UDC 539.4

Process Analysis and Trial Tests for Hot-Rolled Stainless Steel/Carbon Steel Clad Plates

Z. Y. Chen,[a,b,1] J. X. Li,[b] Z. G. Lin,[b] J. J. Qi,[b] L. Sun,[b] and G. D. Wang[a]

[a] The State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang, China

[b] Technical Department, Technology Research Institute of HBIS, Shijiazhuang, China

[1] chenzhenye@hbisco.com

The trials of 304 stainless steel-clad plate made of plain Q345B carbon steel were performed on hot-rolling line of the Hesteel Group. After the two runs of pilot production, the key process parameters for the stainless steel/carbon steel clad plate were found to meet the GB/T 8165-2008 requirements. The interface shear strength of the clad plate was higher than 360 MPa, the yield strength of the final product was over 257 MPa, the clad plate tensile strength and elongation exceeded 351 MPa and 39.8%, respectively. The interpenetration of stainless steel and plain carbon steel layers was established to be complete, with the adequate composite interface. The tensile and shear properties of stainless steel-clad plates produced by the rolling process were at the same level as those obtained via the explosive method as an alternative, while their production cost were somewhat reduced.

Keywords: clad plate, stainless steel, plain carbon steel, hot-rolling process, shear and tensile strength, fracture morphology.

Introduction. The hot-rolled stainless steel clad plate is a laminar composite material obtained by the solid-phase bonding of the stainless steel composite material and a low-carbon steel base material, blended under high temperature, high pressure or shock wave, and combines the structure and the function of the individual constituents [1, 2].

As a resource-saving product, the stainless steel clad plate reduces the consumption of the precious metal, and the engineering cost. This perfectly combines the high performance with cost-effectiveness and manifests pronounced economic effects. The demand of the stainless steel clad plates has escalated in the domestic market, and has been widely used in various sectors, like oil, chemical engineering, spaceflight, shipbuilding, metallurgy, construction and power generation [3–6].

Currently, the domestic manufacturing approaches of stainless steel composite plate mainly include: the cold rolling, hot rolling, explosive welding, explosive welding with rolling, etc. [7, 8]. Among them, the “explosive welding with rolling” technique combines the characteristics of the two techniques viz. the “explosive welding” and the “hot rolling method,” which offsets the thickness, length, width, and size restriction of the product by merely using the explosive welding method. This method is used to in the production of thin, coil and irregular composite material [9, 10].

In this study, we successfully conducted the pilot-scale production of the composite blank by using the “explosive welding method accompanied with the rolling” technique.

1. **Development of the Composite Blank**. The substrate material was the Q345B steel, with a thickness of 100 mm, and the composite layer was made using the 304 stainless steel, with a thickness of 10 mm. Tables 1 and 2 show the chemical composition and carbon equivalent of stainless steel 304 and Q345B, respectively.

One of the two surfaces of the 304 stainless steel and Q345B steel was machined, in order to make it smooth. Subsequently, the oxide layers over both the steels were removed. The explosive cladding technique was used to make the steel blank, and the composite blank had the dimensions: 105×1600×1000 mm. The 304 stainless steel had a thickness of

Table 1

Chemical Composition of 304 Stainless Steel (wt.%)

C	Si	Mn	P	S	Cr	Ni	N	C_{eq}*
≤0.08	≤1.00	≤2.00	≤0.035	≤0.03	18.0–20.0	8.0–10.5	≤0.10	4.53

* C_{eq} = [C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15]×100%.

Table 2

Chemical Composition of Q345B Steel (wt.%)

C	Si	Mn	P	S	Cr	Nb	Ti	C_{eq}*
≤0.20	≤0.55	≤1.70	≤0.040	≤0.040	0.02–0.15	0.015–0.060	0.02–0.20	0.32

* C_{eq} = [C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15]×100%.

