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Fabrication of a thick copper-stainless steel clad plate for nuclear fusion equipment by explosive welding

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ABSTRACT

TU1/316 l clad plates with a high thickness are used in nuclear fusion equipment as coil terminals. The technical specifications of clad plates for nuclear fusion equipment, such as the composite ratio, tensile strength, shear strength and scale of the interfacial wave, are significantly higher than those of clad plates for conventional applications. It is difficult to produce high-quality clad plates through explosive welding experiments alone. To manufacture high-quality TU1/316 L clad plates, the technical parameters of the explosive welding process were obtained and optimized by theoretical analysis and numerical calculations. A procedure for fabricating explosion bonded TU1/316 L clad plates was successfully determined through the combination of numerical calculations and experiments, and the bimetallic plates were used to manufacture international thermonuclear experimental reactor (ITER) components.

1. Introduction

Currently, the international thermonuclear experimental reactor (ITER) program is the largest and most influential international scientific cooperation project in the world. This program integrates the global scientific knowledge and technology of controlled magnetic confinement fusion [1]. A large-scale fusion experimental reactor can be realized at the first attempt of its construction, which is a key step for controlling nuclear fusion in practical applications. Bimetallic clad plates must be used in ITER nuclear fusion equipment [2]. Explosive welding is usually used to manufacture high-quality bimetallic clad plates, and these clad plates have been used as components in nuclear fusion equipment [3–6].

Copper-stainless steel clad plates with a high thickness have been used as coil joints in controlled nuclear fusion equipment. In this configuration, the flying plate was composed of 20 mm thick oxygen-free copper TU1, and the base plate was 316 L stainless steel with a thickness of 90 mm. The coil joint working environment temperature was 4.5–6 K, and the liquid helium pressure was 0.6–3.0 MPa. Under these conditions, the technical requirements of the TU1/316 L clad plate are as follows: (1) There should be no defects on the interface as determined through ultrasonic testing (UT) and liquid penetrant testing (PT). (2) The size of the interface wave should be less than 1 mm, and no oxide should be present on the joint interface. (3) A sample of the clad plate must be subjected to temperature cycle testing from 300 K to 77 K. (4) The minimum tensile strength of the clad plate should be higher than that of the copper plate. (5) The shear strength of the joint interface must be higher than 110 MPa. For a clad plate to meet the above technical requirements, explosive welding technology offers a feasible manufacturing process solution.

Because the above technical requirements are much higher than those of conventional clad plates, some key technical parameters of the explosive welding, such as the explosive performance, welding window, and flight attitude of the flying plate, must be strictly controlled and optimized. If the technical parameters of the explosive welding process are not reasonable, then it is difficult to ensure the composite rate and bonding strength of the clad plate. Therefore, a TU1/316 L clad plate with a large thickness should be manufactured through the combination of theoretical analysis, numerical calculations and experiments.

2. Theoretical analysis and numerical calculations

2.1. Explosive welding window

The welding quality of clad plates significantly depends on the explosive welding window [7]. To manufacture a TU1/316 L clad plate for nuclear fusion equipment by explosive welding, the explosive welding window should be obtained and optimized. The explosive welding window includes the flow limit, upper limit, lower limit and sound speed limit (see Fig. 1).

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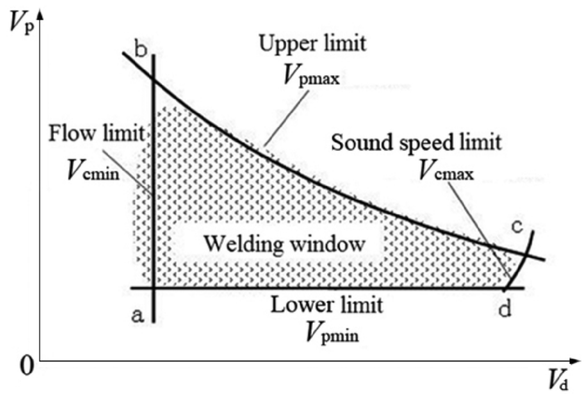

Fig. 1. Explosive welding window.

Generally, the explosive welding window can be obtained using different experimental methods, such as the semicylinder method, bench method, and small dip angle method. The welding window can also be determined by combining experiments and theoretical calculations. The method used to calculate the four parameters of an explosive welding window is as follows [8].

The lower limit V_{pmin} is the minimum collision velocity between the base plate and the flying plate to form a metal jet on the joint interface. The lower limit formula is:

$$V_{pmin} = K_c \sqrt{H_V/\rho} \quad (1)$$

where H_v is Vickers hardness; > is the density of the metal plate; and K_c is the empirical coefficient, whose range is 0.6–1.2.

The flow limit V_{cmin} is the minimum moving velocity of the collision point between the base plate and the flying plate. As a condition for the formation of metal jets, the stagnation pressure at the collision point is more than ten times the static yield strength of the metal plate. The flow limit formula is:

$$V_{cmin} = \sqrt{2.0K_V \frac{\mathrm{Max}(\sigma_{b1},\sigma_{b2})}{\mathrm{Min}(\rho_1,\rho_2)}} \quad (2)$$

where K_v is the metal strength coefficient, σ_b is the yield strength, and subscripts 1 and 2 denote the base plate and flying plate, respectively.

