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Plasma Transferred Arc (PTA) Cladding and TOPTIG Cladding of Tubes Made of Steel 13CrMo4-5

Abstract: The article presents test results concerning the effect of a cladding method and technological process parameters on geometrical properties and dilution of overlay welds. Test overlay welds were deposited on tubes made of steel 13CrMo4-5. The chemical composition of the filler material used in the deposition process corresponded to that of alloy Inconel 625. The study involved the performance of macro and microscopic metallographic tests of the overlay welds as well as the identification of related dilution. The study also included hardness measurements involving the cross-section of the overlay welds as well as tests of the chemical composition of the overlay weld surface (paying attention to the maximum content of iron in the overlay weld, which should not exceed 5%). Adopted PTA and TOPTIG cladding parameters enabled the satisfaction of the maximum criterion related to the acceptable content of iron in the overlay weld, ensuring the stability of the cladding process and the invariable geometry of the overlay welds around the entire tube circumference.

Keywords: 13CrMo4-5; PTA, TOPTIG, tube cladding, overlay welds

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Introduction

Cladding is a process where welding methods are used to deposit a metal layer on the work surface of tools and machinery elements. The cladding process involves the metallurgical melting of the base material [1]. In cases of repair cladding, aimed to restore the nominal dimensions of elements worn in operation and made with easy-to-weld structural steels, the primary criterion determining the selection of a given cladding method is process efficiency. The significant dilution of the base metal in the overlay weld is, in this particular case, ignored. In turn, as regards the cladding of working elements with a material characterised by specific properties (e.g. high corrosion resistance, high hardness, high resistance to wear, erosion or flue gas), the selection of an appropriate cladding method is usually a compromise between the relatively high efficiency of the cladding process and the minimum dilution of the base metal in the overlay weld. Filler materials used in such cases tend to be very expensive, whereas the change of their nominal chemical composition in the overlay weld (caused by the excessive dilution with the base metal) leads to significant, usually unfavourable, changes of filler material properties.

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In situations requiring the limited amount of the base metal in the overlay weld it is necessary to select an appropriate cladding method (whose characteristic ensures the minimum partial melting of the base metal) and develop an appropriate technology.

For many years, Instytut Spawalnictwa has been performing technological tests concerning the possibility of making deposited layers characterised by strictly specified properties in relation to the minimum dilution of the base metal in the overlay weld. This article presents selected examples of technological development concerning the PTA (plasma transferred arc) cladding and TOPTIG cladding involving the use of the filler material in the form of a solid wire.

TOPTIG cladding

The TIG method-based cladding process is commonly known and, owing to the continuous development of welding technologies, has given rise to many of its variants. One of such variants is the TOPTIG method characterised by the mechanised feeding of the filler materials (in the form of a wire) to an area affected by welding arc. In the above-named process, the system of mechanised wire feed is integrated with a gas nozzle so that the angle at which the wire is fed in relation to the tungsten electrode amounts to ~20°. During the classical TIG welding involving mechanised wire feed, the aforesaid angle is usually restricted within the range of 40° to 60° [2]. Because of the fact that the shielding gas nozzle and the terminal positioning the wire constitute an integrated element, it is not possible to deflect the wire during the welding process (Fig. 1).

Fig. 1. TOPTIG welding torch

The TOPTIG method has been originally designed to enable the high-performance TIG welding of thin-walled elements in poorly accessible areas, where the classical wire feeder would make it impossible to place the welding torch near the weld area. In addition, the TOPTIG method enables the performance of the welding process with the wire fed before arc, thus reducing its dynamic force and limiting penetration depth. Interestingly, in the TOPTIG process the wire can also be fed behind welding arc, making it possible to obtain deep penetration in the base metal. When using the classical wire feeder in the TIG method, the feeding of the wire behind welding arc is significantly impeded (or even impossible) by the "freezing" of the electrode wire to the liquid metal pool.

Test rig and materials

The tests involved seamless tubes (ø 45 mm x 5.0 mm) made of high temperature resistant (up to 550°C) structural steel 13CrMo4-5 used primarily in the fabrication of boilers and equipment dedicated to the power industry. The chemical composition of the steel is presented in Table 1. The filler material used in the tests was an OK Autorod NiCrMo-3 solid wire having a diameter of 1.0 mm (ESAB). The chemical composition of the filler material indicates nickel superalloy Inconel 625 (Table 2).

