Radosław Ciokan, Michał Urbańczyk

The Development of a Technology of the Laser-Based Welding of Butt Joints in Composite Tubes

Abstract: The article presents the results concerning the development of a technology combining laser welding and hybrid surfacing enabling the making of butt joints in composite tube grades Sanicro 38/4L7 and 3R12/4L7. The tests involved the determination of the parameters of the laser welding of tube grade 4L7 and the hybrid surfacing of the external layer of tube grade Sanicro 38 and 3R12. The article also presents the results of the macro and microscopic tests of the joints.

Keywords: composite tube, Sanicro 38/4L7, 3R12/4L7, laser, welding, hybrid surfacing

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Introduction

A growth in demand for electric energy, an increase in the efficiency of incinerating plants and European Union directive regulations (e.g. 2014/68/UE) necessitate the modernisation of European industry, particularly of the power engineering sector. To this end, power generation companies have to undertake activities aimed to design, manufacture and operate power generation equipment and systems [1–3]. Important elements in boilers making up modern power units are tubes used in heat exchangers and superheaters, thick-walled pipes for transporting fresh steam, finned tubes and waterwalls used, among other things, in modern water-tube boilers, soda recovery boilers and incinerating plants. [4]. The development of materials engineering has provided designers and design engineers with modern structural materials, e.g. composite tubes manufactured by the Sandvik company.

Composite tube Sandvik 3R12/4L7 is the latest product combining two materials, i.e. one having the austenitic structure (3R12) and the other having the ferritic-pearlitic structure (4L7). The combination of the above-named metallurgical alloys has enabled the obtainment of superior technical properties. Material 3R12 (X2CrNi18-10) provides high corrosion resistance and, for this reason, is located on the external surface of the composite tube. In turn, material 4L7 (P235GH) is used inside, i.e. where the tube is exposed to higher pressure-triggered plastic deformations.

In turn, composite tube Sandvik Sanicro 38/4L7 is the combination of two materials, i.e. nickel (Sanicro 38, Inconel 825) and ferritic-pearlitic steel (4L7). The combination of the above-named metallurgical alloys has enabled the obtainment of superior heat flow properties, higher corrosion resistance and low thermal

mgr inż. Radosław Ciokan (MSc Eng.) – ERBUD INDUSTRY Południe Sp. z o.o.;
dr inż. Michał Urbańczyk (PhD (DSc) Eng.) – Łukasiewicz Research Network – Instytut Spawalnictwa, Welding Technologies Department

Fig. 1. Use of composite tubes: a) deflection for the nozzle in the combustion chamber (made of tubes 3R12/4L7) and b) waterwall of the soda recovery boiler (made of composite tubes)

expansion. The tube is used in the power engineering industry, where external and internal conditions affecting the material require the latter to represent properties not available where only one material is used [5, 6].

Because of their properties, composite tubes Sanicro 38/4L7 and 3R12/4L7 are used, among other things, in soda recovery boilers in incinerating plants (in combustion chamber waterwalls or membrane walls) (Fig. 1).

The making of waterwalls consists in joining flat bar-tube-flat bar elements (approximately 12 tubes) to obtain panels having a length of up to 24 m. The joints of the elements must be characterised by appropriate properties, particularly leaktightness, as the formation of leaks may result in explosion leading to the damage of power generation system elements beyond repair.

The power engineering industry has seen the use of new structural materials and joining technologies (based on, e.g. laser or hybrid solutions), leading to the increased effectiveness of production and the higher quality of products. In Poland, both in large companies and small firms, laser welding processes are enjoying growing popularity. The use of lasers is justified by the balance between their technical parameters (high power) and the costs of their purchase, operation and service. The advantages of laser and decreasing prices of laser equipment contribute to the increased interest in laser technologies in the power engineering industry. Guidelines formulated by the Sandvik company related to the welding of composite tubes are exclusively concerned with the arc welding technology (MMA, TIG, and MIG/MAG). There is no information concerning the use of laser technologies, including hybrid technologies, in the joining of the above-named tube grades. The article presents results of individual research on the development of a laser solution-based technology enabling the welding of composite tubes made of steel Sanicro 38/4L7 and 3R12/4L7.