9 mm, while the Q345B steel had a thickness of 96 mm in the obtained blank. The composite billets of stainless steel and carbon steel were obtained by means of an explosion. After the explosion, the base material and the composite layer were found to be firmly bonded, and the composite material bent slightly after being combined, but the surface remained smooth. The quality of the composite was perfect in the head, end and edge areas.

2. **Trial Rolling of the Composite Blank**.

2.1. ***Preset Heating and Rolling Process Parameters***. Two pieces of the composite slab (304 stainless steel+Q345B steel) were procured with the dimensions 105×1600×1000 mm. The expected specifications of the finished product were: 8.0×1460 and 5.0×1500 mm.

The slabs were placed in the heating furnace with the stainless steel side downward, using the heating process parameters as shown in Table 3. The temperature of the soaking section was set at 1220±20°C. The furnace was kept in a weakly oxidizing atmosphere, and the lower surface of the composite billet was required to be at a temperature, about 10–20°C higher than the upper surface. The total residence time of the composite billet in the furnace was more than 120 min. During the heating process, the composite slab was monitored at to prevent the sinking of the slab.

Table 3

Heating Process Parameters of Compound Billet

Reheating schedule	Preheating section	Reheating section I	Reheating section II	Soaking section	Slab temperature
Furnace gas temperature (°C)	≤ 960	≤ 1050	1150±20	1220±20	1180±20
Time (min)	≥ 50		45	20	
Remarks	Weak oxidation atmosphere. Temperature of the lower surface was 20°C higher than upper surface				

The rough rolling process was set at three passes. The thickness of the intermediate slab was 38 mm. During the rough rolling stage, the load dynamic balancing function between the upper and lower connecting shafts was canceled. The sled coefficient was adjusted such that: at 1 m length from the head of blank, the speed of lower roll was 5–18%

higher than that of the upper roll during the rough rolling. 7 rounds of finish rolling were conducted, and cooling water was not used between the passes. The specifications of finished products were: 8.0×1460 and 5.0×1500 mm. During the rolling process, the temperatures of main process nodes: RT5 = 1050°C, FT = 910°C, and CT = 690°C.

2.2. ***Summary of Production Process***.

(1) During the rolling process, the composite slab was put into the heating furnace with the stainless steel side downward. The soaking temperature was 1220°C, while the initial rolling temperature was 1180°C, and a 16% reduction rate was set during the first pass. The load dynamic balancing function of rolling mill control system was canceled. During the rolling process of the 8 mm clad plate, a speed difference of 12–15% was set between the two rolls, while during the rolling process of 5 mm clad plate, a speed difference of 17–18% was set between the two rolls. The rolling process of the two steel plates was successful.

(2) During this rolling process, the asymmetrical rolling function was adopted, but the difference in the speed between the two rolls did not reach the maximum limit. However, during the next trial rolling, the asymmetrical rolling speed of the work roll was set to the maximum value.

(3) The rolling process was adopted to produce single-side stainless steel composite board using the two rolls of different diameters. The procedure to remove the high-pressure water descaler improved the quality of the surface during the next rolling.

3. **Properties of the Stainless Steel Composite Plate**. The clad plates were tested for different physical and mechanical. The tests results showed that the surface quality, shear strength, yield strength, tensile strength and percentage elongation after fracture met the requirements of GB/T 8165-2008. The results of the impact test indicated that, the stainless steel composite layer exhibited a very little influence on the impact performance of the base material under room temperature, and the stainless steel layer and plain carbon steel layer had a strong combination. Besides, the composite interfaces were straight and smooth, and there was an absence of any non-composite surface.

3.1. ***Mechanical Property Test***.

