Baosteel Technical Research
Volume 12, Number 2, June 2018, Page 25

Gas metal arc welding of duplex stainless clad steel plates

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Abstract: The 2205 duplex stainless + DH36 clad steel plate was welded by gas metal arc welding (GMAW), and the welding performance of the clad steel plate was investigated. The results show that the adaptability of the welding procedure for the base metal of carbon steel, the transition layer, and the cladding material is excellent. The test results indicate that the phase proportion and component dilution of the GMAW-welded joints of clad steel plate can be effectively controlled to yield joints with good mechanical properties and corrosion resistance.

Key words: duplex stainless clad steel plates; gas metal arc welding; deposited weld metal; welding process; corrosion resistance

doi: 10.3969/j.issn.1674-3458.2018.02.005

1 Introduction

In terms of engineering materials, today's rapid economic development in China requires the materials to be economical while also ensuring their functionality and reliability. This implies a higher demand for the steel products than before, which has promoted the popularization and application of many new materials. Among these, duplex stainless steel is the most demanded because of its economy and reliability. Compared with traditional austenitic stainless steel, duplex stainless steel has better resistance against chloride stress corrosion, better weldability, and better mechanical properties. In recent years, the proportion of duplex stainless steel used in industrial and engineering applications has risen rapidly. The use of duplex stainless steel reduces the cost of corrosion-resistant materials, improves the economic benefits of engineering projects, and increases the reliability of industrial equipment due to its superior performance[1]. Since the 20^{th} century, a great deal of research has been devoted to the corrosion resistance, mechanical properties, and weldability of duplex stainless steel both in China and abroad, effectively promoting the application of duplex stainless steel in the industrial fields[2-3].

In recent years, with the demands for engineering applications and breakthroughs in steel production technology, the application of roll-bonded stainless clad steel plate is becoming increasingly extensive. Stainless clad steel plate combines high strength, high corrosion resistance, and low cost, and is becoming the key material for addressing the requirements of high strength, long life expectancy, and high corrosion resistance in a variety of industrial fields, including shipbuilding, construction, and manufacturing. The roll-bonded stainless clad steel plate produced by Baosteel and the explosion cladding plate produced by Taiyuan Steel Group used in the nuclear power unit safety injection tank have achieved domestic substitution, and China's third-generation nuclear power technology also has independent access to strong material support. In the chemical transport manufacturing process, Baosteel's roll-bonded stainless clad steel plate has achieved its first domestic application, thereby breaking the monopoly of Japanese products in this field. The use of stainless clad steel plates rather than pure stainless steel plates is associated with considerable economic benefits, thereby reducing manufacturing costs and increasing

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the competition for related products.

2205 stainless steel combines the advantages of ultralow carbon composition, the austenitic and ferritic duplex structure at room temperature, high Cr content, and the additions of Mo and N, which provide excellent corrosion resistance. This steel is the most commonly used product in duplex stainless steel, reaching a proportion of about 80%. Multilayer fusion welding is widely used in industrial production, and 2205 duplex stainless steel undergoes multiple weld thermal cycles. The rapid heating and cooling, however, leads to changes in the phase ratio and phase distribution in the weld and heat affected zone, which affect the corrosion resistance of the welded joints. Therefore, it is necessary to ensure the appropriate phase ratio in the welding process to promote balance between the two phases and prevent the aggregation and growth of the α phase[4]. The manufacture and application of the 2205 duplex stainless clad steel plate is in its infancy. Although the investigation of the corrosion resistance of cladding materials has promoted the application of clad steel plate, there are only a few studies and reports on the weldability and corrosion resistance of welded joints of the 2205 duplex stainless clad steel plate. Therefore, it is necessary to study and consider the influence of the welding process on both the corrosion resistance and overall performance of the welded joints of the 2205 duplex stainless clad steel plate.

