Janusz Adamiec, Michał Więcek

Technology for Laser Welding of Ribbed Pipes Made of Inconel 625 Nickel Alloy

Abstract: The increasing demand for electric energy in Europe requires continuous search for new energy sources as well as structural and technological solutions. Maintaining the present level of electric energy production requires the modernisation of previously used objects and the construction of new units for supercritical and ultrasupercritical parameters. The increase in thermal efficiency with the simultaneous energy cost reduction is possible due to ribbed pipes used in heat exchangers. The article presents ribbed pipe manufacturing technologies with special attention paid to an innovative laser welding technology developed at Energoinstal S.A. The use of high-power disc lasers enables welding ribbed pipes made of nickel alloys such as, for instance, Inconel 625. Due to their heat resistance and high-temperature creep resistance laser welded ribbed pipes made of the Inconel 625 alloy are elements of heat exchanger characterised by high usability potential. The article presents the results of technological tests involving laser welding of ribbed pipes made of the Inconel 625 alloy conducted at Energoinstal S.A. It was ascertained that the technology developed meets related requirements and can be qualified according to PN EN 15614-11.

Keywords: finned tubes, laser welding, Inconel 625, power boiler, energy efficiency

Introduction

The constant development of civilisation and industry increases the demand for electric energy. Presently, no economy in the world is able to exist and develop without reliable systems for the generation and transmission of energy [1,2]. The power demand growth and requirements of EU 2001/77/EC, 2001/80/WE and 1997/97/23/WE, among others, entail the necessity of European power sector modernisation, i.e. undertaking activities concerned with the design, manufacture and operation of power generation devices [1-3]. Modern structural solutions of power boiler units utilise welded ribbed pipes in heat exchangers. In order to increase heat exchange efficiency gas boilers are provided with welded ribbed pipes, among others, in water heaters, evaporators and steam superheaters (Fig. 1a) [4]. The use of welded ribbed pipes in heat exchangers causes gas units to be characterised by very good electric energy production efficiency indicators with their availability factor reaching 98% [5]. Welded ribbed pipes are usually used when the convective heat-transfer coefficients on both sides of the barrier significantly differ in their value (e.g. flue gas and steam). Ribs on heat exchanger pipes enable increasing the heat exchange surface even 30 times if

dr hab. inż. Janusz Adamiec (PhD (DSc) hab. Eng.), Professor at Silesian University of Technology – Faculty of Materials Engineering and Metallurgy; mgr inż. Michał Więcek (MSc Eng.) – Energoinstal S.A. (JSC) Katowice

compared with pipes without ribs. As a result, the unitary heat exchange flux increases by almost 300% (Fig. 1b).

Fig. 1. Heat exchanger made of ribbed pipes in the vertical system of the waste-heat boiler (a), ribbed pipes used in power sector heat exchangers (b)

There are many ribbed pipe manufacture technologies (Fig. 2). The simplest methods consist in winding metal strips on pipes. This method is relatively cheap, yet the heat exchanger divided structure does not provide sufficiently good heat exchange conditions. In addition, with the passage of operation time, the quality of joints decreases due to thermal expansion and vibration, which, in turn, leads to thermal efficiency reduction. For this reason, technologies enabling the production of undivided structure pipes have been developed. The undivided structure pipes are characterised by better thermal efficiency (approximately 2.5 times greater than in relation to smooth pipes and approximately 1.5 times greater in relation to pipes with wound ribs) and operational stability. The technologies used for producing the pipes mentioned above include mainly plastic working and joining. A limitation regarding wrought ribbed pipes is the fact that due to the necessity of exerting high plastic strains, such pipes can be made only of well-formable materials; therefore, plastic working is used primarily for making pipes with low ribs, i.e. not exceeding 10 mm.

The basic technology for making ribbed pipes by way of plastic working is rolling [6,7]. This method enables the production of monometallic (integral) pipes and bimetal pipes (two pipes, one put in the other; rolling is conducted without a mandrel).

