SUPPLEMENT TO THE *WELDING JOURNAL,* DECEMBER 2008
Sponsored by the American Welding Society and the Welding Research Council

Evaluation of Dissimilar Welds between Ferritic Stainless Steel Modified 12% Cr and Carbon Steel S355

A modified ferritic stainless steel was subjected to a barrage of testing to determine its suitability for a variety of structural applications

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ABSTRACT. In this research, 20-mm-thick, modified X2CrNi12 ferritic stainless steel conforming in composition to Grades UNS S41003 in ASTM A240 and 1.4003 in EN 10088-2 and EN 10028-7 with a carbon content below 0.015% was welded to nonalloy S355 steel by means of shielded metal arc (SMA) and submerged arc (SA) welding processes using AISI 309 type of filler metal. Microstructural examinations were carried out including macro and micrographs, hardness and ferrite content measurements, and grain size analysis. Charpy impact and crack tip opening displacement (CTOD) fracture toughness tests, transverse and longitudinal tensile, and bend tests were carried out. Corrosion testing by means of salt spray and blister tests was done in order to investigate all aspects of the weld properties of the joints. Cross-weld tensile specimens tested at room temperature all broke in the base metals. Heat-affected zone (HAZ) Charpy impact values ranged from 17 to 30 J and could be correlated with the microstructure.

Introduction

The ferritic stainless steel family, including the iron-based alloys with 10.5 to 30% Cr content with small amounts of austenite-forming elements such as carbon, nitrogen, and nickel, is the second most commonly used group of stainless steels because of their good corrosion resistance and lower cost compared to austenitic grades. Since these steels were considered low-weldable steels, they had mostly been used for applications not requiring welding until the early 1980s. A fully ferritic structure has poor low-temperature toughness and high-temperature strength with regard to austenite. Primarily, when exhaust tubes and connections began to be welded with these stainless steels, their weldability started to receive increased attention and interest for engineering applications (Refs. 1–6).

Ferritic stainless steels with 11–12% chromium have been widely used as low-cost utility stainless steels and have been developed to fill the gap between stainless steels and the rust-prone carbon steels, thus providing an alternative that displays both the advantages of stainless steels and engineering properties of carbon steels (Refs. 6–12). The former generation of these steels is known as 3Cr12 stainless steel, which was commercialized in 1979 in South Africa with 0.03% carbon. It is used by several steel suppliers and conforms in ASTM A240 as UNS S41003 and in Europe as Material Number 1.4003. A series of studies describing the research and the use of 3Cr12 ferritic stainless steel in various applications can be found in the literature (Refs. 7–34).

Although 3Cr12 has excellent corrosion resistance in many environments, its weldability is limited. EN 1.4003 steel is modified from conventional 12%Cr stainless steel by decreasing the C content to well below 0.03% to improve the weldability, which is regarded as the limit for low-carbon steels. With advanced steelmaking technology, modified X2CrNi12 ferritic stainless steel can be fabricated to still comply with EN 10088-2 and EN 10028-7, and low-carbon (<0.015% C) levels and reduced impurity levels, consequently improving weldability and mechanical properties. Although initial applications of these steels were for materials handling equipment in corrosive/abrasive environments, they are now commonly used in the coal mining industry for bulk transport of coal and gold, for cane and beet sugar processing equipment, road and rail transport, power generation; petrochemical, metallurgical, pulp and paper industries; and also in structural applications and in aerospace engineering. The use of these steels in the past few years increased markedly with their successful application in passenger vehicles, coaches, buses, trucks, freight and passenger wagons, and rail infrastructure (Refs. 7, 8, 12–34).

When compared with carbon steels for long-term maintenance costs, modified X2CrNi12 stainless steel requires fewer coating renewals, which provides substantial economic and environmental advantages. For other applications, when compared with higher alloyed stainless steels, the use of this modified 12% Cr steel with improved weldability would be more economical (Refs. 7, 8, 35–41).

Since not much study has been carried out on the weldability and the properties of the welded joints of modified X2CrNi12 stainless steel, and considering

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KEYWORDS

Modified X2CrNi12
12% Cr
S355
Dissimilar Welding
Weldability

the intent to use this modified steel in more structural applications, dissimilar welding was taken into account for this study. In this paper, modified X2CrNi12 stainless steel and S355 steel plates were shielded metal arc (SMA) and submerged arc (SA) welded. The joints were evaluated by means of microstructural, toughness, mechanical, and corrosion properties.