The detonation velocity of the explosive should not be greater than the sound speed of the base plate and flying plate. The maximum detonation velocity is the sound speed limit V_{cmax}, whose formula is:

$$V_{cmax} = \mathrm{Min}(C_1,\ C_2) \quad (3)$$

where C_1 is the sound speed of the base plate and C_2 is the sound speed of the flying plate.

The upper limit V_{pmax} is a limitation of the maximum energy at the collision point of the base plate and flying plate. The formula of the upper limit V_{pmax} is:

$$V_{pmax} = \frac{f}{V_c}\sqrt{1+\frac{\rho_1 h_1}{\rho_2 h_2}}\sqrt[4]{\mathrm{Min}\left(1,\ \frac{h_2 C_1}{h_1 C_2}\right)\Big/ h_1} \quad (4)$$

where h_1 is the thickness of the base plate; h_2 is the thickness of the flying plate; V_c is the detonation velocity of the explosive; f is the experimental coefficient, which is a constant whose value must be experimentally obtained, related to the physical properties of the metal.

To calculate the explosive welding window of the TU1 copper plate and the 316 L stainless steel plate, the material properties of the two metal plates are shown in Table 1.

The explosive welding windows of TU1 copper and 316 L stainless steel can be obtained using Eqs. (1)–(4). Thus, the flow limit, lower limit, upper limit and sound speed limit of the two metal plates can be numerically calculated, and the results are shown in Fig. 2.

In Fig. 2, V_p is the collision point velocity between the base plate and the flying plate, and V_d is the detonation velocity of the explosive.

Table 1
Material properties of TU1 and 316 L.

Property	TU1	316 L
Density ρ (kg. m^{-3})	8930	7980
Vickers hardness H_v(kg.f)	89.9	200
Yield strength σ_b(MPa)	196	170
Sound velocity C(m.s^{-1})	3810	4977
Surface coefficient K_c	0.6	0.6
Strength coefficient K_v	10	10
Plate thickness h(mm)	20	90

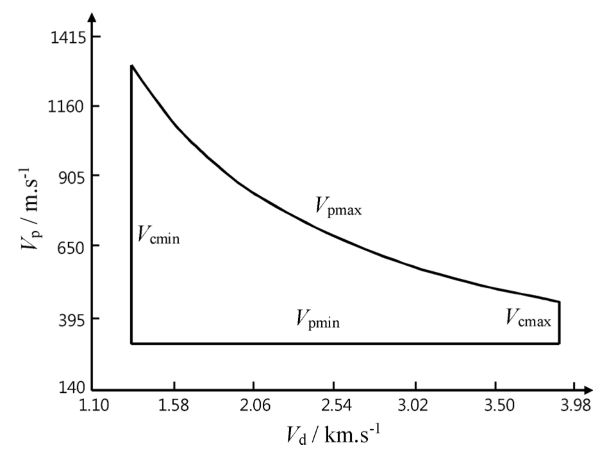

Fig. 2. Explosive welding window for TU1/316 L.

To ensure the bonding quality of TU1 copper and 316 L stainless steel, the collision velocity V_p is the most important parameter in the explosive welding window. In particular, the lower limit V_{pmin} should first be calculated. The lower limit V_{pmin} is equal to 303 m/s according to Eq. (1). Commonly, the adjustment range of the detonation velocity for ammonium nitrate (AN) is 2000–3500 in explosive welding projects. Because a thickness of 20 mm for the copper plate is considered large in explosive welding compared with the thickness of thin plates for explosive welding, the detonation velocity of the explosive should be slightly lower. Therefore, to manufacture high-quality clad plates, the detonation velocity of the explosive should be controlled at 2500–2700 m/s. According to the curve of the explosive welding window in Fig. 2, the collision velocities of the base plate and flying plate are best selected near the lower limit, and a reasonable value for V_p should be 320–350 m/s.

2.2. Flight attitude of the flying plate

After the explosive welding window of the TU1/316 L clad plate is obtained, the stand-off distance between the base plate and the flying plate and the density and thickness of the explosive should be designed according to the collision velocity V_p of the base plate and flying plate. For these reasons, the flight attitude of the flying plate should be obtained by numerical calculations [9].

When the explosive is ignited, the flying plate bends in front of the detonation wave under the rolling of the slippage detonation load. Meanwhile, the flying plate with a certain bending angle θ impacts the base plate at a high speed. When the detonation wave of the explosive continues, the flight attitude of the flying plate appears as shown in Fig. 3.

The flight attitude of the flying plate includes displacements in the horizontal and vertical directions, the collision angle and the collision velocity V_p [10–12]. In addition to the Richter formula, the characteristic line method is often used to calculate the flight attitude. The characteristic line method using the integral iterative algorithm can