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INTEGRITY OF WELDED JOINTS MADE OF ALLOY NiCr21Mo

INTEGRITET ZAVARENIH SPOJEVA LEGURE NiCr21Mo

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- analiza mikrostrukture
- integritet konstrukcije

Abstract

The research covers the investigation of mechanical properties of welded joint made on NiCr21Mo alloy (commercial trademark Incoloy 825), and joints of steels P355GH and X2CrNiMo17-12-2, as well as the influence of the achieved mechanical properties on structural integrity. Ongoing research is oriented on welded joints made of NiCr21Mo, i.e., the alloy to be introduced for certain parts (made of the aforementioned materials P355GH and X2CrNiMo17-12-2) of processing equipment exposed to elevated temperatures and high corrosive environment. Three preliminary welding technologies are presented in the first part of the paper. Tungsten inert gas (TIG) welding technique is used due to the type of filler material. The filler material features mechanical properties that provide an overmatching effect. After non-destructive tests (NDT), mechanical properties of all three welded joints are examined according to criteria that guarantee safe work and welded component integrity. In addition to mechanical tests (uniaxial tension, bending, impact toughness, hardness measurements), a microstructural analysis is performed to verify the applied preliminary welding technologies and evaluate the integrity of the obtained joints. After analysing all tests it is confirmed that the application of the preliminary welding technology has met all the requirements according to the applied criteria.

Izvod

Istraživanje obuhvata ispitivanje mehaničkih osobina zavarenog spoja legure NiCr21Mo (komercijalne oznake Incoloy 825) kao i zavarenih spojeva ove legure sa čelicima P355GH i X2CrNiMo17-12-2, kao i uticajem postignutih osobina na integritet konstrukcije. Studija je usmerena ka istraživanju zavarenih spojeva legure NiCr21Mo, kao i zavarenih spojeva delova izvedenih od ove legure, koje je potrebno spojiti sa čeličnim delovima procesne opreme (izrađenih od čelika P355GH i X2CrNiMo17-12-2) koji su izloženi povišenoj temperaturi i aktivnom korozivnom okruženju. U prvom delu rada predstavljene su tri preliminarne tehnologije zavarivanja. Primenjeno je zavarivanje netopljivom volframovom elektrodom (TIG) zbog vrste osnovnog materijala. Primenjeni dodatni materijal poseduje mehaničke osobine koje obezbeđuju overmečing efekat. Nakon ispitivanja bez razaranja (IBR), sprovedena su ispitivanja mehaničkih osobina sva tri zavarena spoja prema kriterijumima koji obezbeđuju siguran rad i integritet zavarene konstrukcije. Pored mehaničkih ispitivanja (jednoosno zatezanje, savijanje, udarna žilavost, merenje tvrdoće), izvršena je i analiza mikrostrukture kako bi se verifikovale primenjene preliminarne tehnologije zavarivanja i procenio integritet dobijenih spojeva. Nakon izvršene analize svih ispitivanja, potvrđeno je da su primenjene preliminarne tehnologije zavarivanja ispunile sve zahteve primenjenih kriterijuma.

INTRODUCTION

Processing equipment presents one of the most important parts in industrial development, with fundamental requirement of avoiding failure during exploitation. Still, parts of processing equipment can be exposed to the conditions that could lead to damage (best scenario) /1-3/, or failure /4-6/, pulling along all other effects, such as economic aspect /7-9/, and general safety issues leading to human casualties (worst scenario), /9-11/. Fracture analysis should provide new relevant data or confirm the already known theory of the fracture mechanism, mostly on how cracks are initiated and their further propagation under working conditions. Not to mention that fractures are neither expected nor acceptable. Structural failure of pressure vessel equipment occurs in almost all stages of production, and failures in the process industry are among the most common and most studied. It should be emphasized that welded joints represent most critical locations where these fractures occur /12-15/, carrying the label of the weakest part of the construction. Available practice data and case studies often provide significant input to avoid equipment failure in exploitation, but that is not a general case.