The process of rolling ribbed pipes is conducted using triaxial skew rolling mills. This technology has two variants, i.e. the plunging method and the thinning method. The plunging method consists in plastic deforming by means of tool inserts of an increasingly big external diameter. The required rib height is obtained by the gradual plunging of tool walls with the rib height at the top remaining unchanged. This method is used solely for making low-ribbed pipes. In the thinning method, due to the use of tools having increasingly thick working walls, it is possible to simultaneously obtain a thinner rib of a greater diameter with a relatively small penetration. This technology requires the use of both radial and axial drafts and is connected with significantly greater deformations, yet it enables the production of high-ribbed pipes [6,7].

The technology of ribbed pipe brazing was developed in response to imperfections of pipes with ribs wound on them such as lower thermal efficiency due to the lack of metallic joint between the pipe and the rib. Brazing enables joining pipes with ribs of various shapes and height. The strip for ribs can be bent or incised, which allows obtaining additional heat exchange area. Quite frequently semiautomatic

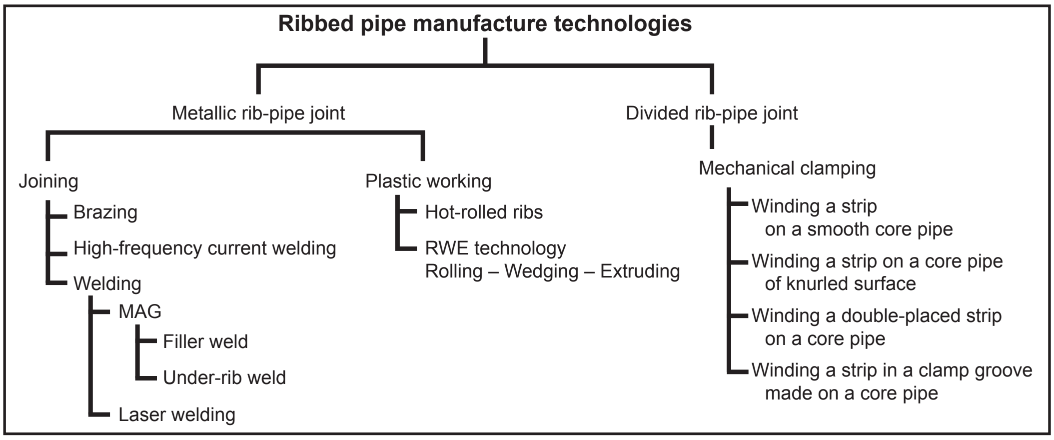


Fig. 2. Division of ribbed pipe manufacture technologies

brazing in furnaces with protective atmosphere is used. The uniform temperature field in the furnace favours the elimination of thermal stresses. The advantages of this method also include the smooth transition between the pipe and the rib, which reduces the accumulation of impurities and concentration of stresses. Brazed ribbed pipes can be used at temperatures up to 350°C, and if provided with a protective coating, up to 650°C.

Another technology for manufacturing pipes permanently connected with ribs is high-frequency current welding (Fig. 3a) [8,9]. Due to applied pressure the rib base undergoes deformation, as a result of which the area of contact with the pipe is greater that the rib cross-section. Welding continuous ribs may be accompanied by difficulties connected with the corrugation of rib edges at rib bases, which disturbs the flow of medium during operation and reduces the element efficiency [10]. Such problems do not accompany welding of incised ribs. However, this process may be troubled by the liquid metal spatters along both rib edges. Another variant of this method assumes the use of high-frequency current and a laser beam as the heat source (Fig. 3b).

Another technology used for ribbed pipe manufacture is welding. Ribbed pipes as welded structures (e.g. heat exchangers) are characterised by a significant weld length per 1 running meter of the pipe (Fig. 4). For pipes having a diameter of 31.8 mm, the weld length per 1 running metre amounts to approximately 20 m, i.e. over 10000 times more than in exchangers made of smooth pipes (girth welds) [4]. Such a weld length translates to the increased likelihood of welding imperfection formation as well as to the characteristic state of internal stresses leading to martensitic crack generation during production or to "reheat" types of cracks caused by post-weld reheating during operation.