The PTA cladding process was performed using a test rig provided with a state-of-the-art Eutronic GAP 3001 (Castolin) and a Multi-Surfacer D2 Weld automatic welding machine

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Table 1. Chemical composition of steel 13CrMo4-5 (% by weight) in accordance with PN-EN 10216-2:2014-02 [3]

C	Mn	Si	P	S	Cu	Cr	Mo	N	Fe
Max. 0.18	Max. 1.0	Max. 0.35	Max. 0.025	Max. 0.01	Max. 0.30	0.7-1.15	0.4 -0.6	Max. 0.012	Bal.

Table 2. Chemical composition of the OK Autrod NiCrMo-3 weld deposit (% by weight)

Ni	Cr	Mo	Nb
74.5	20	3	2.5

(Welding Alloys). The TOPTIG cladding process was performed using a robotic welding station provided with a Romat 310 robot (CLOSS), the wrist of which was equipped with a TOPTIG welding torch (Air Liquid) (Fig. 2).

Plasma transferred arc (PTA) and TOPTIG cladding of tubes made of steel 13CrMo4-5

The adjustment of optimum PTA and TOPTIG cladding parameters ensuring the obtainment of high-quality overlay welds (characterised by the constant geometry along their entire length and the minimum dilution of the base metal in the deposited layer as well as the minimum amount of iron Fe in the external zone (max. 5%)) required the performance of many single test overlay welds on 10 mm thick plates made of steel S355J2+N using various sets of process parameters.

The study involved visual tests and the calculation of the dilution of the base metal in the overlay welds as the proportion of the area of penetration in the material to the area of the entire overlay weld (Fig. 3).

The macrostructure of single overlay welds as well as technological parameters and measurement results are presented in Tables 3 and 4.

The initial PTA and TOPTIG cladding tests involving the plates made of steel S355J2+N and the nickel-based filler material (OK Autrod NiCrMo-3) as well as results of measurements concerning deposited layers revealed that the dilution of the base metal in the overlay weld made using the PTA method was by 25–45% higher than that in the overlay weld made

Fig. 2. Station for PTA mechanised cladding (a) and TOPTIG robotic cladding (b)

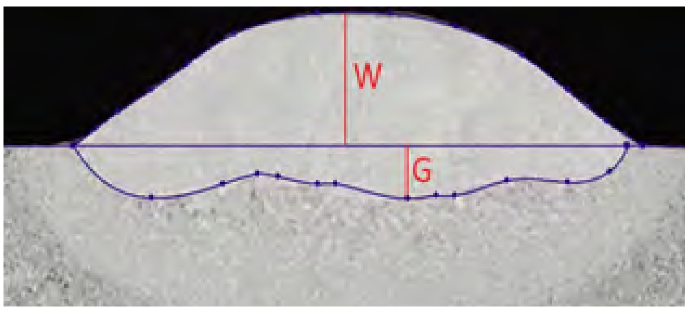

Fig. 3. Identification cross-sectional areas, height (H) and penetration depth (D) in the overlay welds

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Table 3. Exemplary results of PTA cladding tests [4–6]

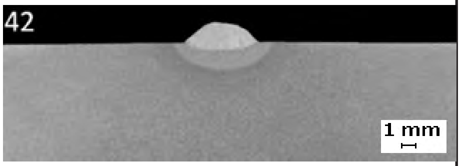
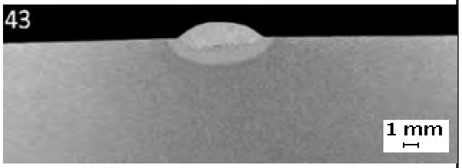
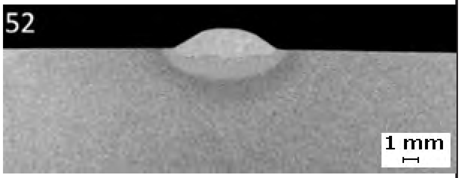
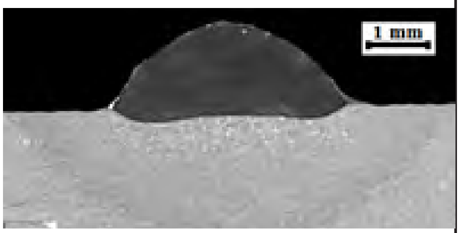
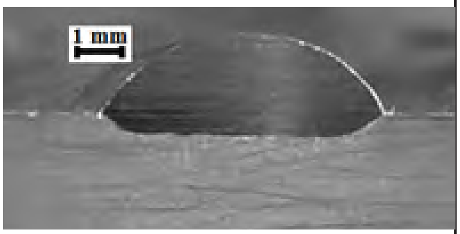
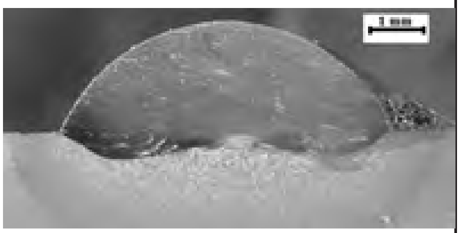
		