From the point of structural integrity (in general), cracks and defects in pressure vessel equipment can be researched by applying various scientific and engineering approaches, such as classic fracture mechanics approach /16-19/, risk analysis and failure assessment diagram /20-23/, or multidisciplinary methods based on fracture mechanics laws /24-26/, etc. Mechanical tensile and impact tests are important in fracture analysis since appropriate material characteristics for the calculation are adopted based on them, /27-28/. Standards and directives in this field provide more conservative methods for design solution, taking into account all of the aforementioned, but still defects are unavoidable requiring repair or risk assessment, /29-30/. Elevated temperature in combination with aggressive environment/working fluid makes the problem more complex. It is known that process equipment (in most) cases encounter corrosion /31-33/, and/or creep damage mechanisms /34-35/, especially in welded joint area, adversely affecting its service life. Beside poor construction, excessive heat input and subsequent material degradation could lead to the shortening of service life /36/. Concerning the connection (with the aforementioned) to material properties, most critical locations affecting structural integrity (i.e. welded joints) require special attention and verification before application to pressure vessel equipment, especially at elevated temperatures.

Austenitic steels are used mainly in environments containing harmful chlorides, acids, etc. They require different welding treatment in comparison to other steels, i.e. ferritic type, /37-38/. Their replacement in some facilities requires additional testing and verification, since different stainless austenitic materials show different sensitization to their worst enemy - intergranular corrosion, /39/. Welding represents just one problem on this matter, and mechanical testing has to be carried out in order to check the welded joint integrity implying its application domain.

Concerning this study (for recall) the NiCr21Mo alloy has to be introduced in certain parts of the process equipment, providing lower sensitivity to intergranular corrosion at higher temperature, and ensuring better toughness, as well as other forms of corrosion (such as stress corrosion, /40/). As a part of this research, here are presented the next stages of this investigation, concerning the examination of NiCr21Mo weldability with other materials. Preliminary welding technologies have to be (initially) verified from the point of mechanical properties.

Welded joints of alloy NiCr21Mo and: 1) alloy NiCr21Mo; 2) steel P355GH; 3) steel X2CrNiMo17-12-2, are examined in this particular case. Three welding technologies and NDT methods preceded mechanical testing (tensile, bending, impact, hardness measuring) of all three welded joints, as well as weld macro- and microstructural analysis. The same filler material is used for all three technologies due to the specific properties of Ni alloy (NiCr21Mo) as a joint parent material. Mechanical testing is performed according to relevant standards, while parent material properties are guaranteed by the manufacturer (according to EN 10204 standard). The presented analysis provides insight into mechanical properties (structural integrity of welded joints) of heterogeneous welded joint made of at least one NiCr21Mo austenitic alloy, as well as steps that have to be carried out in order to perform successful welding, requiring low heat input (as mandatory).

WELDING TECHNOLOGIES

Parent material properties

Some general materials properties used in this investigation are given in this chapter.

NiCr21Mo alloy is a Ni-Fe-Cr stainless alloy, containing small amounts of Ti, Cu, and Mo. Its chemical composition provides great resistance to many corrosive environments, such as pitting-, crevice-, intergranular-, and stress-corrosion cracking. This Ni alloy has good mechanical properties at moderate to high temperatures.

On the other hand, P355GH represents a non-alloy C-Mn steel (both elements affecting tensile strength) used for heat-resistant pressure vessels (i.e. boilers etc). Designated as steel EN 1.0473, this normalized steel is used worldwide by fabricators of welded pressure vessels, industrial boilers, and heat exchangers, and is engineered for applications at elevated temperatures. These types of steels are characterised by good weldability, creep resistance, having both good properties at elevated and low temperatures, as well.

