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Structure and Properties of Nickel Alloy Overlay Welds Plasma Cladded on Creep-Resistant Steel Tubes

Abstract: The article presents tests aimed to develop technological parameters of the plasma surfacing of Inconel 625 overlay welds onto boiler tubes (φ 45 × 5 mm) made of steel 13CrMo4-5, providing the content of iron on the overlay weld surface below 5%. The research work involved macroscopic metallographic tests of overlay welds, the identification of the chemical composition of the overlay weld surface as well as microscopic metallographic tests and the microanalysis of the chemical composition across the overlay weld. It was ascertained that, under certain conditions, the use of plasma surfacing enables the obtainment of high-quality single-run overlay welds having a thickness of below 2 mm and characterised by the minimum stirring of the overlay weld metal with the substrate metal as well as the obtainment of an iron content of 2.5% on the overly weld surface.

Keywords: cladding, plasma surfacing, Inconel 625 alloy, boiler tubes, waste incineration boilers

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Introduction

Power plants fed with fossil fuels and waste incineration plants used for power generation must satisfy strict requirements as regards power boiler components including furnaces, collectors, superheaters and pipings. The above-named requirements result from extreme working conditions of components exposed to abrasion and erosion. The incineration of waste in boilers results in the formation of flue gas containing aggressive chlorides and fluorides, the detrimental effect of which requires the use of appropriately effective protections from erosion and corrosion of e.g. tubes of heat exchangers and combustion chambers. Presently, the service life of such elements is increased by the surfacing of layers of nickel alloys, particularly having the composition of alloy Inconel 625, providing appropriate creep resistance at high temperature and corrosion resistance in the aggressive environment of fluorides and chlorides. Presently used surfacing methods include gas-shielded metal arc surfacing (using pulsed current and the low-energy CMT method), plasma– powder surfacing, laser surfacing and non-consumable electrode inert gas surfacing (TIG) [1-11].

Plasma-powder surfacing consists in using plasma arc to melt filler metal in the form of

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nickel, cobalt, iron or copper-based alloy metallic powder or ceramic powder of spherical grains (0.04-0.3 mm in size) and transferring molten filler metal onto a previously prepared element surface using plasma arc. In plasma surfacing, the heat source is concentrated electric arc burning between a non-consumable electrode placed in the plasma torch and the base material. The major advantages of plasma-powder surfacing include high arc stability, high smoothness of a surfaced layer, thus small allowances for mechanical working, high metallurgical purity of overlay welds and the wide range of thicknesses of layers made in one run.

One of the primary criteria to be satisfied by a surfaced coating is low iron content (maximum 5% in the external zone), a thickness not exceeding 2.0÷2.5 mm as well as the lack of the microsegregation of alloying elements in the overlay weld. Iron content higher than that mentioned above reduces corrosion resistance, whereas an excessive thickness increases both the weight of structures and the costs of surfacing processes. In turn, the microsegregations of elements, particularly Nb and Mo, trigger the formation of intermetallic phases decreasing the corrosion resistance of overlay welds [2,3,7,8,10].

This article presents the course and selected results of structural tests concerning one and two-layer overlay welds made of nickel alloy Inconel 625, applied on the substrate made of steel 13CrMo4-5 in the plasma-powder surfacing process.

Materials, Test Rig and Testing Methodology

The base material used in the tests had the form seamless tubes (φ 45×5.0 mm) made of structural steel 13CrMo4-5. The above-named steel is characterised by resistance to high temperature (up to 550°C) and, for this reason, is used in the making of boilers and equipment applied in the power generation industry. The filler metal used in the tests was powder EuTroloy 16625G-04 having the composition of alloy Inconel 625, produced by Messer Eutectic Castolin. The tests were performed using a test rig provided with a Eutronic GAP 3001 device (Castolin). The welding torch along with the powder feeder was installed on an automated MultiSurfacer D2 Weld station (WeldingAlloys) equipped with a microprocessor-based control system enabling the adjustment of the direction and the rate of surfacing as well as the repeatable positioning of the torch.