Experimental Procedure

Chemical compositions and tensile properties transverse to the rolling direction of the 20-mm-thick base metals are given in Table 1. The X2CrNi12 stainless steel microstructure contained about 20 to 30% martensite, while the S355 carbon steel was a hot-rolled nonalloy structural steel.

Although matching welding electrodes are commercially available for welding the EN10088:X2CrNi12 stainless steel, it is not recommended in applications where impact, fatigue, or any other form of nonstatic loading is anticipated. Reported weldability studies have shown instead that austenitic stainless steel consumables, especially 309 type, are recommended to produce welds with a minimum risk for heat-affected zone (HAZ) hydrogen cracking and to ensure deposition of tough weld metal with adequate properties required for structural purposes. Taking this into account, Type 309 austenitic stainless steel consumable was used for this study, as the tough austenitic weld metal absorbs some of the impact during service thus improving the overall deformability of the weld (Refs. 7–19).

Dissimilar metal joining with SMAW was done with rutile-basic E309L-16 electrodes of 2.5 to 4.0 mm diameter with DC+ polarity. The V-shaped plate preparation consisted of an opening angle of 70 deg and a root opening and root face both of 2 mm. Submerged arc welding of the dissimilar metals was realized with a 4.0-mm ER309L welding wire in combination with a proper flux. A wide root opening of 18 mm and a root face of 2 mm were used in combination with a V-shaped plate preparation of only 14 deg. Both welds were supported by an X2CrNi12 stainless steel plate as backing material. Each joint was produced with dimensions of 2000 × 1000 × 20 mm.

After welding, chemical analysis samples consisting entirely of the weld metal were prepared as longitudinal sections perpendicular to the plate surface. The measurements were done by glow discharge optical emission spectrometry. Nitrogen was determined by the melt extraction method.

Macro sections were removed from the joints, prepared, and etched with Vilella's reagent and nital in order to make macro and micrographs with a magnification of 200×. According to the EN 1043-1 standard, Vickers hardness measurements were made at the subsurface from the face and the root sides of the welds under a load of 5 kg. Ferrite content of the weld metal was determined by means of Ferritscope.

Several series of standard notch impact test samples with a cross section of 10 × 10 mm by 2-mm-deep V-shaped notch were extracted, conforming to EN 10045-1, from both face and root sides, through thickness and transverse to the weld. They were then prepared with notches positioned at the weld metal center (WM), weld interface (WI), and at the HAZ 2 mm away from the weld interface (WI+2). Charpy impact testing was done at –20° and 0°C test temperatures.

The welds were investigated with regard to their full-thickness crack tip opening displacement (CTOD) fracture toughness properties at –20°C with reference to BS 7884. The CTOD fracture toughness is expressed in millimeters and measured with three-point bending under static loading conditions. Similar to the Charpy test, CTOD samples were notched at the WM and the WI from both 12 Cr and S355 sides and the samples were precracked. After CTOD testing, the fracture surfaces of the samples were examined by scanning electron microscope (SEM).

Depending on the toughness test results of the welded joints, ASTM grain size numbers were measured on the existing macro sections at the thickness positions from subsurface to midthickness to investigate for a possible correlation between toughness and microstructure. Due to the inclined weld interface, the positions were sampled in specimens notched at WI and WI+2. Fine-grained microstructures have high ASTM grain size numbers (i.e., 7 to 10) while coarse-grained microstructures are identified by small ASTM grain size numbers (i.e., 1 to 4).

Transverse full-thickness tensile specimens, transverse to the weld with respect to EN 10002-1- EN 895 and cylindrical test samples completely positioned at the weld metal in the longitudinal direction in accordance with EN 10002-1-EN 876, were extracted from both dissimilar welds. The net section diameter of all cylindrical samples was 10 mm, while strain at fracture was determined over a reference length of 50 mm, or five times the specimen diameter.

The static tensile testing of transverse and longitudinal samples was carried out at room temperature using a hydraulically controlled test machine. Moreover, two face and two root bend test specimens from each weld were prepared from the welded plates. A nominal specimen width of 30 mm, a mandrel diameter of 91 mm, and bending angle of 180 deg were used.

