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Interface Characteristics and Properties of a High-Strength Corrosion-Resistant Stainless Steel Clad Rebar

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Abstract: This paper aims at manufacturing stainless steel clad (SSC) rebars by metal deposition and a hot rolling method as well as characterizing its interface features and mechanical properties. The interface of the SSC rebar is relatively flat and clean, exhibiting a metallurgical bonding state at the microscale. Decarburization occurred at the interface in the carbon steel side of the SSC rebar. The diffusion of C, Cr, as well as Mn was measured across the interface of the SSC rebar, and the diffusion distance of Cr and Mn was found at 32 µm and 25 µm, respectively. The Vickers hardness testing in the transition zone of the SSC rebar near the carbon side showed 545 HV due to the martensite phase formed by the diffusion of key elements C, Cr, and Mn. The microstructure in the transition zone near the stainless steel reveals the duplex structure of martensite and ferrite. The carbide precipitations were observed near the interface, both in the transition zone and in the base metal of the stainless steel zone. The yield strength, tensile strength, and elongation of the SSC rebar were found as 423 MPa, 602 MPa, and 22%. No macroscopic crack was observed after the positive or negative bending tests.

Keywords: metal deposition; hot rolling; interface; diffusion distance; mechanical properties; SSC rebar; carbide; martensite; Vickers hardness; bending

1. Introduction

With an ever-increasing demand for enhanced durability and strength, the prospect of widespread applications of stainless steel clad (SSC) rebars is promising in the realm of infrastructure, chemical industry, oil industry, and construction engineering [1–3]. Since 2000, SSC rebar research has been widely implemented in some American states, such as Texas and Virginia, and the results revealed that a SSC rebar shows the same corrosion resistance as that of stainless steel when subjected to accelerated cyclic wetting and drying tests in a corrosive solution [4,5].

By using various techniques, SSC rebars have been effectively prepared by manufacturing technologies. A major American steel bar company (SMI-Texas) applies the Osprey process. The liquid stainless steel in an atomizing chamber is sprayed with nitrogen gas on the surface of a carbon billet, which is heated to 1100 °C in the induction furnace, and then cladding billets are transferred to a rolling mill where they are hot rolled into bars with appropriate dimensions [2]. In this manner, SSC rebar with a clad layer of 2205 or Cr13 stainless steel and a carbon steel core was successfully manufactured.

Explosive cladding is applied as a solid-state cladding method in which two dissimilar metals are welded by an instantaneous impact. However, due to the environmental concerns, this method raised some skepticism [6].
Kazuyuki Nakasuji and Chihiro Hayashi published a patent to manufacture a clad bar where an outside layer of 304 stainless steel is assembled with a core part of carbon steel, and then the resulting assembly is cold drawn and then rolled with rotary cone rolls. Other bimetallic composite metals, such as Cu/Al, can also be produced by this method [7].

Xie et al. expounded a way to fabricate SSC rebars, a clad assembly which consisted of 304 stainless steel and carbon steel was hot rolled in the laboratory mill. The features of the metallurgical bonding interface were researched in detail. Through the combination of finite element simulation and rolling experiment, the stress and strain state of composite steel bars at high temperature and the distributed situation of stainless steel cladding on carbon steel were revealed [8,9].

It was reported that SSC rebars can be manufactured using ferrous metal debris and a stainless steel tube. Firstly, tiny divided ferrous metal debris was compacted into briquettes in a stainless steel tube to make SSC billet. Then the SSC billet was heated to 1250 °C and rolled in the bar production line into the suitable dimension when the core of the SSC billet was soft and plastic enough [10].

Tuominen et al. applied the laser cladding method to fabricate two different kinds of round SSC rebars. The first one was made by the cladding layer of St21 and substrate metal of S355, and the other was made by the cladding layer of In625 and the base metal of 42CrMo4 [11].