X2CrNiMo17-12-2 is the basic grade from the Cr-Ni-Mo group with Mo, the addition of which significantly increases resistance to pitting and crevice corrosion. This steel is an austenitic stainless steel and is suitable for use in aggressive environments, such as phosphoric, nitric, citric, lactic, formic, etc. This steel shows relatively good mechanical properties at cryogenic temperatures and possess good weldability, not requiring additional post-weld heat treatment /40/.

All 3 materials belong to different material groups with their own characteristic. The main difference between NiCr21Mo and X2CrNiMo17-12-2 is in the sensitization on intergranular corrosion, as aforementioned, in favour of NiCr21Mo. Contents of Ni, Cr, and Mo in NiCr21Mo provide a high level of resistance to chloride pitting. All 3 materials have low hot cracking sensitivity and low sensitivity (or none at all in case of austenitic steels) to cold cracks. During welding of austenitic steels (i.e. NiCr21Mo and X2CrNiMo17-12-2) the low heat input would be mandatory without preheating in order to avoid the appearance of micro fissures, while general recommendation for P355GH requires preheating due to cold cracking (which mostly depends on the applied welding technique, thickness, and wire/filler material properties along with hydrogen content) /41/.

Chemical compositions of all three materials are given in Table 1, while mechanical properties are given in Table 2.

Table 1. Chemical composition of alloy NiCr21Mo, steel P355GH and steel X2CrNiMo17-12-2 [wt. %]

	C	Mn	Si	S	P	Cu	Cr	Ni	Al	Fe	Ti	Mo	N
NiCr21Mo	0.008	0.71	0.24	0.002	0.01	2.30	22.6	42.3	0.17	27.1	0.82	3.21	-
P355GH	0.171	1.444	0.346	0.004	0.012	0.017	0.012	0.012	0.035	bal.	0.001	0.002	0.0041
X2CrNiMo17-12-2	0.025	1.33	0.49	0.003	0.03	/	16.54	10.12	/	bal.	/	2.03	-

Table 2. Mechanical properties of NiCr21Mo, P355GH, and X2CrNiMo17-12-2 (at 20 °C).

	Re [MPa]	Rm [MPa]	A_5 [%]
NiCr21Mo	309	664	47.3
P355GH	405	549	29
X2CrNiMo17-12-2	346	594	51

Welding parameters

Welding was performed according to plan given in Table 3, along with plates thickness and V grooves, creating butt welded (BW) joints. Due to the low heat input requirement described previously, the TIG technique was used. Moreover, this was predominantly dictated by both austenitic material microstructure and delivery condition. The WT20 Ø2.4 electrode is used. Despite the general recommendation on using wire providing 4-10 % δ-ferrite /41/, the NiCr20Mn3Nb wire (according to EN ISO 18275, EN designation 2.4806) was used as a filler material for all three BW joints, i.e., Ni-based alloy possessing high-temperature and creep resisting properties. This Ni-alloy wire is a pure austenitic, excellent corrosion resistant, weld metal. Chemical composition and mechanical properties of NiCr20Mn3Nb pure weld are given in Tables 4 and 5, respectively, providing slight overmatching effects compared to parent material. Differences in mechanical properties of filler and parent material are emphasized here.

Table 3. Welding plan.

Joint	Material 1	Material 2	Thickness [mm]	Groove
1	NiCr21Mo	NiCr21Mo	12	V
2	NiCr21Mo	P355GH	10	V
3	NiCr21Mo	X2CrNiMo17-12-2	12	V

Table 4. Chemical composition of NiCr20Mn3Nb [wt. %].

C	Mn	Si	Cr	Ni	Nb	Fe	Ti
0.02	3.1	0.1	20.5	rest	2.6	≤ 1.0	+

Table 5. Mechanical properties of filler NiCr20Mn3Nb (at 20 °C).

