DOI: 10.1515/adms-2017-0026

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STRUCTURE AND PROPERTIES OF WELDED JOINTS OF 7CrMoVTiB10-10 (T24) STEEL

ABSTRACT

Gas Tungsten Arc butt welded joints of tubes of 7CrMoVTiB10-10 made using bainitic-martensitic P 24-IG filler metal were found to be susceptible to root cracking. This was avoided by using the CMS-IG filler metal and austenitic EPRI P87 filler metal. Detailed coefficient of thermal expansion analysis for both filler metals was performed. Unfortunately, CMS-IG filler metal is characterized by a lower creep rupture strength than P 24-IG. For this reason, the joints were produced by the 141 method with using two filler metals: P 24- IG and EPRI P87. All the welded joints was characterized by the B quality level. Macrostructural, microstructural and hardness data for both welded joints are presented. The standard requirement, < 350 HV10, was marginally not met and was achieved through post weld heat treatment.

Keywords: *7CrMoVTiB10-10 steel, welded joint, root cracking*

INTRODUCTION

7CrMoVTiB10-10 (T24) is a low-alloy steel, designed on the basis of ferritic 10CrMo9-10 (T22) steel, developed to manufacture membrane walls of boilers in supercritical power plants. Its chemical composition is shown in Table 1.

Table 1. *Chemical compositions of relevant steels, mass fraction %*

Steel	10CrMo9-10	T22	7CrMoVTiB10-10	T24
Standard	EN 10216-2	ASTM A213	EN 10216-2	ASTM A213
C	0.08-0.14	0.05-0.15	0.05-0.10	0.05-0.10
Si	0.50	0.50	0.15-0.45	0.15-0.45
Mn	0.30-0.70	0.30-0.60	0.30-0.70	0.30-0.70
Cr	2.00-2.50	1.90-2.60	2.20-2.60	2.20-2.60
Mo	0.90-1.10	0.87-1.13	0.90-1.10	0.90-1.10
Ti	-	-	0.05-0.10	0.06-0.10
V	-	-	0.20-0.30	0.20-0.30
B	-	-	0.0015-0.0070	0.0015-0.0070

Heat treatment, defined in EN 10216-2 “Seamless steel tubes for pressure purposes. Technical delivery conditions. Non-alloy and alloy steel tubes with specified elevated temperature properties”, consists of normalizing and tempering at 750±20°C (NT) or quenching and tempering (QT) if the wall thickness is higher than 16 mm. These heat treatments result in a mixture of tempered bainitic-martensitic microstructure. T24 steel is characterized by good mechanical properties in delivery condition [1-3] and as-received [4-6].

Modification of chemical composition, compared to the T22 steel, ensured good weldability [7-10], without pre-heat and post-weld heat treatments of thin-wall parts, i.e. below 10 mm [7]. Industrial practice showed that welded joints of T24 steel are low ductility [11-14] and susceptible to cracking [15-17], especially cracks in the root pass in butt welded joints of tubes or pipes [18-21]. Examples of such macro-cracks in the root pass are shown in Fig. 1a-c. The initiators of cracks are micro discontinuities in the crater (Fig. 1d), but, due to their small size, it is impossible to detect them with classical nondestructive testing methods.

