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Purity of Backing Gas and the Quality of TIG Orbitally Welded Joints in Stainless Austenitic Steels

Abstract: The article discusses research involving tests aimed to identify the effect of the purity of backing gas on the quality of TIG orbitally welded joints in tubes made of stainless austenitic steel X5CrNi18-10 (1.4301) having dimensions of ϕ 50.8 x 1.5 mm, without the use of a filler metal. The research-related tests included the analysis of the chemical composition, the identification of the content of ferrite delta, non-destructive tests of welded joints (including visual tests involving the evaluation of temper colours on the face side and on the root side), radiographic tests, metallographic tests and destructive tests of welded joints. The metallurgical shield of the weld face was provided by the shielding gas (argon; purity class 5.0) , the flow rate of which amounted to 8 dm3/min. Initially, the root of a weld was shielded by the backing gas (argon; purity class 5.0) and, afterwards, by mixtures of argon and air. The tests revealed that an increase in the content of residual oxygen in the backing gas mixture was accompanied by a change in the colour of oxide layers present in the HAZ area and in the weld root area. Because of the requirements contained in Danish report no. 94.34 by the FORCE Technology Institute and American Standard no. ASME BPE-2012, related to temper colours, only the joint containing 4 and 25 ppm of residual oxygen in the mixture of backing gases can be applied after previous purification and passivation.

Keywords: TIG orbital welding, purity of backing gas, quality of joints

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Introduction

Ever-developing industries relay on many various manufacturing technologies, with welding processes used on a massive scale. Because of high efficiency and increasingly high quality requirements, human labour is frequently supported by mechanised and automated processes. Continuous progress requires the development of new or the improvement of previously applied welding methods. As a result, when developing welding processes it is necessary to view such processes through the prism of their usability in joining various material groups and necessary operational safety.

An important aspect accompanying the welding of tubes made of stainless steels is concerned

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with the providing of gas shielding in a manner enabling the prevention of the detrimental effect of air constituents (particularly oxygen), responsible, among other things, for the formation of coloured oxide layers. The presence of the above-named layers (stains) on the surface of joined elements is treated as a welding imperfection which must be removed so that a pipe containing welded joints could meet related operational conditions. When welding stainless steels, in addition to providing the gas shielding of the liquid metal pool, it is necessary to protect the root of the weld against the access of oxygen responsible for the formation of oxidised layers located on the weld surface and having the form of coloured stains (tarnish). The presence of the above-named oxide layers adversely affects the corrosion resistance of stainless steels. For this reason it is important for the welding process to be performed in the atmosphere of high-purity shielding gases. It is also necessary to protect the weld root against oxidation. Both the selection of the method and the adjustment of appropriate welding parameters and process conditions affect the final form of welded joints. In the food and pharmaceutical (and other) industries, where the transport of various media requires the use of systems made of stainless steels, the satisfaction of quality requirements concerning welded joints is of particular importance. Because of materials used and requirements related to the making of the above-named systems, an appropriate joining method selected for the tests constituted the modification of the classical TIG method, i.e. automated orbital TIG welding. The above-named welding method makes it possible to control and correct welding parameters (during welding processes) on a continuous basis, which cannot be achieved when making joints manually. The high precision of the method as well as the possibility of programming and controlling the process leads to the obtainment of joints characterised by high aesthetics and very good mechanical properties [1-12].

Test rig and materials

The study aimed to identify the effect of the purity of backing gas on the quality of joints made of stainless austenitic steel X5CrNi18-10 (1.4301) having dimensions of ϕ 50.8 x 1.5 mm, using the TIG orbital welding method without the filler metal.

