,b). Analysis of the phase composition with the application of an X-ray diffraction method has identified the presence of composite chromium and iron oxides in both types of steel (Fig. 4c,d). The presence of

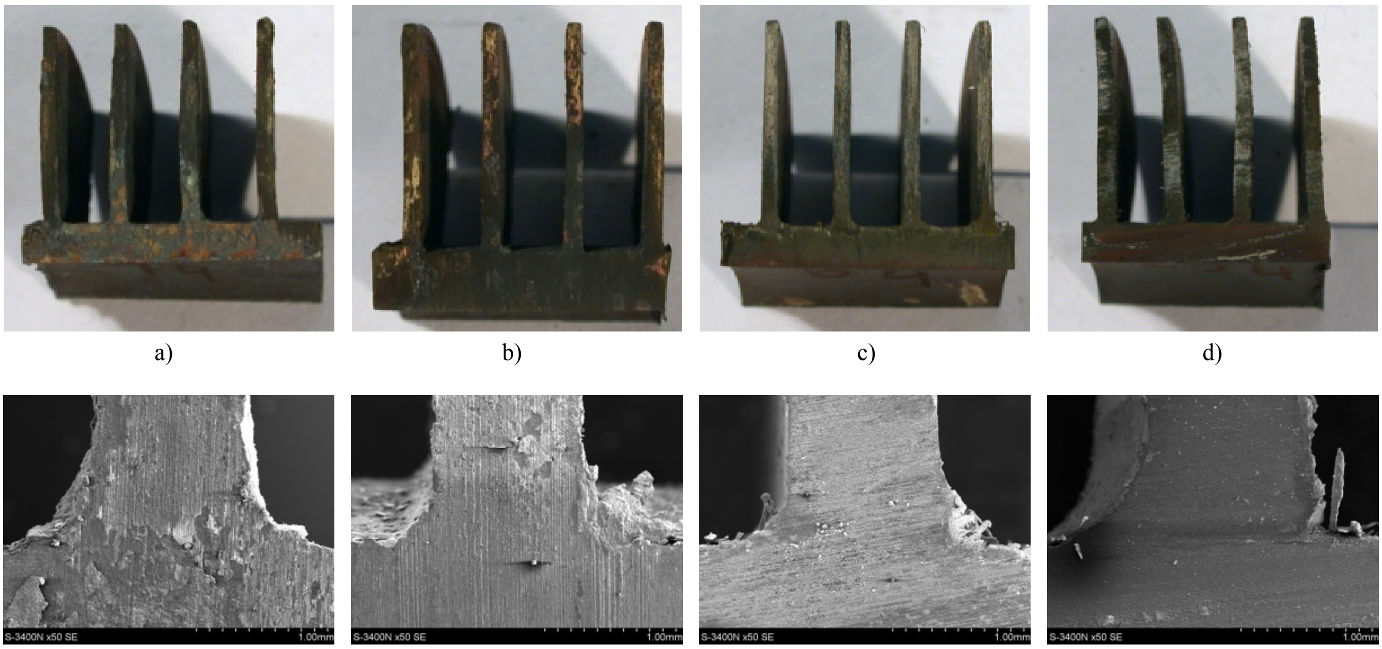

Fig. 3. The surface of samples cut out of finned tubes after the performance of high temperature corrosion tests: a) surface of the 304 steel sample, SM, 7 × magnification, b) surface of the 304H steel sample, SM, 7 × magnification, c) surface of the Inconel 600 alloy sample, SM, 7 × magnification, d) surface of the Inconel 625 alloy sample, SM, 7 × magnification, e) products of corrosion in the area of the 304 steel weld, SE, 50 × magnification, f) products of corrosion in the area of the 304H steel weld, SE, 50x magnification, g) products of corrosion in the area of the Inconel 600 alloy weld, SE, 50 × magnification, h) products of corrosion in the area of the Inconel 625 alloy weld, SE, 50 × magnification

oxides protects the tubes against further oxidation, ensuring an adequate resistance to high temperature corrosion.

The results of microanalysis of the chemical composition (EDS) of corrosion products in the case of finned tubes made of Inconel 600 and Inconel 625 alloys showed an increased content of chromium and oxygen, which may indicate a presence of chromium oxide passivation layer (Fig. 5a,b). Analysis of the results of the phase analysis confirmed the presence of Cr_2O_3 in the corrosion products layer (Fig. 5c,d). It is quite advantageous considering the fact that the Cr_2O_3 layer is continuous and it adheres well to the surface. It can also be easily reconstructed, which ensures a permanent protection against corrosion. Furthermore the Ni_3Nb phase was revealed in the Inconel 625 alloy (Fig. 5c). The presence of this phase in the elements operating at temperatures above 650°C results in a decrease of the resistance properties [5].