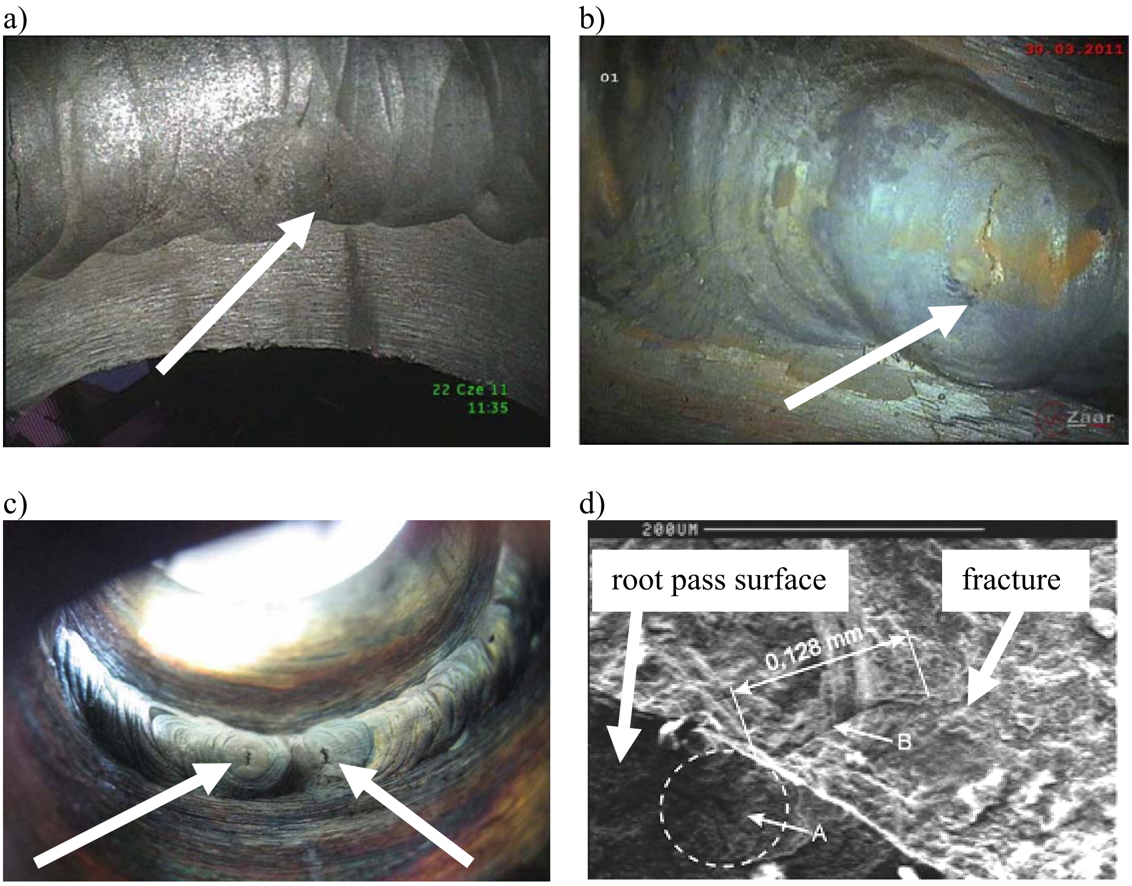

Fig. 1. End crater crack at the root pass in butt weld joint of T24 steel:
a-c) macro-cracks, d) micro-crack (A) and in root pass at a depth below 0.15 mm [18-21]

A possible solution, in a root pass, is the use of filler metal with a lower susceptibility to cracking, for example W CrMo2 Si, designated to 10CrMo9-10. Unfortunately, this material is characterized by a lower creep rupture strength than W ZCrMo2VTi/Nb, designated as 7CrMoVTiB10-10. Other possible solutions are to use a more expensive nickel base filler metal (i.e. NiCr20Mn3Nb) with high plasticity and good creep rupture strength, or a new filler metal EPRI P87 with an austenitic microstructure.

MATERIALS AND EXPERIMENTAL PROCEDURES

Weld metal from classic filler metal for 7CrMoVTiB10-10 steel, 10CrMo9-10 steel and nickel base filler metals were investigated by the dilatometry. Interpretation of dilatometric diagrams can assist studies of CCT diagrams [22-25], CHT diagrams [26-27] and CTE (coefficient of thermal expansion) [28]. In this investigation coefficients of thermal expansion of P 24-IG (designated to 7CrMoVTiB10-10 steel), CMS-IG (designated to 10CrMo9-10 steel) and EPRI P87 weld metals were investigated. Specimens were taken from padding welds, where the filler metal was not mixed with the base material.

Next, experiments were carried out on butt weld joints of tubes of 7CrMoVTiB10-10 (T24) with these dimensions: outside diameter 48.3 mm and wall thickness 11.2 mm The joints were produced by the 141 method, in accord with the EN ISO 4063 *"Welding and allied processes. Nomenclature of processes and reference numbers"* standard, in two configurations, using two filler metals. Welding was performed in the horizontal position (PC) in accord with EN ISO 6947 "Welding and allied processes. Welding positions" standard, characterized by the smallest amount of heat input. The welds were made with a direct current electrode negative at a speed of 100 mm/min, welding current of 120 A, and arc length of 3 mm. Gas shielding (argon) was kept in a flowing rate of 10 l/min. Scheme of weld joints preparation and welding technology configurations are shown in Fig. 2. Chemical compositions of EPRI P87 and P 24-IG filler metals are given in Table 2.