Before welding, the material was degreased using acetone and subjected to square butt weld preparation. The test joints were made in accordance with a related welding procedure specification prepared on the basis of the initial tests. The orbital TIG welding process was performed using an ORBIMAT 165 CA automated welding machine (Orbitalum) (welding

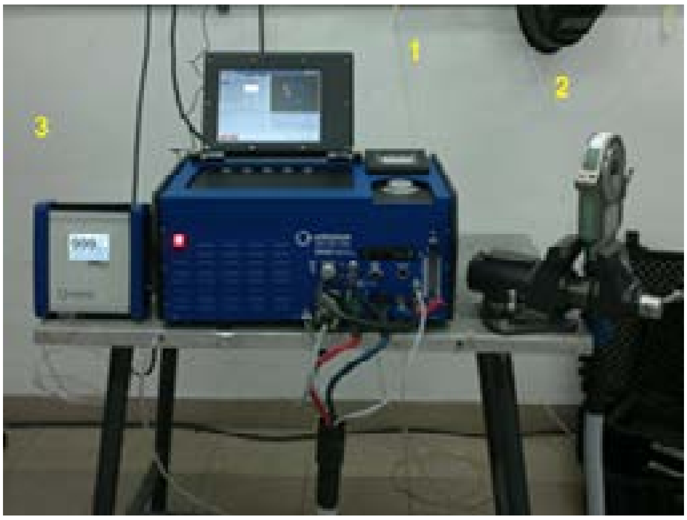

Fig. 1. Station for TIG orbital welding performed using a closed welding head, 1- ORBIMAT 165 automatic welding machine CA, 2- ORBIWELD 76S closed welding head, 3- ORBmax residual oxygen meter

Fig. 2. Tubes prepared for the welding process

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power source with a built-in orbital controller) equipped with an ORBIWELD 76S closed welding head (Fig. 1). The content of oxygen in the backing gas was monitored using an ORBmax residual oxygen meter (Orbitalum). The welding head was fixed in a manner enabling the horizontal positioning of the tubes during welding (Fig. 2).

Tests and results

The face of the weld was shielded using argon of purity class 5.0, the flow rate of which amounted to 8 dm3/min. The root was initially shielded by argon (purity class 5.0) and next, by mixtures of argon and air. The backing gas was transported to the tubes by means of a conduit ending with a diffuser. To provide shielding atmosphere inside the tubes, on one side the inside diameter of the tubes was covered with a sealing screen (provided with an opening for the conduit transporting the backing gas), whereas on the other side the access of air was restrained by a screen made of a special welding strip provided with small openings enabling the discharge of fumes. The pressure of gas inside the tubes was measured where the screen made of a welding strip was fixed. Pressure was measured using a relative pressure manometer. The flow rate of backing gases was adjusted to provide a relative pressure of 300 Pa. The above-named value, ensuring the proper shape of welds, was determined experimentally. The content of air in the root-backing argon was adjusted by means of precise pneumatic valves, whereas the content of residual oxygen in the mixture was adjusted using an ORBmax meter. In relation to individual specimens the content of oxygen was determined on the basis of Danish report 94.34 by the FORCE Technology Institute (Table 1) [13].

Chemical composition analysis

The chemical composition of steel X5CrNi18-10 was analysed using an S1 TITAN X-ray spectrometer (BRUKER). The approximate contents of individual chemical elements in the test steel were the following: 17.5 % of chromium, 8.4 % of nickel, 1.5 % of manganese, 0.3 % of molybdenum, 0.2 % of cobalt, 0.5 % of copper and 0.03 % of titanium.

Tests of ferrite delta content

The tests concerning the content of ferrite delta in the joints were performed using an FMP30 ferrite meter (FISCHER). The results were expressed in the form of a ferrite number (FN). The tests were performed on the circumference of each weld, on the face side. The measurement results are presented in Table 2.