Salt spray and blister corrosion tests were executed to assess the resistance to

Table 1 — Properties of 20-mm-Thick X2CrNi12 Stainless Steel and S355 Plates

Chemical Composition of Modified X2CrNi12 Stainless Steel and S355, Respectively (wt-%) (Data from chemical analysis)

C	Si	Mn	P	S	Cr	Cu	Ni	Mo	Ti	V	Al	Nb	N (ppm)
<0.01	0.32	0.97	0.033	0.003	12.2	0.39	0.52	0.14	0.001	0.040	0.029	0.031	88
0.09	0.33	1.53	0.011	0.003	0.11	0.06	0.08	<0.01	<0.001	<0.001	0.049	—	45

Transverse Tensile Properties of Modified X2CrNi12 Stainless Steel and S355, Respectively

R_e(MPa)	R_m(MPa)	Strain at fracture (%)
353	506	28
379	504	37

Table 2 — Chemical Composition of the Weld Deposits of Dissimilar Joints

Welding process	C (%)	Si (%)	Mn (%)	P ppm	S ppm	Cr (%)	Cu (%)	Ni (%)	Mo (%)	Ti ppm	V ppm	Al ppm	Nb ppm	N ppm
111 SMAW	0.03	0.98	0.73	230	160	23.1	0.04	11.9	0.06	140	850	320	90	806
121 SAW	0.02	0.52	1.48	210	50	22.5	0.09	10.2	0.08	50	910	430	<10	462

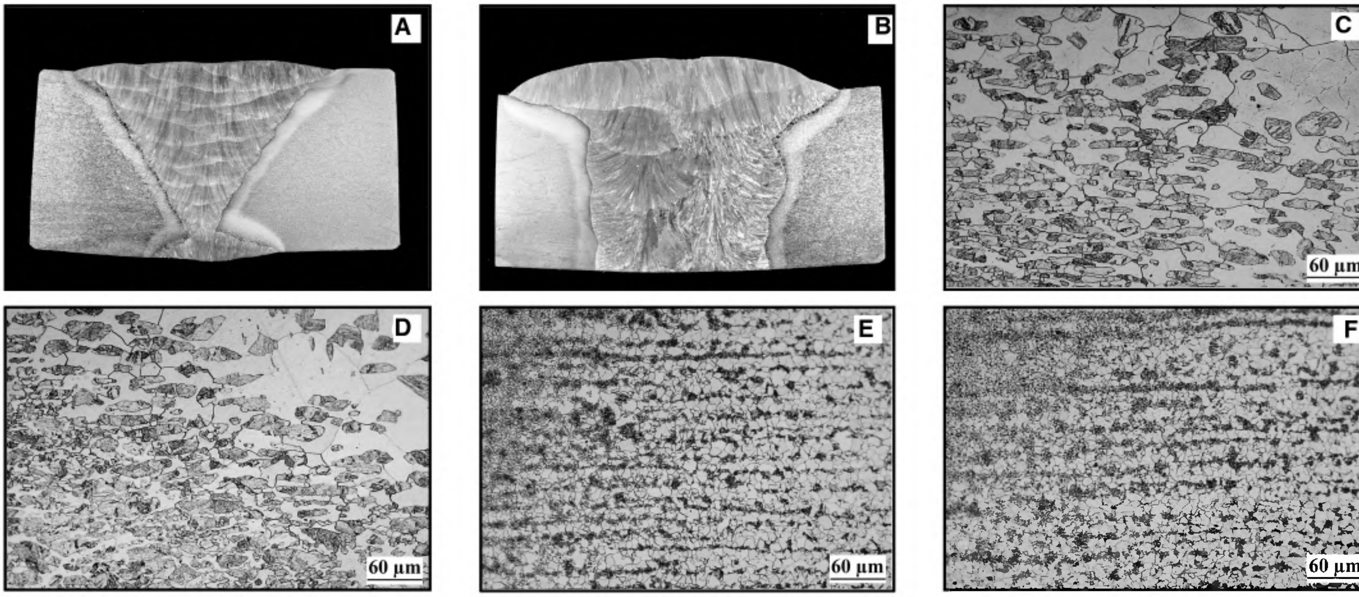

Fig. 1 — Macro sections. A — Shielded metal arc weld; B — submerged arc weld. micrographs; C — 12Cr HTHAZ, shielded metal arc weld; D — 12Cr HTHAZ, submerged arc weld; E — S355 HAZ, shielded metal arc weld; F — S355 HAZ, submerged arc weld.