Presently, ribbed pipes are often made using the MAG welding method (Fig. 4a, 5a). This technology has two variants. The first variant consists in making a fillet weld (Fig. 4b), yet it is characterised by low efficiency (welding rate up to 18 rev/min) and numerous welding imperfections, such as weld discontinuity and joint asymmetry [11].

The second variant consists in welding under the rib, at a welding rate of up to 60 rev/min, which reduces the amount of filler metal used and enables joining the pipe with a bent strip (Fig. 5a). However, this method is also accompanied by numerous welding imperfections including the lack of penetration, undercuts and spatters (Fig. 5b).

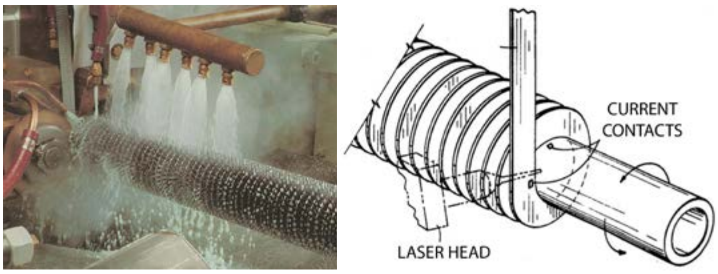


Fig. 3. Pipe manufacture using high-frequency current welding: a) pipe–rib high-frequency current welding process [8] b) diffusion welding by means of high-frequency current and laser [9]

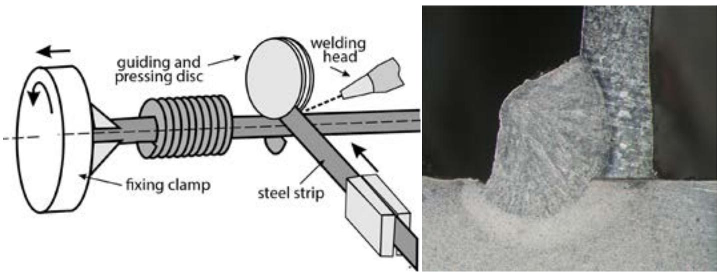


Fig. 4. MAG welding of ribbed pipes: a) scheme of welding utilising a fillet weld, b) ribbed pipe with a smooth rib made using MAG welding with a fillet weld [11]

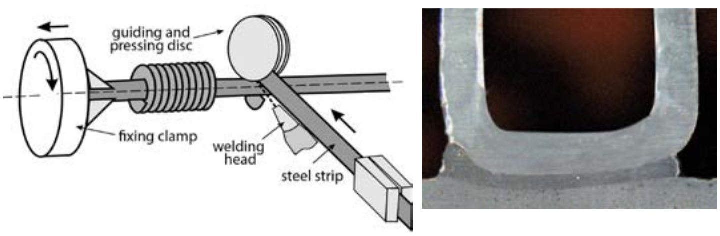


Fig. 5. MAG welding of ribbed pipes: a) scheme of under-rib welding, b) ribbed pipe with a smooth rib made using under-rib welding [11]

An alternative to MAG welding and HF current welding is laser welding [4,11]. Until recently the main factors limiting the possibility of using lasers for welding boiler elements included beam power, problems connected with precise joint preparation, possibility of hardening in the weld and narrow HAZ as well as hot crack susceptibility. On the other hand, laser welding is characterised by significant advantages such as increased process efficiency and stability. The advantages of disc lasers, particularly high beam energy concentration and the significant increase in welding process efficiency make laser-based methods important joining technologies.

Welded ribbed pipes are made of unalloyed steels (e.g. P235) or C-Mo/C-CrMo 15Mo3, 13CrMo4.4 and 10CrMo4.10 grade low-alloy steels according to DIN 17175, belonging to the group of weldable steels. While designing units of supercritical parameters it was determined that due to the decrease in creep resistance and oxidation resistance the application scope for classical steels and martensitic steels in power sector was used up at an operating temperature level of 650°C. The design of higher steam outlet parameters up to 720°C and 35 MPa requires the use of austenitic steels and nickel alloys. These materials are hard to obtain and are not fully recognised both technologically and as regards the material aspect.