Db =33.2%	Db =32.8%	Db =28.7%
H=1.50 mm	H=1.17 mm	H=1.51 mm
I=140A	I=140 A	I=140 A
Gp = 1.0 l/min	Gp = 1.0 l/min	Gp = 1.0 l/min
Vw =1.81 m/min	Vw =1.81 m/min	Vw =1.81 m/min
Vc =35 cm/min	Vc =40 cm/min	Vc =30 cm/min
Note: Db – dilution of the base metal in the overlay weld [%], H – overlay weld height [mm], I – welding current [A], Gp – plasma gas flow rate [l/min], Vw – filler material wire feed rate [m/min], Vc – cladding rate [cm/min]		

Table 4. Exemplary results of TOPTIG cladding tests

		
Db =12.6%	Db =22.9%	Db =18.7%
H=1.63 mm	H=1.78 mm	H=2.11 mm
Ib=100A	Ib=140 A	Ib=130 A
Ii=140A	Ii=120 A	Ii=120 A
Vw =1.0 m/min	Vw =1.2 m/min	Vw =1.5 m/min
Vc =15 cm/min	Vc =15 cm/min	Vc =15 cm/min
Note: Db – dilution of the base metal in the overlay weld [%], H – overlay weld height [mm], Ib – base current [A], Ii – impulse current [A], Vw – filler material wire feed rate [m/min], Vc – cladding rate [cm/min]		

using the TOPTIG method (in spite of applying higher (by twice and even thrice) welding rates. The technological tests aimed to obtain reduced penetration led to arc instability when using the plasma-based method and, consequently, to the formation of defective overlay welds.

The above-presented diagnostic tests enabled the identification of parameters ensuring the obtainment of the minimum dilution of the base metal in the deposited layer (in relation to each technology). Overlay welds were deposited on tubes (ø 45 mm x 5.0 mm) made of steel 13CrMo4-5. The process was performed using an overlap of between 30% and 60% as well as additional technological procedures. After cladding the tubes were subjected to visual tests. The visual tests confirmed the correct identification of parameters ensuring the obtainment of the high quality of tubes subjected to cladding (Fig. 4). The overlay welds were smooth and free from surface impurities.

Fig. 4. Surface obtained using the PTA cladding method

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The macroscopic metallographic tests revealed that, depending on applied technological parameters, individual overlay welds differed in terms of width, height (between 2.0 mm and 3.0 mm) and the depth of penetration in the base material. Particularly in relation to the PTA overlay welds it was possible to observe that the macroscopic metallographic specimens (Fig. 5) were characterised by the specific corrugated shape of penetration resulting, among other things, from the helical movement of the tool (welding torch) along the tube subjected to cladding. In cases of some specimens the foresaid phenomenon resulted in slight incomplete fusion, detected only during detailed microscopic metallographic tests. The shape and the dimensions of individual humps depended on technological parameters, i.e. cladding current, tool movement and the cladding rate/rate of tube rotation.

The macroscopic metallographic tests were followed by the determination (based on metallographic specimen photographs) of the cross-sectional areas of excess overlay weld metal and the partly melted base material as well as the overlay weld height (H), penetration depth (D) and the dilution of the base metal in the overlay weld. The macrostructures of the overlay welds characterised by the lowest dilution of the base metal in the deposited layer are presented in Figures 5 and 6. As can be seen in the photographs, the overlay weld made using the TOPTIG method was characterised by minimum penetration (3.28% - nearly as shallow incomplete fusion) in the base metal. The minimum dilution of the base metal in the deposited layer obtained using the PTA method amounted to 5.11%, which confirmed the results of the initial technological tests performed using the plates made of steel S355J+N. The analysis of related measurement results revealed that the PTA overlay welds were characterised by greater height (restricted within the range of 2.4 mm to 3.0 mm) than the height of the TOPTIG overlay welds (restricted within the range of 1.8 mm to 2.7 mm).