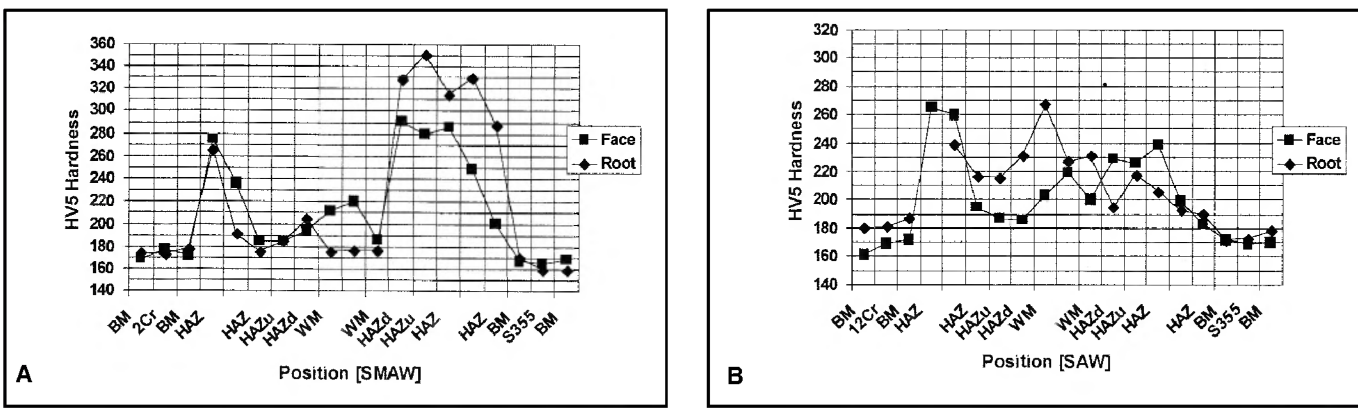

Fig. 2 — HV5 hardness across macro sections. A — Shielded metal arc weld; B — submerged arcweld.

atmospheric attack. Salt spray tests were done with reference to ASTM B117 on uncoated and coated corrosion samples for 350 and 1000 h of exposure, respectively. Coating consisted of a two-layer protection system similar to paint that is used in practice by a railway coach manufacturer. The samples were provided with a cross-shaped scratch over the entire test surface across the weld and also with paraffin at the sawed and machined surfaces. This allowed an estimation of the welds' resistance when the coating is accidentally damaged prior to or during operation. Salt spray testing was done in a 5% NaCl aqueous solution with a fog volume of 24 to 28 mL per 24 h, a pH of 6.5 to 7.2, and at a temperature of 35°C. Dissimilar weld specimens were positioned with the carbon steel S355 side downward. Blister tests were executed on coated samples prepared similarly as those for salt spray testing. Samples were exposed to real atmospheric conditions for 3120 h from their face side, which exposed the most weld metal, and with their test surface oriented to direct sunlight (Ref. 39).

Results and Discussion

The chemical compositions of all weld deposits are summarized in Table 2. The SMA weld with an E309L-16 type of electrode contained more Si than the SA weld. Elements like vanadium and nitrogen increased strongly with regard to the base metals.

Relevant macro and micrographs of the dissimilar welds are shown in Fig. 1.

The 20-mm-thick dissimilar SMA weld

Table 3 — CTOD Fracture Toughness at –20°C of the Dissimilar Welds

Welding Process/ Type of Consumables	Notch Position (-)	CTOD (mm)	Failure Mode (-)
111 SMAW/ E309L-16	WMC	0.274	Maximum force plateau
		0.274	Maximum force plateau
	WI (12Cr)	0.101	Fracture
		0.076	Fracture
	WI (S355)	0.756	Maximum force plateau
121 SAW/ ER309L	WMC	0.626	Maximum force plateau
		0.599	Maximum force plateau
	WI (12Cr)	0.047	Fracture
		0.023	Pop-in
	WI (S355)	0.312	Fracture