Xiang et al. reported that the SSC billet was interference fit jointed by the outer part of a 304 stainless steel tube and inner core part of carbon steel. Then, the SSC billet was hot rolled in a temperature of 1150 °C through 18 passes. The metallurgical bonding interface and good mechanical properties can be obtained simultaneously by this method [12].

In the industrial production of SSC rebars, the first step is to prepare the SSC billet with uniform stainless steel cladding and qualified quality, and subsequently to conduct hot processing or cold processing for the SSC billet. In the actual production process, environmental protection, production stability, and production efficiency should be considered at the same time.

Because of the risk to harm the environment, the prospect of explosive cladding is not good. The production efficiency of laser recombination is low, so the application of laser cladding to make SSC rebars is limited. In the case of a mechanical cladding method or a clad assembly method, because the interface of the SSC billet cannot reach the metallurgical bonding state, some production accidents, such as the separation of the stainless steel coating and the carbon steel matrix, often occur in the first passes of hot processing. Our research group also solved this problem using liquid–solid casting and the hot rolling method to prepare the SSC rebar because the metallurgical bonding state could be achieved in the liquid–solid casting process [13].

In the present study, metal deposition and hot rolling methods were applied in a steel plant, which manufactures wire and bar products in Guangdong. A SSC rebar can be successfully manufactured by metal deposition and the hot rolling method. Not only was the steady rolling of the SSC rebar demonstrated, but the fine metallurgical bonding preference of the interface of the SSC rebar was also achieved. The method described in this paper not only saves a lot of stainless steel but can also improve the corrosion resistance of the project.

2. Experimental

2.1. Raw Materials

The chemical compositions of stainless steel and carbon steel are presented in Table 1. The carbon steel HRB400E was designed to serve as the core of the SSC rebar due to its higher strength and lower cost. The stainless steel Cr13 was chosen as the coating layer because of its corrosion resistance and low cost. These two materials are picked to make composite rebars because of their good comprehensive performance and because they are of lower cost.
### 2.2. Production Process

#### 2.2.1. The Fabrication of SSC Rebar Using Metal Deposition and Hot Rolling Method

Figure 1 shows the concept of metal deposition and hot rolling to fabricate the SSC rebar. The carbon billets were surface-treated and then cladded into an SSC billet, which was covered by stainless steel on the surface of the original carbon billet, except for the two cross sections through the metal deposition method (Figure 1a,b). The original dimensions of a carbon steel billet is 150 mm × 150 mm × 3000 mm, and a 5 mm stainless steel layer is overlaid on the surface. The built-up billet is hot-rolled to produce a SSC rebar (Figure 1c,d).

![Figure 1. Schematic of the metal deposition and hot rolling process for stainless steel clad (SSC) rebar: (a) surface treatment, (b) stainless steel cladding on a billet, (c) heating in the furnace, and (d) hot rolling.](image)

Before the production of the SSC rebar, obtaining a clean interface between the original carbon billet and SSC is important to achieve a high bonding quality. Pellet blasting, which reveals the fresh metal of the billet surface, is required to form a high-quality SSC billet. The surface treatment removes the scale and other foreign matters, and the metal deposition process with flux ensures the high bonding strength at the interface of the SSC billet and avoids interface oxidation during heating in a furnace and hot rolling. In the field of composite plate manufacturing, surface treatment is also a crucial factor to the bonding strength of a composite interface [14].

#### 2.2.2. Rolling Process of SSC Billet

Hot rolling was carried out through 16 passes after soaking the SSC billet at 1150 °C for 180 min, and the initial rolling temperature and the final rolling temperature was 1100 °C and 980 °C, respectively (Figure 2a). After rolling (Figure 2b), the SSC rebar was cooling in the air.

Cr13 stainless steel with a carbon content of 0.026% is ferritic stainless steel and generally needs heat treatment after rolling to reduce stress concentration [15]. HRB400E needs water cooling after rolling to improve strength [16]. Concerning the interface characteristics of bimetals, heterogeneous phases always form at the interface. In order to ensure that the mechanical properties meet the requirements, the final rolling temperature was reduced from 1030 °C to 980 °C.