Nickel superalloys have a microstructure composed of the γ (FCC) matrix hardened by the precipitates of the γ'' (Ni_3Nb) metastable phase, γ' ($Ni_3(Ti,Al)$) phase and MC carbide precipitates ensuring the obtainment of appropriate properties. High nickel and chromium contents provide good resistance to high-temperature corrosion in ashes containing sodium and potassium sulphates (so-called "hot corrosion") as well as resistance to oxidation in the steam atmosphere. Molybdenum favourably affects creep resistance whilst titanium, zircon and boron additions improve the alloy weldability [12]. Nickel alloys tend to be characterised by better properties than those of steels, yet due to their high price they are used for elements exposed to the most difficult operating conditions.

One of heat resistant and high-temperature creep resisting nickel alloys of high application potential is Inconel 625 alloy containing 20-23% of chromium and characterised by good creep resistance and very good resistance to oxidation and corrosion in various environments [12,13]. These favourable properties result from the presence of alloying agents, i.e. 8-10% of molybdenum, 3.15-4.15% of niobium and up to 5% of iron. The use of a modern laser welding technology and nickel alloys in the production of ribbed pipes provides new possibilities of designing heat exchangers in boilers for supercritical and ultrasupercritical parameters.

The work presents the technological test results related to laser welding of ribbed pipes made of the Inconel 625 alloy performed at Energoinstal S.A. within project no. PBS1/A5/13/2012 financed by the National Centre for Research and Development and entitled "Technology for Laser Welding of Ribbed Pipes Made of Austenitic Steels and Nickel Alloys Intended for Operation in Boilers of Supercritical and Ultrasupercritical Parameters".

Test Materials

On the basis of gas boiler operation parameters and proposed structural solutions of new boiler units for supercritical and ultrasupercritical parameters, it was determined that ribbed pipes should be made of the heat resistant and high-temperature creep resisting Inconel 625 alloy. The technological tests involved the use of pipes having a diameter of 48.3 mm × 3.6 mm and a flat bar in the form of a strip (15 mm × 1.0 mm). The chemical composition and mechanical properties of the materials used in the tests are presented in Table 1.

Table 1. Chemical composition and properties of materials used in ribbed pipe welding technological tests

Inconel 625	Chemical composition [% wt.]												
	C	Mn	P	S	Si	Cr	Ni	Al	Mo	Nb+Ta	Ti	Co	Fe
Pipe ϕ 48.3×3.6 Special Metal Cert. 1367361	0.028	0.10	0.005	<0.001	0.09	21.94	rest	0.24	8.85	3.63	0.27	0.13	4.0
Strip 15×1.0 ATI heat 520715-05	0.04	0.16	0.010	0.0001	0.18	22.04	rest	0.20	8.31	3.48	0.24	0.09	4.46
Req. accord. to ASTM B 444-06	<0.10	<0.50	<0.015	<0.015	<0.50	23.0-20.0	rest	<0.40	10.0-8.0	4.15-3.15	<0.40	<1.0	<5.0
Inconel 625				Mechanical properties at 20°C Heat treatment annealing at 1020°C, cooling in water									
				R_{e02} [MPa]			R_m [MPa]			A_5 [%]			
Pipe ϕ 48.3×3.6 Special Metal Cert. 1367361				466			911			49			
Strip 15×1.0 ATI heat 520715-05				490			938			50			

Technological tests of Ribbed Pipe Laser Welding

The automatic stand for welding ribbed pipes developed at Energoinstal S.A. is composed of a Trumph-manufactured TRUDISK 8002 disc laser with a system of laser beam division into two welding stations equipped with systems for rotating and shifting pipes during welding and an automatic painting system. The welding system scheme is presented in Figure 6.