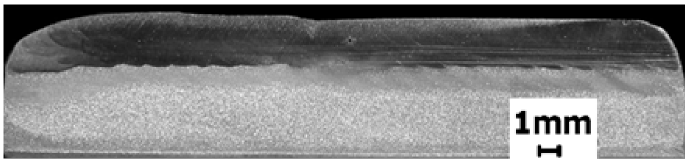

Fig. 5. Macroscopic metallographic specimen of the (tube ø 45 mm x 5.0 mm) made of steel 13CrMo4-5 subjected to PTA cladding

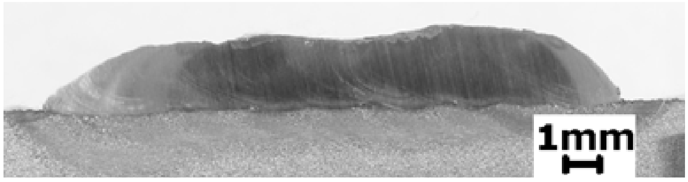

Fig. 6. Macroscopic metallographic specimen of the (tube ø 45 mm x 5.0 mm) made of steel 13CrMo4-5 subjected to TOPTIG cladding

The subsequent stage included tests involving the use of a light microscope. Selected specimens were subjected to two-stage polishing and etching. The initial polishing was performed using Monocrystalline Diamond Suspension having a granularity of 3 μm (Buehler), whereas the finishing polishing was performed using OP-S Suspension having a granularity of 0.05 μm (Struers). The identification of the base material structure (13CrMo4-5) was performed using Nital. In turn, the structure of the nickel-based alloy (deposited layer) was identified through electrolytic etching involving the use of the mixture of distilled water and sulphuric acid. The selected results of the microscopic tests are presented in Figures 7–9.

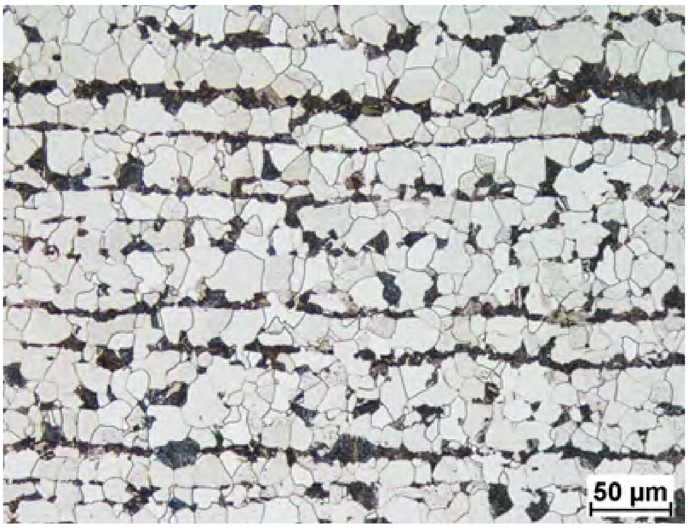

Fig. 7. Microstructure of the base material of steel 13CrMo4-5; etchant: Nital, mag. 200x, structure: ferrite + banded pearlite

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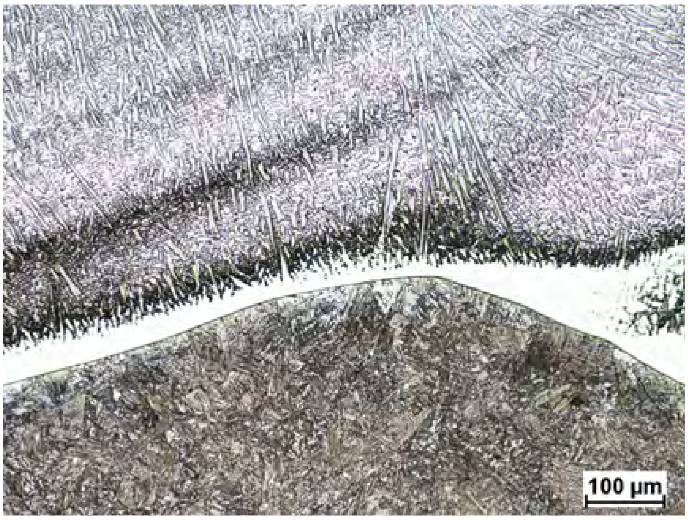

Fig. 8. Microstructure of the fusion line of steel 13CrMo4-5 subjected to cladding with the nickel alloy; electrolytic etching, mag. 100x, visible decarbonised zone (cluster of Fe an Cr)