3.1.1. *Tensile Shear Test*. Samples for the tensile shear test were collected from the final composite coils, according to the GB/T 6396-2008 specifications. The sample size was 25 (width) and 350 mm (length). Figure 1 shows the specimen of the stainless steel clad plate after pull shear. The results of the tensile test and tensile shear test of the stainless steel composite board are shown in Table 4, and it was found that all mechanical properties fulfilled the GB/T 8165-2008 requirement. The shear strength of the interface was significantly higher than 210 MPa (requirements of Chinese National Standards for stainless steel clad plate). The tensile and shear mechanical properties of the 304 stainless steel clad plates produced by the explosion process and rolling process are compared in Table 4. According to the test data, the mechanical properties of the 304 stainless steel clad plate produced by the rolling process were similar to those obtained by the explosion process.

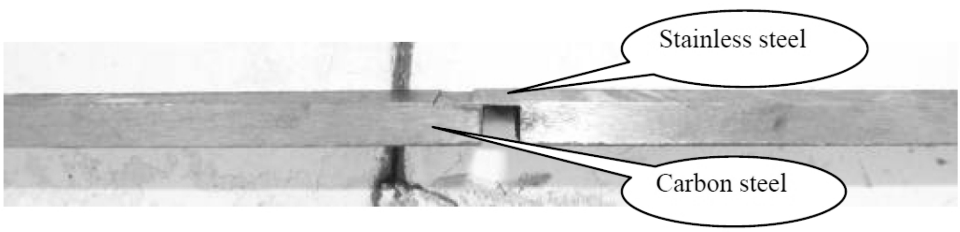


Fig. 1. Specimen of stainless steel clad plate after pull shear.

Table 4

Tensile and Shear Properties of Test Composite Plates

Stainless steel clad plate and production process	Shear strength of interfaces τ, MPa	Upper yield strength ReH, MPa	Tensile strength Rm, MPa	Elongation A, %
Q345B+304, explosive welding with rolling, 5 mm	392	288	382	39.8
Q345B+304, explosive welding with rolling, 8 mm	360	257	351	46
Q345B+304, explosive welding, 5 mm	409	289	393	41
Q345B+304, explosive welding, 8 mm	395	278	376	47
GB/T 8165-2008	≥ 210	≥ 196	≥ 290	≥ 33

3.1.2. *Impact Test*. The impact test was conducted below the room temperature. The dimensions of the impact samples of 5 and 8 mm stainless steel composite plates were 4.5×10×55 and 7×10×55 mm, respectively. The impact of the stainless steel composite panel is shown in Fig. 2. Two samples were prepared for this test, wherein the sample code A and B represented a groove in the stainless steel layer and the carbon steel layer, respectively. The results of the impact test for stainless steel composite plate at room temperature is shown in Table 5. In accordance with the experimental data, it can be seen that the pilot-production of hot-rolled stainless steel composite plate exhibited good impact toughness, with a quite stable impact value.

Table 5

Impact Test of the Stainless Steel Clad Plate

Clad plate	Test temperature	Sample number	Group I $KV2$, J	Group II $KV2$, J	Group III $KV2$, J
5 mm	Room temperature	A	101.17	98.85	94.23
		B	108.71	105.87	105.87
	0℃	A	86.07	93.77	98.19
		B	88.97	87.45	88.85
8 mm	Room temperature	A	99.56	97.89	102.38
		B	98.99	97.98	95.67
	0℃	A	85.55	87.89	90.98
		B	87.96	89.57	90.77

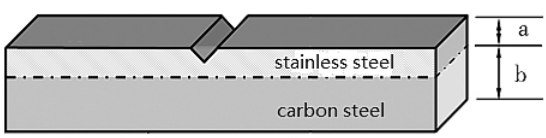
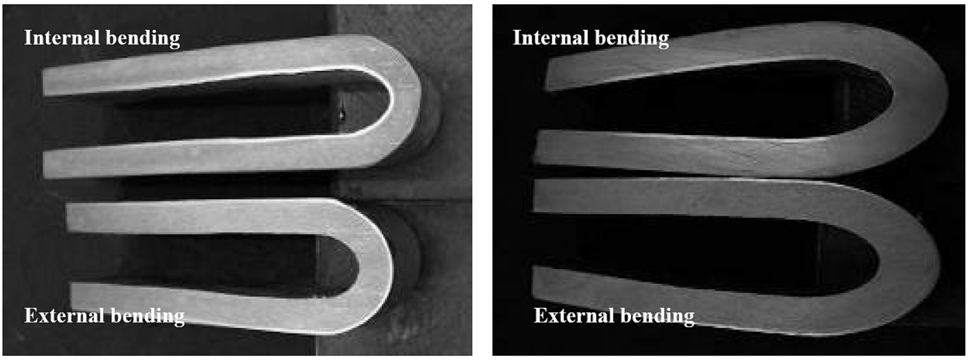


