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Research progress on material properties of clad steel

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Abstract

Clad steel possesses benefits of the both component metals in terms of mechanical performance, corrosion resistance, sustainability and lower full lifecycle cost, etc. As a result, it has been more and more widely used in the petroleum, chemical, marine, shipbuilding and metallurgical industries, including stainless-clad steel and titanium clad steel. Such clad steel has also great potential for application in building and bridge structures. For better understanding material properties of such clad steel, a review of research progress available in the literature is conducted herein, as well as recent research undertaken by the authors' group at Tsinghua University. It can be found that very limited research reported in the literature mainly concerns static material properties of the clad steel, and primary relations between clad ratio and strength are suggested. The authors carried out material tests on both titanium and stainless-clad steel plates, with different clad ratios being incorporated. For the stainless-clad steel tests, both material and butt welded connections are tested, and various elevated temperatures are considered. In addition, tension coupon tests under cyclic loadings are also briefly introduced herein. Primary constitutive relations developed by the authors are reviewed in this paper. All the research findings and proposed formulae may provide an essential basis for future structural analysis, and may promote its application in structural engineering.

Keywords: *Clad steel; mechanical properties; experiment; elevated temperatures; cyclic loading.*

1. Introduction

With development of metallurgical industries, various new high-performance (HP) structural steels and metals have been produced, such as high-strength steel [1], low-yield-point steel [2], fire-resistant steel [3], stainless steel [4], aluminium alloy [5], etc. Clad steel is a kind of material of HP structural steel, bonded with two different metals [6], which not only has good strength and plastic properties of the base metal, but also has cladding metal's high performance [7]. Clad steel with excellent performance and relatively low cost [8] has been developed by using hot-rolling process [9]. Such advanced steel has been widely used in petrochemical industries, and has great potential for application in structural engineering as structural steel [10]. However, due to insufficient understanding of the mechanical properties of the clad steel, it has been only used in building curtain walls as shown in Fig. 1 and bridge decks in construction projects.

Fig. 1. EXIM Bank Tower.

In Europe, through experimental investigations, researchers developed formulae for evaluating the relationship between ratio of thicknesses of the two components and the tensile mechanical properties [11] as review in Section 5 herein, and concluded that mechanical properties of the low-carbon steel can be improved by hot-roll bonding with austenitic stainless steel [12]. While in China, it has begun to produce this kind of advanced steel [13, 14] and some standards for such bi-metallic products have been released, which are reviewed in the following sections.

In this paper, production process, welding and material properties of the clad steel are introduced comprehensively, and limit requirements in different standards are reviewed, including those of America [15, 16], Japan [17] and China [18–20]. Recently, titanium-clad (TC) steel's and stainless-clad (SC) steel's monotonic tensile tests, cyclic loading tests, and tensile tests at elevated temperatures were carried out by the authors. Comparisons for some important mechanical property indices such as the elastic modulus, yield strength, tensile strength and elongation of the tested clad steel were conducted. The research work and outcomes are expected to be helpful for understanding the material properties of the clad steel.

2. Production process of clad steel

There are two major ways to manufacture the clad steel: hot roll-bonding and explosive bonding [9].

For hot roll-bonding process, the production efficiency is high while the requirements are not high, and restriction of the type of composite material is less; it is beneficial to production of thinner plates and to prevention of separation between the two metals [21]. Compared with the explosive bonding process, the hot roll-bonding process may produce the clad steel with more stable quality in terms of the bonding interface performance. Li *et al*. [22] used TEM, SEM and X-ray energy spectrum techniques to observe the interfacial microstructures and composition alteration of hot-rolled 316L+16MnR composite plate. The microstructure at the interface shows the coexistence of ferrite, martensite and austenite. Dong *et al*. [23] used software MARC to get the distribution of stress and strain at interface of Q235 carbon steel and 304 stainless steel after initial five passes of the multi-pass hot rolling process. It shows that using small reduction ratio at single pass with large cumulative deformation rate is favourable to get excellent combined carbon/stainless clad sheet. Li [24] composited austenitic stainless steel and carbon steel by vacuum hot roll-bonding, and compared the different process parameters on the material properties. The results show that the interfacial shear strength increases with an increase of heating temperature and reduction rate; Increasing the interface degree of vacuum and surface condition before welding can improve the mechanical properties of the composite interface; In addition, the interlayer (nickel foil) and diffusion annealing treatment can effectively promote the proliferation of metal parts to improve the composite strength.

By explosive bonding technique, the bonding surface may be well corrugated, so that shear strength of the interface is high. However, this process requires a specific place for explosion, resulting in serious pollution, and limiting the thickness of the cladding metal [6]. Because of these shortcomings, very few researchers are studying this production process in recent years.