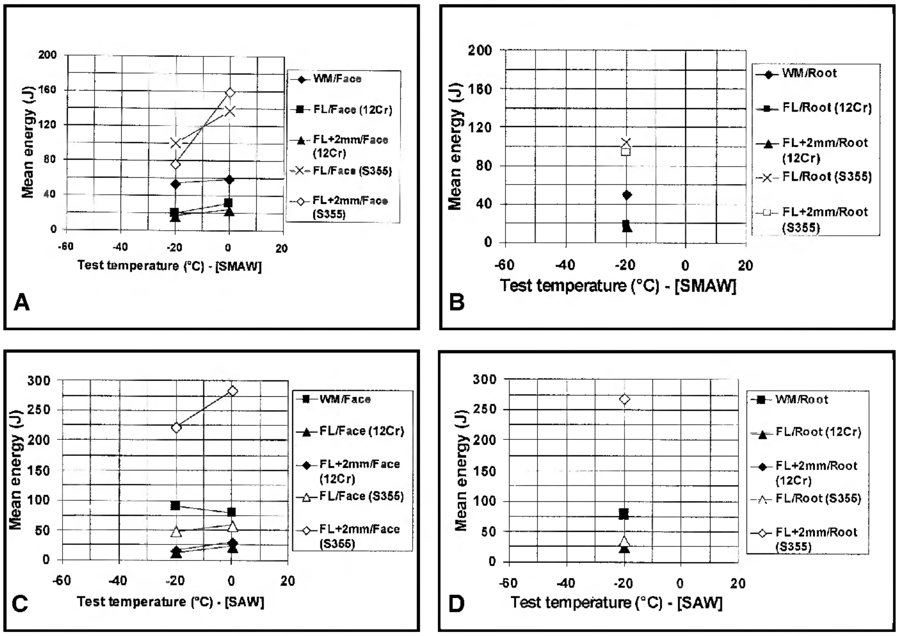

Fig. 3 — Notch impact toughness of the dissimilar welds. A and B — Shielded metal arc welds; C and D — submerged arcwelds.

shows a normal weld profile with some misalignment and/or angular distortion. The dissimilar SA weld shows straight weld interfaces that are perpendicular to the plate surface. The large width of the weld is due to the wide root opening. Macro and micrographs reveal some grain coarsening and martensite islands in the high-temperature heat-affected zones (HTHAZ) of the 12Cr stainless steel — Fig. 1C and D.

Hardness measured over the entire weld cross sections is illustrated in Fig. 2. Values for locations 0.7 mm, respectively, above and below the line of indentations for the left and right HAZ were also measured.

Weld metal hardness for the welds varied between 170 and 270 HV5 . The maximum HAZ hardness for the welds measured about 270 HV5 from the 12%Cr side. Maximum hardness of the nonalloy structural steel in dissimilar welds is about 350 HV5 and was measured at the HAZ of the root of the macro section removed from the SMA weld. Ferrite content of the WM of the SMA welded sample is between 10.12 and 13.87% while the values between 15.69 and 19.69% were measured for the SA welded samples.

Notch impact test results, expressed in Joules (J) are illustrated in Fig. 3. Interpreting the data, when 27 J is considered as the required mean toughness level, both welds failed in the 12Cr side at the WI and WI+2. Based on the results, notch impact transition temperature for the welds was assumed between 0° and 10°C by WI or by HAZ toughness properties.

The CTOD test data for the dissimilar welds are given in Table 3. In general, weld metal toughness is good to excellent, which most surely is attributed to the austenitic filler metal used. However, none of the welds proved to have a WI CTOD fracture toughness of 0.100 mm or higher except one. Scanning electron microscope fractographs with 1000× magnification of CTOD samples are illustrated in Fig. 4. As clearly seen, ductile fracture was observed for the samples notched at the weld metal with quite good CTOD test results, and brittle fracture was determined on the samples notched at the weld interface, which have relatively insufficient results for both welds. The CTOD fracture toughness tests at –20°C on 20-mm-thick welds delivered some disappointing results at the WI. Because of its slant orientation with regard to the plate surface, a mixture of WM, HAZ, and BM microstructures was tested. This can be attributed to the fact that in the case of CTOD fracture toughness testing, a lot of test material is sampled by the notch traveling the entire thickness of the weld. But if the grain coarsening can be controlled, then it is anticipated that CTOD fracture toughness will also be increased to values probably above 0.200 mm. CTOD test results of the WI and WI+2 notched for the SMA welded samples were better than the SA welded ones due to the higher heat input. Slightly better ASTM grain size numbers were obtained from the SMA weld.

Low-carbon 12% Cr steels with ferritic-martensitic structure have the tendency to transform to ferrite in the HTHAZ of fusion welds resulting in grain coarsening and toughness reduction (Refs. 12, 13). A correlation between impact toughness and grain size of the welds was examined with ASTM grain size number measurements at the HAZs. As seen from Table 4, coarse-grained microstructures are identified by small ASTM grain size numbers and this coincides with the low impact test results. This situation can also be confirmed with the article by Meyer and du Toit (Ref. 11) stating that ferrite grain size has a marked effect on the impact properties of the HAZ. Ductile-to-brittle transition temperatures (DBTT) obtained through temperature-cycle simulation by Gooch and Ginn (Ref. 19) indicate that DBTT of 12% Cr steel increases with ferrite grain size. And with

Table 4 — Correlation between Notch Impact Toughness at –20°C and Grain Size Analysis of Samples Removed from the Welds