The TRUDISK 8002 laser was equipped with two 30 m long optical fibres, which in combination with two welding heads enabled interchangeable welding on each line of the stand. Such a system maximises the use of laser operation. During welding performed on line no. 1, on line no. 2 the next pipe to be welded was being prepared. The pipe transport system moved pipes at a linear travel rate of up to 5 m/min with a pipe rotation rate of 350 rev/min. Pipe lengths were between 3 m and 24 m; a coasting amounted to between 50 mm and 250 mm. An important factor decisive for the possibility of welding ribbed pipes at a rotation rate exceeding 100 rev/min was the welding head positioning system. The system designed for this purpose was triaxial and provided with stepless adjustment in each axis, which enabled the precise adjustment of welding head position, automatic pre-weld tacking of the strip and automatic post-weld strip cutting off with a laser beam. In order to heat pipes before welding it was necessary to design a pipe induction heating system, which unlike gas heating, offered full adjustment and control of pre-heating temperature. This system was integrated with the whole line and enabled heating pipes having a diameter of 44.5 mm and wall thickness of 5 mm up to a temperature of 300°C at a linear travel rate of 5m/min.

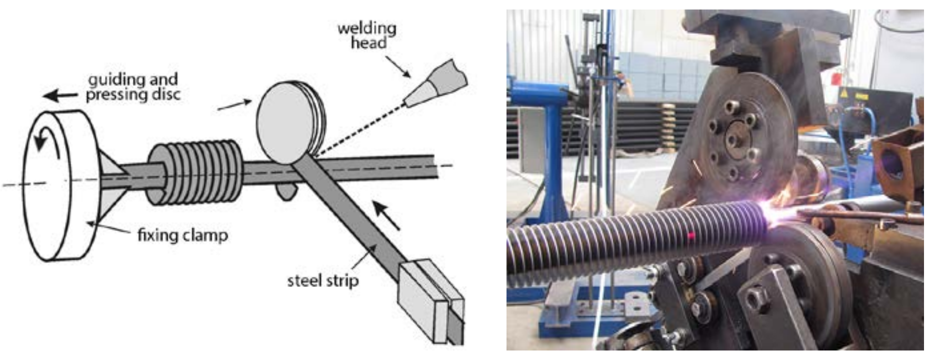


Fig. 6. Stand for laser welding of ribbed pipes developed at Energoinstal S.A.: a) general welding system scheme, b) laser welding of pipes

Energoinstal S.A. conducted tests involving laser welding of Inconel 625 alloy pipes with a rib wound continuously from an Inconel 625 alloy strip using a power of 2.0-3.0 kW. The pipe rotation rate amounted to 20-40 rev/min, welding was conducted with argon used as shielding gas fed at a flow rate of 5 l/min; the laser beam focal distance from the pipe surface amounted to 180 mm; filler metal was not used. Figure 7 presents examples of laser welded ribbed pipes.

Structural Test Results of Laser Welded Ribbed Pipe Joints

The visual tests conducted following the requirements of EN ISO 17637 revealed that the weld was continuous along the whole pipe length (Fig. 7), had a uniform spatter-free face (Fig. 7a) and was characterised by full penetration (Fig. 7b). The visual examination was supplemented with macrostructural observation (Fig. 8a). The test results confirmed that the joint had been made properly, with full penetration and proper transition between the weld face and the parent metal (Fig. 8a). The tests did not reveal the presence of welding imperfections such as cracks, discontinuities etc. On this basis it was possible to qualify the joint as representing quality level B according to PN-EN ISO 13919. This indicates that laser welded ribbed pipes made of Inconel 625 alloy can be used in power sector heat exchangers.

The results of microstructural tests performed using a Hitachi S 3400N scanning electron microscope (SEM) in the second electron (SE) technique on unetched metallographic specimens did not reveal any discontinuity on the fusion line (Fig. 8b). It was revealed that the weld was characterised by a dendritic structure with long directional crystals building up perpendicularly to the fusion surface (Fig. 8b).

The linear chemical composition microanalysis performed using the EDS method did not reveal chemical composition diversification on the line passing from the rib through the weld to the pipe parent metal (Fig. 9). The surface content of the elements was the same as the parent metal chemical composition, which indicated that the welding process was carried out properly and ensured appropriate joint heat resistance and high temperature creep resistance.