Test materials

The research-related tests involved the use of composite tubes Sanicro 38/4L7 and 3R12/4L7

Table 1. Chemical composition of composite tube Sanicro 38/4L7 [5]

	C	Si	Mn	Cr	Ni	Mo	Cu	Ti
Internal layer 4L7 (P265GH)	0.18	0.30	0.69	0.14	0.25	0.04	0.030	0.005
External layer Sanicro 38 (Alloy 825)	0.012	0.15	0.47	19.92	38.24	2.57	1.61	0.75

Table 2. Chemical composition of composite tube 3R12/4L7 [6]

	C	Si	Mn	Cr	Ni	Mo	Cu	Ti
Internal layer 4L7 (P265GH)	0,18	0,31	0,69	0,13	0,07	0,01	0,022	0,005
External layer Sanicro 38 (Alloy 825)	0,008	0,36	1,11	18,22	10,04	0,24	0,26	0,004

(Sandvik), having dimensions ø 63.5 × 6.53 mm and a length of 140 mm (Fig. 2). The chemical composition of the base material is presented in Tables 1 and 2.

The filler metal used for the joining of tube Sanicro 38 was filler metal wire grade OK Autrod NiCrMo-3 (PN-EN ISO 18274: S Ni 6625 NiCr22Mo9Nb) having a diameter of 1.0 mm (Esab). The filler metal used for the joining of tube 3R12 was filler metal wire grade Lincoln MIG-308LSi (PN-EN ISO 14343:G 19 9 LSi) having a diameter of 1.2 mm (Lincoln Electric Europe). The above-named filler metals are recommended for welding by manufacturers of composite tubes. The shielding gas used in the MAG method was the M12 mixture (97.5% Ar and 2.5% CO_2) (PN-EN ISO 14175 – M12 – ArC-2,5), recommended by producers for the welding of the above-named steel grades. The shielding gas flow rate amounted to 16 l/min.

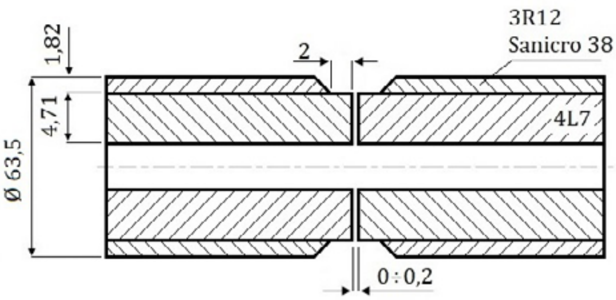


Fig. 2. Preparation of the joint for the laser and hybrid welding of composite tube grades 3R12/4L7 and Sanicro 38/4L7

Pre-weld preparation of specimens

The preparation of specimens for laser welding involved the mechanical removal of the external layer of the material (3R12, Sanicro 38) in order to enable the making of the joint of the internal layer. The shape and the geometrical dimensions of the joint are presented in Figure 2.