R_e [MPa]	R_m [MPa]	A_5 [%]
440	680	> 42

In order to avoid preheating requirement for P355GH, plates were 10 mm thick only for joint with NiCr21Mo. Plates of the other two BW joints were 12 mm thick with no preheating requirements. Welding was performed in the PA (horizontal) position. Argon (Ar) flow rate (as a backing) during root welding was in the range 7-9 l/min, while Ar flow rate (as shielding gas) was in the range 5-8 l/min (both of 100 % purity). Filler material diameter of Ø1.6 mm was used for root welding (2 layers), while Ø2.0 mm was used for filling the grooves for all 3 joints. Figure 1 shows the grooves sizes of all three BW joints, groove geometries along with the groove filling plan.

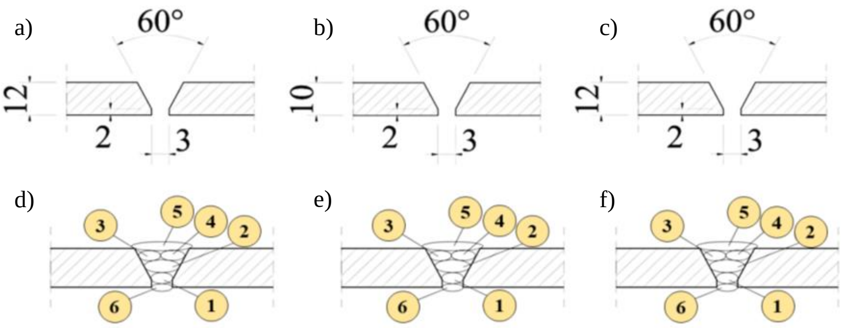


Figure 1. Groove geometries for: a) NiCr21Mo-NiCr21Mo BW; b) NiCr21Mo-P355GH BW; c) NiCr21Mo-X2CrNiMo17-12-2; filling plans for: d) NiCr21Mo-NiCr21Mo BW; e) NiCr21Mo-P355GH BW; f) NiCr21Mo-X2CrNiMo17-12-2 BW.

Table 6. Welding parameters.

BW joint	Layer	Filler material diameter [mm]	Current [A]	Voltage [V]	Polarity	Travel speed [cm/min]	Heat input [kJ/cm]
1. NiCr21Mo and NiCr21Mo	1	Ø1.6	111	12.4	DC/-	5.2	11.85
	2	Ø1.6	117	12.8	DC/-	5.5	12.40
	3-6	Ø2.0	131	15.2	DC/-	5.8	15.05
2. NiCr21Mo and P355GH	1	Ø1.6	110	12.3	DC/-	5.2	11.80
	2	Ø1.6	116	12.7	DC/-	5.5	12.20
	3-6	Ø2.0	130	15.0	DC/-	5.9	15.15
3. NiCr21Mo and X2CrNiMo17-12-2	1	Ø1.6	112	12.4	DC/-	5.3	11.79
	2	Ø1.6	118	12.8	DC/-	5.5	12.36
	3-6	Ø2.0	131	15.1	DC/-	5.9	15.09

Welding parameters (current, voltage, polarity, travel speed, and heat input) are given in Table 6, with an emphasized controlled heat input. Interpass temperature for all three BW joints was not above 100 °C. Taking into account specific properties (predominantly) of the NiCr21Mo alloy in every joint, the post weld heat treatment was not performed.

Macrostructures

Macrostructures of all three welded joints (with magnifications ×2) are shown in Fig. 2.

NDT examination

After welding, all three welded joints were subjected to NDT methods of examination. Following the general recommendation, using (at least) 1 surface and 1 volumetric NDT method on the welding joint, three methods were used:
- visual test (scope of 100 %, EN ISO 17637:2017),
- penetrant test (scope of 100 %, EN ISO 3452-1:2014),
- radiographic test (scope of 100 %, ISO 17636-1),

according to acceptance criteria defined in ISO 5817 class B.

No indications and defects were identified for class B on examined welded joints. After NDT examination, experimental (destructive) tests followed.