The pipe-flat bar joint quality assessment was supplemented with a technological rib rupture test. The test involved fragments of a pipe-rib joint cut out of a production pipe. The tensile tests were performed using a Comtech-manufactured testing machine. The testing machine

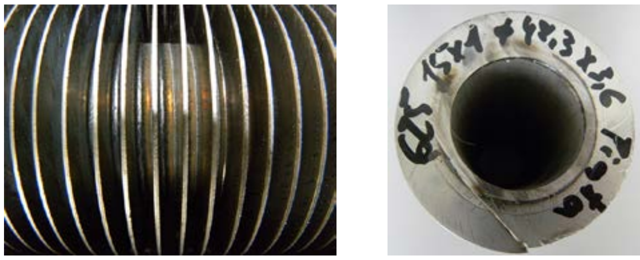


Fig. 7. Laser welded Inconel 625 alloy ribbed pipes: a) pipe-rib weld face, b) joint cross-section

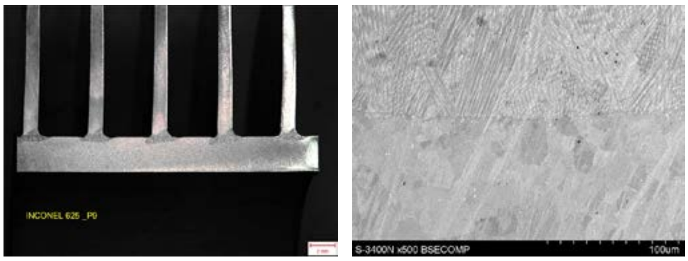
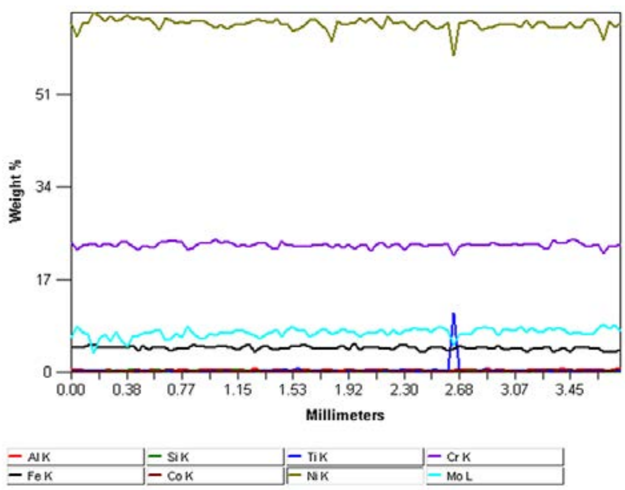


Fig. 8. Macrostructure of the laser beam welded joint made using a power of 2kW, rotation rate of 20 rev./min (a); microstructure of the Inconel 625 alloy welded joint (b)



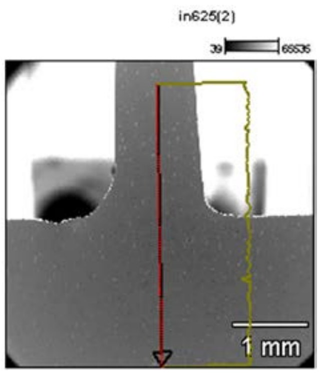


Fig. 9. EDS linear chemical composition microanalysis results of the laser welded Inconel 625 alloy ribbed pipe joint

clamps enabled the perpendicular fixing of the specimen. It was ascertained that in all the joints tested the rupture took place outside the joint, which indicated that the strength of the whole joint was greater than that of the rib and, as a result, that the laser welded pipe-flat bar joint met related structural requirements. The structural test results and the result of the rib rupture technological test revealed that the laser welded pipe-flat bar (rib) joint satisfied the requirements of quality level B according to PN-EN ISO 13919; therefore, the technology can be qualified in accordance with PN-EN ISO 15614-11.

Summary

The use of welded ribbed pipes in power generation devices leads to energy-saving and cost reduction in industrial boiler operation processes, recovery of condensation heat and its purposeful utilisation as well as to the minimisation of energy losses by lowering the temperature of flue gases. There are several ribbed pipe manufacturing technologies used in the power industry, the most important of which include plastic working-based manufacturing process, high-frequency current welding and electric arc welding in the MAG process. These methods in spite of such advantages as the possibility of obtaining continuous pipe-rib joints (significantly increasing thermal efficiency) are characterised by low efficiency and possible presence of such welding imperfections as incomplete fusions, lacks of penetration, spatters, etc. The Energoinstal S.A. company has developed the innovative technology for ribbed pipe laser welding.