Welding Process/ Type of Consumables	Test Temperature (°C)	Thickness Position	Notch Position (12 Cr sides)	Impact Toughness (J)	Max. Grain Size No. of Microstructures 12 Cr HAZ
111 SMAW/ E309L-16	–20	Face	WI	21-18-25/21	WI:3
			WI+2mm	26-11-14/17	WI+2:1
	–20	Through root	WI	18-17-22/19	WI+2-3
			WI+2mm	13-25-13/17	WI+2:1
121 SAW/ ER309L	–20	Face	WI	15-11-13/13	WI:1-2
			WI+2mm	16-17-18/17	WI+2:2
	–20	Through root	WI	42-21-15/26	WI:3
			WI+2mm	65-6-18/30	WI+2:3-4

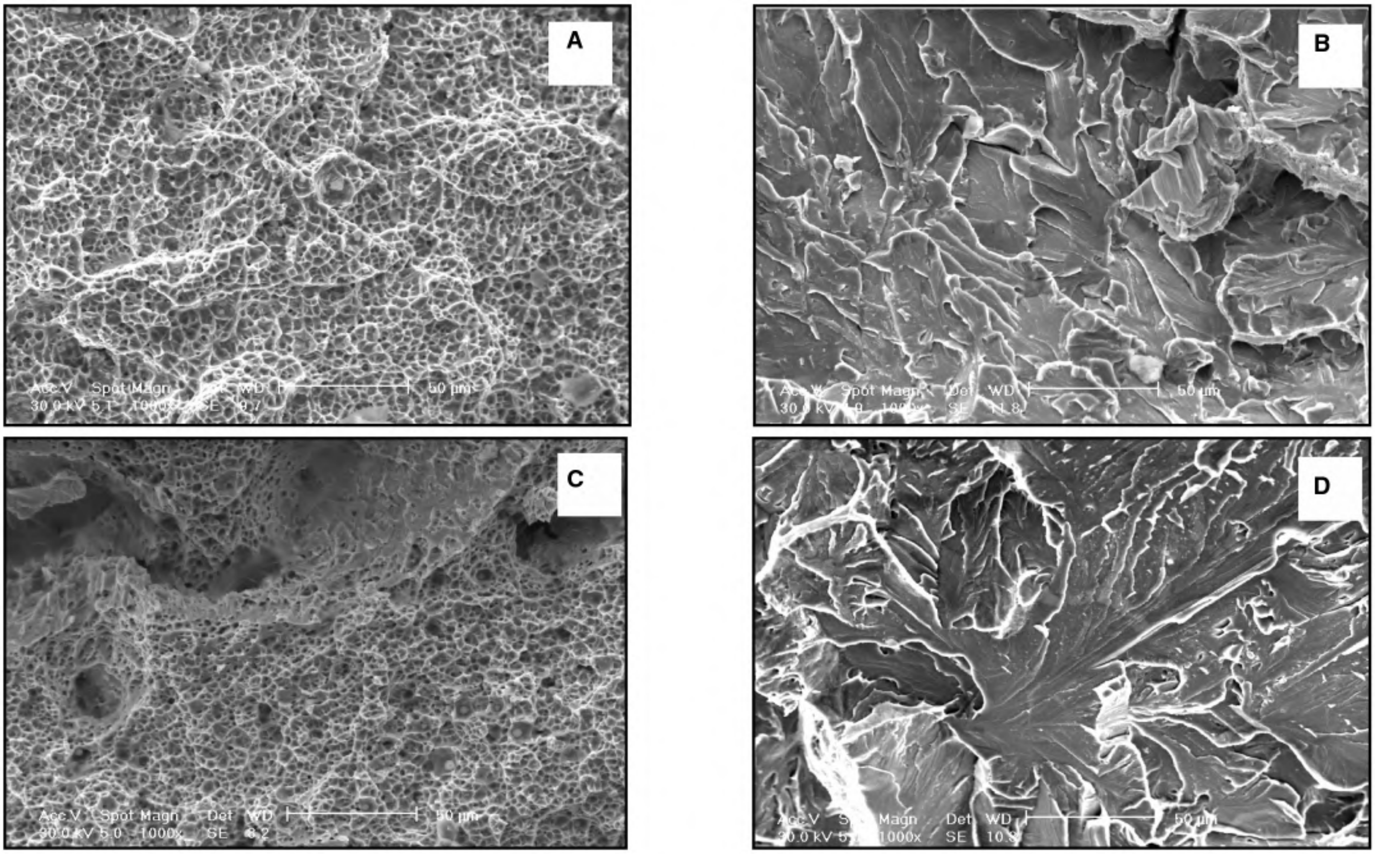

Fig. 4 — SEM fractographs of the CTOD samples. A and C — Weld metal; B and D — weld interface from the 12Cr side of SMA and SA welds, respectively.

reference to Krauss (Ref. 42), the factors that influence the DBTT of ferritic stainless steels are grain size, interstitial C and N, and the presence of various types of secondary phases. Thus, in accordance with the literature, it can be concluded that a fine grain size helps to enhance toughness properties. To enhance grain sizes, heat input should be kept as low as possible (Refs. 11–13).

