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Results of Non-Destructive and Destructive Tests of Welded Joints Made of Heat-Resistant Cast Steel GX40NiCrSiNb35-25 in Welding Procedure Qualification

Abstract: The article presents test results concerning the welding procedure qualification of the production welding of heat-resistant cast steel GX40NiCrSiNb35-25 (1.4852) performed using filler metal WZ 25 35 Zr according to PN-EN ISO 14343. The welding procedure qualification test was performed in accordance with PN-EN ISO 11970. The test joint made using the TIG method (141) was subjected to non-destructive and destructive tests enabling the identification of the mechanical properties of the joint. The test results satisfied the requirements contained in PN-EN ISO 11970 and constituted the basis enabling the preparation of a related welding procedure qualification report.

Keywords: GX40NiCrSiNb35-25, heat-resistant cast steel, production welding procedure qualification, destructive tests

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Introduction

Heat-resistant cast steel casts used in elements of oil, petrochemical and chemical systems must be characterised by creep, oxidation, carburisation and nitration resistance at temperature exceeding 650°C [1]. Depending on their iron, nickel and chromium content, creep-resistant cast steel casts can be divided into the following groups [1, 3-5]:

I. Iron-chromium alloys containing 10 ÷ 30% Cr;
II. Iron-nickel-chromium alloys containing more than 13% Cr and 7% Ni;
III. Iron-nickel-chromium alloys containing more than 25% Ni and over 10% Cr (always more nickel than chromium).

Heat-resistant cast steel casts are characterised by various mechanisms of microstructural degradation including creep-triggered brittleness, high-temperature fatigue, sigma phase-triggered brittleness, carburisation, hydrogen-induced brittleness, graphitisation, erosion and high-temperature corrosion [6]. The operation of the above-named casts at higher temperature leads to the formation of precipitates including carbides rich in chromium $Cr_{23}C_6$, $M_6(C, N)$, carbides rich in niobium NbC and carbo-nitrides $Cr_2(C, N)$ [6].

The weldability of alloy cast steel casts is limited through dendritic segregation and 1.5x greater linear expansion coefficient in comparison with those of unalloyed cast steels. Some variables including welding energy, pre-heating temperature and interpass temperature are important during welding. Publication [7]

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presented a welding technique involving the use of a pre-heating temperature of 600°C, increasing ductility and decreasing stresses.

According to publication [8], the probable reason for crack formation during the welding of modified heat-resistant cast steel HP-Nb (designation according to ASTM A 297 – equivalent to designation GX40NiCrSiNb35-25) was the presence of chromium carbide $Cr_{23}C_6$ and brittle intermetallic compound Ni-Nb-Si. The authors of publication [8] ascribed the above-named cracking to the transformation of intermetallic compound Ni-Nb-Si into carbide NbC. The high content of silicon remaining after the transformation significantly reduced the melting point (locally), which, during cooling, led to a decrease in plasticity. During thermal cycles, in the areas of dendritic segregation, e.g. along the boundaries of crystallites, the equilibrium partial melting or the dissolution of eutectic carbides NbC took place. The solidification of carbide eutectics was related to contraction and crack formation along grain boundaries [9].

Testing Methodology and Test Materials

The research work described in the article aimed to develop a welding technology in accordance with PN-EN ISO 11970 [10]. The related welding procedure qualification involved the making of a test joint using the TIG method (141) and filler metal grade WZ 25 35 Zr (Table 2) according to PN-EN ISO 14343 [11]. The chemical composition and the primary mechanical properties according to a mill certificate are presented in Table 2. The material used in the tests had the form of a heat-resistant cast steel pipe (φ 889 × 7.85 mm) made in cast steel grade GX40NiCrSiNb35-25 according to PN-EN 10295 [12]. The welding conditions involved the use of pipe position for welding upwards, shielding gas I1 – argon 5.0 and a maximum interpass temperature of 150°C. In accordance with Table 1 of PN-EN ISO 11970 [10], test joints should be subjected to 100% of non-destructive surface and volumetric tests, i.e. visual (VT), penetrant (PT) and radiographic (RT) tests as well as transverse tensile tests (destructive tests). If necessary, the above-named tests should be supplemented by transverse bend tests, impact strength tests, hardness measurements as well as macro and microscopic metallographic tests.