A linear nature of the course of the corrosion process and a defined relation of the change in time of the fin thickness enabled one to determine the durability of the finned tube understood as the time during which a metallic connection between the tube and the fin is maintained, which ensures a proper heat exchange [1]. Based on the measurements of the changes in the fin thickness in the function of time, one found that a properly made 1mm-wide tube-flat bar joint, under high temperature

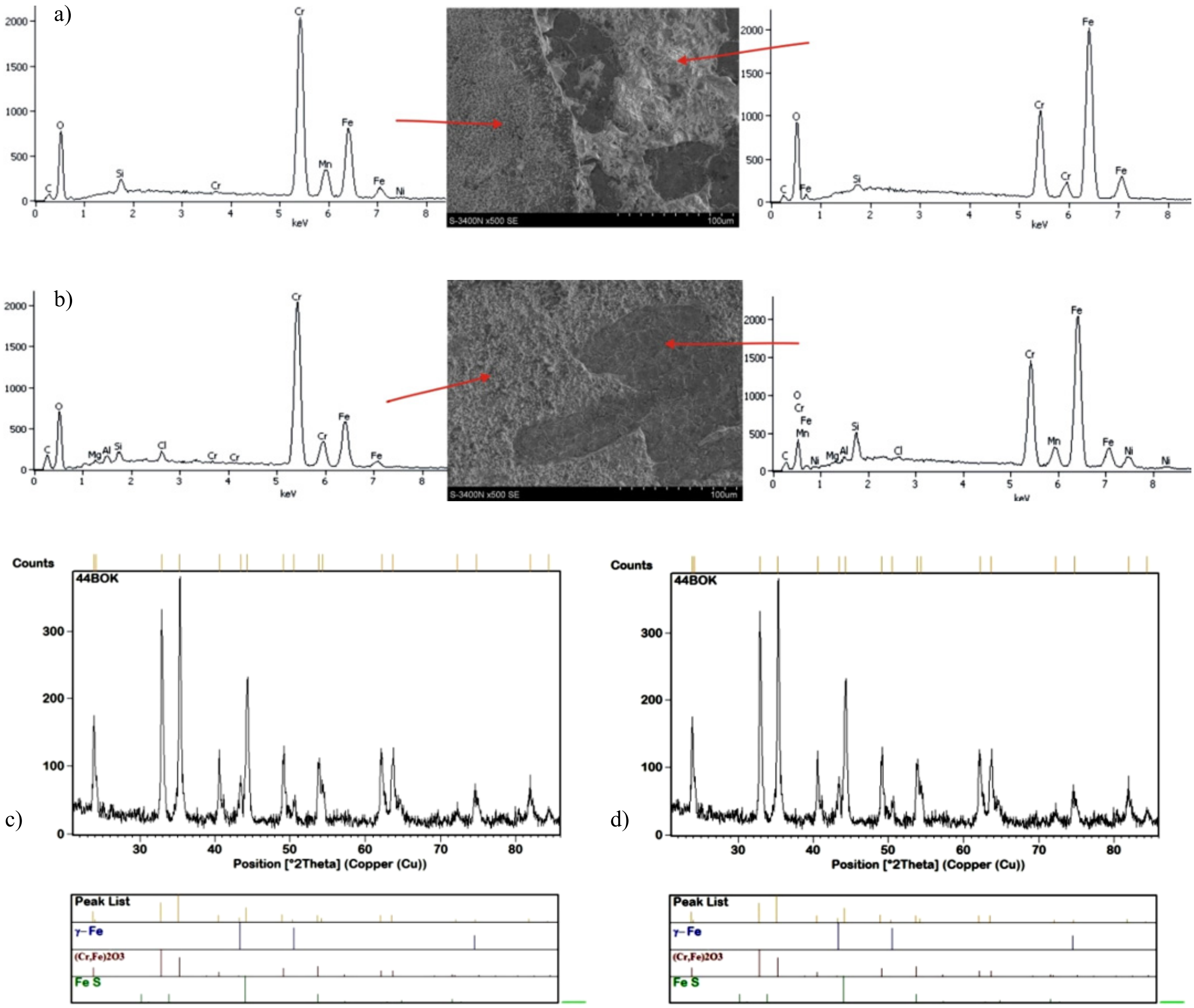

Fig. 4. Results of the tests of austenitic steel corrosion products after the performance of high temperature corrosion resistance tests: a) results of the microanalysis of chemical composition of the 304 steel corrosion products, b) results of the microanalysis of chemical composition of the 304H steel corrosion products, c) results of the analysis of phase composition of the 304 steel corrosion products, d) results of the analysis of phase composition of the 304H steel corrosion product

corrosion in the atmosphere of exhaust gases of chemical composition: N_2 + 9% O_2 + 0.08% SO_2 + 0.2%HCl (exhaust gases typical for waste-heat boilers in CDQ system) was characterised by a durability of over 8 years in the case of tubes made of the austenitic steel and a durability of more than 10 years in the case of tubes made of nickel alloys. Any welding imperfection in the form of undersized face of the weld, incomplete penetration, cracks, blowholes or pores resulting in the reduction of the cross-section of the weld may decrease the durability of the finned tube. Similar tests [1] performed for finned tubes made of conventional ferritic – pearlitic steel of the P265GH grade showed that the durability of finned tubes was about 40 months, which confirms the validity of the application of austenitic steel and nickel alloys to increase the efficiency and durability of electrical power equipment.