The transverse tensile test results have demonstrated without exception the actual overmatching strength of the weld vs. the base metals. Fracture occurred as well in the stainless steel as in the structural steel because the actual strength for both steels is very similar. As a result of the weld metal tensile test on the cylindrical test samples completely positioned at the weld metal, the SMA weld demonstrated superior yield strength values compared to the SA weld. None of the face and root bend test specimens failed during 180 deg bending. All welds were found to be sound and extremely ductile.

Photographs of uncoated and coated samples are shown in Fig. 5 after exposure times of 350 and 1000 h for salt spray and 3120 h for blister tests. The purpose here is to distinguish between the resistant and less-resistant welds.

The 350 h of exposure of the uncoated salt spray test samples showed that the SA weld revealed less deterioration than the SMA weld. Long-term (1000 h) salt spray corrosion behavior of coated samples heavily scratched across the weld revealed in both cases some corrosion products at the scratch. The SA weld revealed more corrosion products than the SMA weld. Obviously, the coating provides a good protection for the weld as in general only the scratched regions were deteriorated. From the photographs of the coated blister test samples, it became apparent that both welds have been found resistant against atmospheric attack over a period of 3120 h even when damaged by a severe scratch across the entire welded joint.

Conclusions

The conclusions that follow have been drawn concerning the weld properties of dissimilar SMAW and SAW joints made between modified X2CrNi12 stainless steel and nonalloy S355 steel.

In general, sound dissimilar welds can be made by SMAW and SAW processes with the use of AISI 309 type of consumables. This means that joining of this stainless steel to carbon steel can be accomplished economically by welding, producing weldments with attractive properties. This is because a lean type of stainless steel with low carbon can be produced today by modern steel manufacturers at a reasonable cost, and it requires less long-term maintenance costs than structural carbon steels or less short-term investments than other more expensive stainless steels. Because of its attractive strength properties, this (martensitic-) ferritic stainless steel can be classified as an intermediate, but missing, link between these two types of popular steels, offering a cost-effective alternative.

The major drawback of the stainless steel is the tendency for grain coarsening in the HAZ on the 12Cr side if the heat input during welding is not properly controlled. The HAZ toughness for subzero temperatures may be disappointing depending on the amount of grain-coarsened microstructures. In general, Charpy results of the samples from a SMA welded joint with the notch positions at the weld interface were higher than those from the SAW joint. This depends, among other factors, on the lower heat input of SMAW joints.

The CTOD fracture toughness tests at –20°C on 20-mm-thick welds have delivered some disappointing results at the weld interface because of its slant orientation with regard to the plate surface. This

