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Gas metal arc welding of modified X2CrNi12 ferritic stainless steel

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Abstract

X2CrNi12 ferritic stainless steel is a low cost stainless steel grade exhibiting good corrosion and abrasion resistance. Typical applications for this steel are bus frames and chassis, railway wagons for coal and iron ore, mining and mineral processing, sugar and chemical process equipment, furnace parts etc. The modern production routes now allow fabricating this grade with low carbon content (< 0.015 %) and low impurity levels improving the weldability substantially. Regarding to these conditions, this modified stainless steel grade becomes more attractive. In this paper, microstructural and toughness properties and mechanical properties of gas metal arc welded 6 mm thick modified X2CrNi12 stainless steel with two different heat inputs are presented. Promising results have been obtained. Interesting correlation has been found between microstructure (e.g. grain size) and impact toughness.

Key words: ferritic stainless steel, X2CrNi12, welding, GMAW, grain size

1. Introduction

Stainless steels are an important group of engineering materials that have widely been used in a variety of industries and developed primarily to withstand especially corrosion. These steels constitute a group of high alloy steels based on the Fe-Cr, Fe-Cr-C and Fe-Cr-Ni systems. As the name implies, stainless steels are more resistant to rusting and staining than are plain carbon and lower alloyed steels. To be stainless, the steel must contain minimum 10.5 wt.% of chromium as this level of chromium ensures the formation of a passive surface film that provides corrosion resistance [1–3].

In general, stainless steels can be divided into five families. Four are based on the characteristic crystallographic structure/microstructure of the alloys in the family: martensitic, ferritic, austenitic and duplex (ferritic plus austenitic). The fifth family, the precipitation hardenable alloys, is based on the type of heat treatment used, rather than microstructure. Ferritic stainless steels are classified as such because of their predominant metallurgical ferrite phase, the same as iron at room temperature and body centered cubic crystal structure. Their yield strengths range from 275 to 350 MPa at annealed condition. Ferritic stainless steels contain between 11 and 30 % Cr, with only small amounts of austenite forming elements such as carbon, nitrogen and nickel. Low chromium (10.5 to 12.5 wt.%) alloys have fair corrosion resistance and low cost fabricability. They have gained wide acceptance for use in automotive exhaust systems. The use of low and medium ferritic stainless steel grades in engineering applications over the past decade has increased dramatically and the weldability of ferritic stainless steels has gained a considerable attention [1, 4–6].

Originally, formerly developed 3Cr12 steel with 0.03 % carbon level is used by several steel suppliers and it appears in ASTM A240 as UNS S41003 and in Europe as Material Number 1.4003 [7]. This ferritic stainless steel is known as a low cost stainless steel grade exhibiting good corrosion and abrasion resistance, but limited weldability. Considerable interest has developed in the use of 3Cr12 especially by the automotive and agricultural industries [8].

Nowadays, steel fabricators with modern produc-

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Table 1. Chemical composition of X2CrNi12 stainless steel base metal

Chemical composition in wt.% (*)						
C	Si	Mn	P	S	Cr	Ni
0.01 [≤ 0.030]	0.32 [≤ 1.00]	1.01 [≤ 1.50]	0.023 [≤ 0.04]	0.002 [≤ 0.015]	12.4 [10.5–12.5]	0.43 [0.30–1.00]
Content of additional elements of the base metal						
Cu (%)	Mo (%)	Ti (ppm)	V (ppm)	Al (%)	Nb (ppm)	N (ppm)
0.38	0.08	10	410	0.025	310	104

(*) Values in square brackets are as specified in EN10088

Table 2. Detailed parameters of welded 6 mm thick modified X2CrNi12 steel

Plate No	Welding position	Type of consumable	Protection	Plate preparation	Welding parameters V/A	Welding speed cm/min
1	PA (flat) 3 passes	OK Autrod 16.51 (ø 1 mm) ER309LSi	67Ar/30He/ 3CO$_2$ M12 (1)	V/60° (3 mm root gap)	17.5–18,7/105–160 or (p3) 30.5/115–120 DC+	11.0–25.5
2	PA (flat) 3 passes	OK Autrod 16.51 (ø 1 mm) ER309LSi	67Ar/30He/ 3CO$_2$ M12 (1)	V/60° (3 mm root gap)	17/110 (p3) 20/170	15–31