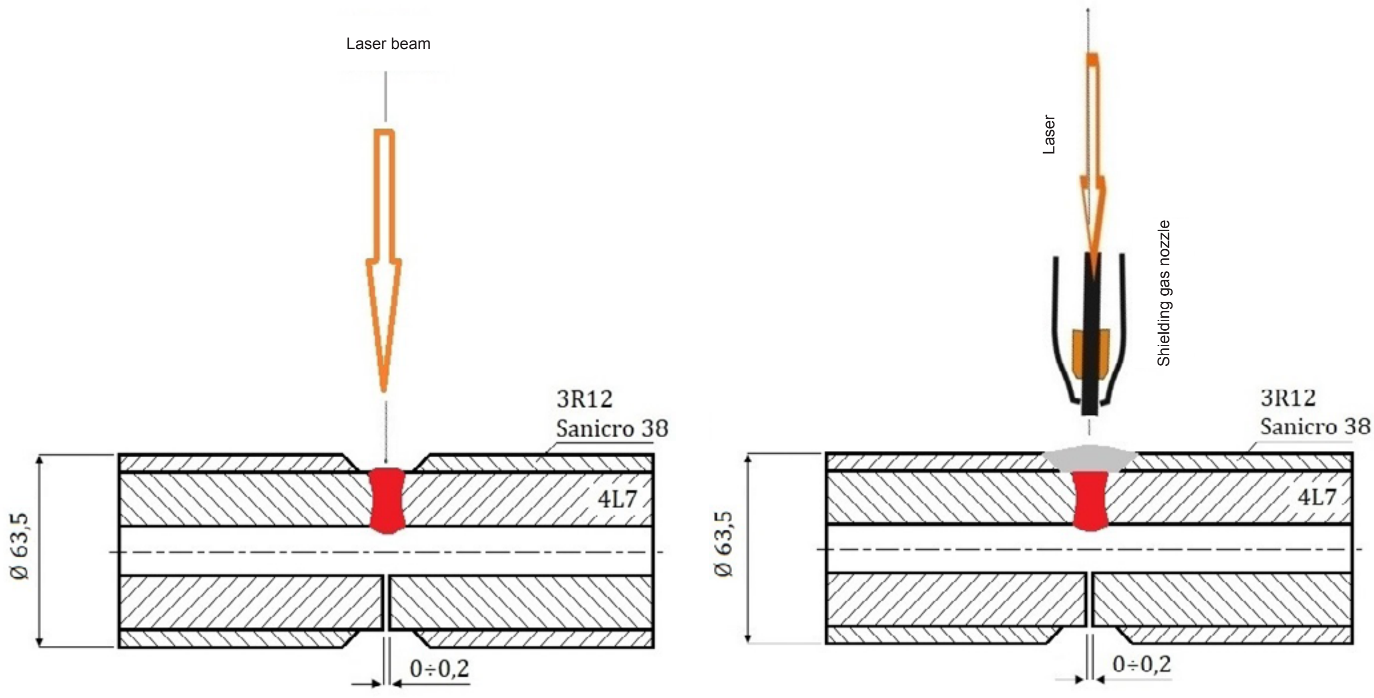


Fig. 3. Welding of composite tubes: a) partial melting of the internal layer and the obtainment of the weld using laser and b) filling the external layer using the laser + MAG hybrid surfacing

Test rig and methodology

The research aimed to test a technology enabling the making of butt welded joints of composite tube grades Sanicro 38/4L7 and 3R12/4L7. The welding process was performed at two stages. The first stage involved the making of the internal layer of the tube (4L7). The layer was made using a disk laser and the butt weld with full penetration was obtained (Fig. 3a). The second stage involved the hybrid surfacing of the external layer using the filler metal wire (Fig. 3b).

The laser welding tests and the hybrid (laser + MAG) surfacing tests were performed at Łukasiewicz – Instytut Spawalnictwa, using a robotic station equipped with:

- TruDisk 12002 disk laser (Trumpf) provided with the welding/surfacing head featuring filler metal wire feeding (Fig. 4a),
- KUKA KR30HA industrial robot (Fig. 4b),
- hybrid welding head (KUKA), enabling the transmission of the beam having a power of 12 kW (Fig. 4b),
- Phoenix 452 RC PULS MIG/MAG method EWM arc welding power source integrated (in terms of software) with the robot control system,
- tilting turntable enabling the positioning of elements being subjected to welding.