The testing methodology involved technological plasma-powder surfacing tests performed under various process conditions and using various process parameters. The initial tests revealed the quality and the geometry of the overlay welds as well as the content of iron on the overlay weld surface were primarily affected by surfacing current, powder mass feeding rate, surfacing rate of rotation and the travel rate of the plasma torch along the tube axis. The surfacing tests were performed on 1000 mm long tubes, where a tube segment subjected to surfacing performed using one set of technological parameters was approximately 300 mm long. To eliminate the heat effect related to a previously made overlay weld, each next segment of the tube was subjected to surfacing once the tube has cooled down. The technological tests were performed changing parameters within the following ranges:

- welding current: from 50 A to 220 A,
- powder mass feeding rate: from 6% to 30%,
- surfacing rate of rotation: from 2 rpm to 20 rpm (surfacing linear energy, allowing for the tube diameter, was restricted within the range of 28 cm/min to 280 cm/min),
- rate of the plasma torch travel along the tube was restricted within the range of 5 cm/min to 25 cm/min.

The first stage involved the performance of technological surfacing tests using one, two and three layers without cooling the tube inside. The subsequent tests included cooling the tubes inside using water supplied by means of appropriate pipe connectors. The overlay welds made using cooling were single-layered.

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After the surfacing of the tubular elements, the overlay welds were subjected to macroscopic metallographic tests and the analysis of the chemical composition of the overlay weld surface performed using spark source optical emission spectrometry and a Q4 Tasman spectrometer (Bruker), particularly to determine the content of iron. The subsequent stage involved microscopic metallographic tests, the microanalysis of cross-sectional chemical composition and the surface distribution of chemical elements. Metallographic specimens were prepared by grinding performed using SiC paper (having a gradation of 280-1200) and polishing performed using diamond slurries (3 and 1 μm). The polished surfaces were etched using a reagent composed of 3 g $FeCl_3$, 10 ml HCl and 90 ml C_2H_5OH. The assessment of the overlay weld quality involved the performance of macrographic tests using an Olympus SZX9 stereoscopic microscope (SM). The observation was performed in the dark field at magnification reaching 500x. The microstructural observations were performed using a Hitachi S-3400N scanning electron microscope in the secondary electrons technique (SE) and in the back-scattered electrons technique (BSE) at magnification reaching 2000x. The microanalysis of the chemical composition of the surfaced layers was conducted using a Hitachi S-3400NV scanning microscope provided with an energy dispersive spectrometer (EDS). The chemical composition analysis was performed using an electron beam accelerating voltage of 15 keV. The chemical composition analysis of the overlay weld was supplemented by the analysis of chemical composition changes along the line perpendicular to the overlay weld and the analysis of the surface distribution of chemical elements in the fusion area.

Test Results

The technological tests revealed that the content of iron in the overlay weld was primarily affected by current, powder mass feeding rate and a surfacing rate (both the rate of rotation and the travel rate along the rube). All of the above-named parameters translate into a heat input during surfacing and considerably affect the course of the process, the flow of powder (melted by the heat of plasma arc) towards the base material and the stirring of the deposited metal with the partially melted base material. At the same time, the above-named parameters influence the thickness of a surfaced layer. The technological surfacing tests and the measurements of iron content on the overlay weld surface revealed that, in spite of applying various settings of technological parameters within a wide range and ensuring the obtainment of high-quality overlay welds (pure, non-oxidised face, regular beading, lack of shape-related imperfections), it was not possible to obtain an iron content of less than 5% in one layer without cooling the tube inside. This resulted from an excessive heat input to the material responsible for the excessive partial melting of the base material and considerable stirring with the molten powder. In addition, the dynamic effect of plasma arc imposed the motion of the liquid metal in the pool leading to the significant content of iron on the overlay weld surface (reaching up to 50% in cases of certain parameters). The lowest content of iron obtainable in relation to a single-run overlay weld amounted to approximately 17%. The thickness of the surfaced layer amounted to 1.3 mm, whereas penetration depth was limited to approximately 0.4 mm (Fig. 1).