tion facilities are able to fabricate the modified X2CrNi12 ferritic stainless steel as specified EN10088 with low carbon (< 0.015 %) and impurity levels improving weldability and mechanical properties. Common applications of this modified steel are mining and mineral process, transport equipment, bus frames and chassis, railway wagons for coal and iron ore etc. By modified X2CrNi12 ferritic stainless steels, the missing link between non-alloy structural steels and corrosion resistant alloys can be bridged. Taking into account of these, it might be an option for some applications against non-alloy steel grades. For the long term maintenance costs, this stainless steel requires less coating renewals offering a substantial economic and considerable environmental advantage. For other applications, when compared with higher alloyed stainless steels, the use of modified X2CrNi12 with improved weldability would be more economical [9, 10].

In this paper, modified X2CrNi12 ferritic stainless steels have been welded using gas metal arc welding (GMAW) process. Microstructural, toughness and mechanical properties of the welded joints have been investigated. The welds have been evaluated on the basis of properties that have to attain proper levels, i.e. strength, ductility, hardness and impact toughness.

2. Material and experimental procedures

The actual chemical composition of 6 mm thick modified X2CrNi12 base metal that has been used for this research is given in Table 1.

2.1. Welding of modified X2CrNi12 ferritic stainless steel

Gas metal arc welding process has been applied to two plates of 6 mm thick modified X2CrNi12 stainless steel using a solid austenitic ER309LSi-wire of 1 mm diameter protected by 67Ar/30He/3CO$_2$ and thus slightly oxidizing EN439-M12(1) shielding gas. V-groove preparation was done with an opening angle of 60° and 3 mm root gap. Three passes were deposited to complete the welds. The heat input values have varied from 0.65 kJ/mm to 1.16 kJ/mm and from 0.63 kJ/mm to 0.75 kJ/mm for plate 1 and 2, respectively. Care was taken to assure an initial temperature of minimum 15 ℃ and an interpass temperature of maximum 80 ℃. Detailed parameters are listed in Table 2.

Table 3. Chemical composition of the weld deposits from the GMAW welded plate

C (%)	Si (%)	Mn (%)	P (ppm)	S (ppm)	Cr (%)	Cu (%)	Ni (%)	Mo (%)	Ti (ppm)	V (ppm)	Al (ppm)	Nb (ppm)	N (ppm)
0.03	0.67	1.70	190	30	22.7	0.06	12.1	0.06	70	1030	300	< 10	961

2.2. Chemical analysis of weld deposit

As ER309LSi austenitic stainless steel wire has been used as filler metal for the gas metal arc welded modified X2CrNi12 ferritic stainless steel, the chemical composition of the weld deposit has been analysed.

2.3. Microstructural investigation

Gas metal arc welded joints of modified X2CrNi12 stainless steel were cross-sectioned perpendicular to the welding direction for metallographic analyses. The specimens were prepared, polished and etched with Villela's reagent at room temperature for about 25 s. They were visualized as macrographs and investigated as micrographs by light microscope. Vickers hardness measurements were carried out with reference to EN 1043-1 standard, over the two weld cross sections obtained from the first and second welded plates, with 5 kgf test load at subsurface from the face and root side of each weld.

2.4. Notch impact toughness

Several series of test samples were extracted from and transverse to each weld and notched at the weld metal centre (WM), the fusion line (FL), at the heat affected zone – 2 mm from the fusion line (FL + 2 mm) and 5 mm from the fusion line (FL + 5 mm). Testing was started at –20 ℃ for the samples from welded plate 1, afterwards two more temperatures 0 ℃ and –40 ℃ were explored for the samples from welded plate 2.

According to the results of the two welded joints with different heat inputs and to investigate for a possible correlation between impact toughness and grain sizes of the welds, ASTM grain size numbers were measured on the existing macro sections at the thickness positions from subsurface to mid-thickness.

2.5. Tensile and bend tests

The tranverse tensile test specimens have been taken and prepared from the welded plates, transverse to the weld seam with reference to EN895. The tests have been carried out using a hydraulically controlled test machine at room temperature.

Two face and two root bend test specimens were prepared from the welded plates with reference to EN 910. Detailed parameters are: nominal specimen width: 30 mm – mandrel diameter: 28 mm – bending angle: 180°.