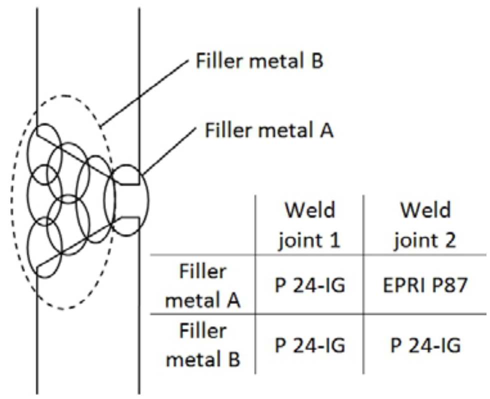

Fig. 2. Scheme of weld joint and welding technology configurations

Table 2. *Chemical compositions of* filler metals, mass fraction %

Filler metal	EPRI P87 (*Metrode*)	P 24-IG (*Böhler*)
Standards	Lack of standard, material covered by U.S.Patent 7,562,807	EN ISO 21952-A:2009 W ZCrMo2VTi/Nb
C	0.10	0.10
Si	0.30	0.25
Mn	1.50	0.55
Cr	9.00	2.50
Mo	2.00	1.00
Nb	1.00	0.05
V	-	0.24
Ni	Balance	-
Fe	38.00	Balance

After welding, non-destructive (visual) and destructive (macroscopic and microscopic examinations and hardness) tests were performed. Visual test was carried out in accordance with EN ISO 17637 "Non-destructive testing of welds - Visual testing of fusion-welded joints" and macro- and microscopic examinations in accordance with EN ISO 17639 "Destructive tests on welds in metallic materials - Macroscopic and microscopic examination of welds" standards. The macrostructure was examined on ground and Nital etched specimens. Preparation of specimens for microscopic examination consisted of grinding, polishing with Al_2O_3 and Nital etching. Additionally, a second specimen with EPRI P87 weld metal was electro-etched in 10% CrO_3 solution. Hardness testing was performed on transverse sections of welded joints by the Vickers method with intender loading of 98.07 N, in accordance with EN ISO 9015-1 "*Destructive tests on welds in metallic materials - Hardness testing - Part 1: Hardness test on arc welded joints*" standard. Hardness was measured along two lines, approximately 2 mm from the face and root of specimen surface. Additionally, in the second specimen, hardness was measured in the mixed zone of EPRI P87 and P 24-IG weld metal.

RESULTS

Dilatometric diagrams of heating of samples of P 24-IG, EPRI P87 and CMS-IG weld metal are presented in Figs. 3-5 and the coefficient of thermal expansion in Fig. 6a, with the relative comparison to P 24-IG weld metal in Fig. 6b. It is seen that EPRI P87 weld metal has the lowest difference of coefficient of thermal expansion to P 24-IG weld metal.

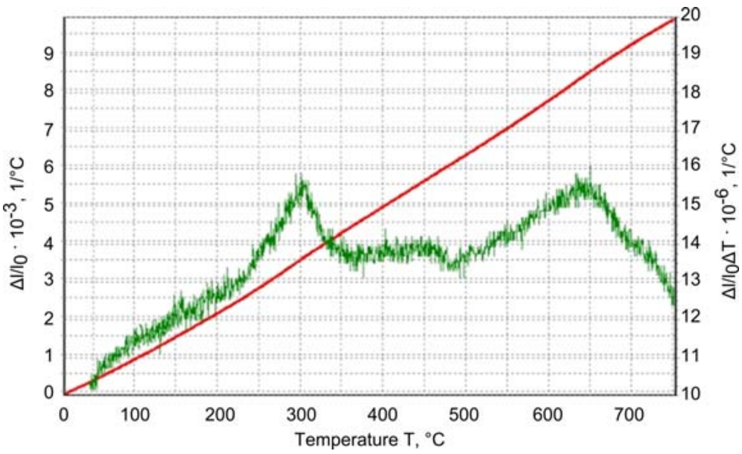

Fig. 3. Dilatometric diagram of heating, at a rate of 0.05°C/s, of P 24-IG weld metal specimens