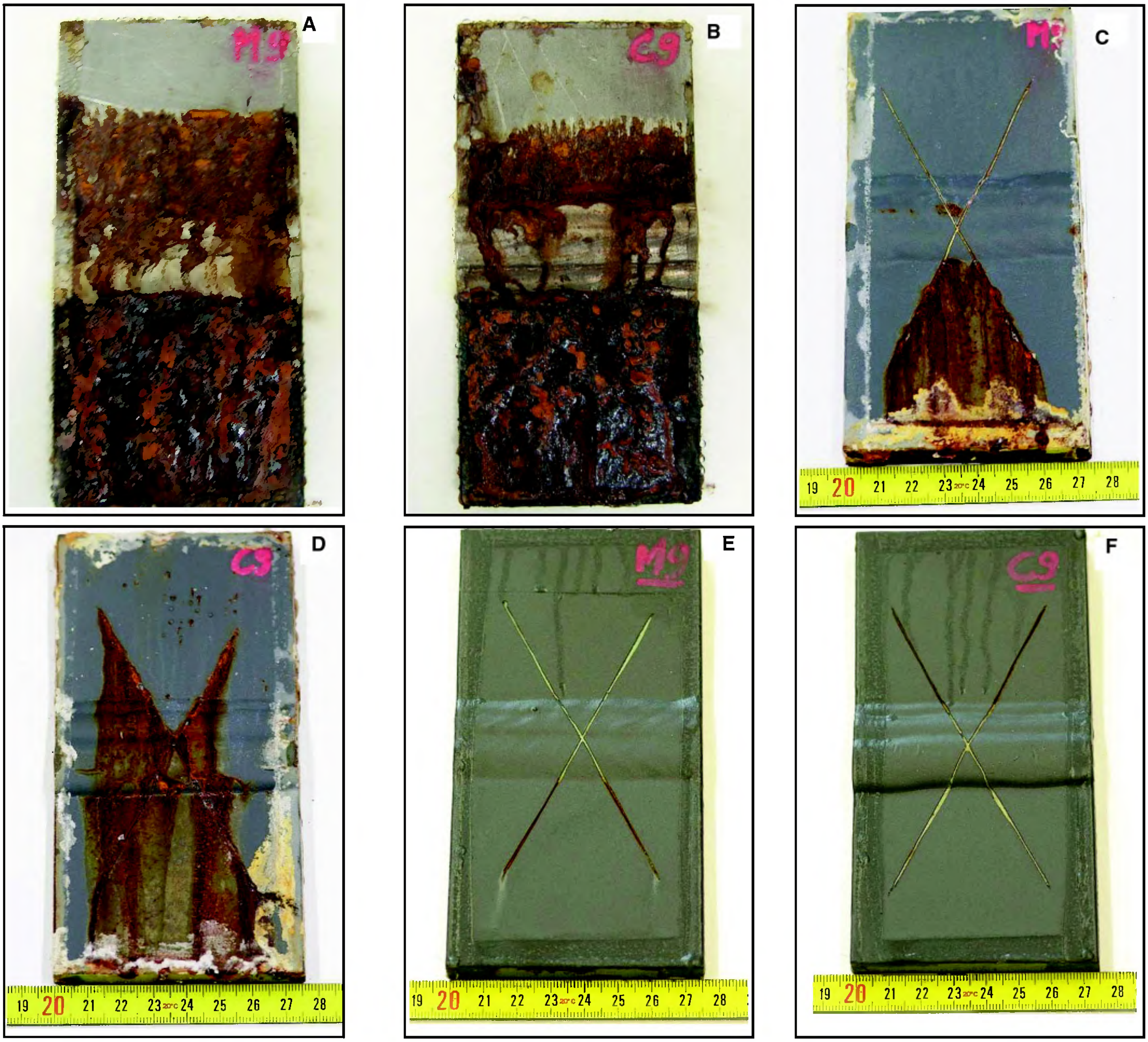

Fig. 5 — Photographs of the corrosion test samples. A and B — Uncoated salt spray samples after 350 h; C and D — coated salt spray samples after 1000 h; E and F — coated blister samples after 3120 h of exposure for SMA and SA welds, respectively.

can be attributed to much more test material is sampled by the notch traveling the entire thickness of the weld. So if the grain coarsening can be controlled, then it is anticipated that CTOD fracture toughness will also increase to values probably above 0.200 mm. The CTOD test results of the WI and WI+2 notched at the SMA welded samples were better than the SA welded ones due to the higher heat input. Slightly better ASTM grain size numbers were obtained from the SMA weld.

Both of the dissimilar welds investigated were produced under conditions comparable to normal practice and so, partially for cosmetic reasons, some capping passes were eccentrically positioned to yield a smooth transition between weld and base metal. This was not done systematically in the same way for both welds, resulting in a different weld profile. This was not considered as a shortcoming to the investigation but rather as a good compromise, simulating actual on-site welding situations.

The weld metal in the present welds without exception was overmatched in tensile strength, while the bend tests revealed the excellent ductility and the absence of any weld defect over the whole welded area. Also, the fact that the transverse tensile test specimens either failed at the stainless steel or at the carbon steel proved that the strength of the modified 12%Cr steel was comparable to that of a commercial structural steel, and this is important to promote the expanded use of this type of stainless steel.

Resistance against atmospheric attack of modified X2CrNi12 stainless steel welds is promising, even when evaluated under severe circumstances, i.e., artificially damaged. Under pure atmospheric conditions, all welds demonstrated the possibility to prevent further development of corrosion, once initiated.

The encouraging aspect is that this stainless steel can be applied to many structural applications.

Acknowledgments

The authors would like to acknowledge the help of all colleagues at the Belgian Welding Institute. In addition, the contributions and technical support of IWT and all members including Industeel, CMI Energy Services, University of Gent, ESAB, Lincoln Smitweld, Ministerie van de Vlaamse Gemeenschap (Metaalstructuren), Bombardier Eurorail, and WTCM are gratefully acknowledged for their contributions, and technical support.

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