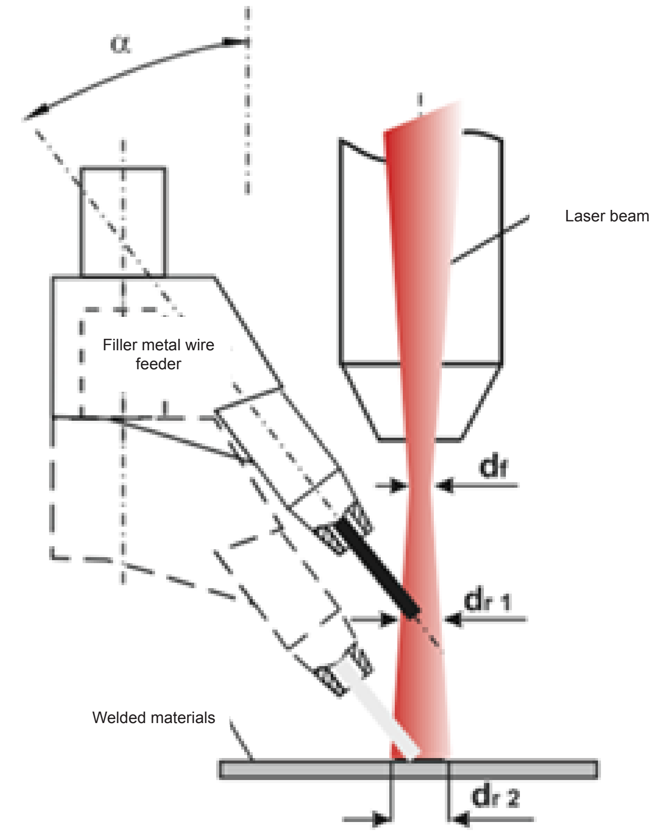
The laser welding process was performed using the Trumpf BEO D70 head (i.e. the same head which was used in the hybrid welding/surfacing process) characterised by the following optical system parameters: collimator f_c = 200 mm and focusing lens f_{og} = 400 mm. The use of an optical fibre having a diameter of 300 μm enabled the obtainment of laser beam focus diameter d_{og} = 0.6 mm, in relation to Rayleigh length Z_R = 10 mm.

The technological hybrid surfacing tests involved the use of an optical fibre having a diameter of 400 μm, enabling the obtainment of laser beam focus diameter d_{og} = 0.8 mm. The hybrid surfacing tests, performed using the defocused beam, required the lifting of the head and the focus position by 20 mm (f = +20 mm). The above-named position resulted in the obtainment of laser beam focus diameter d_{og} = 1.6 mm (Fig. 5a). The lifting of the head by 20 mm required the lowering of the welding torch (using adjustment screws) so that the electrode tip touched the surface of the tube (Fig. 5b) [7, 8].

The tubes prepared for welding were tacked using the TIG method and, next, placed in the fixing clamp on the welding table and inclined at an angle of 90° (Fig. 6a). The positioning of the laser beam (involving the use of a CCD camera) at the interface of the tubes and the place struck by the pilot laser are presented in Figures 6 b and c.

Both the laser welding and the hybrid surfacing process were performed in the flat position (PA). During the laser welding of the

Fig. 4. Robotic laser welding/surfacing station featuring the TruDisk 12002 disk laser: a) main view and b) head D70 for hybrid welding/surfacing mounted on the industrial robot wrist



