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Ultrasonic evaluation of TiAl and ^{40}Cr diffusion bonding quality based on time-scale characteristics extraction

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ABSTRACT

To solve the problem of ultrasonic pulse-echo method in the evaluation of kissing bond and unbond in TiAl and ^{40}Cr diffusion bonding, a characteristics extraction algorithm was proposed. The algorithm was based on continuous wavelet transform to convert ultrasonic TiAl and ^{40}Cr diffusion bonding interface signals into time-scale domain. The ultrasonic tests were performed by an ultrasonic C-scan imaging system using a 10 MHz focused transducer. The time-scale amplitude and phase of the interface signals were calculated and analyzed to distinguish the kissing bond and the unbond from the perfectly bonded interface. The kissing bond can be detected by the scale-dependent amplitude combined with phase variation and the unbond can be measured by the opposite phase. The amplitude and phase characteristics were extracted to reconstruct the amplitude and phase characteristics images for TiAl and ^{40}Cr diffusion bonding specimens evaluation. The amplitude and phase characteristics images are effective in the evaluation of bonding quality.

1. Introduction

Diffusion bonding has been considered as a potential welding method and increasingly used in the field of aerospace and industry, which has many advantages such as high performance, significant cost and weight savings, and low requirement for the weldability of materials [1,2]. However, imperfections such as kissing bond and unbond may occur at the interface due to improper surface preparation and upset bonding conditions [3]. These defects can degrade bonding strength, especially fracture toughness and fatigue strength [4–6]. Thus, it is necessary to develop non-destructive evaluation of diffusion bonding.

The interfacial imperfections are parallel to the specimen surface, which is a suitable position for ultrasonic test [7]. A variety of ultrasonic methods have been applied in the evaluation of bonding quality, such as pulse-echo method, laser ultrasonic system [8], guided waves [9–11], and nonlinear ultrasonic measurement [12–14]. Pulse-echo method is the most popular technique among these ultrasonic methods. Palmer et al. [15] described the application of ultrasonic reflectivity for the characterization of copper diffusion bonds with different bonding qualities. Ultrasonic reflection coefficients at 10 MHz were correlated with the ultimate tensile strength. Kato and Abe [16] measured diffusion bondings of steel to titanium plates to obtain the relationships among bonding strength, state of bonding interface, and two major components derived from ultrasonic testing. Considerable progress was made by Greenberg et al. [17] in developing a real-time system for the monitoring of bonding process by analyzing the amplitude ratio and attenuation of acoustic waves. In other efforts, the C-scan images at the bonding interface were used to calculate the ratio of non-bonded area of diffusion bonded joints of mild steel, combined with impact tests for threshold level determination [18]. Similar technique was applied to field-assisted diffusion bonding joints to assess the mechanical quality by increasing the ultrasonic frequency up to 20 MHz [19].

In general, the unbonds in similar diffusion bondings are readily detectable by normal incidence wave since the ultrasonic wave will be reflected at the defects whereas passing through the perfectly bonded regions. The bonding quality can be assessed by the amplitude of the reflected signals. However, the kissing bonds are only a few micrometers in size, which result in weak reflection. The bonding joints appear to be flawless under ultrasonic inspection [20]. As for the dissimilar diffusion bondings, some ultrasonic energy is still reflected from the perfectly bonded interface due to the effect of impedance mismatch between materials to be bonded [7]. It is difficult to distinguish the defect signals from the interface signals so that the bonding quality cannot be assessed by the amplitude of the reflected signals.

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In this paper, we focus on the evaluation of TiAl and ^{40}Cr diffusion bonding quality. A time-scale characteristics extraction algorithm is proposed to measure TiAl and ^{40}Cr diffusion bonding interfacial imperfections. The algorithm is based on continuous wavelet transform to analyze the amplitude and phase variation of ultrasonic interface signals in the time-scale domain. The authors shall demonstrate that the defects can be assessed by the time-scale amplitude and phase characteristics.

2. Theoretical background

Classical boundary condition for ultrasonic wave interaction with welded or perfectly bonded interface assumes that stress and displacement across the interface is continuous. When an ultrasonic wave is normally incident to such an interface, the reflection coefficient R_{12} is given by [21]

$$R_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (1)$$

where Z_1 and Z_2 are the acoustic impedances of the materials on either side of the interface. Note that the reflection coefficient from the perfectly bonded interface is just a function of the impedances.

If the bonding is imperfect and the size of imperfections is considerably smaller than the wavelength of ultrasound, the interface can be modeled by a set of distributed springs. The ultrasonic wave interaction with such an interface can be described using spring boundary condition. The reflection coefficient of normal incidence ultrasonic wave from imperfect interface is given by [22]

$$R_{12} = \frac{Z_2 - Z_1 + i(\omega/k_n)Z_1Z_2}{Z_2 + Z_1 - i(\omega/k_n)Z_1Z_2} \quad (2)$$

where ω is the angular frequency of the ultrasonic wave and k_n is the normal interfacial stiffness, which is defined as distributed spring contacts per unit area. The normal interfacial stiffness varies from infinity when perfectly bonded is achieved, to zero for an unbond surface. The normal interfacial stiffness must be much less than infinity when kissing bond occurs at the interface.