The cast steel pipe in the cast state was characterised by the entirely austenitic structure with carbide precipitates rich in chromium and niobium ($M_{23}C_6$, M_7C_3, and MC) and a maximum operating temperature of 1100°C without additional heat treatment. Cast steel pipes are made using the centrifugal casting method. The chemical composition of the cast steel and the primary mechanical properties according to a mill certificate are presented in Table 1.

Metallographic specimens were etched using the 10% aqueous solution of CrO_3. The microstructure was observed using a Zeiss Axio Imager M1m light microscope. The mechanical tests were performed using an MTS810 testing machine. The Vickers hardness tests were performed using a HPO 250 hardness tester under a load of 9.81 N (10 kg). The impact strength tests were performed

Table 1. Chemical composition and mechanical properties of cast steel GX40NiCrSiNb35-25 (% by weight)

C	Si	Mn	P	S	Cr	Ni	N	W	Nb	Ti	As, Pb, Sn, Zn	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
0.44	1.93	1.28	0.021	0.005	25.01	34.37	0.09	0.50	1.05	0.30	≤50 ppm	246	506	10.4

Table 2. Chemical composition and mechanical properties of filler metal WZ 25 35 Zr (% by weight)

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Ti	Nb	Zr	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
0.42	1.05	1.73	0.009	0.002	26.59	0.34	34.50	0.01	0.10	1.24	0.05	≥ 400	≥ 650	≥ 8

using specimens (5×10×55 mm) with a V-notch and the Charpy impact testing machine where the initial energy amounted to 300 J.

Test Results and Discussion

The visual (VT) and penetrant (PT) tests did not reveal the presence of welding imperfections. The view of the test joint on the face side is presented in Figure 1. The macroscopic tests of the joints revealed the proper arrangement of the runs in the weld without visible internal welding imperfections (Fig. 2).

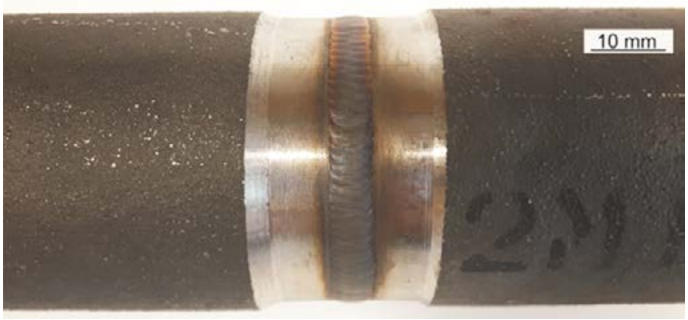

Fig. 1. Test joint

Fig. 2. Macrostructure of the test joint

The base material microstructure (Fig. 3) was entirely austenitic and contained numerous primary carbide phase precipitates along the crystallite boundaries. At greater magnification (Fig. 3b) it was possible to observe the cellular structure with (probably) chromium carbides $M_{23}C_6$. The fusion line microstructure is presented in Figure 4. The base material and the filler metal had similar chemical compositions (Tables 1 and 2) and the same crystallographic lattice (hence the visible epitaxial crystallisation of the weld). The austenitic microstructure of the weld is presented in Figure 5. The photographs taken at greater magnification revealed the presence of fine precipitates along crystallite boundaries.