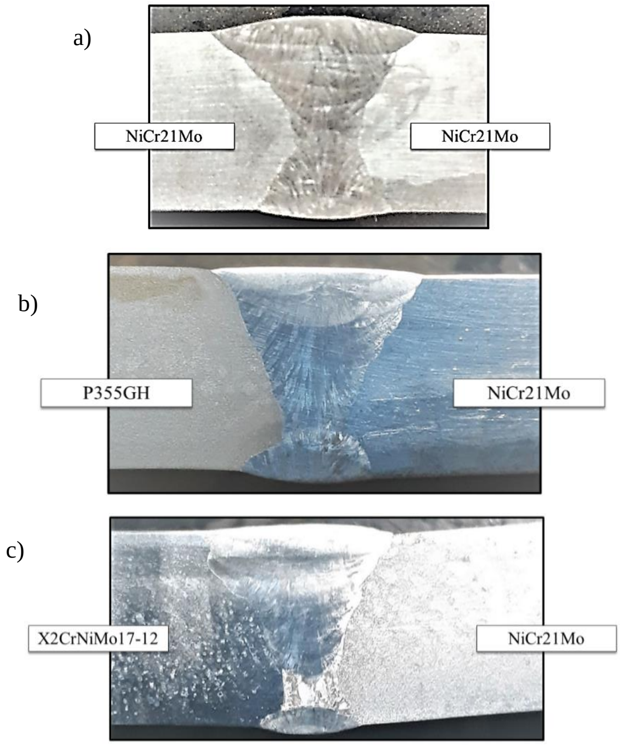


Figure 2. BW joints made of: a) NiCr21Mo; b) NiCr21Mo and P355GH; c) NiCr21Mo and X2CrNiMo17-12-2 (magn. ×2).

EXPERIMENTAL TESTING

The following mechanical tests were carried out on each welded plate:
- tensile test (EN ISO 4136 and EN ISO 6892-1),
- bend test (EN ISO 5173),
- impact test (EN ISO 9016),
- hardness measurements (ISO 6507-1 and ISO 9051-1),
- and microstructural analysis (ISO 17639) of each welded joint zone.

Specimens were taken from all three welded plates according to EN ISO 15614 standard recommendation. This standard defines the procedure and locations for specimens intended for a certain type of mechanical test, as given in Fig. 3. Tests provided an insight into the welded joint characteristics, as will be presented in the following.

Tensile testing

Cross section sizes of specimens for tensile tests were 25×12 mm. Tensile tests were conducted at 20 °C requiring minimal value of ultimate tensile strength and elongation, according to EN 10028. A total of 6 specimens were tested, i.e. two of each welding plates, and the results are given in Table 7. It can be seen that the fracture on both specimens occurred in the weaker parent material.

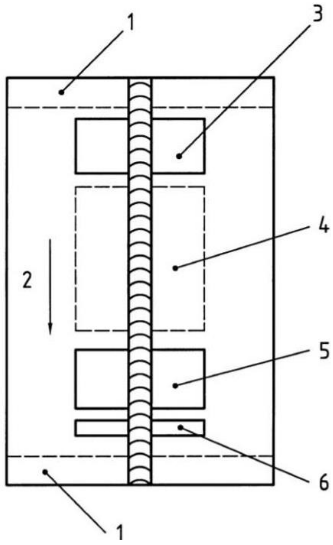


Figure 3. Welded plate: 1) discardable section (width 25 mm); 2) welding direction; specimens for: 3) tensile and bend tests; 4) impact test; 5) tensile and bend tests; 6) hardness measurements, macro- and microstructural analysis.

Bend testing

Specimen cross section used for bend testing was also 25×12 mm. Four specimens from each weld plate were tested (two face bends and two root bends). Results of bend tests (given in Table 8) showed no cracks, defects, or lack of fusion on BW joints, thus providing certain confirmation of welding technologies in this way.