The SSC billet was reduced from the rectangular section (160 mm × 160 mm) down to the circular section (Ø20 mm) to achieve a steady rolling process.

Figure 2c presents that the SSC rebar was cooling on the colling bed in the air. Figure 2d displays a bright and clean surface of the SSC rebar after polishing, which demonstrates the typical gloss of stainless steel.

### Table 1. Chemical composition of Cr13 stainless steel and mild carbon steel (mass %).

| Elements | C  | Si  | Mn  | P  | S  | Cr  | Ni  | Nb  | Ti  | Fe  |
|----------|----|-----|-----|----|----|-----|-----|-----|-----|-----|
| HRB400E  | 0.244 | 0.494 | 1.21 | 0.010 | 0.026 | 0.21 | 0.04 | -   | 0.04 | Bal. |
| Cr13     | 0.026 | 0.412 | 0.35 | 0.021 | 0.015 | 12.8 | 0.16 | 0.02 | -   | Bal. |
2.2.3. Microstructural Research and Mechanical Test

To observe the metallographic morphology of the interface, a solution of 5 mL nitric acid and 95 mL ethanol was used. The microstructure of carbon steel can be well etched with this solution, and the distribution of stainless steel can be easily observed and measured. A total of 4 g trinitrophenol, 5 ml hydrochloric acid, and 95 mL ethanol were used to observe the microstructure from the base metal of the carbon steel to the substrate of stainless steel.

The microstructure and interface morphology were studied with optical microscopy (Zeiss 40MAT, Oberkochen, Germany), field emission environment scanning electron microscope of Quant 650-FEG (FEI Corp., Hillsborough, OR, USA), equipped with energy-dispersive X-Ray spectroscopy (EDS) of Pegasus Apex 4. Second phase or precipitates are often analyzed by EDS. In this paper, EDS was used to analyze the element composition of carbides.

The diffusion phenomenon of key elements was researched with electron probe micro-analyzer (EPMA) of JXA8230 (JEOL Corp., Tokyo, Japan). The line and map scan data of key elements, such as Cr and Mn, near the SSC interface can be accurately analyzed by EPMA. Although carbon is a light element and cannot be quantitatively analyzed by EPMA, some qualitative analysis can be performed through the peak distribution detected by carbon element near the interface.

The equilibrium phase diagram of Fe-Cr was calculated by the thermodynamic software Thermo-Cal 2019a (Solna, Sweden), which is authorized by the Central Iron and Steel Research Institute.

Vickers hardness was measured by the Vickers hardness tester FM-300 (FUTURE-TECH Corp., Tokyo, Japan) with a 200 g load for 10 s. The change of microhardness at the interface can reflect the change trend of phase transition, precipitation, or element diffusion to a certain extent.

The yield and tensile strengths of SSC rebars were measured using a tensile testing machine (WE-300 type, hensgrand, Shangdong, China). The testing sample was prepared according to the Chinese national standard of «GB/T 228.1-2010 Metallic materials -tensile testing-Part 1: Method of..."
Chinese national standard of «GB/T 228.1-2010 Metallic materials-tensile testing-Part 1: Method of test at ambient temperature». The sample was a proportional sample with a gauge length 10 times the diameter.

3. Results and Discussion

Mild carbon steel (HRB400E) was successfully cladded with Cr13 stainless steel to manufacture a SSC rebar.

3.1. The Manufacturing of SSC Billet Using Metal Deposition

During the metal deposition process, the stainless steel melted and covered the carbon billet. The flux can avoid the metal oxidation at high temperature, which can ensure the cleanliness of the interface of the SSC rebar, just as shown in Figure 3a. A carbon steel billet with dimensions of 150 mm × 150 mm × 3000 mm overlaid with a 5 mm stainless steel layer was obtained (Figure 3b).