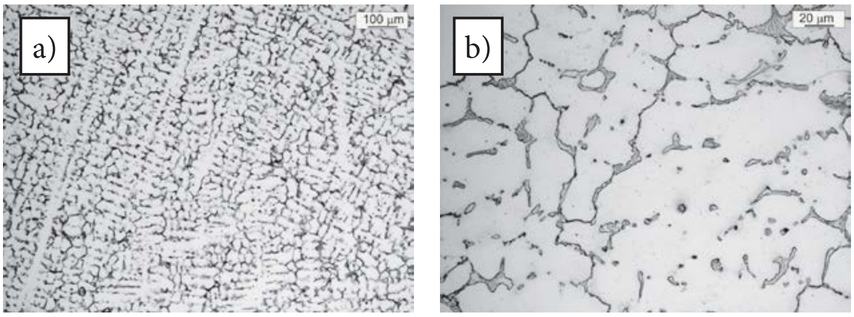

Fig. 3. Microstructure of the base material of cast steel GX40NiCrSiNb35-25

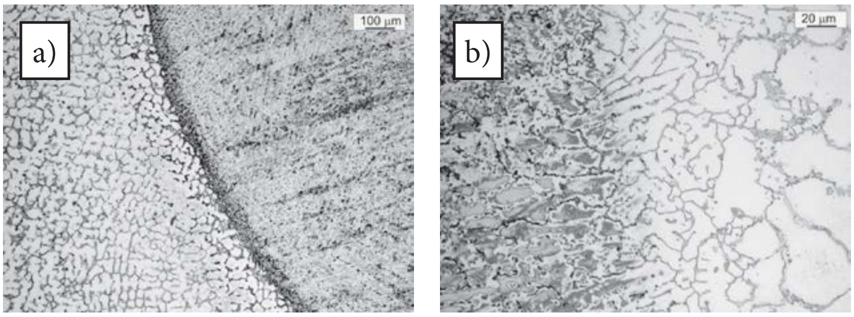

Fig. 4. Fusion line microstructure in the welded joint made of cast steel GX40NiCrSiNb35-25

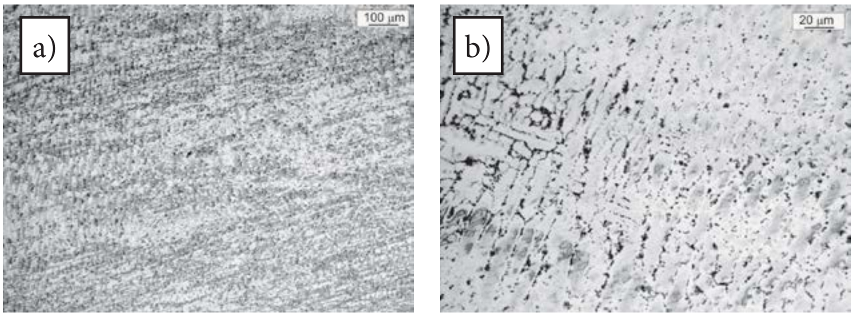

Fig. 5. Weld microstructure in the welded joint made of cast steel GX40NiCrSiNb35-25

Tables 3 to 5 present the results of the destructive tests. To extensively identify the mechanical properties of the test joint, the tests required by the PN-EN ISO 11970 [10] standard were supplemented by bend tests, impact strength tests, hardness measurements as well as macro and microscopic metallographic tests. The transverse tensile test finished positively, i.e. the rupture took place outside the weld and the required tensile strength was exceeded.

Table 3. Transverse tensile test results concerning the test joint made in cast steel GX40NiCrSiNb35-25

Specimen designation	R_e [MPa]	R_e^t [MPa]	R_m [MPa]	A [%]	Z [%]	Rupture area	Test result
Requirements	-	-	440	-	-	-	-
R1	-	-	462	-	-	outside the weld	positive
R2	-	-	443	-	-	outside the weld	positive

The transverse tensile tests involved two specimens and were performed on the face and on the root side of the weld. The bend angle at which the specimens fractured is presented in Table 4. The transverse tensile test was performed to verify the plasticity of the joints and to detect welding imperfections (if any), e.g. incomplete fusions. The angles at which the specimens fractured revealed that the joints were characterised by very low plasticity.