Impact testing

Cross section size of Charpy specimens used for impact tests were 10 × 10 mm (i.e. KV 150/5). Impact testing was conducted according to EN ISO 10028-7 criteria, at 20 °C. Six specimens were taken from first BW (made of Ni-alloy), the second BW (NiCr21Mo and P355GH joint), and the third (NiCr21Mo and X2CrNiMo17-12-2), 9 specimens were taken for testing, with a notch located at different positions in the welded joint (as illustrated in Fig. 4). Notches are located on each HAZ side and weld metal itself. Results of impact tests are given in Table 9. Various distribution of impact toughness values in the weld metal zone (depending on the parent material) can be observed, still fulfilling the criterion of being above 30 J.

Table 7. Tensile testing results.

BW	Spec. no.	Max. load [kN]	Rm [MPa]	A [%]	Remarks
1	1	212.0	706 (criterion ≥660)	57.6 (criterion ≥45)	Breaks in parent material NiCr21Mo
	2	212.0	706 (criterion ≥660)	57.6 (criterion ≥45)	Breaks in parent material NiCr21Mo
2	1	144.0	576 (criterion 510-650)	23.4 (criterion ≥21)	Breaks in parent material P355GH
	2	146.0	587(criterion 510- 660)	24.5 (criterion ≥21)	Breaks in parent material P355GH
3	1	186.2	620 (criterion ≥530)	49.3 (criterion ≥40)	Breaks in parent material X2CrNiMo17-12-2
	2	187.0	623 (criterion ≥530)	49.6 (criterion ≥40)	Breaks in parent material X2CrNiMo17-12-2

Table 8. Bend test results.

BW	Specimen no.	Side	Bend angle [°]	Inspection result
1	1	Face	180	No cracks/lack of fusion
	2	Face	180	No cracks/lack of fusion
	3	Root	180	No cracks/lack of fusion
	4	Root	180	No cracks/lack of fusion
2	1	Face	180	No cracks/lack of fusion
	2	Face	180	No cracks/lack of fusion
	3	Root	180	No cracks/lack of fusion
	4	Root	180	No cracks/lack of fusion
2	1	Face	180	No cracks/lack of fusion
	2	Face	180	No cracks/lack of fusion
	3	Root	180	No cracks/lack of fusion
	4	Root	180	No cracks/lack of fusion

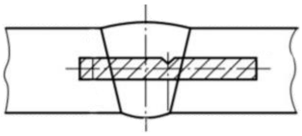


Figure 4. Charpy specimen with notch in weld (illustration).

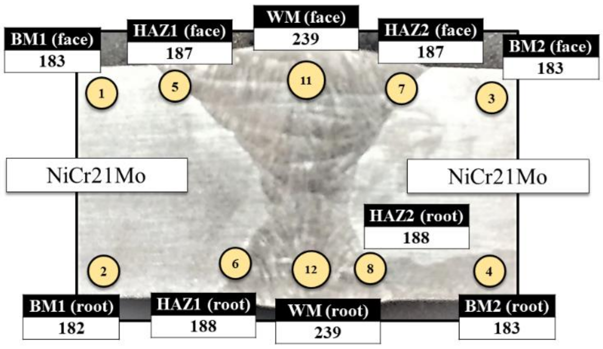
Table 9. Impact testing results.

BW	Notch position	Toughness [J] Criterion ≥ 30			Aver. [J]
		1	2	3	
1	notch in HAZ	109	112	114	112
	notch in weld	106	109	108	108
2	notch in HAZ on NiCr21Mo side	99	108	102	103
	notch in weld	104	100	95	100
	notch in HAZ on P355GH side	96	99	94	96
3	notch in HAZ on NiCr21Mo side	102	108	105	105
	notch in weld	106	108	111	108
	notch in HAZ on X2CrNiMo17-12-2 side	115	110	116	114