$$d_{og} = \frac{f_{og} \times d_{LLK}}{f_c}$$

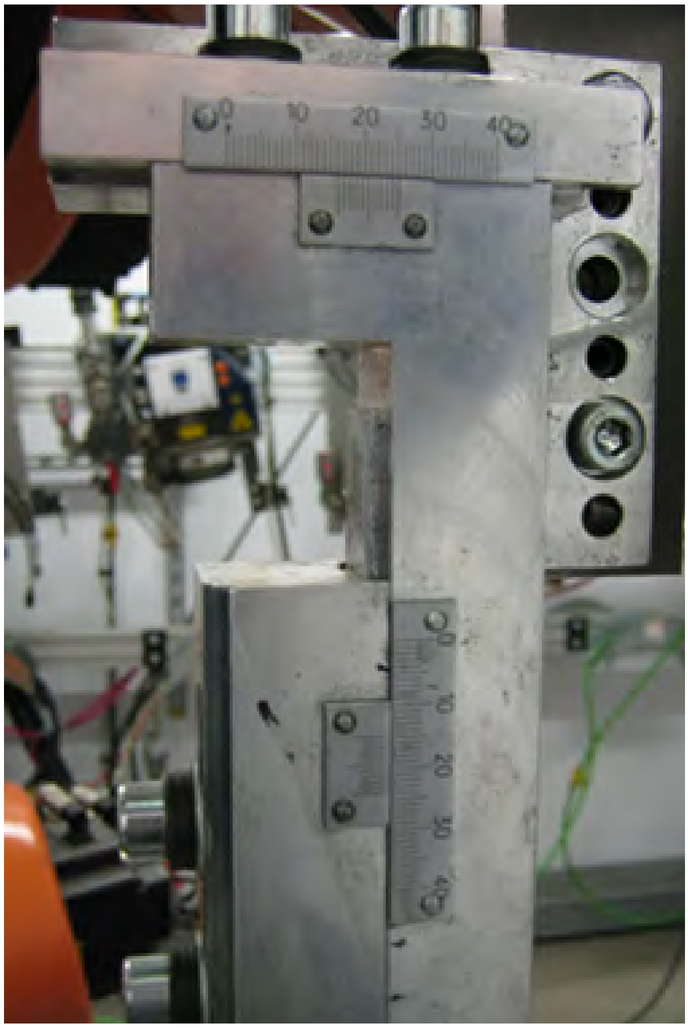


Fig. 5. a) adjustment of the position of the electrode tip in relation to the plate surface and the laser beam focus diameter, where d_{og} – laser beam focus diameter [mm], f_{og} – focusing lens focal length [mm], d_{LLK} – optical fibre core diameter [mm], f_c – collimator lens focal length [mm]; b) head adjustment screws enabling the adjustment of the position of the filler metal wire feeder

internal layer, the element subjected to welding (tube) was set in the rotational motion while the head remained still. The hybrid surfacing process was conducted in the manner similar to that used during the laser welding process except that the head located on the robot wrist additionally performed weaving moves, where the length of the pitch amounted to 1.5 mm and the amplitude amounted to 6 mm.

Test results

The laser welding tests involving tube grades Sanicro 38/4L7 and 3R12/4L7 were performed using a laser power of 4.5 kW and a welding rate of 0.8 m/min. The joints obtained in the laser welding process are presented in Figure 7.

The laser welded joints were subjected to visual tests performed in accordance with the requirements of the PN-EN ISO 17637 standard [9]. The visual tests revealed that the joint of the internal layer of tube grade 3R12/4L7 and that of tube grade Sanicro 38/4L7 were characterised by the uniformly smooth spatter-free weld face and the weld root formed properly around the entire circumference. The joints represented quality level B in accordance with the requirements of the PN-EN ISO 13919-1 standard [10].

Figure 8 presents the macrostructure of the joint of tube grade Sanicro 38/4L7. Test specimens were sampled from two areas of the joint. Metallographic tests did not reveal the presence of welding imperfections in the weld area and in the HAZ.

The subsequent stage of the tests involved hybrid surfacing aimed to fill the external layer. The hybrid surfacing process was performed