Table 2. Test results concerning the content of ferrite delta in the joints made of steel X5CrNi18-10; FN – ferrite number

Joint no.	Shielding gas	Backing gas	Content of residual oxygen in the backing gas [ppm]		Pressure of gases inside the tubes [Pa]
			used during the welding process	according to report 94.34 by the Force Technology Institute	
1	argon 5.0	argon 5.0	4	< 1	300
2	argon 5.0	argon 5.0 and air	25	15	300
3	argon 5.0	argon 5.0 and air	55	57	300
4	argon 5.0	argon 5.0 and air	90	92	300
5	argon 5.0	argon 5.0 and air	180	200	300
6	argon 5.0	argon 5.0 and air	500	520	300
7	argon 5.0	argon 5.0 and air	900	1000	300
8	argon 5.0	argon 5.0 and air	9000	9000	300
9	argon 5.0	air	230000	-	300

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Table 2. Test results concerning the content of ferrite delta in the joints made of steel X5CrNi18-10; FN – ferrite number

Joint no.	**Content of residual oxygen in the backing gas mixture**	**Weld test no.**			**Mean FN**
		1	**2**	**3**	
1	4 ppm	7.5	6.6	7	7.03
2	25 ppm	7	7.8	6.9	7.23
3	55 ppm	7.1	7.1	7.5	7.23
4	90 ppm	7.4	6.9	7.5	7.27
5	180 ppm	7.5	7.4	7.1	7.33
6	500 ppm	7.7	6.6	6.3	6.87
7	900 ppm	7.1	7.1	6.5	6.9
8	9000 ppm	7.9	6.8	7.7	7.47
9	230000 ppm	6.3	8.1	7.3	7.23
Mean content of ferrite delta in the base material expressed by ferrite number 7.03 FN					

Visual tests air

The classification of welding imperfections and the assessment of the quality of the joints required the performance of visual tests conducted in accordance with the PN-EN ISO 17637 standard, American standard ASME BPE- 2012 [14] as well as Danish report 94.34 by the FORCE Technology Institute. To observe the joints on the root side, the joints were cut mechanically across the weld. The observation results are presented in Table 3.

Radiographic tests

To detect internal imperfections, if any, the joints were subjected to X-ray tests performed using a SITEX CP200D X-ray tube (ICM). The X-raying of the specimens involved the use of elliptic technique, applied during the X-raying of girth welds

Table 3. Joints visible from the root side of the weld (steel X5CrNi18-10)

Joint no.	Joint no. 1	Joint no. 2	Joint no. 3	Joint no. 4
Backing gas	Ar	Ar + air	Ar + air	Ar + air
				
Residual oxygen	4 ppm	25 ppm	55 ppm	90 ppm
Joint no.	Joint no. 5	Joint no. 6	Joint no. 7	Joint no. 9
Backing gas	Ar + air	Ar + air	Ar + air	air
				
Residual oxygen	180 ppm	500 ppm	900 ppm	230000 ppm

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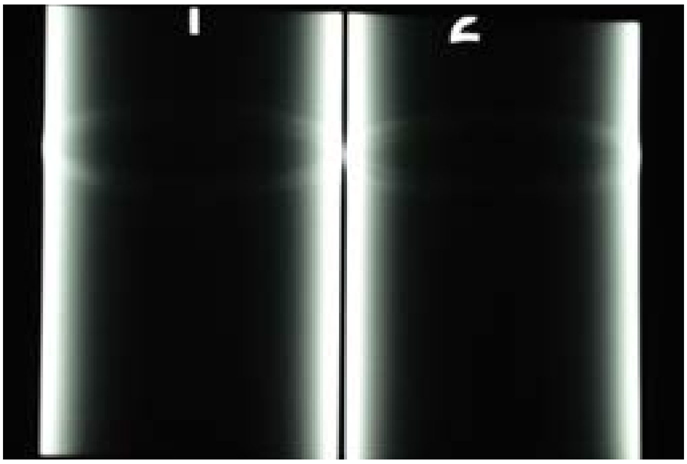