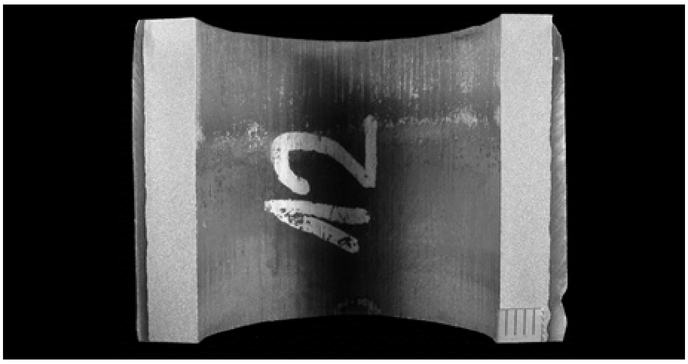

Fig. 1. Macrostructure of the tube (φ 44.5 x 5.0) mm made of steel 13CrMo4-5 with the one-layer overlay weld made of nickel alloy Inconel 625

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Further technological tests and iron content measurements revealed that the application of two-layer surfacing and the reduction of current made it possible to decrease the content of iron below 5%, yet only the at the beginning of the overlay weld. Approximately 30 cm away from the start, the content of iron amounted to approximately 20%. Further current reduction was responsible for the irregular melting of the powder leading to considerable overlay surface porosity and to irregular overlay weld face formation. Figure 2 presents the macrostructure of the two-layer overlay weld having a thickness of 2.5 mm.

Fig. 2. Macrostructure of the tube (φ 44.5 x 5.0) mm made of steel 13CrMo4-5 with the two-layer overlay weld made of nickel alloy Inconel 625

It appeared possible to reduce the content of iron (to approximately 2-3% on the overlay weld surface) only in the third layer, yet interpass temperature should not exceed 100°C. The obtained quality and repeatability of overlay welds were satisfactory, yet considerable disadvantages of the above-named solution were low process efficiency (necessity of surfacing one element three times) and a significant thickness of the overlay weld amounting to approximately 3.7 mm (Fig. 3).

Having taken the above-named circumstances into consideration, another approach was developed whereby the heat discharge from the surfacing area was intensified by cooling the tube inside. To this end, both ends of the tube were threaded and provided with appropriate pipe connectors enabling the free rotation of the tube following the connection of water-transporting hoses. The technological surfacing tests, visual tests of the overlay welds as well as the analysis of iron content measurement results enabled the adjustment of appropriate technological parameters used in the surfacing of 1000 mm long tube segments (φ 44.5 × 5.6 mm). The developed parameters enabled the obtainment of the lowest iron content (approximately 2.5%), a thickness of approximately 1.6 mm and the highest overlay weld quality manifested by the clean and smooth face as well as by the lack of oxidation traces, porosity and cavities (Fig. 4). During the surfacing involving the cooling the heat discharge rate was so high that the temperature of the overlay weld directly behind the torch made it possible to touch the tube with a hand ($T \leq 30°C$). After surfacing the tube did not reveal any deformations.

The microscopic metallographic tests were performed in the base material area, the HAZ, the fusion line and in the one-layer overlay weld. Figure 5 presents the HAZ photographs made using the scanning microscope, Figure 6 presents

Fig. 3. Macrostructure of the tube (φ 44.5 x 5.0) mm made of steel 13CrMo4-5 with the three-layer overlay weld made of nickel alloy Inconel 625

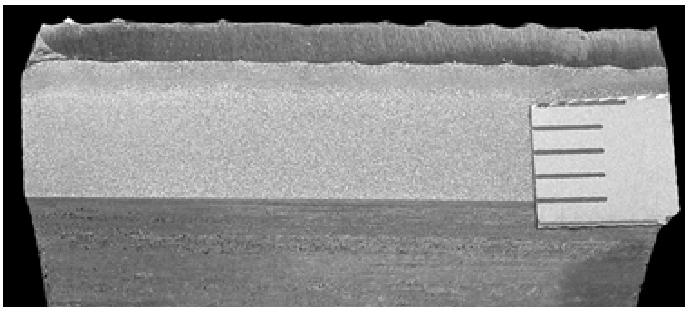

Fig. 4. Macrostructure of the tube (φ 44.5 x 5.0) mm made of steel 13CrMo4-5 with the one-layer overlay weld made of nickel alloy Inconel 625; surfacing performed with the simultaneous cooling of the tube inside

