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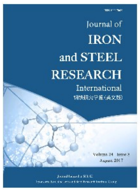

Lower limit law of welding windows for explosive welding of dissimilar metals

Chang-gen Shi[1,*], Xuan Yang[1], Yu-heng Ge[1], Jun You[1], Hong-bao Hou[2]
[1] PLA University of Science and Technology, Nanjing 210007, Jiangsu, China
[2] Baicheng Ordnance Test Center, Baicheng 137001, Jilin, China

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ABSTRACT

The influence of explosive charge thickness on the quality of explosive welding of dissimilar metals was investigated. The lower limit law should be followed in the course of explosive welding. Three welding experiments of stainless steel (410S) and steel (Q345R) were carried out in three different kinds of explosive charge thicknesses, namely 15, 25 and 35 mm. Interfaces of morphology and mechanical properties of three samples were observed and tested. It was found that micro and small wavy bonding is mainly formed for charge thickness of 15 mm whose strength is the highest with minor deformation and few defects in the interface; small and middle wavy bonding are mainly formed for charge thickness of 25 mm whose strength is comparatively mediocre; big wavy bonding is mainly formed for charge thickness of 35 mm whose strength is the lowest. The cause of high bonding strength of the micro and small wavy interface was analyzed and verified on the basis of the results of Electron Probe Micro-Analyzer (EPMA) tests of three selected samples.

1. Introduction

Explosive welding window theory is an important research perspective in explosive welding technology. The proper welding parameters can be adopted quickly through the welding window, which greatly reduces experiment frequencies and enhances the quality of the cladding plate.

In 1983, Blazynaki[1] raised the conception of explosive welding window. Explosive welding window of dissimilar metals was studied by many scholars including Gulenc[2,3], who designed the experiments of Cu-Ti plates bonded through explosive welding with different parameters and obtained different microstructures and mechanical properties to select the optimum parameter. On the basis of previous experiments, Shao and Zhang[4] carried out theoretical calculation in the range of explosive welding parameters and obtained the primary welding window. Li[5] obtained the upper limit of bimetal explosive welding parameters by analyzing the heat conduction theory. The weldability domain of commercial pure titanium/AISI 304 stainless steel was defined by Sartangi and Mousavi[6] in 2009, and the proper welding parameters for welding were also predicted by it. Zhao et al.[7] developed explosive welding window calculation (EWWC) procedure and drew the explosive welding window of Ti-steel composite plate by VC++6.0.

Many scholars who established the new welding windows experimented to further improve the quality of the explosive plates. Lysak and Kuzmin[8] established the lower boundary of explosive welding, "Pressure-Time-Temperature". Shi et al.[9] constructed a new R-δ_f-type welding window (where R is loading ratio; and δ_f is the thickness of flyer plate) on charge parameters which has strong practicability as well as accuracy and is helpful to the physical production and application of explosive welding cladding plate. The researches of Mendesa et al.[10] showed that the type of explosive and proportion of explosive sensitizers affect the main welding parameters, particularly collision point velocity. Raghukandan[11] addressed the analytical estimation of the weldability domain for aluminum-low carbon steel and copper-stainless steel combinations. It has been studied that the use of an interlayer was proposed for the control of kinetic energy loss to alleviate the

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[*] Corresponding author. Assoc. Prof., Ph.D.
E-mail address: *shichanggen71@sina.com (C.G. Shi)*.

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formation of intermetallic at the interface.

However, it is inevitable that bonding interface has flaws because of the excess energy of upper limit charge in welding windows. To get good interface without melt, explosive charge must be selected according to the low limit of welding windows. Meanwhile, the lower charge can be obtained under the condition that the maximum bending moment of explosive loading should be bigger than the dynamic yield strength moment and smaller than dynamic tensile strength moment of flyer plate in the explosive welding[12,13]. In the practice of explosive welding, the best quality of the explosive welding interface can be obtained without considering the upper limit of the explosive charge if the explosive charge is calculated in accordance with the lower limit of the window.

In this paper, three kinds of interfaces microstructures were tested by adopting SEM (scanning electron microscope) and EPMA (Electron Probe Micro-Analyzer), and the interfaces were obtained with three kinds of welding parameters respectively.