3. Welding and qualification of clad steel

3.1. Welding

Back in 1988, Chen [25] introduced research results of welding materials, welding sequences and non-destructive detection testing of SC steel materials by Japan Steel Corporation Muroran Research Institute. Wang [26] carried out fatigue tests of 321+Q370qE clad plate welding joints produced by HAW and MW individually. The tests results indicated that fatigue performance of the welding joint produced by MW was superior to that of the joint welded by HAW. Wang and Zhang [27] carried out an experimental investigation on splice welding of duplex stainless steel plate 2205 and repair welding of 2205+Q345R clad plate according to weldability of the clad plate. The test results indicated that performance of the weld joints could meet regulations accordingly.

3.2. Welding procedure qualification

Tsinghua University recently conducted a SC steel welding process assessment. The specimen tested were fabricated through hot-rolling process by using Q235B steel (5 mm thick) as the base material and 316L austenitic stainless steel (3 mm thick) as the clad one. The welding region includes welding of base layer, welding of transition layer and welding of cover layer. It is noteworthy that the transition layer is designed to prevent the base layer from being incorporated into the high alloy component. The welding sequence is shown in Fig. 2. The welding parameters are given in Table 1. It has been demonstrated that the welding technique is adequate for such clad steel, and the static strength of the welded connection is no less than the clad steel plate. In addition, no cracks were observed in the cold bending tests for the welded connection. This may provide important bases for practical usage of the clad steel in structural engineering, as welding is one of the most common fabrication and construction method in steel structures.

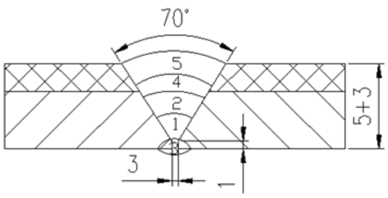

Fig. 2. Welding sequence.

Table 1. Welding parameters.

Sequence	Welding electrodes and wires		Protective gas
	Grade	Φ(mm)	
1~3	ER50-6	2.4	Ar
4	ER309LMo	2.5	Ar
5	ER316L	2.5	Ar

4. Standards for clad steel

Ban *et al.* introduced various technical specifications for clad steel and some classifications were pointed out [10]. America, Japan and China have the corresponding product and welding technology standards, which have extensive application. Table 2 summarizes limit requirements for SC steel in different countries. Based on the comparison, it can be found that China's performance values are basically the same with other countries', but some values such as shear strength and elongation even exceed the requirements of ASTM and JIS standards.

Table 2. Comparison of code limit values in different standards.

Standard	Country	Tensile strength	Yield strength	Elongation	Bending	Interface shear strength
JIS G3601-2012 [17]	Japan	$\sigma_B \geq \frac{t_1\sigma_1 + t_2\sigma_2}{t_1 + t_2}$	——	>Base metal standard	according to the base metal standard	≥ 200 MPa
ASTM263 [15], ASTM264 [16]	America	< 38.1 mm, when the tensile strength of the base metal below the standard minimum 482.6 MPa, the full thickness tensile test is required, and more than the base metal standard value	>Base metal standard	>Base metal standard	A264: according to the base metal standard A263: according to stainless steel standards for positive bending; according to the base metal for reverse bending standard	≥ 140 MPa
GB/T8165-2008 [20]	China	Not less than the lower limit value of base metal with corresponding thickness, and not exceed the upper limit by 35 MPa	≥Base metal standard	≥Base metal standard	No cracks should form on the outside of the bent part	I,II grade，≥ 210 MPa III grade，≥ 200 MPa

Note: σ_B means the tensile strength of SC steel, t means the thickness of SC steel, σ_1 means the tensile strength of stainless steel, t_1 means the thickness of stainless steel, σ_2 means the tensile strength of base steel, t_2 means the thickness of base steel.

5. Material properties of clad steel

Ma *et al*. studied the stamping performance of 0.8 mm thick SC steel, providing the basis for its forming process and mold design [28]. Two formulae correlating relative thickness of the two components and strengths were developed by Motarjemi et al. [11] as shown in Eqs. (1) and (2),

$$\sigma_y = 378.3 - 71.4e^{-0.5\beta} \quad (1)$$

$$\sigma_u = 675.1 - 191.0e^{-2.4\beta} \quad (2)$$

The authors conducted a series of TC steel tension coupon tests, full-range stress-strain curves of the TC steel plates were obtained and influence of clad ratio was clarified [29], as shown in Fig. 3. It was found that with an increase of the clad ratio, the yield plateau disappeared gradually, the yield strength increased, whilst the tensile stress varied slightly. This phenomenon is more clearly shown in Fig. 4. An averaged curve of the base and cover layers are used to represent the clad steel based on the observation that the development of strain through the clad steel thickness is uniform, and separate stress within the two layers is difficult to be got in the tests.