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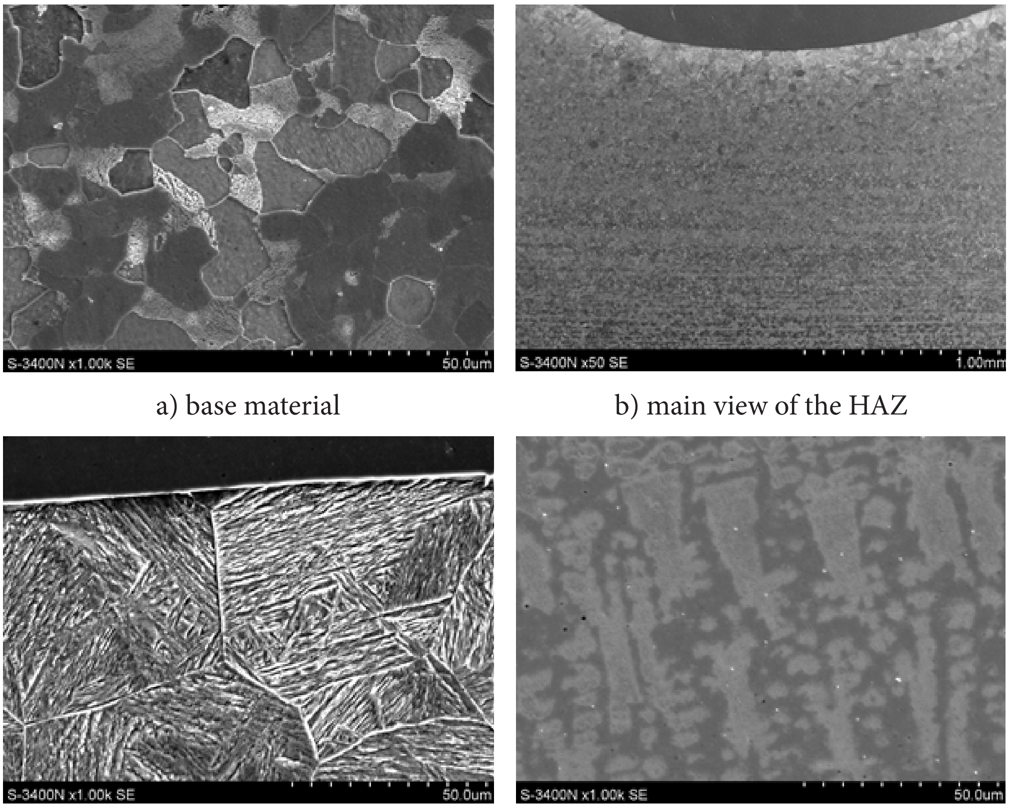
the microstructural photographs made using the light microscope, Figure 7 presents the linear distribution of chemical elements, whereas Figure 8 presents the surface distribution of chemical elements in the overlay weld fusion zone.

The next stage included hardness measurements involving the surfaced specimens made of steel 13CrMo4-5 without cooling (one and two-layer specimens) and the specimens sampled from the tubes subjected to surfacing and cooling at the same time. Vickers hardness tests were performed using a KB50BYZ-FA hardness tester (KB Prüftechnik) under a nominal load of 1.96 N (HV0.2). Hardness was measured in the coating, directly under the coating and on the cross-section of the remaining area (base material). Figure 9 presents the schematic arrangement of the measurement points, whereas Table 3 contains hardness measurement results.

Analysis of Test Results

The technological tests concerning the plasma-powder surfacing of pipes (φ 44.5×5 mm) made of steel 13CrMo4-5,



a) base material
b) main view of the HAZ
c) HAZ near the fusion line
d) overlay weld near the fusion line

Fig. 5. Microstructure of the HAZ and of the overlay weld made of alloy Inconel 625 on the tube made of steel 13CrMo4-5, observed using the scanning microscope

