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Tensile shear sample design and interfacial shear strength of stainless steel clad plate

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ABSTRACT

Tensile shear test is a suitable method to measure the interfacial bonding properties of stainless steel clad plates with thin cladding layer. Herein, three kinds of testing samples with different shapes (modes I, II and III) fractured at carbon steel substrate, stainless steel cladding, and interfacial zone, respectively. Interestingly, the tensile strength of carbon steel substrate (σ_{bcs}), stainless steel cladding (σ_{bss}), and the interfacial shear strength of stainless steel clad plate (τ_{in}) can be obtained from the three testing samples. The values of σ_{bcs} and σ_{bss} were decreased, while τ_{in} was increased with the increasing rolling temperature, which were attributed to mechanisms of matrix softening and interface strengthening at high rolling temperatures. Moreover, under mode III, the shear fractures of clad plates rolled at 1375 K and 1475 K were located at interface and decarburized layer, respectively. The different fracture characteristics may be related to the sufficient carbon diffusion and interface toughening at a high rolling temperature.

1. Introduction

In the last decades, an increasing demand for stainless steel with superior high temperature oxidation resistance and corrosion resistance has been strongly requested by the industry [1]. However, stainless steel containing high content of expensive alloying elements and high cost has limited its widespread applications.

Recently, it has become increasingly popular for engineering material field to use stainless steel clad plate take as the substitute of stainless steel. The stainless clad plates allow for the possibility of combining the excellent weldability, formability, ductility and thermal conductivity of carbon steel substrate with the superior corrosion resistance, abrasion resistance, heat resistance, magnetic resistance of stainless steel cladding. They have been used widely in many applications, such as nuclear industry, pressure vessels, heat exchangers, transferring pipes and reservoirs etc [2–6]. Several processing techniques, such as overlayer welding, explosion welding, diffusion welding, hot pressing, vacuum brazing, transient-liquid-phase bonding, inversion bonding, common casting and hot rolling, are used to manufacture stainless steel clad plates [7–10]. Herein, explosive welding is a well known solid state bonding method to join two surfaces of metal together using high energy impulse of an explosion and big shock waves, and the wave-like interface of explosive clad plate is originated from the severe plastic deformation and metal melting in the localized contact zone [3,11–15]. The advantage of this method lies in that high interface shear strength (520 MPa) of austenite stainless steel clad plate can be obtained [11]. However, such an interface always contains unbonded regions, high residual stress, melt pockets, as well as brittle martensite phase, which can lead to a low interface toughness. Therefore, the explosive welding clad plate must be under heat treatment to eliminate microstructural defects before application [11–15]. In addition, the explosive welding has many shortcomings, such as low production, poor product quality, low dimensional accuracy, high level of contaminant and high thermal residual stress etc. Jing et al. [2,4] and Zhang et al. [6] reported that vacuum hot rolling is the most economic and effective production process among these various technologies, which is a solid phase bonding process to join the same or dissimilar metals at a high rolling temperature for making laminated metal matrix composites.

As one of the critical part in the nuclear power plants, the low alloy steel can be used in the reactor pressure vessels (RPVs), and the inner surface of RPVs should possess high corrosion resistance. Carbon steel has benefit relative to concrete measurement on ITER or some demo-reactor design, such as the containment structure, piping, drain pump, diesel generator, turbine, oil tank and steam generator tube as shown in Fig. 1 [16], and these supporting parts always susceptible to be corroded by boiled or sea water. Therefore, several millimeter thick austenite steel taken as cladding are

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Table 1
Standard specification and corresponding interfacial shear strength for stainless steel clad plates [29].

Standard	NB/T47002.1-2009	GB/T8165-2008	JIS G3601-2012	A263-03
Shear strength	≥210 MPa	≥200–210 MPa	≥200 MPa	≥140 MPa