3. Results and discussion

3.1. Chemical analysis of weld deposit

The actual chemical composition of the austenitic weld deposit is summarized in Table 3. Vanadium, nitrogen and titanium are higher while niobium is lower when compared to the base metal.

3.2. Microstructural properties

Gas metal arc welded joints of modified X2CrNi12 ferritic stainless steel metallography samples have been prepared and visualized as macrographs and investigated by light microscope. Relevant macro- and microphotographs are given in Figs. 1 and 2. The microstructural investigation has been carried out on the metallographic specimens of the joints using a light microscope with 200× magnification. The investigation of the weld was performed from base metal (BM) across the heat affected zone (HAZ) to weld metal (WM), respectively. On the micrographs, martensite islands can be observed and adjacent to the fusion line, some grain coarsening at the heat affected zones (HAZ) of the stainless steel was observed. As the grain size analyses have been done on the cross sections of both welded joints, the degree of grain coarsening of the heat affected zones (HAZ) differs for the welded plates according to the heat input level. The grain coarsening of the HAZ in the sample originating from the first welded plate with high heat input was higher than in the sample extracted from the second weld with less heat input. This grain coarsening has an effect on the impact toughness of the samples as explained below.

The hardness distributions of the welded joints are illustrated in Fig. 3. For each sample, heat affected zone measurements include two indentations 0.7 mm above and below the line of indentations for the left HAZ and for locations 0.7 mm below and above the line of indentations for the right HAZ with reference to EN 1043-1. When hardness data are compared, it can be seen that the HV 5 values of the

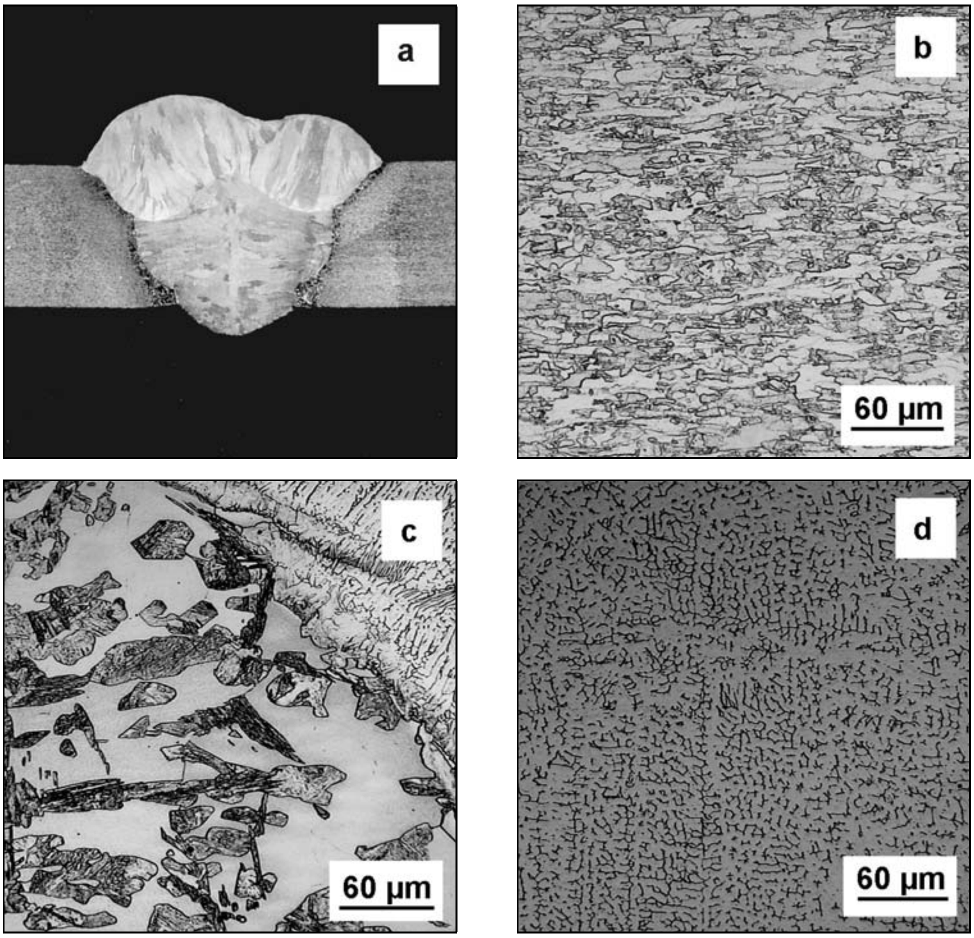

Fig. 1. Light macro- (a) and microstructures of GMAW welded X2CrNi12 from plate 1: (b) BM, (c) HAZ, (d) WM.