Fig. 3. Radiogram of joint no. 1 and joint no. 2, the first exposure

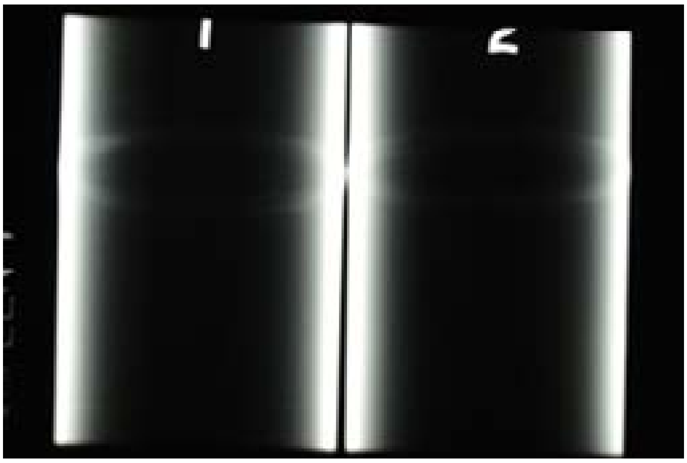

Fig. 4. Radiogram of joint no. 1 and joint no. 2, the second exposure

and enabling the X-raying of two walls of the joints. The two X-raying sessions performed within the tests were offset by 90° in relation to each other. Exemplary radiograms are presented in Figures 3 and 4.

Mechanical tests

The joints were subjected to static tensile tests and transverse bend tests (RBB and FBB). The tests were performed using an R20 tester under a load of 40 kN. The static tensile test was performed in accordance with PN-EN ISO 4136-1:2010 [15], whereas the root bend test of the butt weld (RBB) and the face bend test of butt weld (FBB) were performed in accordance with PN-EN ISO 5173:2010 [16]. The bend tests were performed using a bending mandrel having a diameter of 10 mm. The mechanical test results are presented in Figures 5 and 6.

Metallographic tests

Macroscopic observations were performed using an Olympus SZX9 stereoscopic microscope. The tests specimens were etched using Adler's reagent (Fig.7). Microscopic observations were performed using a Nikon Eclipse light microscope. The microstructure was revealed using aqua regia (Fig. 8).