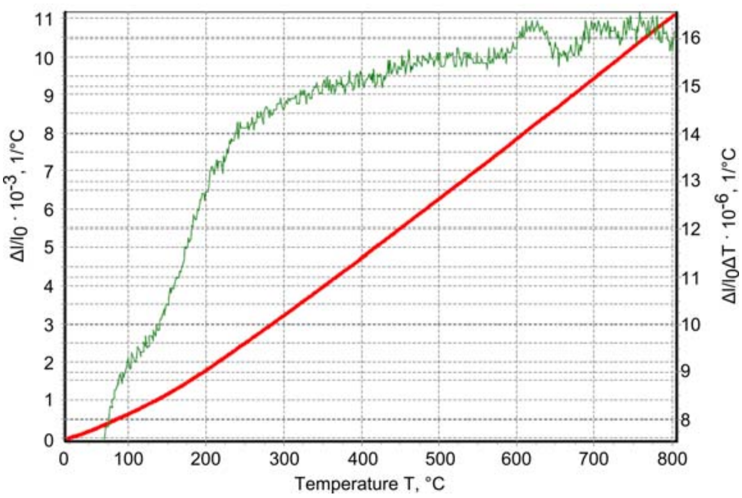

Fig. 4. Dilatometric diagram of heating, at a rate of 0.05°C/s, of EPRI P87 weld metal specimens

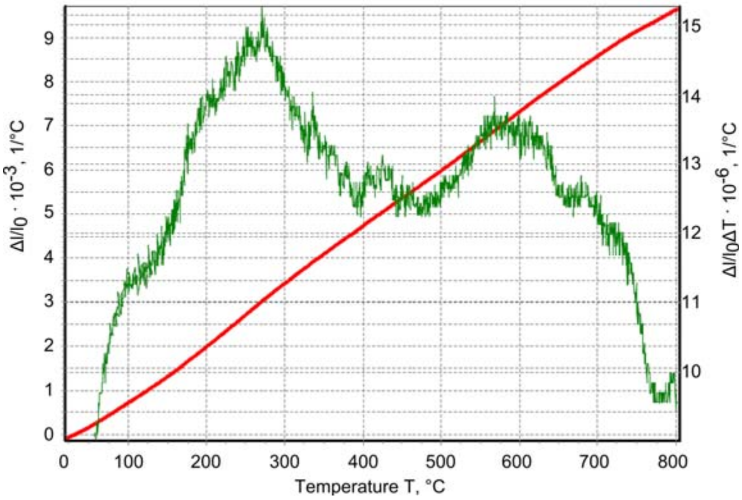

Fig. 5. Dilatometric diagram of heating, at a rate of 0.05°C/s, of CMS-IG weld metal specimens