Table 4. Absorbed energy values measured on sub-sized test samples extracted from the 6 mm thick weld in X2CrNi12 stainless steel

Welding process/ Type of consumables	Test temperature (℃)	Notch position (–)	Impact toughness (J)
GMAW/ ER309LSi 67Ar/30He/3CO$_2$	−20	WMC	50-49-45/48
		FL	9-11-8/9
		FL + 2 mm	54-54-62/57
		FL + 5 mm	43-41-45/43
	0	WMC	54-51-55/53
		FL	15-37-12/21
		FL + 2 mm	48-74-53/58
		FL + 5 mm	50-50-53/51
	−40	WMC	45-45-43/44
		FL	16-19-9/15
		FL + 2 mm	47-43-41/44
		FL + 5 mm	45-39-48/44

first joint with high heat input have increased more than in case of the second joint with low heat input.

3.3. Notch impact toughness

The individual and mean values of the notch impact toughness samples after the tests are given in

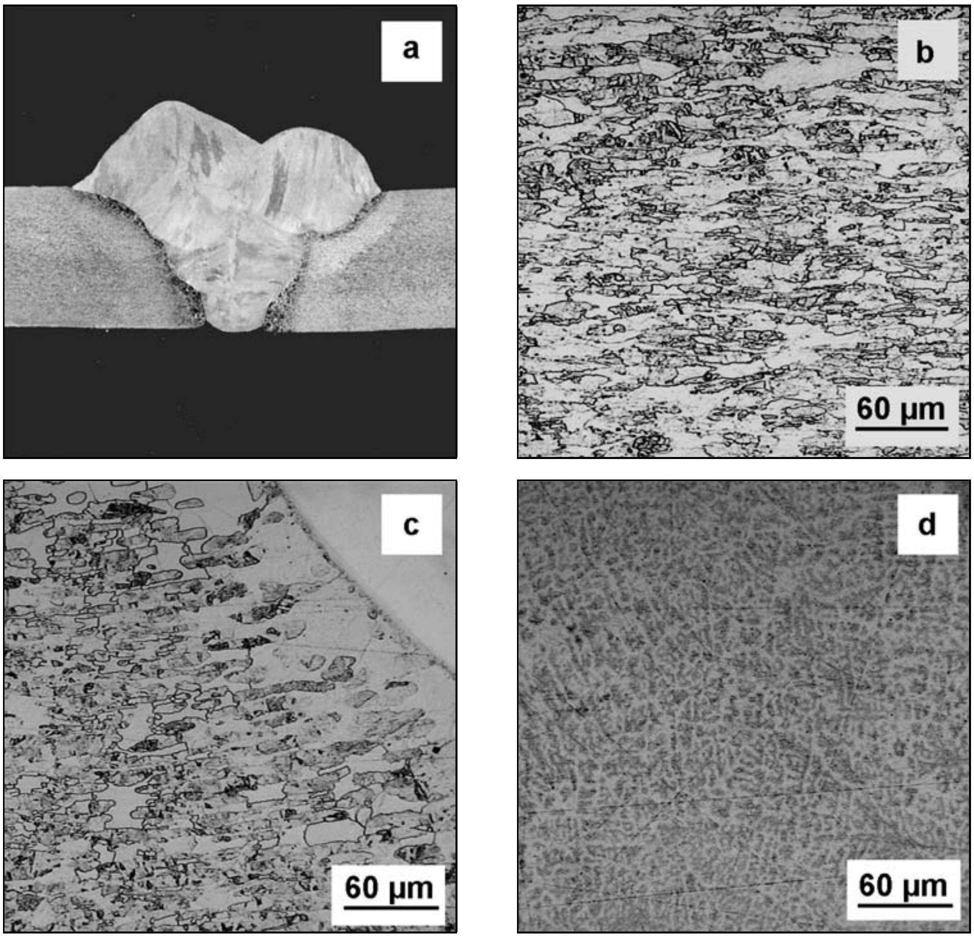

Fig. 2. Macro- (a) and microstructures of GMAW welded X2CrNi12 from plate 2: (b) BM, (c) HAZ, (d) WM.