Due to the higher deposited temperature, the as-cast carbon billet was bonded to the stainless steel at the atomic scale, and a metallurgical bonding state was subsequently achieved. The microstructure of the weld heat affected zone (HAZ) was observed on the carbon steel side. Figure 3c shows the interface of the SSC billet after metal deposition, the etched part was the carbon steel, the unetched part was Cr13 stainless steel. On the side of carbon steel, a typical weld HAZ microstructure existed. On the position adjacent to the composite interface, a typical welding overheating microstructure with coarse grains was observed, whereas on the position far away the fusion line, tiny grains were observed because the microstructure was completely recrystallized in the cooling process after deposition.
Figure 3d shows the microstructure of incomplete recrystallization on HAZ near the core of the carbon steel billet. The as-cast microstructure of the carbon billet has disappeared.

After severe rolling deformation at high temperature, sound metallurgical bonding between the two metals was achieved at the clad interface of the SSC rebar.

3.2. Macroscopic and Microscopic Morphologies of SSC Rebar

To observe whether the stainless steel fully covers the carbon steel, the SSC rebar was split longitudinally. Figure 4a,b displays that both in the transverse ribs and the longitudinal ribs, the SSC layer was fully distributed on the surface of the carbon steel.

Figure 4c exhibits a clear and clean interface of the SSC rebar after etched by nitric acid and alcohol. No pores and crack near the interface of the SSC rebar were observed. It reveals the microstructure of ferrite and pearlite at the carbon steel side, and near the interface, decarburization was observed. After heating in the furnace with subsequent hot rolling, the microstructure of the HAZ, as shown in Figure 2c, fully recrystallized into the ferritic and pearlitic microstructure with equiaxed grains.

Sawicki et al. studied the clad rebar by the tungsten inert gas (TIG) cladding method and the electroslag surface layer remelting (ESS LM) method, the core of which was steel C45E or 20GS and the cladding metal was stainless steel X2CrNi18-10. A decarburization phenomenon was observed at the carbon side near the interface [17].

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3.3. Electron Probe Microanalysis

Diffusion of key elements such as C, Cr, and Mn was detected at the interface of the SSC rebar due to the concentration gradient between the carbon steel and stainless steel. The SSC billet was made by the metal deposition process and then heated up in the furnace for 180 min. With time, the carbon continued to diffuse from carbon to stainless steel, and Cr diffused in the opposite direction; hence, the transition region in the SSC billet increased. After 16 passes, the transition region in the SSC billet was reduced depending on the value of total rolling deformation. EPMA map scan and line scan data, which are measured across the bond interface of the transverse section of the SSC rebar, are presented in Figure 5b–d, respectively.

![Figure 5](image_url)

*Figure 5. (a) The interface region of electron probe micro-analyzer (EPMA) map scans, (b) map scan of element Cr, (c) map scan of element Mn, and (d) EPMA line scans of the SSC rebar.*

Xie et al. reported that Cr diffuses through the interface from stainless steel to High-Strength Low-Alloy (HSLA) steel because of the concentration gradient at the interface, while the SSC plate fabricated by HSLA steel clad with 304 stainless steel was discussed [18].
Line scans of the key elements C, Si, Mn, and Cr were carried out in three different positions in the SSC rebar, respectively. One of the three group data is shown in Figure 5d, which shows that the diffusion distances of Cr and Mn are 32 µm and 25 µm, respectively, in the SSC rebar.

EPMA line scan was used to characterize key elements in the interface transition region. Table 2 shows the diffusion distance of Cr and Mn in the other two positions.

| Alloying Element | Mn  | Cr  |
|------------------|-----|-----|
| Set 1            | 26  | 34  |
| Set 2            | 25  | 33  |

It was reported that the diffusion coefficients in austenitic iron at 1180 °C of major alloy elements such as Cr and Mn were $4.6 \times 10^{-11}$ cm$^2$/s and $2.92 \times 10^{-11}$ cm$^2$/s, respectively [19]. In the metal deposition process and annealing of the SSC billet, the temperature was expected to reach or approach 1180 °C. This also verified that the results of the diffusion distance in Figure 5d were valid.