2 Test method

The test material used in this study was a 2205 + DH36 duplex stainless clad steel plate with a thickness of (3.2 + 9) mm. This duplex stainless steel clad steel plate was produced by bond rolling, and the chemical composition is shown in Table 1. For this study, V-type groove shape machining was chosen, and the shape of the resulting butt-welded joint is shown in Fig. 1.

Table 1 Chemical composition of the duplex stainless clad steel plate %

Metal	w_C	w_{Si}	w_{Mn}	w_S	w_P	w_{Cu}	w_{Ni}	w_{Cr}	w_{Mo}	w_V	w_{Ti}	w_{Al}	w_{Nb}
Base metal (DH36)	0.068 0	0.190 0	1.430 0	0.001 6	0.012 0	0.009 0	0.007 0	0.019 0	0.012 0	0.004 0	0.012 0	0.044 0	0.012 0
Cladding material (2205)	0.030 0	0.500 0	1.420 0	0.002 1	0.026 0	0.190 0	5.440 0	22.270 0	3.000 0	0.100 0	0.004 2	0.006 0	0.019 0

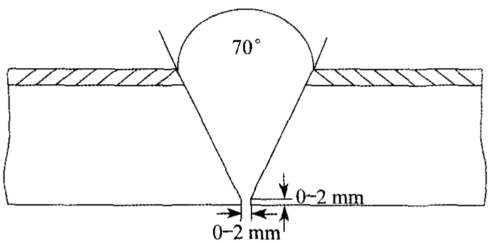


Fig. 1 V-type groove shape

In general, the welding material is selected to meet both the strength requirement of the base metal and the specific characteristics of the engineering application. In this study, the flux-cored wire REDLANE F71T-1C was used to match the weld properties of carbon steel DH36. To ensure that the welded joint of the duplex stainless clad steel plate has a corrosion resistance similar to that of the cladding material, ESAB SHIELD BRIGHTI 2209 (E2209) was used to finish the welding of the transition layer and cladding material. The welding of the base metal was completed first. A ceramic liner was used to ensure an identical weld shaping of the two sides while welding the base metal. At the same time, fusion of the cladding material with the weld metal of the base metal had to be avoided. The welding thickness of the base metal had to be suppressed to less than that of the base metal 1 – 1.5 mm. To ensure corrosion resistance in the welded joint, the transition layer and cladding material were welded to obtain a certain phase ratio and microstructure. Considering that the welding of the transition layer is affected by the dilution of the base metal, the same E2209 flux-cored wire was used in the welding of the transition layer to reduce the dilution of the Cr, Ni, and Mo elements, thereby ensuring the thickness of the transition layer at about 2.5 mm. The welding heat input of the cladding material also had to be controlled to ensure a suitable phase ratio and dilution of the composition, and thus, a good corrosion resistance. The composition of the flux-cored wire E2209 is shown in Table 2, the welding process parameters in Table 3, and the macroscopic appearance of the welded joint in Fig. 2.

Table 2 Chemical composition of a typical E2209 flux-cored wire %

w_C	w_{Si}	w_{Mn}	w_P	w_S	w_{Cr}	w_{Ni}	w_{Mo}	w_N
0.015	0.800	0.900	0.015	0.015	22.700	9.000	3.200	0.130

Table 3 Welding process parameters

Weld bead	Welding process	Welding material		Polarity	Welding current/A	Welding voltage/V	Welding speed/ ($cm \cdot min^{-1}$)
		Diameter/ mm	Welding consumable				
Backing weld	GMAW	1.2	F71T-1C	DCEP	190 – 210	22 – 28	12 – 18
Fill bead	GMAW	1.2	F71T-1C	DCEP	215 – 228	22 – 28	22 – 30
Fill bead	GMAW	1.2	F71T-1C	DCEP	220 – 232	22 – 28	26 – 34
Transition layer	GMAW	1.2	E2209	DCEP	140 – 150	22 – 28	12 – 18
Welding of cladding material	GMAW	1.2	E2209	DCEP	135 – 145	22 – 28	10 – 15