The reflection coefficient of the imperfect interface is related to three factors: the acoustic impedances of the materials on either side of the interface, the ultrasonic frequency, and the normal interfacial stiffness. The amplitude and phase of the reflection coefficient of TiAl and ^{40}Cr diffusion bonding interface as shown in Fig. 1 are calculated to illustrate the relationship among the reflection coefficient and the three factors. The acoustic impedances of TiAl and ^{40}Cr are 2.73×10^7 and 4.68×10^7 Pa s m^{-1}, respectively. As the phase is a periodic function with period π, the result is only shown between $-\pi/2$ and $\pi/2$. As $k_n \to \infty$, corresponding to the case of perfectly bonded, the amplitude of the reflection coefficient $|R| \to (Z_2 - Z_1)/(Z_2 + Z_1)$ at all frequencies. The phase of the reflection coefficient tends to zero from the positive direction, which means the reflected wave and the incident wave are in-phase. As $k_n \to 0$, corresponding to the case of unbond, the amplitude of the reflection coefficient $|R| \to 1$ and also no frequency dependence is observed. There is an exception to the rule. $|R|$ tends to $(Z_2 - Z_1)/(Z_2 + Z_1)$ when f is close to zero. The frequency used in ultrasonic testing is usually greater than 2.5 MHz, even greater than 5 MHz. So this tendency has little effect on the practical ultrasonic testing. The phase of the reflection coefficient tends to zero from the negative direction, which is equivalent to $\Phi \to \pi$. The reflected wave is opposite in phase to the incident wave. As k_n is much less than infinity, corresponding to the case of kissing bond, part of the ultrasonic energy is reflected from the interface and the amplitude of the reflection coefficient increases with the frequency. The phase of the reflection coefficient is the same at low frequencies and opposite at high frequencies. The phase transition occurs when $\Phi \to \pm \pi/2$.

3. Experimental

3.1. Specimens preparation

TiAl intermetallic compound and ^{40}Cr steel were used in the study. The specimens were a rectangular shape of 45 mm $\times$ 30 mm, and the thicknesses of TiAl and ^{40}Cr were 4.2 and 14.8 mm, respectively. TiAl specimens were given chemical cleaning by 5% hydrofluoric acid, then rinsed in water and finally dried in hot airflow. ^{40}Cr specimens were cleaned using acetone. Six specimens were then bonded at various temperatures under a constant pressure of 1.33×10^{-3} Pa in a vacuum furnace. The welding temperatures were 900, 950 and 1000 °C to obtain unbond, kissing bond, and perfectly bonded joints, respectively. The welding pressure was 15 MPa for 15 min. A TiAl plate without diffusion bonding was prepared as reference specimen.

3.2. Ultrasonic measurement

Ultrasonic tests were performed using ULTRAPAC C-scan immersion system produced by Physical Acoustic Corporation. The system consists of an immersion system including a scanning frame assemble, motorized axis adjusters, an immersion tank, and a computer with ULTRAWIN software to control test and provide result display. A broadband focused transducer with central

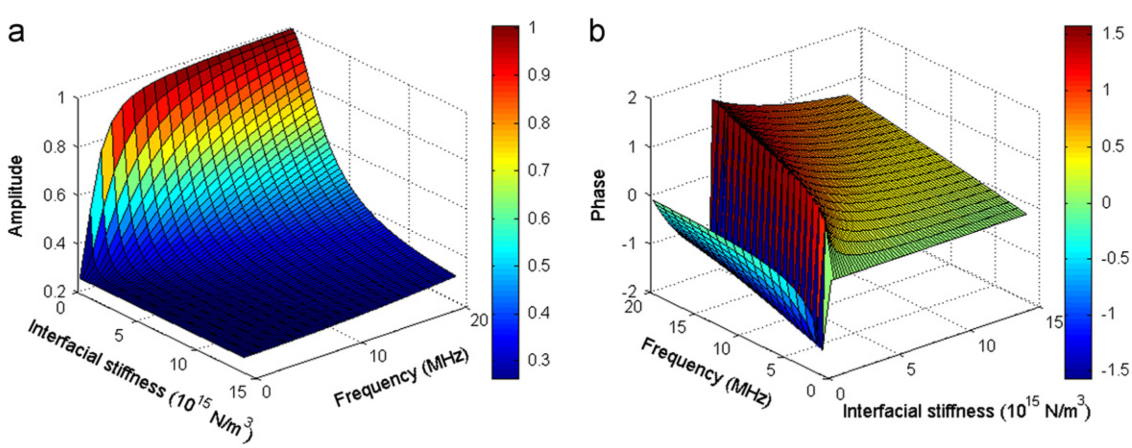

Fig. 1. Calculated reflection coefficient of TiAl and ^{40}Cr diffusion bonding interface: (a) amplitude of reflection coefficient and (b) phase of reflection coefficient.