A much higher diffusion speed of carbon atom occurs at high temperatures compared to Cr, Mn due to the interstitial diffusion of element C in austenitic lattice. This also explains why the width of the whole transition zone is much larger than the diffusion distance of Cr, Mn.

A similar phenomenon was discussed by Rao et al. on the interface of a composite plate fabricated by HSLA steel clad with 347 SS using the welding overlay method. It was found that the diffusion distances of Cr and Mn were 29 µm and 24 µm, but the diffusion distance of carbon was much more than those of Cr and Mn [20].

3.4. Interface Microstructure of the SSC Rebar

Figure 6a shows the heterogeneous zone, which is distinguished by the corresponding microstructure near the interface. Due to lower austenitizing elements, the stainless steel of Cr13 displays α-ferrite in the hot-rolled state as in the stainless steel zone. Near the interface, the carbon concentration was much higher than in stainless steel, and the large concentration gradient causes carbon to spread to the stainless steel [21], leading to the formation of a decarburization zone. Therefore, the transition region exhibited a heterogeneous phase due to the diffusion of elements.

In the transition zone near the carbon steel side, because of the diffusion of Cr, Mn, and C, especially due to the relatively high carbon content, martensite was formed even in the air cooling condition. The formation of martensite was attributed to two reasons, one is the enlarging of the austenitic region due to the diffusion of Mn and C, the other is the reducing of the critical cooling rate of martensite transformation. The width of the martensite zone was more than 100 µm, which is more than the diffusion distance of Cr and Mn.

The Fe-Cr equilibrium phase diagram (Figure 6d) shows that the austenitic single-phase region was present when the content of Cr is <12%, whereas the ferritic single-phase was present when the content of Cr is >12.7%. In the alloy diffusion region, with a width of 25–34 µm, the formation of martensite can be explained by the decrease in the ferrite-forming element (Cr) and the increase in the austenite-forming elements (Mn and C). Furthermore, these alloying elements reduced the critical cooling rate of martensite transformation. However, in the region in which the content of the alloying element approximately equals the content of Cr13 stainless steel, the formation of martensite was attributed to the long-range diffusivity of carbon. The reaction of carbon elements caused the high-temperature austenite to turn into martensite as it cooled.

Because of the heterogeneous phases and complicated elemental distribution in the transition zone, the Schaeffler diagram (Figure 6c) was used to predict the microstructural evolution [22]. The structure depends on the ratio of the chromium equivalent to the nickel equivalent (Creq/Nieq) [23], as Figure 6c shows. The structure of the transition zone may include two different parts, the microstructure that was of martensite phase and duplex phase of ferrite and martensite, respectively.
As the distance from carbon steel increased, the carbon content decreased so that the duplex phase of ferrite and martensite was formed. Feng et al. reported that the composite rebar, the core of which was 20 MnSi and the cladding metal was 304 stainless steel, heterogeneous phases containing bainite phase were formed at the interface due to diffusion [24].

Figure 6b expounds hardness distribution that is measured from the carbon steel side to the stainless steel side. It shows that a hardness valley adjacent to the interface on the carbon steel side was attributed to the decarbonization in the SSC rebar.

![Figure 6](image)

**Figure 6.** (a) Microstructure and indentation near the interface of the stainless steel clad (SSC) rebar, (b) hardness distribution for the SSC rebar, (c) Schaeffler diagram for predicting microstructural evolution within the transition zone, and (d) the Fe-Cr equilibrium phase diagram.

The indentation images identified the martensite phase, as shown in Figure 6a. However, Figure 6b shows a special zone hardness that fell in between the hardness peak and the hardness platform of the stainless steel substrate, and was attributed to the duplex structure of ferrite and martensite.

The abundant variations of hardness measured in the present research were similar to the reports on bimetals [25,26]. The hardness valley, the hardness peak, and the hardness falling in from the peak were attributed to softening due to the decarbonization, the formation of hard phase of martensite, and the formation of the duplex phase structure of martensite and ferrite, respectively, that were observed near the interface in Figure 6b.