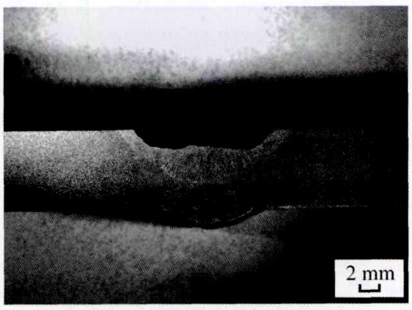


Fig. 2 Macroscopic morphology of the welded joint

3 Analysis of the mechanical properties of the welded joints of clad steel plate

The mechanical properties of the welded joints of clad steel plates were tested to determine the effect of the welding process on the cold bending properties, toughness, and hardness of the weld bead and heat affected zone. After mechanically processing the metallographic and tensile specimens, a German ZWICK/Roell Z2000 tensile testing machine was used to measure the tensile strength of full-size specimens of the welded joints, a German AMSLER RKP450 impact testing machine was used to test the impact properties of the welded joints of the base metal, and a YJW-2000 electrohydraulic servo bending test machine was used to test the face bend and back bend performance of the welded joints of the full-size specimens. An HV-10 small-load Vickers hardness tester was used to measure the hardness of the welded joints.

The full-size tensile specimens of the welded joints were broken in the base metal, and the tensile strength met the requirements, as shown in Table 4 and Fig. 3. The impact toughness test results show that the toughness of the welded joint and heat affected zone of the base metal was excellent, and the impact toughness index of −20 ℃ met the requirements of BV NR216 as shown in Table 5. For the application of clad steel plates, the strength and toughness of the welded joints of the base metal must meet the structural-strength design requirements of the engineering application. Cracks were observed neither in the face or back bends of the welded joints nor in the heat affected zone of the base metal and cladding material in the 180° bending test, as shown in Table 6 and Fig. 4. The plasticity of the welded joints was satisfactory, such that the welding process used on the transition layer and cladding material was successful in ensuring a good combination of the deposited weld metal in the base metal and cladding material, in avoiding interfacial cracking, and in achieving good overall mechanical properties. The hardness test results of the welded joint indicate that the hardness of the deposited weld metal of the base metal slightly decreased as compared with that of the base metal and the heat affected zone. In addition, the hardness of the deposited weld metal of the transition layer and cladding material was slightly lower than that of the 2205 duplex stainless steel base metal. No abnormally hardened area was observed, as shown in Figs. 5 and 6.

Table 4 Tensile properties of the welded joints

Sample No.	Width/ mm	Thickness/ mm	Cross-sectional area/mm²	Tensile strength/ MPa	Fracture location
1	12.60	20.12	253.50	642.00	Base metal
2	12.60	20.28	255.50	634.00	Base metal

Fig. 3 Tensile samples

Table 5 Impact performance of the welded joints

Sample No.	Sample size/ (mm × mm × mm)	Notch part	Ballistic work (−20 ℃, mean value)/J
1	55 × 5 × 10	Weld metal(WM)	83
2	55 × 5 × 10	Fusion line(FL)	93
3	55 × 5 × 10	FL + 2 mm	123

Table 6 Bending properties of the welded joints

Sample No.	Test type	Sample size/ (mm × mm × mm)	Bend core diameter/ mm	Bending angle/ (°)	Test results
1	Face bend	300 × 20 × 12.6	50	180	No cracks
2	Face bend	300 × 20 × 12.6	50	180	No cracks
3	Back bend	300 × 20 × 12.6	50	180	No cracks
4	Back bend	300 × 20 × 12.6	50	180	No cracks

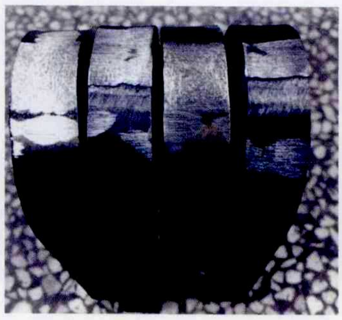


Fig. 4 Bending samples

4 Analysis of the microstructural transformation of the welded joint

The interface between the base metal and cladding material of the duplex stainless clad steel plate exhibited good uniformity, as shown in Fig. 7. The expansion coefficient of the 2205 stainless steel is close to that of the base metal; thus, the working temperature range is generally limited to −40 – 280 ℃. The 2205 stainless clad steel plate demonstrated both corrosion resistance and high strength, with its microstructure being nearly 50% ferrite and 50% austenite, as shown in Fig. 8.