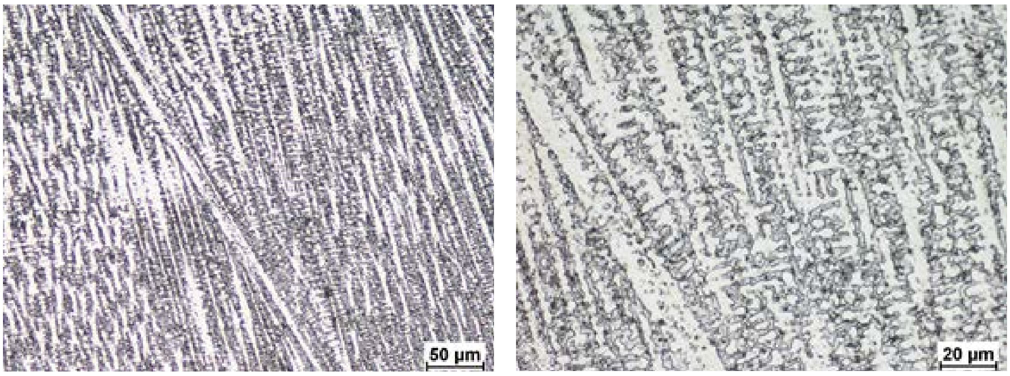


Fig. 6. Microstructure of the overlay weld made of alloy Inconel 625 on the tube made of steel 13CrMo4-5, observed using the light microscope

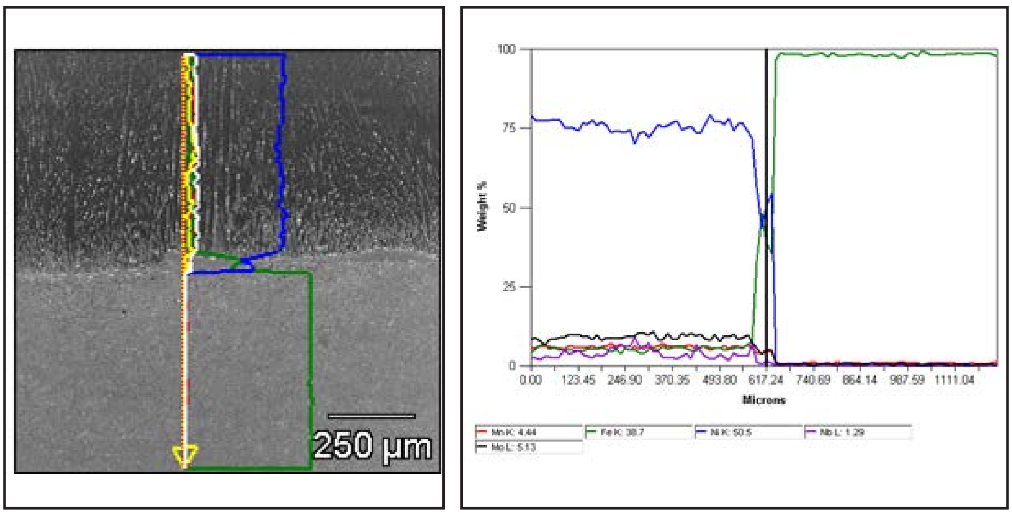


Fig. 7. Linear distribution of chemical elements across the fusion line

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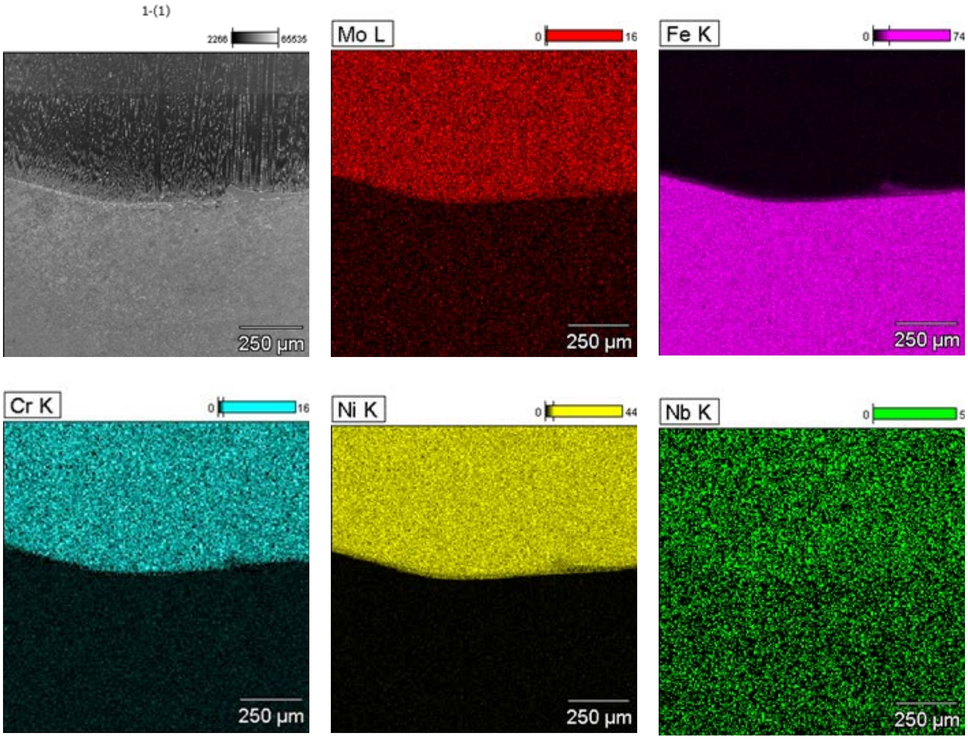