Figure 7a,b shows the structure of the transition region, which was divided into two sections: one is martensite (Figure 7a) and the other is martensite and ferrite (Figure 7b), which is attributed to the different levels of diffusion of C. The martensite lath in the original austenite grain boundary can be clearly seen in Figure 7a, and the precipitation of carbides can be observed too. This is a good
explanation for the hardness peak in Figure 6b because the martensite phase was a hard phase and the precipitate increased the dislocation resistance during plastic deformation.

Figure 6. (a) Microstructure and indentation near the interface of the stainless steel clad (SSC) rebar, (b) hardness distribution for the SSC rebar, (c) Schaeffler diagram for predicting microstructural evolution within the transition zone, and (d) the Fe-Cr equilibrium phase diagram.

Figure 7. SEM images of (a) martensite phase in the transition zone, (b) duplex phase of ferrite and martensite, (c) stainless steel, and (d) EDS analysis of precipitates in the transition region and in the stainless steel zone.

Heterogeneous phases, which are depended on Creq and Nieq elements equivalents, were observed near the interface. Because of the complicated elemental distribution in the transition zone, the ratio of Creq and Nieq changed, and the heterogeneous phase structure was formed. However, the normal structure of low carbon hot rolling Cr13 was ferrite, as shown in Figure 7c.

EDS results in Figure 7d show carbide precipitation, which mainly contained Cr, Ti, Nb, and C mainly precipitated in grain boundaries or within grains in the transition region due to the mutual diffusion of the above elements in the transition zone. However, in the substrate of Cr13 stainless steel, which contained 0.026% carbon, niobium carbides were dominant due to the strong carbide-forming element niobium.

3.5. Mechanical Properties

Figure 8 shows no macroscopic crack near the bending position whether it is subjected to positive or negative bending. The experimental results also suggested that the interface formed a metallurgical bonding and possessed some ductility. The yield strength, tensile strength, and elongation of the SSC rebar were determined as 423 MPa, 602 MPa, and 22%, respectively. These experimental data were the...
average of five different samples, the specifications of which were Ø20 mm × 400 mm. Figure 9 shows the typical stress–strain curve of the SSC rebar.

![Figure 8](image1.png)

**Figure 8.** Macrographs of the SSC rebar after bending experiment: (a) positive bending and (b) negative bending.

![Figure 9](image2.png)

**Figure 9.** Stress–strain curve of SSC rebar.

These mechanical properties satisfied the requirements of «GBT 36707-2018 Hot-rolled carbon steel and stainless steel clad bars for the reinforcement of concrete» and met the standards for engineering applications.

4. Conclusions

Mild carbon steel HRB400E was successfully cladded with Cr13 stainless steel by metal deposition and the hot rolling method. The mechanical quality of the manufactured SSC rebar meets the requirements of the Chinese hot-rolled composite rebar standards. The following conclusions were drawn:

1. Uniaxial tensile testing of the SSC bar with metal deposition and the hot rolling method at 25 ºC exhibited a yield point of 423 MPa and ultimate tensile strength of 602 MPa, while the elongation reached 22%. The positive and negative bending experiments showed no cracks during bending;
2. Vickers hardness in the transition zone was higher than in carbon steel and in the base metal of stainless steel, and the transition zone was divided into two districts: one was martensite phase region with the maximum hardness of 545 HV0.2 that was conducted by mutual diffusion of Cr and C, as well as Mn. The other was the region of duplex phases of ferrite and martensite which were located adjacent to the stainless steel zone;
3. The SSC rebar with a flat interface possessed a metallurgical bonding interface nearby of which the microstructure showed a relatively clean state;
4. EPMA line scan showed the diffusion behavior of key elements measured at the interface, among which the diffusion distances of Cr and Mn reached 32 µm and 25 µm, respectively.
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