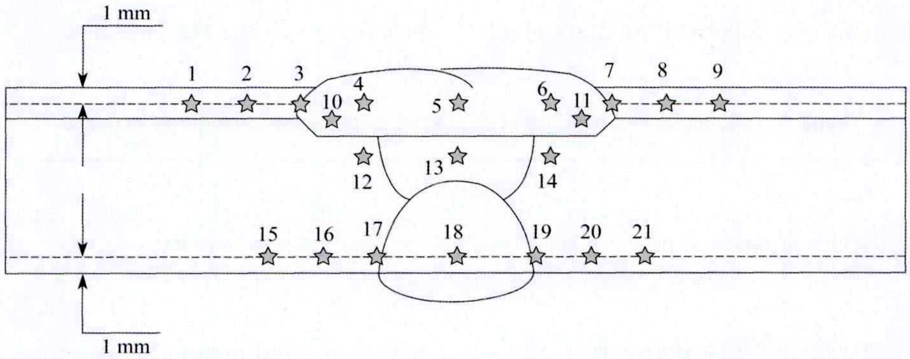


Fig. 5 Hardness diagram

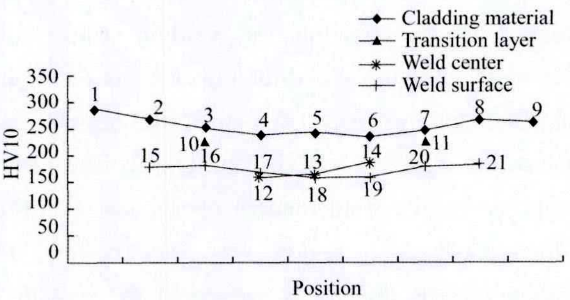


Fig. 6 Hardness of the welded joints

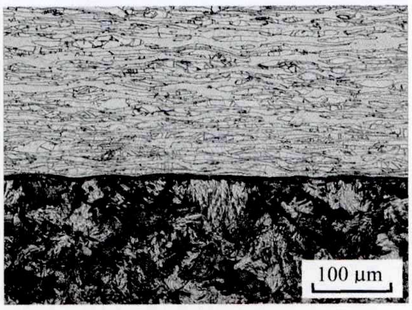


Fig. 7 Microstructure of clad steel plate

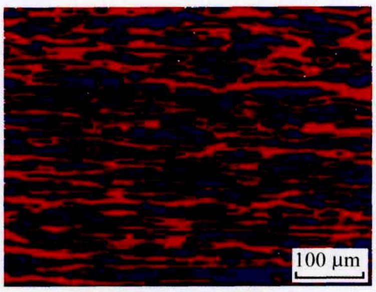


Fig. 8 Phase distribution of the cladding material 2205

To ensure that the corrosion resistance of the deposited weld metal in the multilayer weld was not less than that of the cladding material, E2209 was selected to increase the nickel content to 9%. The appropriate cooling rate ensured that the deposited weld metal of the cladding material exhibited a phase balance comparable to that of the cladding material, as shown in Fig. 9.