5. Conclusions

Based on the conducted research and analysis of their results it has been found that:

- laser welded finned tubes made of 304 and 304H austenitic steel and of Inconel 600 and Inconel 625 nickel alloys are resistant to high temperature corrosion in the atmosphere of exhaust gases (N_2 + 9% O_2 + 0.08% SO_2 + 0.2 %HCl) typical for CDQ installations at the temperature of up to 800°C,
- high temperature corrosion process within the range up to 1000 hours is linear with the corrosion rate of 0.0016g/1000h in the case of austenitic steel and of 0.0002g/1000h in the case of nickel alloys, which confirms high resistance to chemical corrosion of finned tubes made of these materials,

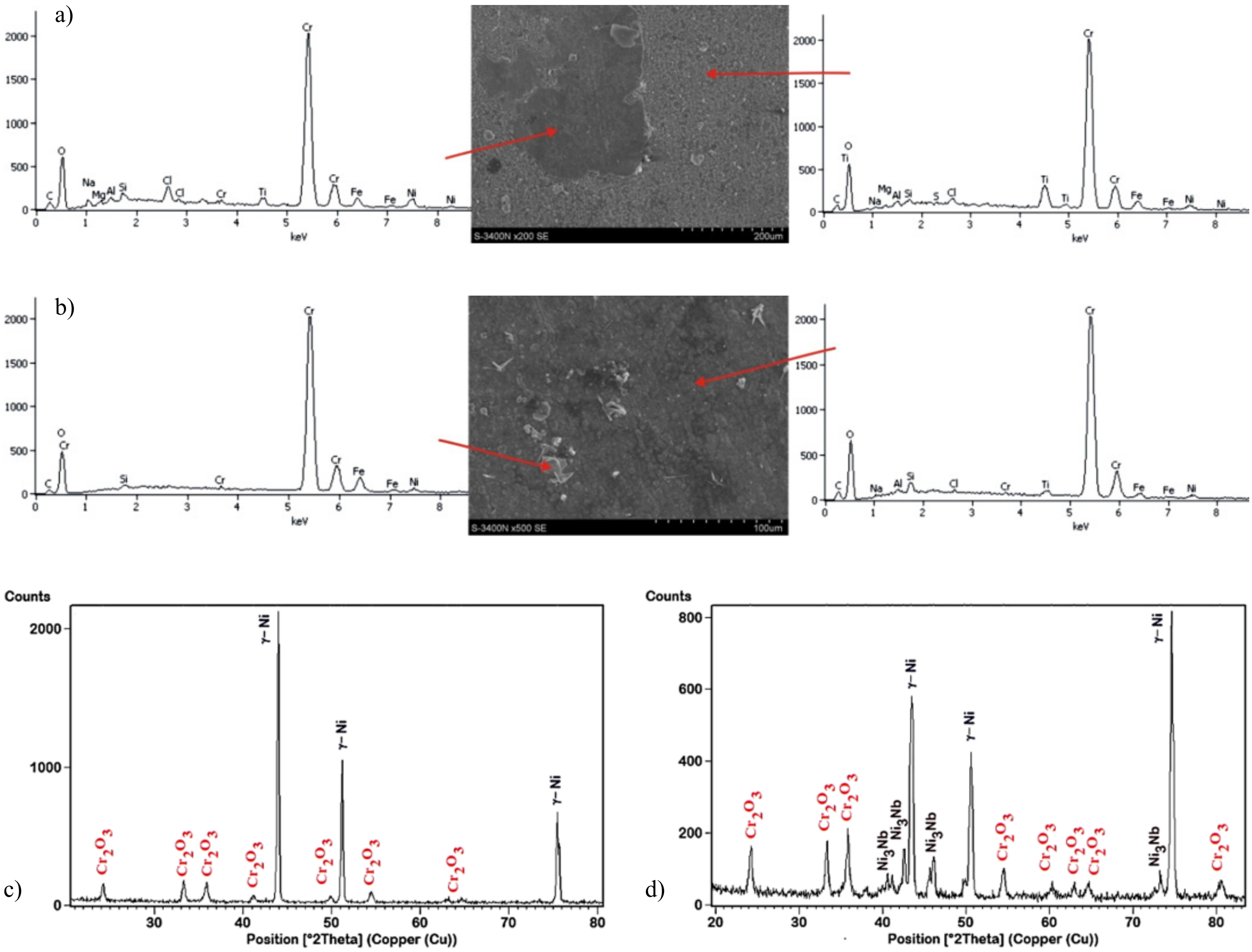

Fig. 5. Results of the tests of nickel alloys corrosion products after the performance of high temperature corrosion resistance tests: a) results of the microanalysis of chemical composition of the Inconel 600 corrosion products, b) results of the microanalysis of chemical composition of the Inconel 625 corrosion products, c) results of the analysis of phase composition of the Inconel 600 corrosion products, d) results of the analysis of phase composition of the Inconel 625 corrosion products

- passivation layer made up mainly of chromium and iron oxygen (steels) and Cr_2O_3 chromium oxygen (alloys) is formed on the surface of the tubes, and it protects the surface of finned tubes against the aggressive environment of exhaust gases.

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