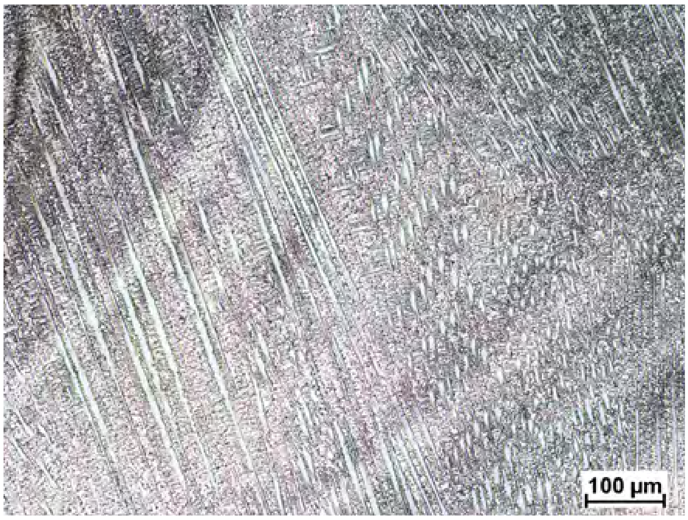

Fig. 9. Microstructure of the overlay weld made of the nickel alloy and deposited on steel 13CrMo4-5, electrolytic etching, mag. 100x, structure: austenite

The microscopic metallographic tests revealed that the base material of the tubes made of steel 13CrMo4-5 had the dual-phase (ferritic-pearlitic) structure (Fig. 7). The structure of the HAZ of the elements after cladding was complex. The area further from the fusion line contained the fine-grained ferritic-pearlitic structure. The area closer to the fusion line contained bainite and martensite. The area directly adjacent to the fusion line was characterised by significant grain growth and the presence of a bright zone, typical of cladded joints in cases of such a material configuration (Fig. 8). The aforesaid area probably contained increased amounts of iron and chromium. The structure of the overlay weld was austenitic, which is typical of nickel alloys (Fig. 9). The photographs revealed the characteristic (i.e. dendritic) structure of the overlay weld. The tests revealed that the elements subjected to cladding performed using higher current parameters (and/or a smaller amount of the filler material and similar other parameters) contained the HAZ characterised by significantly larger grains and a higher amount of martensite. Regardless of technologies applied, the structure of the tubes subjected to cladding was nearly identical [3–6].

The subsequent stage included chemical composition-related tests and tests concerning the content of iron on the surface of the tubes subjected to cladding [7]. The tests were performed using a Q4 TASMAN spark emission spectrometer (Bruker). The method involves the evaporation and the excitation of the material using an electric spark as well as the observation of electromagnetic radiation emitted during the process. Related measurements were performed on the surface of the face of the deposited layers. The percentage content of iron and of other chemical components of selected specimens are presented in Table 5.

The analysis of the percentage chemical analysis (including Fe) related to the surfaces of all the specimens revealed that the overlay welds characterised by the lower content of Fe on the surface also contained smaller amounts of Cu and Mn and higher amounts of Mo, Cr and Ni. Only four specimens (i.e. specimens nos. 1 and 3 in relation to the PTA method and specimens nos. 1 and 2 in relation to the TOPTIG method, see Table 5) satisfied the criterion of the maximum 5% content of iron on the surface of the deposited layer. The thickness of the layer deposited on the specimens was restricted within the range of 2.5 mm to 3.0 mm.

The final measurement involving the cross-section of the tubes subjected to cladding was the Vickers hardness test. The examination

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Table 5. Chemical composition of the overlay weld surface

Cladding method	Specimen	Chemical element content in % by weight											
		C	Mn	Si	Cu	Cr	Mo	W	Fe	Al	Nb	Ti	Ni
PTA	1	0.020	0.02	0.12	0.013	21.52	7.86	0.096	2.81	0.11	3.42	0.02	63.60
	2	0.009	0.04	0.12	0.020	20.53	7.61	0.13	7.9	0.10	3.24	0.02	59.84
	3	0.016	0.03	0.12	0.017	20.98	7.75	0.104	4.67	0.13	3.27	0.02	61.48
TOPTIG	1	0.019	0.02	0.12	0.013	21.69	8.25	0.045	2.75	0.11	3.44	0.02	63.64
	2	0.020	0.03	0.12	0.019	20.13	7.97	0.021	4.29	0.08	3.62	0.15	62.92
	3	0.030	0.14	0.12	0.019	20.51	7.98	0.015	8.47	0.07	3.38	0.16	59.50

was performed using a KB50BYZ-FA hardness tester (KB Prütechnik GmbH) and a load of HV 10. Figure 10 presents the schematic diagram of the measurement mesh adopted during the hardness tests. Selected measurement results are presented in Table 6.