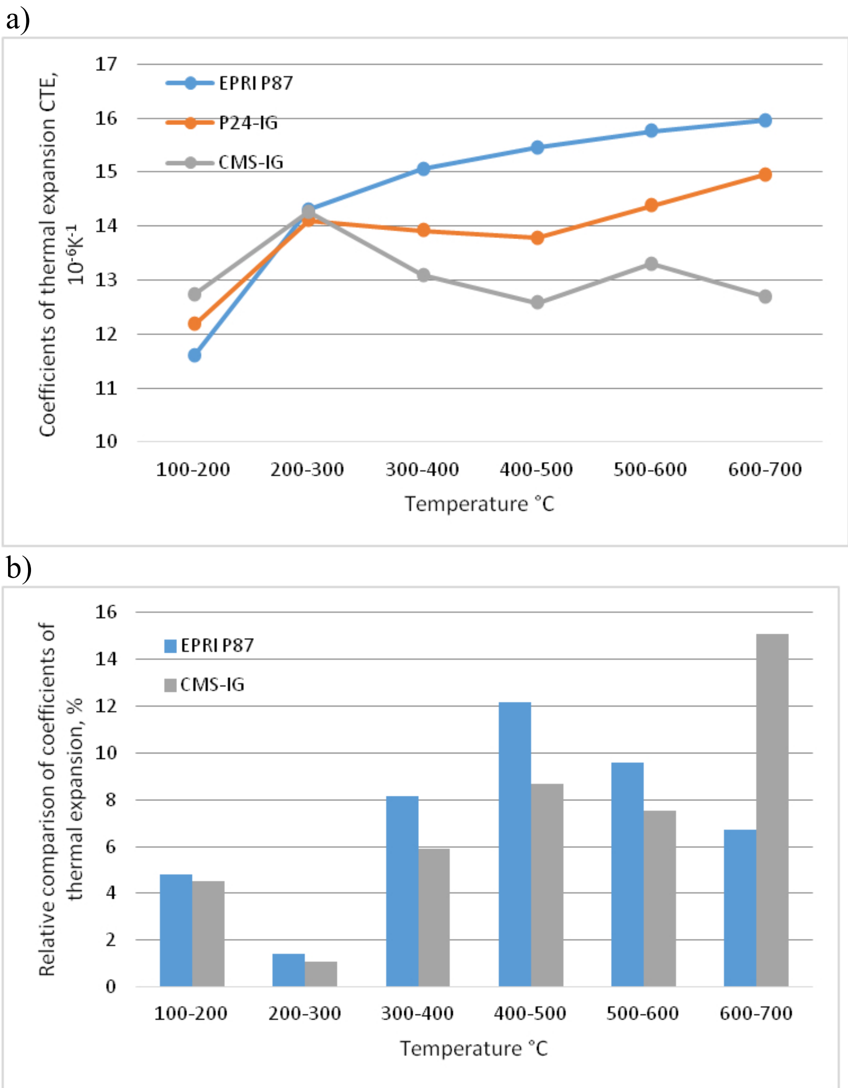

Fig. 6. Results of dilatometry tests: a) coefficients of thermal expansion of selected filler metals, b) relative comparison of coefficients of thermal expansion of selected filler metals to the P 24-IG weld metal

All the welded joints covered by the analysis complied with the requirements for the B quality level (highest level), in accordance with EN ISO 5817 “Welding - Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) - Quality levels for imperfections”. Fig. 7 show the macrographs of the joints. The shape of a weld is correct and without any welding imperfections.

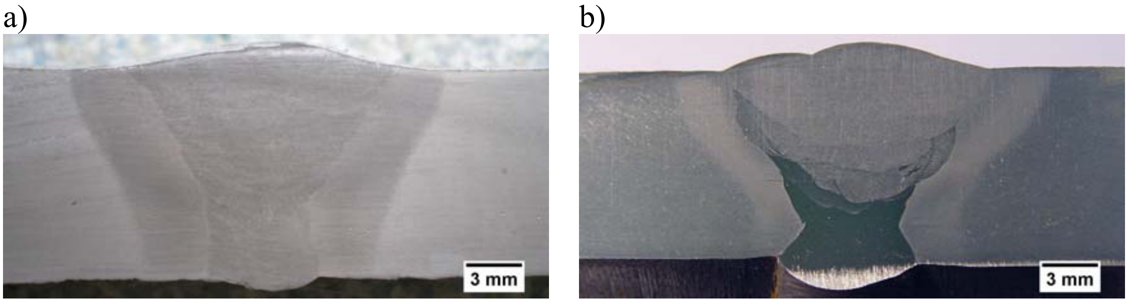

Fig. 7. Macrostructure of joint welded by: a) P 24-IG filler metal b) EPRI P87 and P 24-IG filler metals, Nital etching