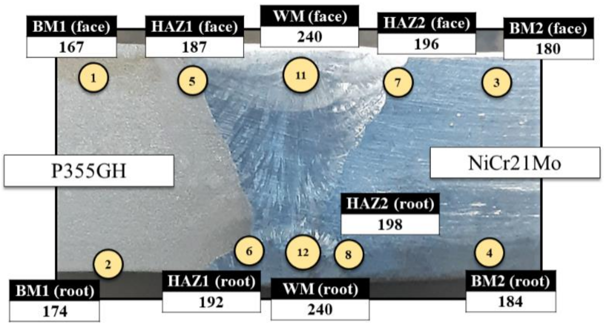
Hardness measurements

Hardness measurements were performed on 12 locations on each welded joint region (i.e. both parent materials, HAZ regions and weld metal) on all three BW joints, using HV10 method. Acceptance criteria was according to the requirements of ISO 156014-1 standard. Etching was carried out with Nital 4 % solution (nitric acid). The results of hardness measurements and measuring points are shown in Fig. 5. The hardness values increase in weld metal zone in comparison to the HAZ regions in all three cases. This was expected, considering the higher strength of the filler material compared to parent material. Also, the hardness values in HAZ were higher than in the parent material.

a)



b)



c)

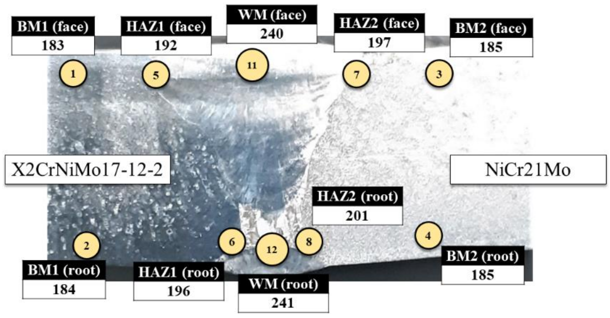


Figure 5. Hardness measurements: a) BW joint made of NiCr2Mo; b) BW joint P355GH and NiCr21Mo; c) X2CrNiMo17-12-2.

Microstructural analysis

Microstructure analysis took place in order to check for potential microstructural changes in the critical regions of the weld, mainly HAZ and fusion line region, as well as in the weld metal itself. Acceptance criteria of welding defects were according to ISO 15614-1. Magnification is 400×. In Figure 6a and 6b presents microstructures in the vicinity of fusion line and HAZ region, respectively, on the first BW (weld made of NiCr21Mo). The macrostructure of welded joint shows no unacceptable defects (such as inclusions, undercuts, lack of fusion, cracks, etc.) Microstructural analysis reveals a fine-grained austenitic structure, along with twinning effect. Coarser austenite grains found near the weld face are not observed in any welded joint regions. Figure 6c shows microstructures on the second BW (weld made of NiCr21Mo-P355GH) in the vicinity of the fusion line on the P355GH side. Although P355GH has fine-grain ferritic-pearlitic microstructure, a ferritic-bainitic microstructure can be observed on the top (face) side of the HAZ, while closer to the root and the fusion line, it is bainitic. Dendrite formation of austenitic weld metal structure can be observed along with the presence of carbides. Figure 6d and 6e show microstructures of the third BW (weld made of NiCr21Mo-X2CrNiMo17-12-2) in the vicinity of the fusion line on the NiCr21Mo side and the weld metal, respectively. Analysis reveals not-so-fine-grained austenitic structure of the HAZ, with a trend of being coarse-grained near the fusion line, and a twinning effect. Fine-grained austenite was observed on HAZ closer to X2CrNiMo17-12-2, along with twinning effect. A nonhomogeneous weld metal microstructure can be observed in this case. Dendrite formation of the austenitic structure can be observed along with the presence of carbides.