Fig. 8. Surface distribution of chemical elements in the fusion zone

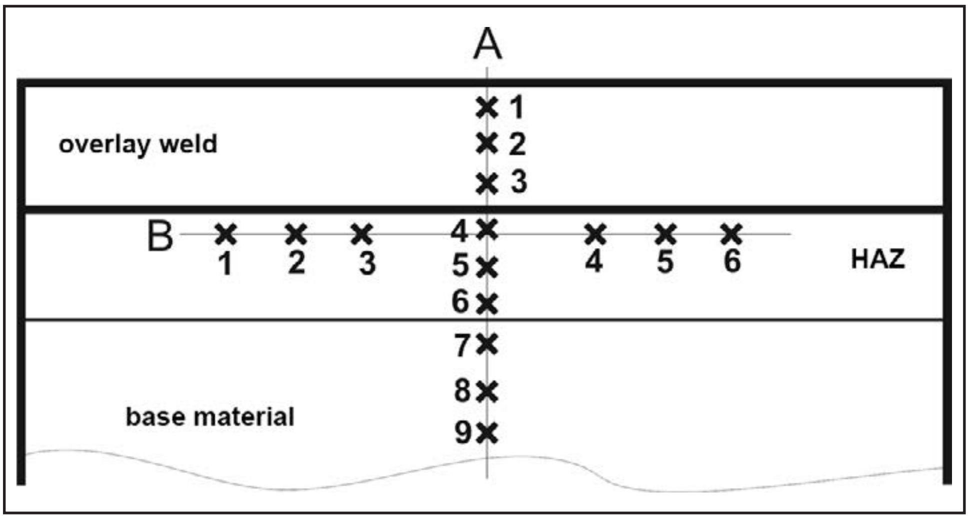

Fig. 9. Schematic arrangement of the measurement points on the cross-section of the tubes (φ 44.5 x 5.6 mm) made of steel 13CrMo4-5

performed using powder having the composition of alloy Inconel 625, combined with the analysis of the chemical composition of the overlay weld revealed that the satisfaction of requirements concerning surfaced elements used in power engineering (content Fe ≤ 5%) required the cooling of the tube inside performed during the process of surfacing. Plasma surfacing is a process entailing the considerable stirring of the overlay weld with the base material, even in cases of very shallow penetration depths. The foregoing results from extremely high plasma laser concentration and the dynamic effect of the plasma beam on the liquid metal pool. As a result of the motion of metal in the pool, the partially melted base material moves towards the surface of the overlay weld, significantly increasing the iron content in this area. An increase in

Table 1. Cross-sectional hardness measurement results in relation to the tubes provided with sprayed coating with melting and without the coating

Specimen description	Test line	Hardness HV0.2 in measurement points according to Figure 9								
		1	2	3	4	5	6	7	8	9
Tube with the one-layer overlay weld made without cooling, steel 13CrMo4-5	A	215	146	201	114	152	201	170	119	169
	B	180	174	186	202	207	179	-	-	-
Tube with the two-layer overlay weld made without cooling, steel 13CrMo4-5	A	241	245	253	149	209	208	187	194	158
	B	189	178	188	208	188	185	-	-	-
Tube with the one-layer overlay weld made with cooling, steel 13CrMo4-5	A	280	285	279	277	304	353	183	182	189
	B	284	244	329	271	294	351	-	-	-