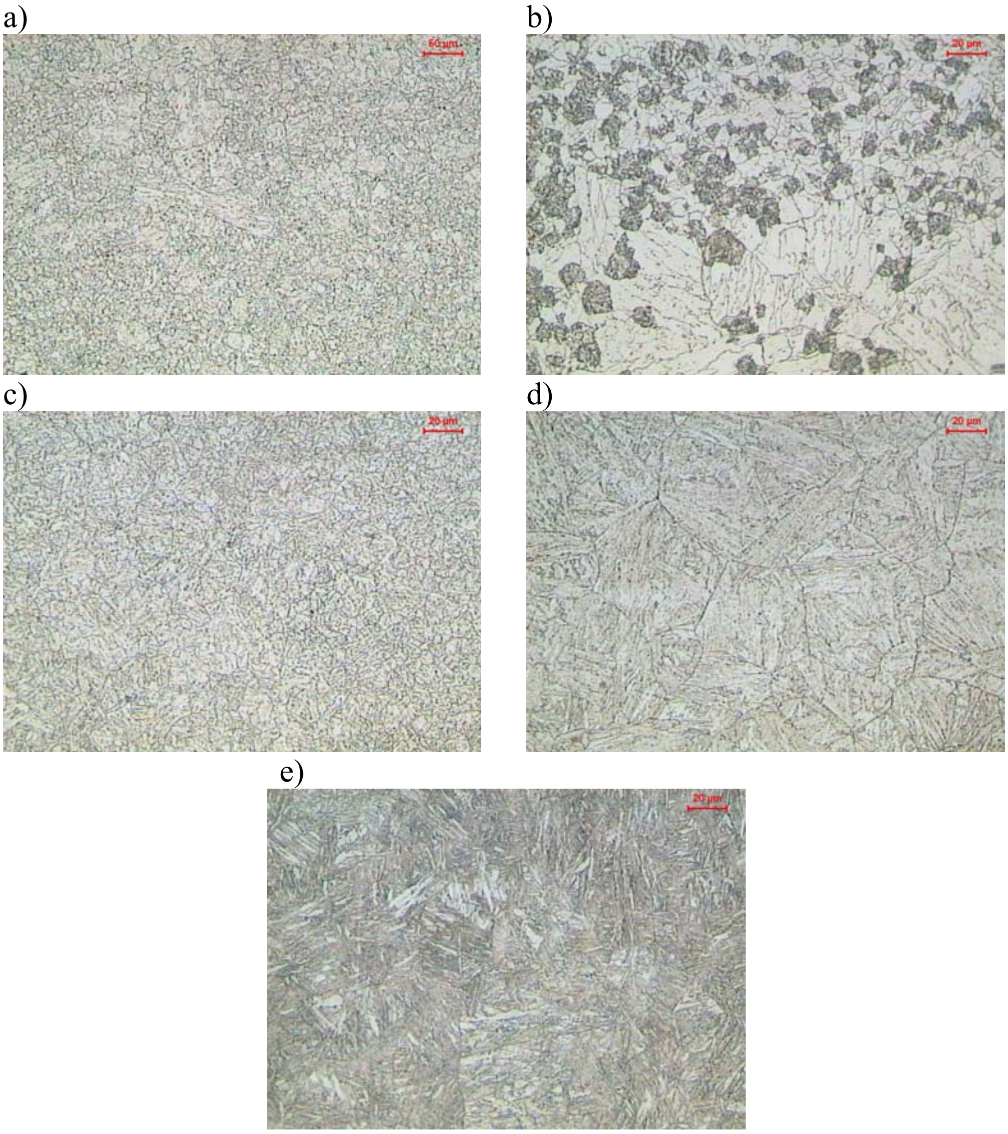

Fig. 8. Microstructures of welded joints in T24 steel: a) base metal, b) intercritical HAZ, c) fine-grained HAZ, d) coarse-grained HAZ, e) P 24-IG weld metal. Nital etching

Microstructural examinations were performed in all zones of the welded joints. Fig. 8a is an light micrograph of the parent material – T24 steel. Presence of a mixture of tempered bainite and martensite structure is in accordance with the CTT diagram [2] and requirements of EN 10216-2 "Seamless steel tubes for pressure purposes - Technical delivery conditions - Part 2: Non-alloy and alloy steel tubes with specified elevated temperature properties".

Regular grain structure of cold deformed tubes indicates that the heat treatment before welding was carried out at a temperature above the recrystallization temperature. Fig. 8b shows a region of heat affected zone (HAZ), so-called intercritical HAZ (ICHAZ), which was heated while welding to the temperature corresponding to the A_1-A_3 range. In this range, the partial of mixture of prior bainite and martensite transform to austenite, which results in a mixture of tempered and "fresh" bainite-martensite microstructures.