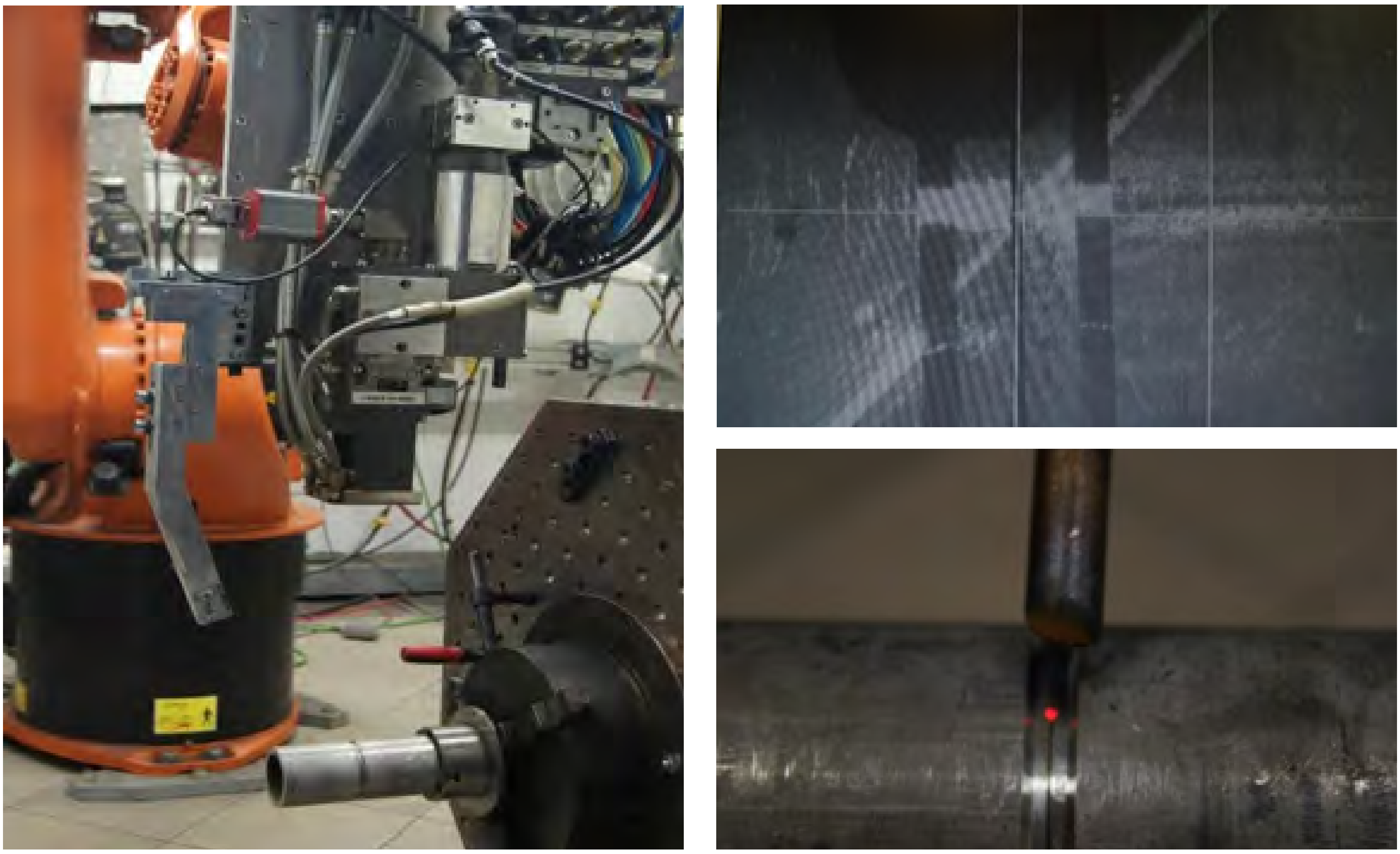


Fig. 6. Welding of composite tubes: a) fixing the tubes in the clamp on the table for laser welding and hybrid surfacing, b) positioning of the laser beam at the interface of the tubes performed using the CCD camera and c) area struck by the laser beam

Fig. 7. Laser joint of the internal layer viewed from the weld face and weld root side: a) weld face and root – tube grade 3R12/4L7 and b) weld face and root – tube grade Sanicro 38/4L7