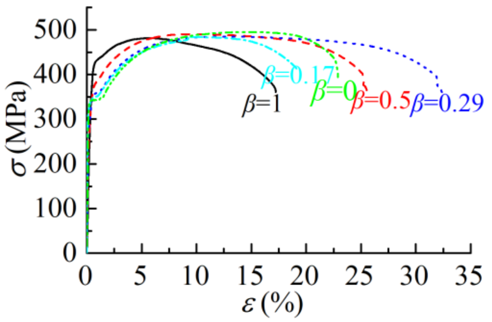

Fig. 3. Comparison of stress-strain curves for TC steel specimens with various clad ratios.

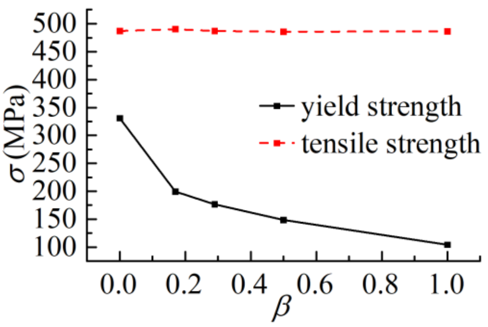

Fig. 4. Relationship between material properties and clad ratios β for TC steel.

The authors investigated experimentally SC steel's material properties with clad ratio's effects being involved, and it was found that the yield strength and tensile strength increased with the clad ratio increasing, as shown in Fig. 5.

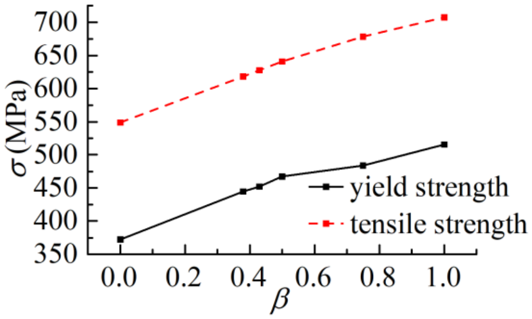

Fig. 5. Relationship between material properties and clad ratios β for SC steel.

Tension coupon tests at elevated temperatures were also conducted on the SC steel plate by Tsinghua University. It was found that with an increase of the temperature, both the yield strength and tensile strength were reduced remarkably, as shown in Fig. 6.

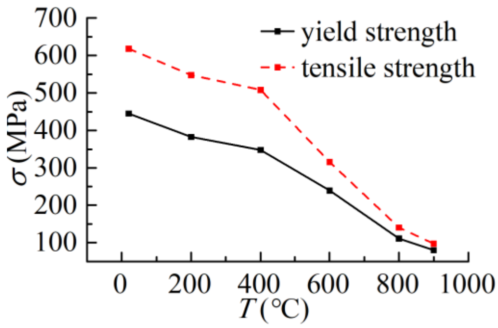

Fig. 6. Relationship between material properties and temperature for SC steel.

The authors also carried out a series of 316L+Q235B SC steel material tests under monotonic tension loading, monotonic compression loading and cyclic loading with 15 different protocols. The test results showed that the mechanical property of the SC steel under cyclic loading exhibited hardening behaviour, which differed from monotonic loading. The plump hysteretic curves indicated good capability of energy consumption. With the cyclic number increasing, the steel's stiffness degraded significantly, which showed mixed hardening behaviour including isotropic hardening and kinematic hardening, and the Ramberg-Osgood model may simulate the cyclic skeleton curves well, as shown in Fig. 7.

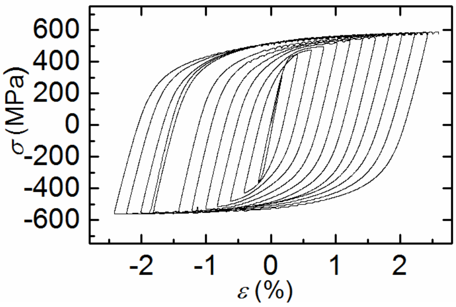

Fig. 7. Cyclic stress-strain curve.

6. Conclusions

Based on the overviews, discussions and comparisons mentioned above, the following conclusions can be obtained:

(1) In general, current research results show that production and welding of clad steel have been widely concerned, but the material property just begun to be studied, so more detailed research is needed.
(2) The clad ratio has great influence on the elastic modulus, yield strength and elongation after fracture of the clad steel, depending on that of the two component materials.
(3) Through the monotonic tension test, cyclic test, and elevated temperature test, it has been demonstrated that the clad steel has excellent mechanical properties, and further study is in need.

Acknowledgements

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