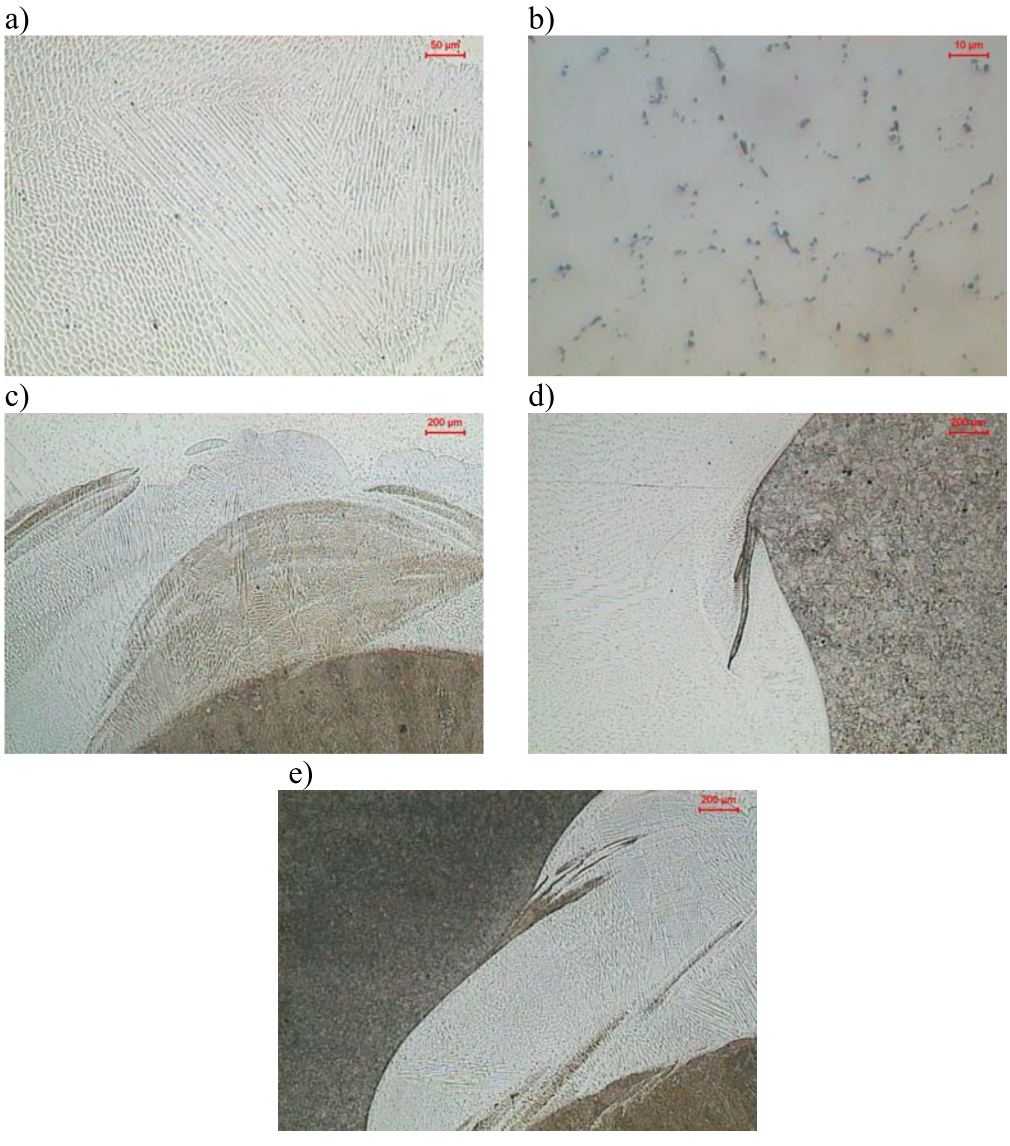

Fig. 9. Microstructures of welded joints in T24 steel: a) and b) EPRI P87 weld metal, c) mixed zone of EPRI P87 and P 24-IG weld metal, d and e) the unmixed zone on the border of root pass (light) and parent material (dark region). Nital and CrO3 solution etching

In fine grain HAZ (FGHAZ) a normalized microstructure was observed, while in the coarse-grained HAZ (CGHAZ) a mixture of bainite and martensite with coarse grain primary austenite, as shown in Fig. 8c - d. The weld metal (WM), using P 24-IG filler metal, has a bainitic-martensitic microstructure with columnar grains (Fig. 8e).

EPRI P87 weld metal has an austenitic microstructure with carbides on column boundaries (Figs. 9a-b). On the border of the root pass, made by EPRI P87, and second part of filling, mixed and unmixed zones (Fig. 9c) were observed. Probably the mixed zone, with dark etching, is composed of a martensitic structure. Fig. 9d and e show an unmixed zone on the border of the root pass and the parent material. Occurrence of an unmixed zone is due to the presence a stationary layer of liquid metal in the bottom of the weld pool. Local fluid flow is not strong enough for thorough mixing, but strong enough to move parts of the liquid base metal [29].

Hardness measurements of homogenous welded joint are show in Fig. 10, and of EPRI P87 and P 24-IG welded joints in Fig. 11. In both cases, hardness of the parent metal is 170-230 HV10. In the homogenous welded joints hardness of HAZ and weld metal are in the range 280-360 HV10, similar hardness to these zones in face layers of the second weld joint. The maximum hardness of EPRI P87 weld metal is as high as 170 HV10.