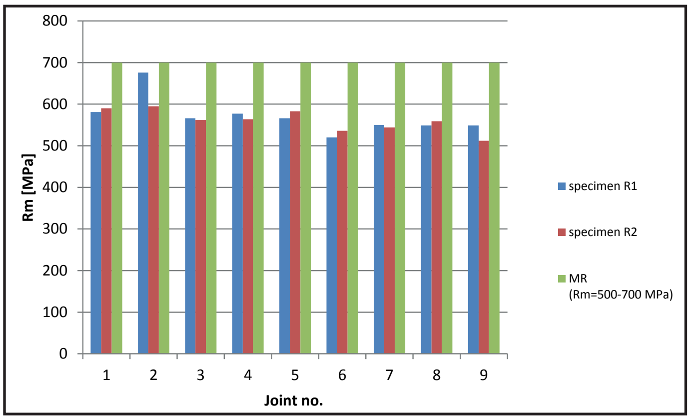

Fig. 5. Tensile strength of the joints made of steel X5CrNi18-10

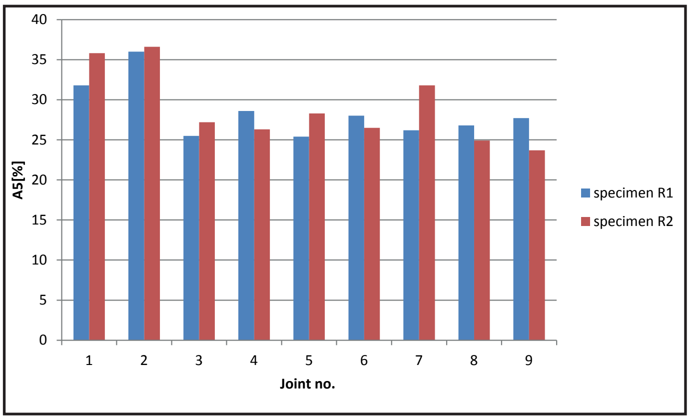

Fig. 6. Elongation of the joints made of steel X5CrNi18-10

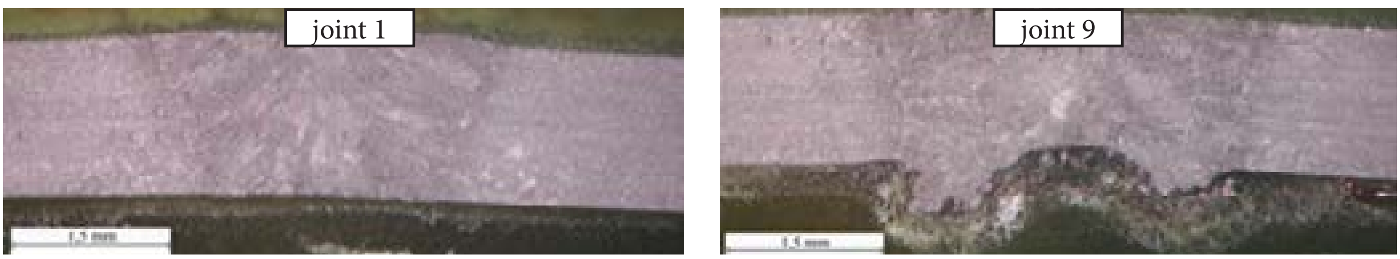

Fig. 7. Exemplary macrostructures of the welded joints

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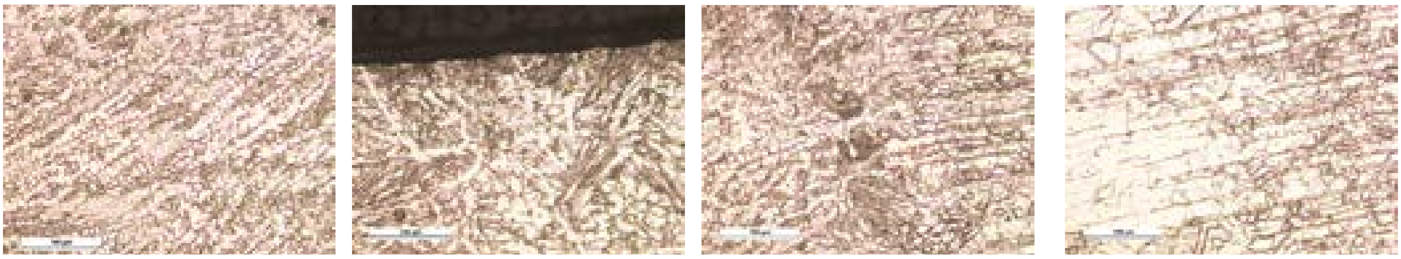

Weld – face Weld – root Fusion line HAZ

Fig. 8. Microstructure of joint no. 4 (containing 90 ppm of residual oxygen in the mixture of backing gases); etchant: aqua regia

Hardness tests

The hardness tests of the joints were performed in accordance with the PN-EN ISO 9015-1:2011 standard along one measurement line running across the cross-section of the welded joint [17]. The hardness measurements were based on the Vickers test (HV1) and performed using a Wolpert Wilson Micro-Vickers 401MVD testing machine. The results of the hardness measurements are presented in Figure 9.