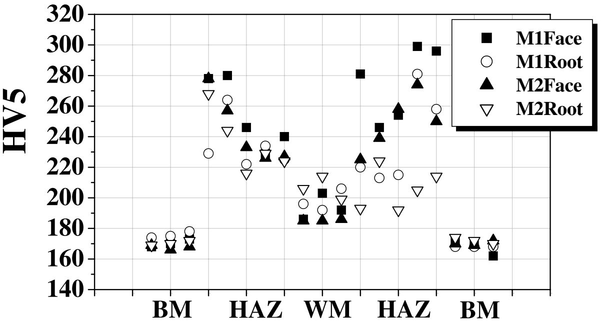

Fig. 3. HV 5 hardness across the GMAW welded samples from plate 1 and 2.

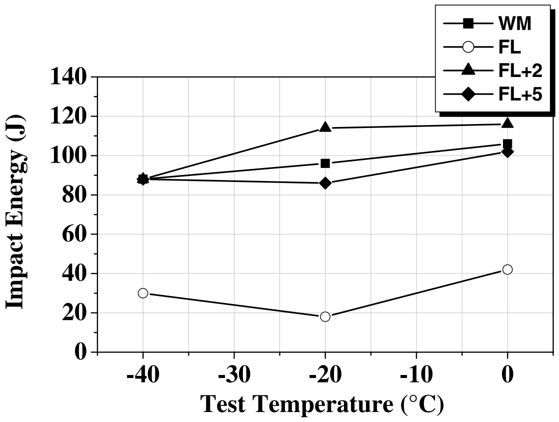

Fig. 4. Absorbed energy values measured for 5 mm thick samples removed from the 6 mm thick plates; at −20 ℃ from welded plate 1 and at 0 ℃ and −40 ℃ from welded plate 2.

Table 4. The data expressed in J are illustrated in Fig. 4 according to the mean values of the Charpy impact tested samples instead of individual values. It should be taken into account that toughness of the 6 mm thick GMAW weld was measured on 5 mm thick and 10 mm wide (reduced to 8 mm by notching) and thus so called ‘sub-sized’ test samples with reference to EN 875 and EN 10045-1. Multiplying these results with a factor of two yields a fairly good estimate for the equivalent toughness of a standard 10 mm thick notch impact specimen.

Considering the values obtained from the Charpy impact test samples originated from plate 1 welded

Table 5. Correlation of notch impact toughness at –20 °C, 0 °C and –40 °C and grain size on samples removed from welds

Origin	Notch position	Test temperature (°C)	Mean impact toughness (J)	Max. grain size no. of microstructures	
				Left HAZ	Right HAZ
Plate 1	FL	–20	18	4	4
	FL + 2 mm		114	9	8–9
Plate 2	FL	0	42	7	7
	FL + 2 mm		116	9–10	9
	FL	–40	30	7	7
	FL + 2 mm		88	9–10	9

with a higher heat input than plate 2, the mean value at the fusion line is 18 J at –20 °C. If 20 J is considered as the required mean toughness level, the fusion line results of the weld of first plate are less adequate. However the results from the same plate for other Charpy positions at –20 °C are more satisfactory. The impact toughness values for the samples originated from plate 2 welded with a lower heat input at the temperatures of 0 °C and –40 °C are quite good for 6 mm thick GMA welded plate.