Note: Measurement points 1 through 6 in line B are situated directly under the overlay weld

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a surfacing rate does not considerably reduce the content of iron. In addition, as a result of the above-named increase, the quality of the overlay weld worsens and powder losses are higher. A further increase in the amount of powder does not reduce the content of iron, making powder losses even higher (more than 30%). A decrease in surfacing enables a decrease in the content of iron, yet in one layer only to approximately 17%. The use of two-sided surfacing combined with the application of lower current makes it possible to reduce the content of iron below 5%, yet only at the beginning of the overlay weld. In the remaining part of the overlay weld the content of iron may reach up to 20%. A further decrease in surfacing current leads to the irregular melting of the powder, manifested by significant porosity. It is possible to reduce the content of iron on the overlay weld surface only by cooling the tube inside, allowing very fast heat discharge, a decrease in penetration depth and the reduction of the stirring of the overlay weld with the base material. The technological tests enabled the development of surfacing conditions and parameters ensuring the obtainment of good-quality overlay welds with the iron content on their surface restricted within the range of 1 to 3%.

The microscopic metallographic tests revealed that the structure of the base material consisted of two phases, i.e. ferritic and pearlitic. The structure of the HAZ of the elements after surfacing was complex. The area further from the fusion line contained the refined ferritic-pearlitic structure. The area near the fusion line contained bainite and martensite, whereas the area directly adjacent to the fusion line was characterised by the significant growth of former austenite. The overlay weld structure was austenitic, characteristic of nickel alloys. Directly near the fusion line, in the poorly etched areas the structure was of cellular nature. The foregoing could be attributed to the fact that during crystallisation the gradient of temperature in the above area was the greatest. An increase in the distance from the fusion line was accompanied by the gradual change in crystallisation, i.e. from cellular through cellular-dendritic to entirely dendritic. The chemical composition of the overlay weld did not change, which was demonstrated and confirmed by the linear and surface distribution of chemical elements.

The hardness tests revealed significant differences in relation to the tubes surfaced with and without cooling performed inside. As regards the one-layer overlay weld made without cooling, the stirring of the overlay weld with the base material (iron content of approximately 20%) resulted in a significant decrease in the hardness of the surfaced layer, even below 200 HV. The use of two-layer surfacing made it possible to reduce the decrease in hardness to approximately 220-240 HV, indicating the lesser stirring of the overlay weld with the base material. Typical hardness values of alloy Inconel 625 amount to approximately 250 HV, yet during surfacing the overlay weld material became hardened as a result of the effect of thermal stresses and stresses related to various thermal expansion. Particular attention should be paid to the low HAZ hardness in the tubes surfaced without cooling. Usually, hardness values in this area do not exceed 200 HV and are similar to the hardness of the base material. The high heat input led to the annealing of the material, where single bainite lamellas did not affect the value of hardness. Significantly higher hardness values were revealed in the HAZ of the tubes cooled inside. In many cases, the above-named values exceeded 300 HV (max. 353 HV), yet were lower than the maximum permissible value of 380 HV required by the standard concerning welding procedure qualification, i.e. PN-EN ISO 15614-7. The hardness increase in the HAZ could be attributed to the fine-grained bainitic–pearlitic structure triggered by the very intense thermal cycle affecting the tube material during surfacing (rapid heating to a high temperature followed by rapid cooling). However, the obtained hardness values indicated

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that the above-named structure was safe as regards the use of surfaced elements.

To summarise, it can be stated that the technology involving the plasma-powder surfacing performed using powdered alloy Inconel 625 can be applied in relation to elements of low-emission boilers used in power units characterised by supercritical parameters. By reducing the content of iron in the overlay weld surface below 5%, the plasma surfacing technology provides appropriate process efficiency, high overlay weld quality and corrosion resistance.