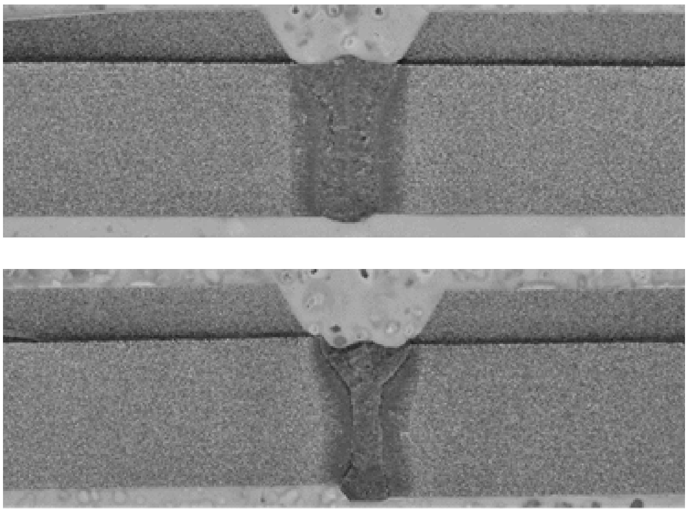


Fig. 8. Macrostructure of the laser joint of tube grade Sanicro 38/4L7

using a laser power of 0.5 kW and a filler metal wire feeding rate of 5 m/min (in relation to tube grade 3R12/4L7) and 8.5 m/min (in relation to tube grade Sanicro 38/4L7). The hybrid surfacing process involved the making of weave runs (triangular) having a pitch length of 1.5 mm and an amplitude of 6 mm. The overlay welds obtained in the hybrid surfacing process are presented in Figure 9.

The hybrid surfaced joints were subjected to visual tests performed in accordance with the requirements of the PN-EN ISO 17637 standard [9]. The visual tests revealed that the overlay welds were characterised by the uniformly smooth face (Fig. 7). Both the Sanicro 38/4L7 and 3R12/4L7 specimens contained welding imperfection no. 602 (spatter, in accordance with PN-EN ISO 6520-1 [11]) located in the areas marking the commencement and the termination of the surfacing process. The joints represented quality level B in accordance with the requirements of the PN-EN ISO 12932 standard [12].

Figure 10 presents the macrostructure of the joint of tube grade Sanicro 38/4L7. The macroscopic tests did not reveal the presence of internal welding imperfections.

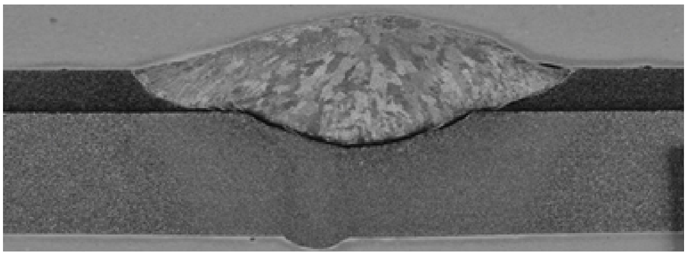


Fig. 10. Macrostructure of overlay weld Sanicro 38/4L7, external cladding layer made through hybrid surfacing involving the use of filler metal wire Lincoln NiCrMo-3 ø1.0 mm

Fig. 9. Hybrid surfaced joints viewed from the face side: a) tube grade 3R12/4L7 and b) tube grade Sanicro 38/4L7

The microstructural tests of specimen Sanicro 38/4L7 revealed the ferritic-pearlitic structure in the base material of the external layer (Fig. 11a). The interface between the weld and the base material contained the banded ferritic-pearlitic structure (Fig. 11 b). The overlay weld (external layer Sanicro 38) and the interface between the overlay weld and the heat affected zone contained the austenitic structure (Fig. 11 c, d).

Summary

Laser welding combined with hybrid (laser + MAG) surfacing provide an innovative joining technology enabling the welding of composite tube grades Sanicro 38/4L7 and 3R12/4L7. The tests revealed that the use of the laser welding technology for the joining of tubes made of steel 4L7 (internal tube layer) having a thickness of 6.53 mm enabled the obtainment of quality butt joints characterised by the smooth weld face and the properly