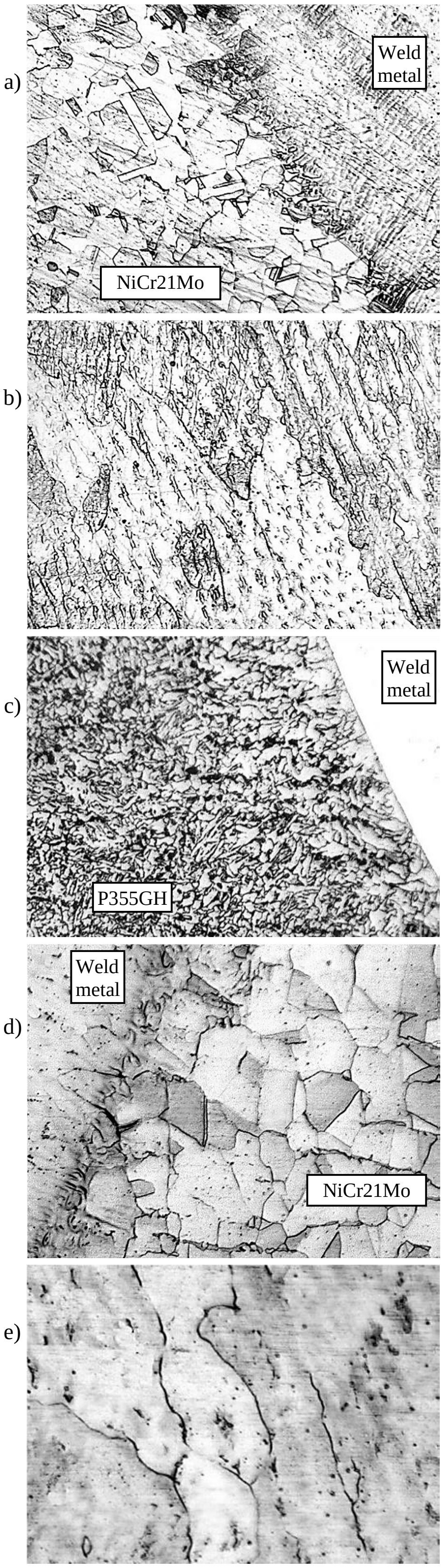


Figure 6. Microstructures of: a) fusion line of NiCr21Mo-NiCr21Mo BW; b) weld metal of NiCr21Mo-NiCr21Mo BW; c) fusion line of NiCr21Mo-P355GH BW (on the P355GH side); d) fusion line of NiCr21Mo-X2CrNiMo17-12-2 BW (on X2CrNiMo17-12-2 side); e) weld metal of NiCr21Mo-X2CrNiMo17-12-2 BW.

CONCLUSIONS

Mechanical properties of three BW joints were examined. Preliminary welding technologies are validated along, taking into account the specificity of each material. To emphasize, low heat input is proven to be mandatory for welding the Ni-alloy. The used NDTs on welded joints confirmed no presence of unacceptable defects providing class B of joints, according to EN ISO 5718 criteria. Bend tests validated the results of NDTs.

The application of pure austenitic Ni-base filler material was investigated as well, and showed satisfying mechanical properties, but to be sure that micro fissuring is not present, it is necessary to conduct SEM and analyse the behaviour at elevated temperatures. In correlation with the previously mentioned, an overmatching effect was observed in every BW joint, confirmed by tensile tests and hardness measurements. Due to the specificity of NiCr21Mo alloy, and other materials in the joints as well (P355GH and X2CrNiMo17-12-2), the required low heat input during welding provided desirable microstructures on all three welded joint regions (especially HAZs of austenitic materials), creating not too coarse-grained structures. Hence, the probability for brittle fracture (in an early stage of use) is very low in all three cases, which was confirmed by the impact test criterion (being ≥ 30 J), and very important for the NiCr21Mo joint. Mechanical testing of all three welded joints, performed according to the aforementioned criteria, contributed, and guaranteed safe work and the integrity of the welded structures. Still space is left for the next phase of this research, i.e., examination of mechanical properties at elevated temperatures of these BW joints, along with SEM, and corrosion resistance.

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