Fig. 2. Impact test of the stainless steel clad plate specimen.

3.1.3. *Bending Test*. The standards of GB/T 6396-2008 were followed during the bending test, and the sample size was 25 (width) and 350 mm (length). Two test samples were selected for the bending test from each coil, with composite material as the tension face (external bending test) and with base material as the tension face (internal bending test). After the bending test, no crack on the internal/external bending test samples (diameter of bending pressure head $D = 2a$) for stainless steel composite plate of two different coils could be observed by the naked eye (as shown in Fig. 3) and all the test results met the standards.



a b

Fig. 3. Bending specimens of 5 (a) and 8 mm (b) of stainless steel clad plate.

3.2. ***Microscopic Structure Observation***. The microstructure of the image around the joint interface of the stainless steel composite plate is shown in Fig. 4. The figure shows that the composite interface was straight and smooth, and there was no non-composite interface. The carbon steel zone far from the composite interface was a classic hot rolling microstructure, made up of ferrite and pearlite. The content of pearlite within the carbon steel near the composite interface was significantly decreased, which indicated that this area had a certain degree of decarburization. The decarburization was caused by the carbon shift (C-shift) since the mass fraction of C at the carbon steel side (0.2%) was higher than that on the stainless steel side (0.066%), and there was a high difference in the chemical potential of C between the two ends of steel. In addition, Si was also found to improve the chemical potential of carbon. Although Cr suppressed the diffusion of carbon, the latter was quite significant across the stainless steel composite layer [11].

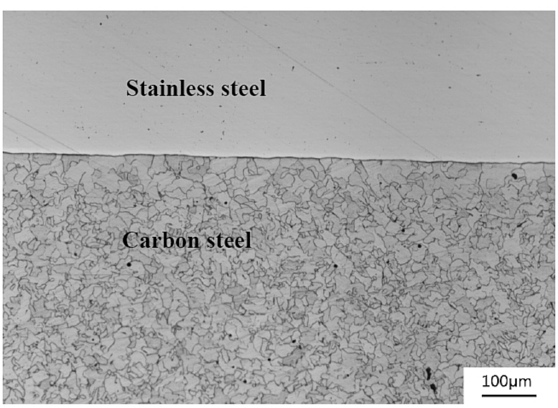
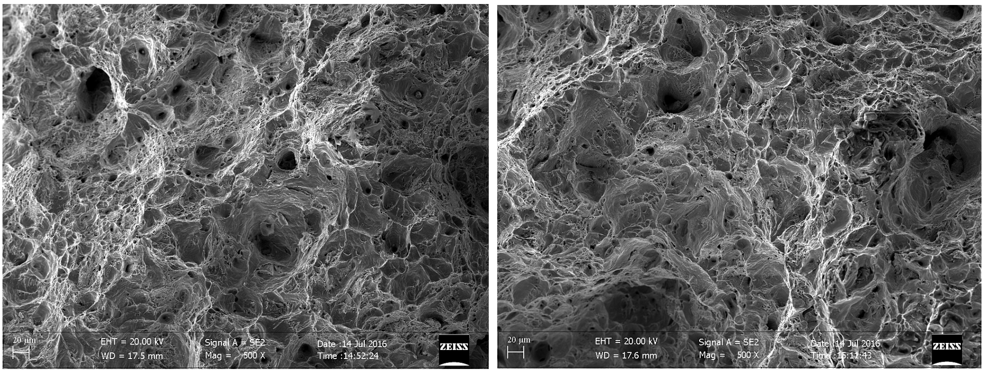


Fig. 4. Microstructure image of the stainless steel composite board.