The impact tests involving the ISO Charpy 5.0 specimens having reduced dimensions (5×10×55 mm) was performed at ambient temperature. The specimens were sampled and the notches were incised in the weld (VWT) and in the HAZ (VHT). Regardless of areas subjected to the test, the impact energy remained very low (Table 5). Because of the lack of information in the PN-EN 10295 materials standard, it was not possible to refer the joint-related impact energy to that of the

Table 4. Test results concerning the bending of the test joint made in cast steel GX40NiCrSiNb35-25

Specimen designation	Bending mandrel/roll diameter	Bend angle	Bend side	Remarks
TFBB1	38 mm	9°	face	entire fraction
TFBB2	38 mm	11°	face	entire fraction
TRBB1	38 mm	14°	root	entire fraction
TRBB2	38 mm	16°	root	entire fraction

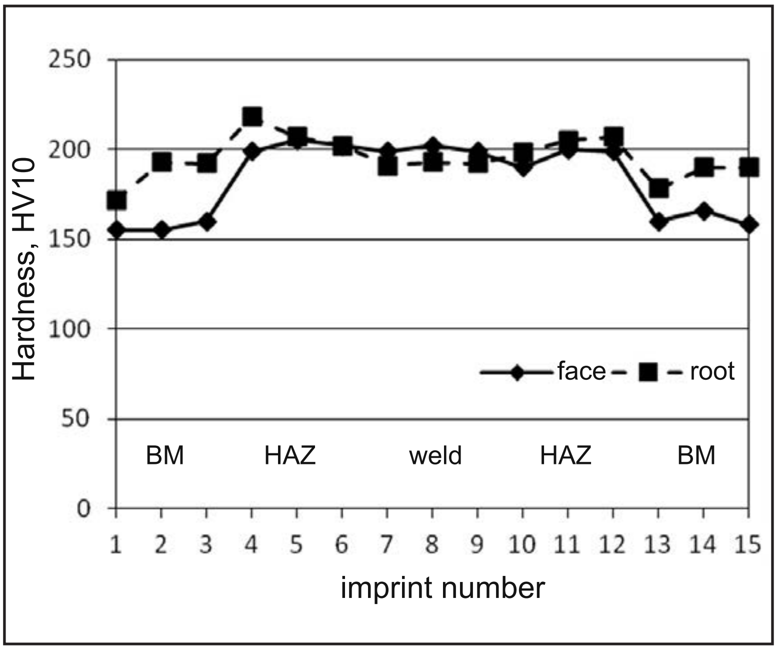

Fig. 6. Diagram of the hardness of the joint

Table 5. Results concerning the impact strength of the joint made in cast steel GX40NiCrSiNb35-25

Specimen designation	Set	Cross-sectional area in the notch, cm^2	Test temperature	Impact energy KV, J			Mean value, J
				1	2	3	
VWT (weld)	1÷3	0.4	+21°C	7	4.8	7	6.3
VHT (HAZ)	4÷6			4	4	3.2	3.7

Table 6. Results of hardness measurements concerning the cross-sectional hardness of the welded joints made in cast steel GX40NiCrSiNb35-25

Measurement line	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
face	155	155	160	199	205	202	199	202	199	190	200	199	160	166	158
root	172	193	192	218	207	202	191	193	192	198	205	207	178	190	190

base material. In addition, it should be noted that the cast material was characterised by low mechanical properties as is the case with all steel castings if compared with materials subjected to plastic working.

The cross-sectional hardness measurements concerning the welded joint made of cast steel GX40NiCrSiNb35-25 did not diverge from values typical of such materials. There were not rapid hardness changes in relation to the tested zones of the joint (Table 6, Figure 6). Similar to the impact test, there was no information concerning the hardness of the base material.

Summary and Concluding Remarks

1. The joint macrostructure was characterised by proper geometry and the arrangement of runs without visible internal welding imperfections.

2. The tests resulted in the obtainment of a positive result, which enabled the issue of a welding procedure qualification record (WPQR) in accordance with PN-EN ISO 11970.

3. The additional destructive tests (transverse bend tests and impact strength tests) revealed the very low plasticity of the test joint.

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