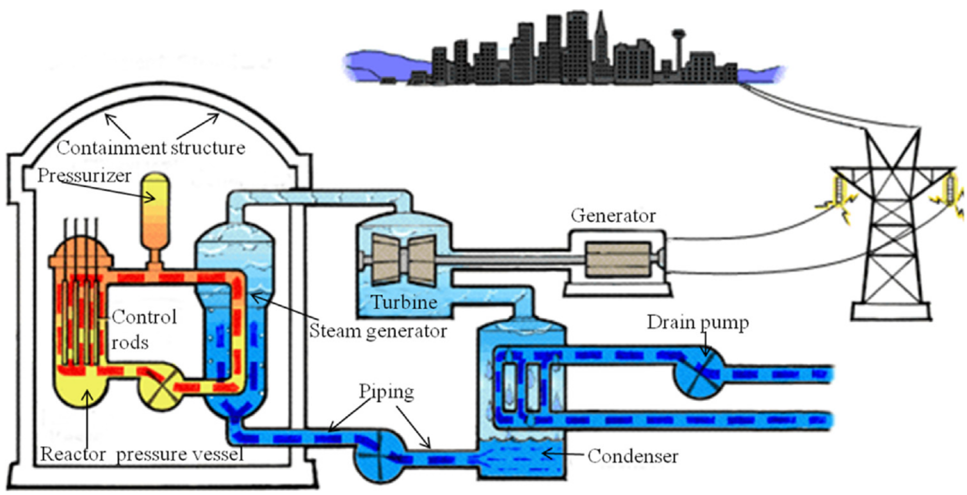

Fig 1. The schematic diagram of nuclear system [16].

overlayer welded on the surface of low alloy steel and carbon steel. The stainless steel clad plate inhibits the corrosion and pressurized thermal shock of reactor coolant, boiled or sea water environment [16–20]. Recently, hot rolling method can make the stainless steel cladding bonded on the surface of base metal, such as carbon steel and low alloy steel, which is expected to replace the present overlayer welding method in the RPVs due to the advantages of low cost, pollution-free and time saving [21–25].

Stainless steel clad plates should be processed in further forming process, such as cutting, rolling, bending, deep drawing and joining etc [18,21–30]. Meanwhile, in the process of service stainless steel clad plates are always subjected to various stress states, complex weather and loading modes. Interfaces of clad plate as the weak position can be affected by fabrication parameters, and the uncontinuous, nonuniform and partial bonding interfaces may be formed, leading to very serious and far-reaching quality accidents in practical applications [11]. Nambu et al. reported that strong interfacial bonding strength is necessary for laminated composites to inhibit the interfacial delamination phenomenon during the bearing service and forming processes [26–28]. Table 1 lists the standard specifications and corresponding requirements on interfacial shear strength for stainless steel clad plates, the value of interfacial bonding strength should be higher than 140 MPa, which is the low limit of stainless steel clad plate [29]. Jing et al. and Sheng et al. [2,4,21,30] indicated that the interfacial bonding status of clad plates is affected by rolling temperature, rolling passes and rolling reduction etc. The strong interface is in a position to prevent wrinkling, premature localized necking, formation and propagation of tunnel cracks, as well as interfacial delamination [31–36]. Moreover, many brittle phases and oxides are always created at the bonding interface during hot rolling process, and the comprehensive mechanical properties of clad plates are deteriorating [37]. Therefore, strong interfacial strength of stainless steel clad plate is necessary in industrial production and practical application, even the high-end field, such as fission or fusion reactors.

Interfacial bonding status is taken as main factor to evaluate the quality of laminated metal composites, and the measurement of interfacial bonding strength is requisite. Actually, the interfacial bonding strength of clad plate can be obtained by many tests qualitatively and quantitatively [38,39]. Herein, the bend test, torsion test, impact test, fatigue test are the qualitative measurement methods, while the tension test, peeling, compression shear, nanometer indentation, multistep shear, roller drum peel test, repeated bending and tensile shear etc. are the quantitative measurement methods. In fact, compression shear test has been defined a variety of acceptance cases for thick metal cladding, but it is not applicable to thin clad plates because of severe buckling phenomenon. Peeling test and peeling strength are always affected by peeling area and thickness of cladding layer, and the value of peeling strength is not normalized. Recently, tensile shear test is the most widely used method for determining the bonding strength of thin metal clad plates. However, the tensile shear sample dimension is not universal to all kinds of metal clad plates, the slot width, notch distance, shear area and cladding thickness have important influences on fracture modes and fracture zones. Therefore, designing the proper dimensions of tensile shear sample is necessary for measuring the interfacial shear strength of stainless steel clad plates [40]. The present work aims to further investigate the effect of rolling temperature on the interfacial bonding status of stainless steel clad plates with tensile shear method, which may be useful to understand the relationship between fabrication and performance. These results could be used as guide to design the optimal dimensions of shear tensile sample.

Table 2
The chemical compositions of the stainless steel and carbon steel (wt.%).

Elements	Fe	Cr	Ni	C	Mn	Si	P	S
SUS304	68.95	18.5	8.5	0.025	2	2	0.025	0.001
Q235	98.91	–	–	0.2	0.5	0.3	0.045	0.05

2. Experimental procedures

Q235 carbon steel as the substrate and 304 austenite stainless steel as the cladding were used to fabricate the stainless steel clad plate by vacuum hot roll bonding. Their main chemical compositions are listed in Table 2. The carbon steel and stainless steel plates, which have thicknesses of 60 mm and 12 mm, were cut into