Figure 5 shows the tensile shear fracture morphology of the stainless steel composite plate. The dimple is clearly visible in the figure. The tensile fracture of stainless steel composite exhibited a ductile fracture. Thus, the microscopic studies revealed excellent tensile properties of the tested composite steel plate.



a b

Fig. 5. Tensile shear fracture morphology of stainless steel composite plate: specimens of 5 (a) and 8 mm (b) clad plate.

Conclusions

1. For the stainless steel/carbon steel composite plates produced by the technique of "explosive welding with rolling", the shear strength was found to esceed 310 MPa, yield strength was over 210 MPa, tensile strength was higher than 340 MPa, and the percentage elongation after fracture exceeded 39.8%. Various indices of the composite plates were found to comply the GB/T 8165-2008 specifications.

2. In the fabricated stainless steel/carbon steel composite plates, the stainless steel layer and plain carbon steel layer showed a strong amalgamation, the composite surface was straight and smooth, and there was an absence of any non-composite surface.

3. During the single-side rolling of the composite plates involving dissimilar materials, the asymmetrical rolling or different-diameter rolling was found to avoid the flatness problems caused by different elongation of two materials.

4. The pilot production in the study has laid down the certain basis for the production of the single-side dissimilar-material composite board.

1. S. C. Pan, M. N. Huang, G. Y. Tzou, and S. W. Syu, "Analysis of asymmetrical cold and hot bond rolling of unbounded clad sheet under constant shear friction," *J. Mater. Process. Tech.*, **177**, Nos. 1–3, 114–120 (2006).
2. L. Li, X.-J. Zhang, H.-Y. Liu, et al., "Shear strength of the interface of hot rolling stainless clad steel," *Iron and Steel*, **48**, No. 12, 52–56 (2013).
3. X.-L. Pan, Z. Gao, S.-K. Xie, et al., "Bonding technology and new development of laminated-metal material," *Nonferr. Met. Process.*, **37**, No. 1, 34–36, 44 (2008).
4. J. M. Yu, Y. Z. Xiao, Q. J. Wang, et al., "New development of technology of clad metal," *Chinese J. Mater. Res.*, **14**, No. 1, 12–16 (2000).
5. X. T. Liu, T. Zhang, and J. Z. Cui, "Technology of clad metal production and its latest progress," *Mater. Rev.*, **16**, No. 7, 41–43 (2002).
6. H.-M. Ding, X.-L. Fan, J.-F. Wang, et al., "Interface characterization of hot-rolled stainless steel/carbon steel clad," *Trans. Mater. Heat Treat.*, **32**, No. 11, 18–22 (2011).

7. L. Li, Z.-C. Zhu, X.-J. Zhang, and H.-Y. Liu, "Experimental study on hot rolled stainless steel clad plate produced by TMCP," *J. Mater. Eng.*, **43**, No. 7, 62–67 (2015).
8. H. X. Zheng, B. K. Li, and Z. Chang, "Current development condition of process of metal clad plate," *Steelmaking*, **17**, No. 2, 20–23 (2001).
9. H. Sun and K. Wang, "Discussion on the production method and manufacturing technology of clad plate of stainless steel," *Shanghai Metals*, **27**, No. 1, 50–54 (2005).
10. M. Yang, X. Q. Zuo, M. W. Zhao, et al., "Research progress of manufacturing technology for stainless steel clad plate," *Mater. Heat Treat.*, **27**, No. 1, 93–96 (2005).
11. A. Z. Hanzaki, P. D. Hodgson, and S. Yue, "The influence of bainite on retained austenite characteristics in Si–Mn TRIP steel," *ISIJ Int.*, **35**, 81–84 (1995).

Received 15. 03. 2018