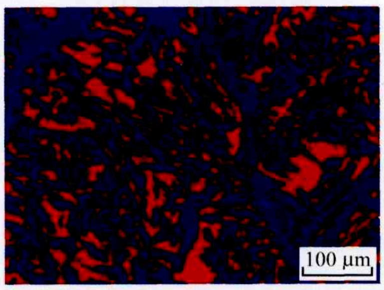


Fig. 9 Phase distribution of the welding of the cladding material

The use of E2209 as the deposited weld metal of the transition layer also reduced dilution in the welding of the cladding material. To ensure proper corrosion resistance, the chemical composition of the flux wire also matched that of the 2205 cladding material (Table 7). The pitting corrosion performance of the welded joint was consistent with ASTM standard A923-08/C, as shown in Table 8 and Fig. 10. Using the above welding wire and welding process, the welded joints of the cladding material met the requirements of the ASTM standard (corrosion rate (mdd) = weight loss (mg)/(specimen area (dm^2) · time (d)), the calculated corrosion rate should not exceed 10 mdd).

The microstructure of the deposited weld metal of carbon steel is shown in Fig. 11. The multilayer welding process resulted in a significantly less or even the disappearance of dendrite and the formation of typical reticular ferrite. After welding the base metal, an obvious tendency was observed for the presence of grain in the fusion zone of the base metal, as shown in Fig. 12.

Table 7 Chemical composition of deposited weld metal of cladding material %

w_C	w_{Si}	w_{Mn}	w_S	w_P	w_{Cu}	w_{Ni}	w_{Cr}	w_{Mo}	w_V	w_{Ti}	w_{Al}	w_{Nb}
0.040	0.630	1.030	0.007	0.022	0.190	8.090	21.750	3.460	0.100	0.023	0.001	0.020

Table 8 Corrosive pitting performance

Sample No.	Mass before corrosion/g	Mass after corrosion/g	Corrosion rate/mdd
1	14.346 7	14.346 5	0.72
2	14.170 6	14.169 9	2.64

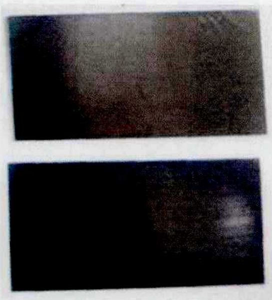


Fig. 10 Image of samples after corrosion test

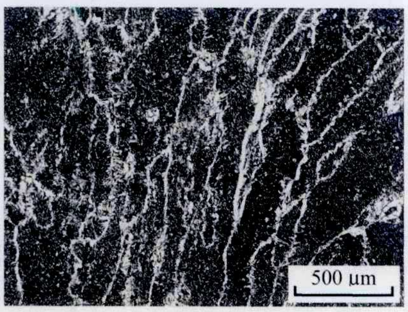


Fig. 11 Microstructure of the carbon steel weld

The deposited weld metal produced ferrite during the cooling process of welding the cladding material, ultimately generating all ferrite at the end of the solidification process. Ferrite is stable over a high temperature range and begins to change to austenite below its solid melting temperature. The microstructure in the upper left area of Fig. 13(a) is that of the deposited weld metal of the transition layer, in which it can be seen that the welding seam of the base metal and the cladding material in the upper right area achieved good fusion. In the heat affected zone of the cladding material, the grains were clearly roughened by the weld thermal cycles, but the width of the coarse grain region was very narrow. The welding process effectively prevented the growth of the organization of the heat affected zone and avoided any weakening of the welded joint. The mixed austenite and ferrite structure obtained in the deposited weld metal of the transition layer depended on the weld-wire composition and cooling rate. The results of the energy spectrum analysis show that the contents of Cr, Ni, and Mo in the deposited weld metal of the transition layer are lower than those in the weld bead of the cladding material. In the upper half of the deposited weld metal of the transition layer, austenite was first formed at the ferrite grain boundary. Then the grain nucleation assumed an austenitic-strip-like morphology, as shown in Fig. 13(b). The above welding process caused the surface of the welded cladding material to exhibit good corrosion resistance. In multipass welding, the deposited weld metal of the transition layer undergoes secondary heating, which causes additional diffusion on the weld bead component, such that the existing austenite grows to form a new nucleated secondary austenite. The phase content of austenite in the deposited weld metal of the transition layer near the carbon-steel base reached 86.9%, which was much higher than that on the surface of the welding of the cladding material, as shown in Fig. 14.

