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°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 heat 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 Trumpf 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
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>
<thead>
<tr>
<th>Material</th>
<th>Beam power [kW]</th>
<th>Rotational speed [n/ min]</th>
<th>Linear speed [m/s]</th>
<th>Feed [mm]</th>
<th>Number of fins [1/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>3.2</td>
<td>50</td>
<td>0.083</td>
<td>5.8</td>
<td>160</td>
</tr>
<tr>
<td>304H</td>
<td>2.8</td>
<td>40</td>
<td>0.067</td>
<td>5.8</td>
<td>160</td>
</tr>
<tr>
<td>IN600</td>
<td>2.4</td>
<td>28</td>
<td>0.08</td>
<td>5.8</td>
<td>160</td>
</tr>
<tr>
<td>IN625</td>
<td>2.4</td>
<td>28</td>
<td>0.08</td>
<td>5.8</td>
<td>160</td>
</tr>
</tbody>
</table>

3. Experiment

The research on the resistance of the tubes to high tem-
perature 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 resist-
ance to high temperature corrosion, one treated the finned tubes
with a mixture of gases (0.2%HCl + 0.08%SO2 + 9.0%O2 + N2)
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 oxida-
tion 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 ex-
change 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 in-
crease 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 per-
formed 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,
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 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$_2$O$_3$ in the corrosion products layer (Fig. 5c,d). It is quite advantageous considering the fact that the Cr$_2$O$_3$ 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$_3$Nb 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
corrosion in the atmosphere of exhaust gases of chemical composition: \( \text{N}_2 + 9\% \, \text{O}_2 + 0.08\% \, \text{SO}_2 + 0.2\% \text{HCl} \) (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 \( (\text{N}_2 + 9\% \, \text{O}_2 + 0.08\% \, \text{SO}_2 + 0.2\% \text{HCl}) \) 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 Cr₂O₃ 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.

Acknowledgements

The project was financed under the Applied Research Programme funded by the National Centre for Research and Development, project entitled: “Technology of laser welding of finned tubes made of austenitic steel and nickel alloys designed for boilers with supercritical and ultra supercritical parameters”, agreement no: PBS1/A5/13/2012

REFERENCES