Requirements set for modern boiler structures entail the necessity of using higher operation parameters, i.e. pressure and temperature (boilers for supercritical and ultrasupercritical parameters). This is due to the necessity of using new materials of advanced properties, particularly heat resistance and high-temperature creep resistance. The conditions mentioned above are satisfied by nickel-chromium-molybdenum alloys (e.g. Inconel). The most common of this group is Inconel 625 characterised by high heat resistance and high usability potential for heat exchanges made of ribbed pipes.

The technological tests involving laser welding of Inconel 625 ribbed pipes (48.3 mm × 3.6 mm) with a continuous rib (15 mm × 1.0 mm) conducted at the Centre for Innovative Laser Technologies Energoinstal S.A. demonstrated the possibility of making proper full penetration joints meeting the quality level B requirements according to PN-EN ISO 13919 (Fig. 7, 8a). Ribbed pipes made of the Inconel 625 alloy should be welded using automated laser stands with a 2kW laser beam and a rotation rate of 20 rev./min.

The analysis of the pipe-flat bar joint weld structure revealed the building-up of columnar crystals parallel to the heat off-take direction (Fig. 8b). The microanalysis results related to the chemical composition on the line passing along the whole laser welded joint did not reveal chemical composition changes in the weld (Fig. 9). The proper quality of the welds was also confirmed by the results of rib rupture technological tests which revealed greater joint strength in relation to the rib material. This justifies the conclusion that the technology for laser welding of Inconel 625 alloy ribbed pipes can be qualified in accordance with the requirements of PN-EN ISO 15614-11 and that the pipes can be used in power industry heat exchangers.

Acknowledgements

The work was financed by the National Centre for Research and Development within the project PBS1/A5/13/2012 entitled “Technology for Laser Welding of Ribbed Pipes Made of Austenitic Steels and Nickel Alloys Intended for Operation in Boilers of Supercritical and Ultrasupercritical Parameters”.

References

1. Breeze P.: Raising steam plant efficiency – Pushing the steam cycle boundaries. PEI Magazine, Vol. 20, Issue 4, April, 2012.
2. Huseman R.: Advanced (7000C) PF Power Plant. A Clean Coal European Technology. Advanced Material for AD700 Boilers, Cesi Auditorium, Milano, 2005.
3. Najgebauer E. Patrycy A.: Zobowiązania polskiej energetyki wobec EU. *www.geoland.p*l
4. Adamiec J., Gawrysiuk W., Więcek M.: Zautomatyzowane stanowisko do spawania rur ożebrowanych laserem dyskowym. Biuletyn Instytutu Spawalnictwa, no. 5, 2010.
5. Effiziente Dampfkesselanlagen für industrielle Heiz- und Heizkraftwerke sowie Hilfskesselanlagen für Kraftwerke, Wolfgang Sobbe, Johannes Janzen, Michael Schiemann, Harald Braun, VGB Powertech 7/2011.
6. Pasierb A.: Nowe rozwiązania w technologii walcowania rur żebrowanych. Rudy i Metale Nieżelazne, no. 10–11 pp. 505–507, 2002.
7. Richert J.: Innowacyjne metody przeróbki plastycznej metali, Wyd. AGH, Kraków, 2010.
8. http://www.thermatool.com/information/brochure/Thermatool-spiral-fin-tube-welding-system.pdf (28.07.2013)
9. US Patent No 5343015 A: Laser assisted high frequency welding (1994)
10. US Patent No 2807074: Manufacturing of brazed fin tube and the like, 1957
11. Hernas, J. Pasternak, J. Brózda, G. Moskal, Stale austenityczne i nadstopy niklu stosowane do budowy kotłów nadkrytycznych i ultranadkrytycznych, Wyd. SITPH, Katowice 2009
12. INCONEL alloy 625 data sheet, http://www.specialmetals.com/documents
13. /Inconel%20alloy%20625.pdf (01.08.2013)