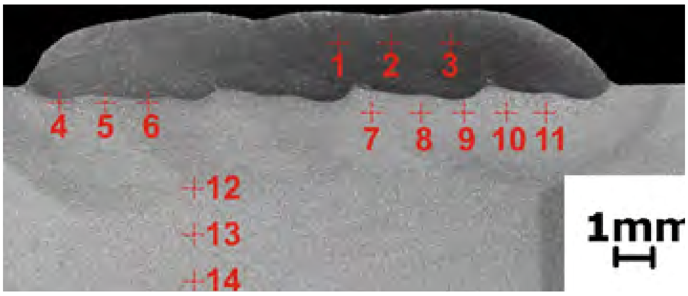

Fig. 10. Arrangement of the measurement points used in the hardness test involving the tubes subjected to cladding

The hardness tests revealed that the highest hardness values (even above 400 HV) were observed in the HAZ, whereas the lowest hardness values were characteristic of the deposited layer itself. The tests also revealed that the hardness values in the individual areas of the HAZ were affected by cladding current, cladding rate/rotation rate and the tool (welding torch) travel rate. The specimens made applying higher current parameters were characterised by lower HAZ-related hardness values and satisfied the hardness test-related assessment criterion (<380 HV in relation to steels of group 5.2 in accordance with ISO TR 15608 and in accordance with the requirements of the PN-EN ISO 15614-1:2017-08 standard [8]).

Table 6. Selected results of hardness measurements concerning the cross-section of the tubes subjected to cladding

Cladding method	**Hardness at a measurement point in accordance with Figure 11**					
	PTA			**TOPTIG**		
Measurement point	**Specimen 1**	**Specimen 2**	**Specimen 3**	**Specimen 1**	**Specimen 2**	**Specimen 3**
1	234	361	229	336	298	297 (s8)
2	240	331	221	318	300	300
3	235	353	215	324	279	291
4	411	232	211	394	375	342
5	402	251	196	381	362	340
6	317	262	206	384	345	358
7	314	254	210	360	321	298
8	303	260	216	374	309	304
9	276	317	331	350	300	274
10	270	277	277	349	287	296
11	344	284	321	364	307	298
12	272	275	310	299	295	262
13	257	267	313	287	237	200
14	180	268	295	261	167	175

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Summary

The technological tests concerning the PTA and TOPTIG processes involving the use of the filler material wire (nickel alloy OK Autrod NiCrMo-3) revealed that it was possible to obtain high-quality and high-aesthetic overlay welds on tubes (ø 45 mm x 5.0 mm) made of steel 13CrMo4-5. In terms of both cladding technologies, the technological tests and related measurements revealed that an increase in the cladding rate combined with the maintaining of the same current parameters and plasma gas-related parameters (only as regards PTA) led to a decrease in the dilution of the base metal in the deposited layer as well as to the reduction of the weld height and penetration depth.

The macroscopic test results and the results of deposited layer height measurements revealed that a significant number of the specimens failed to satisfy the industrial criterion of the maximum surface layer thickness (i.e. 2.0 mm), primarily because of economic reasons. The comparison of the results concerning the tubes subjected to PTA and TOPTIG cladding revealed that the PTA method was more efficient, yet the heights of the overlay welds obtained using the PTA process were restricted within the range of 2.8 mm to 3.0 mm. In turn, the TOPTIG process, in spite of being less efficient, enabled the deposition of layers having a height of approximately 2.0 mm.

The analysis of the microscopic metallographic test results and the chemical analysis of the specimens made using the PTA and TOPTIG methods led to the conclusion that the individual processes and their technological parameters did not significantly affect the structure of the overlay weld and that of the HAZ and that their chemical composition on the surface of deposited layers was similar. The HAZ of some specimens contained the martensitic structure and was characterised by hardness exceeding 380 HV, which is an undesired and unacceptable phenomenon in accordance with the PN-EN ISO 15614-7 [9] standard (concerning welding procedure qualification).

Both cladding technologies require laborious preparation, numerous tests and a meticulous approach. However, in spite of the above-named difficulties, the cladding process performed using the PTA and TOPTIG methods provides process stability, better control and fewer imperfections (if any) in comparison with TIG and MAG methods. The cladding techniques discussed in the article satisfy the criteria formulated by the power industry and concerned with the chemical composition of overlay welds and the maximum iron content on the surface.

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