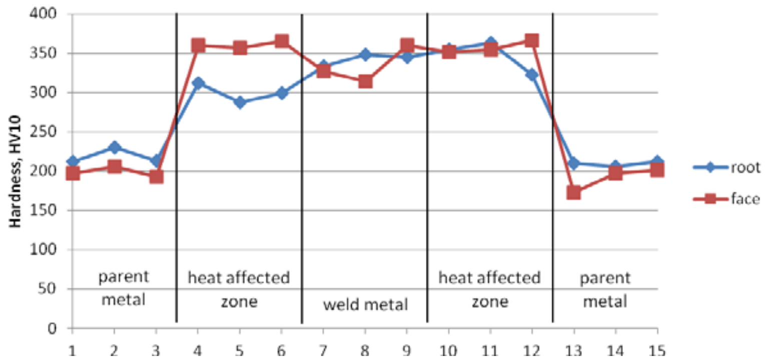

Fig. 10. Hardness results of a joint welded by P 24-IG filler metal

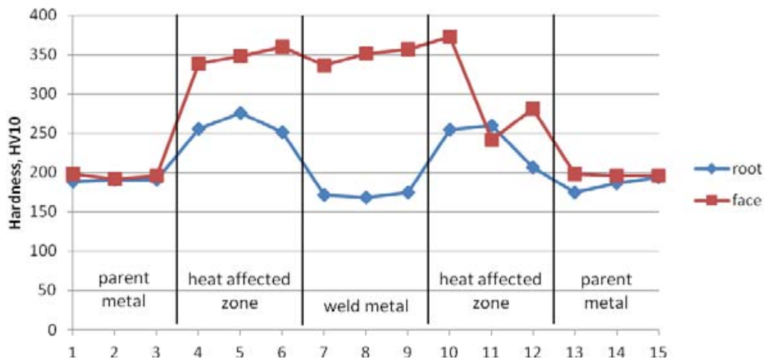

Fig. 11. Hardness results of a joint welded by EPRI P87 and P 24-IG filler metals

Qualification of welding procedure standard ISO 15614-1 "Specification and qualification of welding procedures for metallic materials - Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys" for materials of group 6.2, acc. to ISO/TR 15608 "Welding - Guidelines for a metallic materials grouping system", does not provide for weld joints without heat treatment. The maximum value of 350 HV10, provided for weld joints after post-weld heat treatment, was marginally exceeded in both the welded joints. This could be possibly associated with the occurrence of cold cracking. Hardness measurements of welded joints, performed by P 24-IG filler metal, are comparable with literature data [30-32], not from manufacturers of steel or filler metals. Additionally, mixed zones of P 24-IG and EPRI P87 filler metals are characterized by a high hardness level of 366±10 HV10. Post weld heat treatment 740°C/30 min results in maximum hardness of 250 HV10 in weld metal and HAZ, but as much as 6 h at 740°C is required to reduce the hardness to less than 350 HV10 in the mixed zone.

SUMMARY

Studies of microstructure of welded joints, performed by 141 method, showed a mixture of lower bainite and tempered martensite in the 7CrMoVTiB10-10 base metal. Each zone of heat affected zone is characterized by standard structures for bainitic-martensitic steels. ICHAZ has a tempered and "fresh" bainite-martensite microstructure, FGHAZ is characterized by a normalized microstructure and CGHAZ has a mixture of bainite and martensite with coarse-grained primary austenite. P 24-IG weld metal showed a bainitic-martensitic microstructure, EPRI P87 weld metal has an austenitic microstructure with carbides on column boundaries. In joints welded with EPRI P87 and P 24-IG filler metals mixed and unmixed zones were observed. Hardness, without post weld heat treatment, was marginally above that required, 350 HV10, for welded joints after heat treatment. High hardness could be a cause of cold cracks. Post weld heat treatment 740°C/6 h reduced a hardness level of less than 350 HV10 in each zone of the welded joint.

ACKNOWLEDGEMENTS

This research work was supported by the Polish Ministry of Science and Higher Education, contract no. 11.11.110.299. The author are grateful to PhD Rafał Dziurka and PhD DSc Piotr Bała (AGH University of Science and Technology in Krakow, Poland) for the dilatometric analysis. Appreciation is also expressed to Prof. A.S. Wroński (University of Bradford, UK) for help in the manuscript editing.

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