2. Experimental Materials and Methods

In this study, 410S and Q345R are selected as the flyer plates and base plates. The dimensions of the flyer plates are 500 mm×380 mm×2 mm, and the dimensions of the base plates are 440 mm×340 mm×20 mm. The welding parameters are listed in Table 1. In this table, s is the spacing between plates and δ_0 is the explosive charge thickness.

Table 1

Experimental materials and welding parameters

Specimen	Materials	Explosive	s/mm	δ_0/mm
I	410S (2 mm) Q345R (20 mm)	No. 38	6	15
II				25
III				35

The powdery emulsion explosive mixed with 38% industrial salt was used in explosive welding, where the effective multi index γ, the density ρ_0 and the detonation velocity D_k are approximately 1.8, 0.8 g/cm^3 and 2200 m/s, respectively. The relative formulas between the thickness of flyer plate (δ_f) and the minimum loading ratio ($R_{\min}$) or the maximum loading ratio ($R_{\max}$) can be determined by the following equations[8]:

$$R = \rho_0 \delta_0 / \rho_f \delta_f \tag{1}$$

$$\delta_{f1} = \frac{2E_{\min}(\gamma^2 - 1)(5 + R_{\min} + 4/R_{\min})}{3D_k^2 \rho_f R_{\min}\left(1 - k_0 \dfrac{R_0}{R_{\min}}\right)} \tag{2}$$

$$\delta_{f2} = \frac{4.48^4 \kappa c t_{mp}^2 v_{sf}^2 (\gamma^2 - 1)^2 (5 + R_{\min} + 4/R_{\max})^2}{9D_k^8 \rho_f R_{\max}^2 \left(1 - k_0 \dfrac{R_0}{R_{\max}}\right)^8} \tag{3}$$

where, R is the loading ratio of the explosive; ρ_f is the density of flyer plate; $E_{\min}$ is the minimum welding energy in unit area; k_0 and R_0 are constants of explosive properties; κ, c and t_{mp} are the coefficients of heat conduction, the specific heat and the melting temperature of the welded metals; and v_{sf} is the sonic velocity of flyer plate.

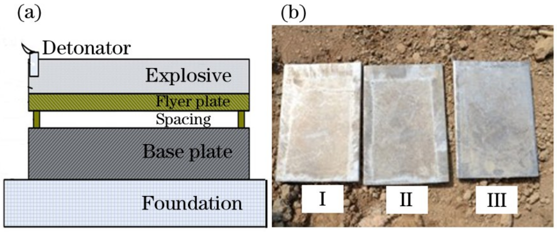
In this experiment, three different kinds of explosive charge thickness are selected:

(1) Specimen I: $\delta_0 = 15$ mm, which is the lower limit charge calculated by Eqs. (1) and (2);

(2) Specimen II: $\delta_0 = 25$ mm, which is commonly used in industry;

(3) Specimen III: $\delta_0 = 35$ mm, which is the upper limit charge calculated by Eqs. (1) and (3).

The schematic diagram of explosive welding is shown in Fig. 1(a). The flyer plate is accelerated with the detonation of explosive into the base plate to create an atomic bonding. Fig. 1(b) shows the three cladding plates after explosive welding, corresponding to three different explosive charge thicknesses respectively. In Fig. 2, the sampling position of microstructure and mechanical property tests has been shown. Nos. 1－6 are metallographic samples of microstructure tests, Nos. 7 and 8 are samples of shear tests, Nos. 9 and 10 are samples of impact ductility tests.



(a) Explosive welding device; (b) Three cladding plates.

Fig. 1. Schematic diagram of explosive welding.

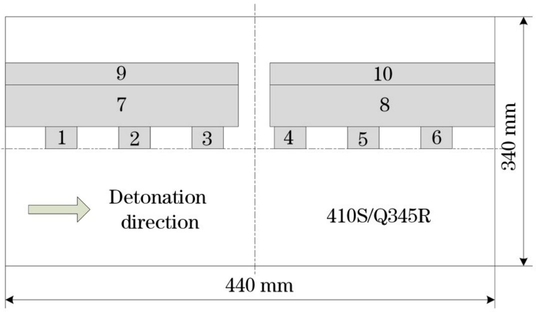


Fig. 2. Sampling position of microstructure and mechanical tests.

3. Results and Discussion

3.1. *Microstructure tests of interfaces*

On the basis of the pre-test, interfaces of six samples, which are selected from three kinds of ex-