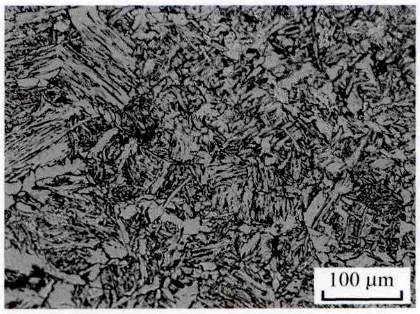
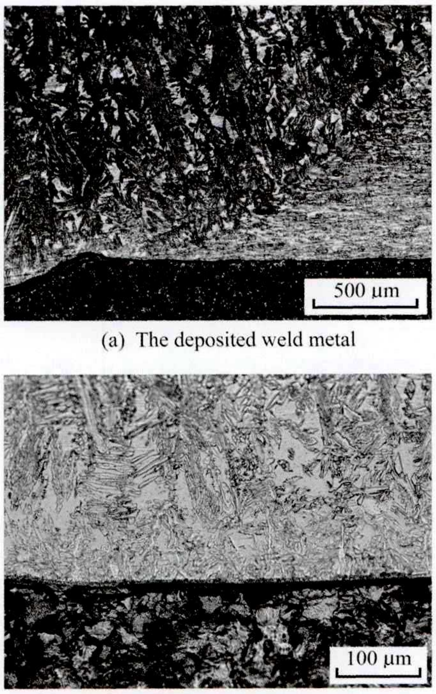


Fig. 12 Microstructure of the fusion zone of the base metal



(a) The deposited weld metal

(b) The deposited weld metal of the transition layer

Fig. 13 Microstructure of the weld metal

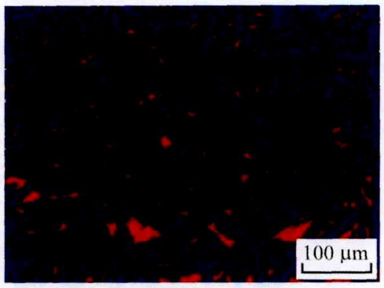


Fig. 14 Phase distribution of the deposited weld metal of the transition layer

The E2209 used in the multilayer welding seam had higher nickel and nitrogen contents than those in the base metal, which effectively reduced the Cr_{eq}/Ni_{eq} ratio to yield a higher solid melting temperature of ferrite. It can also form austenite at a higher temperature, thereby prompting the austenite to form faster when cooled, to achieve further ferrite-austenite phase transformation. The proportion of the components in the deposited weld metal of the cladding material is close to that of the cladding material, which prevents pitting corrosion of the welded joint. In addition, the relatively low ferrite content prevents any decrease in ductility and toughness, which benefits its overall performance. The microstructure of the welded cladding material is shown in Fig. 15.

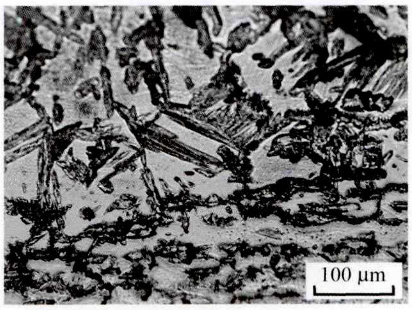


Fig. 15 Microstructure of the welded cladding material

5 Conclusions

(1) Using the above welding process, the welded joints of clad steel plate obtain excellent mechanical properties that meet the structural strength requirements of engineering applications.

(2) The deposited weld metal of the transition layer effectively reduces the dilution of carbon steel in the welding of cladding material and prevents corrosion resistance.

(3) The proper selection of welding materials and the appropriate welding cooling rate ensure a matching composition of the cladding material, good ferrite-austenite balance, and good austenite distribution, thereby ensuring that the welding of the

cladding material has the same corrosion resistance as the cladding material itself.

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WU Wei