Analysis of test results

The tests concerned with the content of ferrite delta in the test joints revealed that the base material was characterised by a ferritic number (FN) of approximately 0.73 FN, whereas after the TIG orbital welding, the content of ferrite in the welds was restricted within the range of 6.87 FN to 7.47 FN. Because of the similar values of the measurement results and taking into consideration a measurement error of the measurement device it was possible to explicitly identify the effect of the content of residual oxygen in the mixture of backing gas on the content of ferrite delta in the weld. The measurement values revealed that the content of ferrite delta in the welds was restricted within the range of 3 FN to 15 FN (in accordance with PN-EN 1011-3), below which the welds could be susceptible to hot cracking. In turn, the content of ferrite delta above 15 FN could lead to a decrease in hardness, ductility and corrosion resistance of the joints. The visual tests revealed that the TIG orbitally welded joints of the tubes did not reveal the axial misalignment and that the weld was characterised by uniform scale in the line of the weld, the face of which was approximately 5 mm wide. The surfaces of the HAZ on the side of the weld face revealed the presence of temper colours, welding imperfection no. 610 according to PN-EN ISO 6520-1, formed through chromium oxidation. The areas under the surface of the temper colours were poor in chromium and likely to lose their anticorrosive properties. It should be noted that on the side of the weld face the liquid metal pool was shielded by argon (purity class 5.0) containing 4 ppm of residual oxygen. The reason for the imperfection could be ascribed to the overly short diameter of the base nozzle. The presence of other surface imperfections on the side of the weld face was not revealed. The observation of the joints on the root side also revealed the presence of oxide layers in the form of coloured