To investigate for a correlation between impact toughness and grain sizes of the welds, ASTM grain size numbers were measured on the existing macro sections at two thickness positions from subsurface to mid-thickness. Taking account of the inclined fusion line, the positions are sampled in specimens notched at the heat affected zone fusion line and fusion line + 2 mm. A summary of these examinations is given in Table 5. It is emphasized that fine grained microstructures have high ASTM grain size numbers (for instance between 6 and 10) while coarse grain microstructures are identified by small ASTM grain size numbers (for instance between 1 and 4). In general limited fusion line toughness corresponds indeed with coarse grains (ASTM M10, 2 or 3). Considering the two welded plates, the macro sections of M1 and M2 samples originating from plate 1 and plate 2, respectively, have been subjected to grain size analyses. For welding of plate 1, a high heat input has been used, consequently the grain coarsening effect can clearly be observed on the samples. As ASTM grain size numbers vary from 4 to 9 between fusion line and fusion line + 5 mm for the samples originating from plate 1 where the heat input is high, the ASTM grain size numbers have been measured between 7 and 10 for the same positions for the samples from plate 2 with low heat input. When ASTM grain size numbers are compared with the impact test results, the Charpy results for the samples from plate 1 are less favourable; however the values for the samples from plate 2, with subzero test temperatures such as –40 °C, are quite good. This might be considered as a correlation between grain size numbers to microstructure and toughness. Also the effect of heat input should be taken into account. When the grain size difference in heat affected zones of the two microstructures in Figs. 1 and 2 is observed, it can also be said that a higher heat input causes grain coarsening in the heat affected zones of this type of ferritic stainless steels and so it results in lower Charpy test data. This indicates that grain size would play a major role in the fracture toughness of HAZ in 12 % Cr steel welds. Referring to the article by Meyer and du Toit [8], ferrite grain size has a marked effect on the impact properties of HAZ. Ductile to brittle transition temperature (DBTT) results from the samples obtained through temperature-cycle simulation by Gooch and Ginn [11] indicate that DBTT of 12 % Cr steel increases with the ferrite grain size. And with reference to Krauss [2], the factors, which influence the ductile to brittle transition temperature of ferritic stainless steels, are grain size, interstitial carbon and nitrogen and the presence of various types of second phases. Thus a fine grain size, low interstitial element contents and the elimination of second phases by proper heat treatment all enhance ductility and toughness. In accordance with the literature a fine grain size helps to enhance toughness properties.

3.4. Tensile test properties

Two transverse, full thickness tensile specimens that were extracted from the welded plate 1 and tested at room temperature with a width at the prismatic section of 25 mm have shown an overmatch. In all cases, fracture of the welds occurred in the base metal. Splitting of the base metal was generally observed close to the fracture surfaces and parallel with the plate surface of all samples.

Table 6. Full-thickness transverse tensile and bend properties of the 6 mm thick weld made in the modified X2CrNi12 stainless steel plate

Test type	Specimen code	Tensile strength (MPa)	Remarks after testing
Transverse tensile	TT1	535	Fracture location: Base metal
	TT2	536	Fracture location: Base metal
Face bend	F1	–	No defect
	F2	–	No defect
Root bend	R1	–	Small harmless undercut
	R2	–	No defect

3.5. Bend test properties

Two face and two root bend specimens were prepared from the welded plate 1 transverse to the weld seam. Detailed parameters are: nominal specimen width: 30 mm – mandrel diameter: 28 mm – bending angle: 180°. None of the samples failed during bending revealing no defects. Transverse tensile and bend test results are presented in Table 6.

4. Conclusions of GMA welded modified X2CrNi12 ferritic stainless steel

The main conclusions of this research work can be summarized as follows:

Ferritic stainless steel complying with EN10088: X2CrNi12 can be fabricated with a low level of carbon and impurities offering attractive mechanical properties fulfilling specifications for non-alloy structural steel.

In general, sound homogeneous welds can be obtained using gas metal arc welding by means of highly alloyed AISI 309 type of consumables with reduced risk for hot and cold cracking.

The hardness at the heat affected zone of the stainless steel can be limited to 300 HV 5 depending on the heat input. The weld metal in the welds without exception was overmatched in tensile strength.

According to our results, grain size has dominant effect on impact toughness, however microstructure cannot be fully omitted. Grain coarsening has no adverse influence either on tensile properties or on bend properties but the heat affected zone impact toughness for sub-zero temperatures generally decreases and this depends on the amount of grain coarsened microstructures and eventual precipitates present. Although it is difficult because of the complexity of microstructures sampled by notches located at the 'fusion line' or at the heat affected zone, microscopic investigations have shown indeed for these welds that the grain coarsening could be restricted to microstructures with ASTM grain size numbers of 6 or higher. The tensile properties such as elongation and contraction are dominantly controlled by microstructure.

The improved weldability of this modified X2CrNi12 ferritic stainless steel with controlled chemical composition and delivery condition is demonstrated, leading to higher productivity during welding, so its field of application will largely be extended.

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