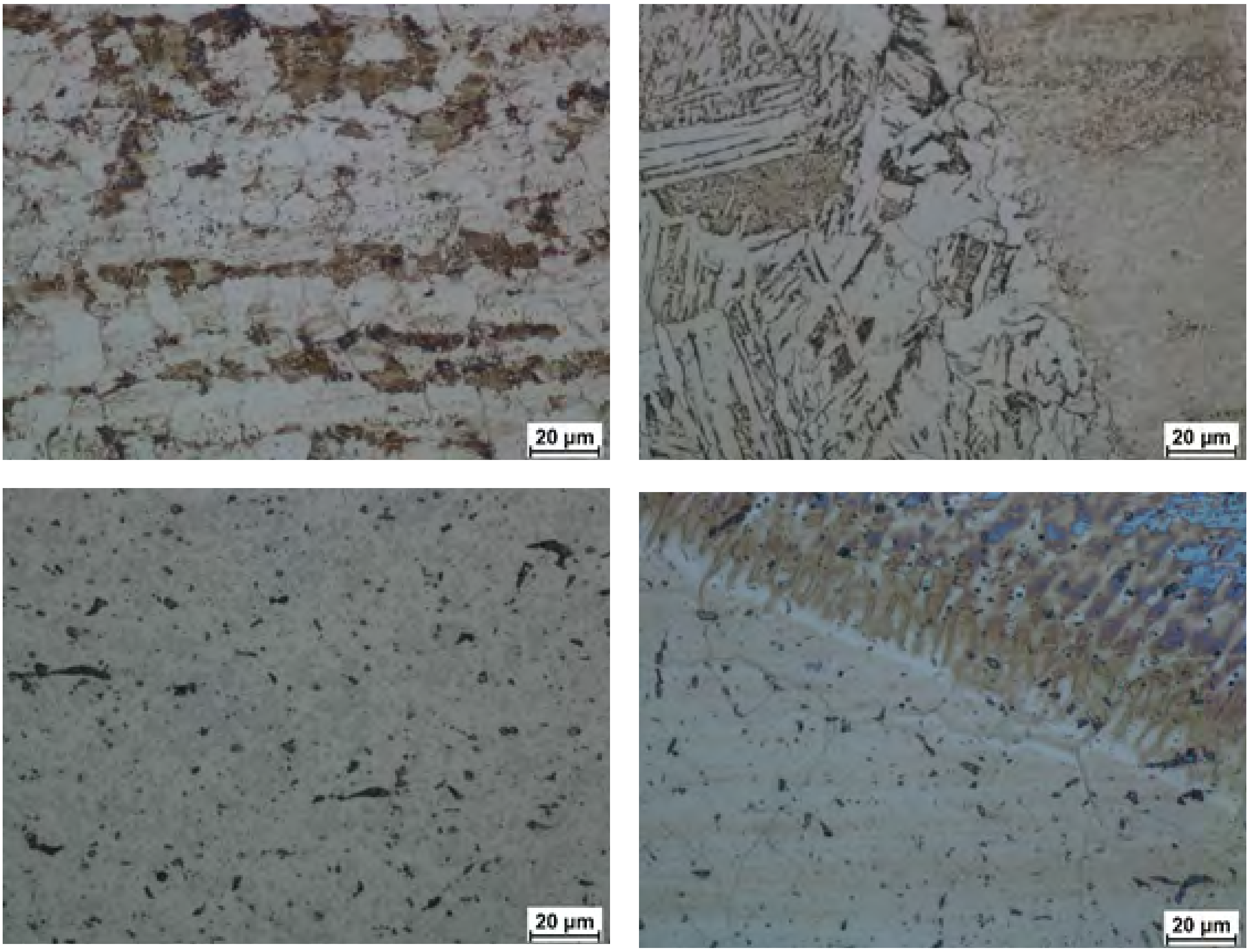


Fig. 11. Microstructure of joint Sanicro 38/4L7: a) base material 4L7 (P265GH) – banded ferritic-pearlitic structure, b) heat affected zone (fusion line: weld–base material 4L7), c) overlay weld – austenitic structure and d) heat affected zone (fusion line: overlay weld– base material Sanicro 38)

shaped weld root, satisfying the requirements of quality level B in accordance with PN-EN ISO 19319-1.

The use of the hybrid (laser + MAG) surfacing to make the external tube layer (Sanicro 38 and 3R12) having a thickness of 1.42 mm enabled the obtainment of an overlay weld characterised by the properly shaped face and satisfying the requirements of quality level B in accordance with PN-EN ISO 12932.

The metallographic macroscopic tests did not reveal the presence of internal welding imperfections. The micrographic tests revealed the austenitic structure in tube grade Sanicro 38 (external layer) and the ferritic-pearlitic structure in tube grade 4L7.

The above-presented technology combining the laser welding and hybrid surfacing of composite layers has been described and submitted to the Polish Patent Office.

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