Concluding remarks

1. Plasma surfacing of tubes (φ 45×5.0 mm) made of steel 13CrMo4-5, performed using alloy Inconel 625, enabled the obtainment of overlay welds characterised by high quality and aesthetics, yet within a very narrow range of parameters.
2. The appropriate adjustment of technological parameters (powder mass feeding rate, current and surfacing rate) makes it possible to control the weld geometry and the base material content in the overlay weld.
3. The satisfaction of the criterion related to the maximum iron content of 5% on the overlay weld surface is possible in cases of one and multilayer surfacing, yet slight changes in technological parameters may lead to a significantly higher Fe content on the overlay weld surface. It is necessary to apply cooling inside the tube.
4. The overlay weld structure contained zones having the cellular structure near the fusion line and dendritic structure in areas far from the FZ. The intercellular and interdendritic spaces were Mo and Nb-enriched. The precipitates present in the above-named spaces were, probably, carbides of the above-named metals.
5. Changes taking place in the base materials of unalloyed tubes characterised by specific properties at higher temperatures, e.g. the formation of the bainitic-structured zone and the hardness increase in the HAZ are typical of arc surfacing. The hardness in the HAZ did not exceed the allowed value of 380 HV according to PN-EN ISO 15614-7.

References

[1] Rozmus-Górnikowska M.: *Badania mikrostruktury i mikrosegregacji składu chemicznego warstw ze stopu Inconel 625 napawanych techniką CMT na podłoże ze stali 16Mo3*. Przegląd Spawalnictwa, 2014, no. 12, pp. 4-8.

[2] Rutzinger B.: *Kierunki rozwoju w przemyśle energetycznym. Zastosowanie napawania metodą CMT w elektrowniach węglowych*. Biuletyn Instytutu Spawalnictwa, 2012, no. 5, pp. 63-66.

[3] Rutzinger B.: *Influence of the welding process to the dilution rate of weld overlays on unalloyed steel using the weld consumable ER-NiCrMo-3 (Alloy 625)*. Biuletyn Instytutu Spawalnictwa, 2014, no. 5, pp. 72-75. http://bulletin.is.gliwice.pl/article/influence-welding-process-dilution-rate-weld-overlays-unalloyed-steel-using-weld-consumable

[4] Adamiec P., Adamiec J.: *Aspekty napawania stopami Inconel 625 i 686 elementów w kotłach do spalania odpadów*. Przegląd Spawalnictwa, 2006, no. 5-6, pp.11-14.

[5] Nowacki J., Wypych A.: *Mikrostruktura i odporność na wysokotemperaturowe utlenianie napoin nadstopu Inconel 625 na stali niskostopowej*. Biuletyn Instytutu Spawalnictwa, 2010, no. 5, pp. 84-87.

[6] Jarosiński J., Błaszczyk M., Tasak E.: *Napawanie stali stosowanych w energetyce stopami na osnowie niklu*. Przegląd Spawalnictwa, 2007, no. 1, pp. 30-33.

[7] Jarosiński J., Błaszczyk M.: *Napawanie stali stosowanych w energetyce stopami na osnowie niklu. Problem praktycznego pomiaru zawartości żelaza*. Spajanie, 2006, no. 2, pp. 18-23.

[8] Abioye T.E., McCartney D.G., Clare A.T.: *Laser cladding of Inconel 625 wire for*

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corrosion protection. Journal of Materials Processing Technology, 2015, vol. 217, pp. 232–240. http://dx.doi.org/10.1016/j.jmatprotec.2014.10.024

[9] Abioye T.E., Folkes J., Clare A.T.: *A parametric study of Inconel 625 wire laser deposition.* Journal of Materials Processing Technology, 2013, vol. 213, pp. 2145–2151. http://dx.doi.org/10.1016/j.jmatprotec.2013.06.007

[10] Pfeifer T., Grobosz W., Rykała J. et al.: Technological Aspects of the Robotic TopTIG Surfacing of Boiler Steel Tubes Using Alloy Inconel 625. The Paton Welding Journal, 2017, no. 5/6, pp. 37-44 http://dx.doi.org/10.15407/tpwj2017.06.08

[11] Рябцев И.А., Сенченков И.К., Турык Э.В.: *Наплавка. Материалы, технологии, математическое моделирование" (Napawanie. Materiały, technologie, modelowanie matematyczne).* Monography no. 589. Wydawnictwo Politechniki Śląskiej, Gliwice, 2015