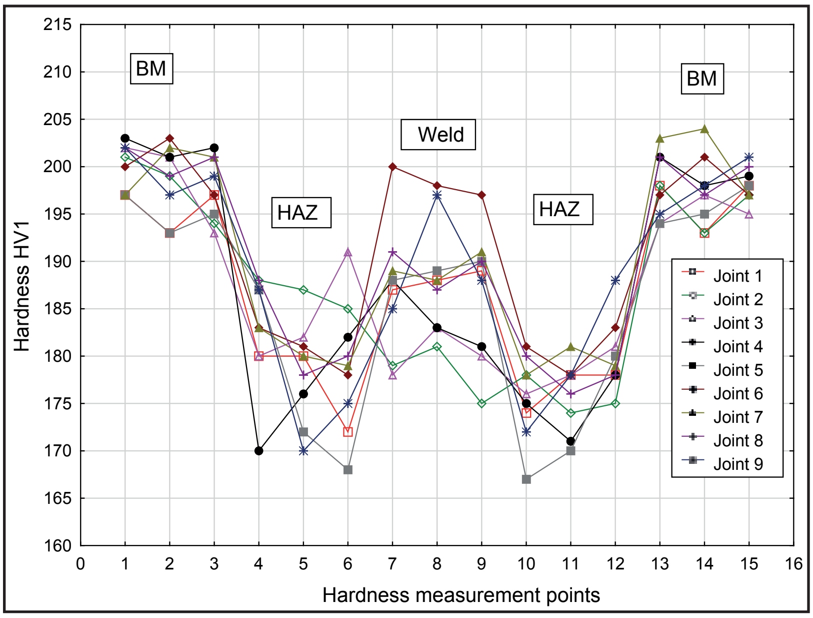

Fig. 9. Hardness distribution in the cross-section of the welded joints

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stain, where the above-named colours varied depending on the content of residual oxygen in the backing gas mixture. Differences in temper colours formed on individual joints indicated various thicknesses of oxide layers, characterised by heterogeneous chemical compositions as well as by defects and stresses present in such layers, resulting in the lower corrosion resistance of such joints. Depending on the intended use of a given structure, welding imperfection no. 610 could be accepted or the removal of the temper colour could be required (e.g. systems used in the pharmaceutical, chemical and food industries), yet joints where oxide layers exceed acceptable levels must be removed and made again. The temper colours were assessed in accordance with the division contained in Danish report 94.34 by the FORCE Technology Institute and in American standard ASME BPE-2012. The division presented in Danish report 94.34 of the FORCE Technology Institute enumerates the following levels of stains present in mechanically polished tubes made of stainless steels: A – invisible temper colours, B – grayscale, C – bright yellow, D – intense yellow, E – bright blue, F – navy blue/violet, G – brown and blue areas; dark grey shade of metal subjected to welding, H – brown and blue areas, a visibly thicker layer of oxide. According to the above-named report, acceptable colours of oxide layers for typical stainless austenitic steels not detrimental for their corrosion resistance are contained within levels B-C, where the content of residual oxygen in argon is restricted within the range of 20 ppm to 30 ppm. In accordance with the above-presented division, only joint no. 1 and no. 2 were made properly as the content of residual oxygen during backing gas (argon)-shielded welding amounted to 4 ppm in relation to joint no. 1 and 25 ppm in relation to joint no. 2. In cases of the remaining joints, the content of residual oxygen in argon exceeded 30 ppm. According to American standard ASME BPE- 2012, when welding mechanically polished tubes made of stainless austenitic steels, the surface of the weld should not contain stains and the permissible level of temper colours on the HAZ surface should not exceed the level presented in specimen no. 3. However, ASME BPE- 2012 does not specify the amount of residual oxygen in the shielding gas, in relation to which stains of individual specimens were obtained. Nevertheless, it can be concluded that only joint no. 1 and joint no. 2 satisfied the requirements of the above-named standard as both on the face and the root side of the weld it was possible to notice delicate stains in the HAZ only. The joints observed from the root side revealed the significant concavity and porosity of the root (imperfection 515 and 516 respectively according to PN-EN ISO 6520-1) in joint no. 9, i.e. the one welded without the shielding gas atmosphere on the root side of the weld. The remaining joints did not reveal the presence of other welding imperfections. The test results obtained in the radiographic examination revealed the presence of welding imperfection no. 515, i.e. root concavity, in joint no. 4 and joint no. 7 as well as welding imperfection no. 403, i.e. spiking, in joint no. 9. The static tensile test revealed that the strength values were restricted within the range of 500 MPa to 700 MPa and satisfied the requirements of standard PN-EN 10217-7 (specimens ruptured in the weld). The elongation was restricted within the range of 25% to 36% A5. The lowest elongation value was that of joint no. 9 (A5~25.7%), which explicitly indicated the significant effect of the purity of shielding gas on the mechanical and plastic properties of the welded joints. The bend tests were performed both on the face and the root side of the weld. The achievement of an angle of 180° in the bend test was not accompanied by the formation of cracks or other damage to the joints. The foregoing revealed high plasticity as well as the lack of imperfections and structural constituents potentially leading to the cracking of the joints in operation. The macroscopic tests revealed that the mean width of the weld at the half of the depth (thickness)

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of the joint was restricted within the range of approximately 3 mm to 3.45 mm. An increase in the content of residual oxygen in the backing gas was accompanied by an increase in the width of the weld root. The microscopic tests revealed the presence of twinned grains in the base material and in the HAZ, resulting from plastic strain affecting the material in the manufacturing process. The microstructure of the welds of the test austenitic steel was characterised by the vermicular structure of ferrite delta. The weld root area revealed locally concentrated ferrite delta. The Vickers hardness tests (HV1) revealed that the hardest area of the joint was the base material, having an approximate hardness of 200 HV. The mean hardness value of the HAZ area amounted to approximately 186 HV, whereas the hardness of the joints amounted to 189 HV.

Summary

The tests involving the TIG orbital welding (without filler metal) of butt joints made in tubes of steel X5CrNi18-10 revealed that an increase in the content of residual oxygen in the backing gas mixture changed the colour of oxide layers present in the HAZ area and, in cases of some joints, even temper colours in the weld root area. The number of ferrite FN in the test joints was restricted within the range of 3 to 15 according to PN-EN 1011-3, which, among other things, resulted in the lack of hot cracks and the lack of a significant decrease in hardness and ductility of the test joints. The test joints satisfied the tensile strength-related requirements according to the PN-EN 10217-7 standard. Because of the requirements specified in Danish report 94.34 by FORCE Technology Institute and American Standard ASME BPE-2012 concerning temper colours, only joint no. 1 (containing 4 ppm of residual oxygen in the mixture of backing gases) and joint no. 2 (containing 25 ppm of residual oxygen in the mixture of backing gases) could be accepted for operation after previous purification and passivation.

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