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Laser ultrasonic technology for residual stress measurement of 7075 aluminum alloy friction stir welding

Yu Zhan [a], Yingmei Li [a], Enda Zhang [a], Yiming Ge [a], Changsheng Liu [b,*]

[a] College of Sciences, Northeastern University, Shenyang 110819, China
[b] Key Laboratory for Anisotropy and Texture of Materials Ministry of Education, Northeastern University, Shenyang 110819, China

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ABSTRACT

Friction stir welding (FSW) is widely used in the welding of aluminum alloys for aerospace applications, because of its low energy consumption, high efficiency and good mechanical properties. However, the problems of deformation, cracking and fatigue degradation caused by residual stress remain to be solved. In this paper, the residual stress in 7075 aluminum alloy FSW has been measured with laser ultrasonic technology. According to the FSW process and the characteristics of thin plate structure, the residual stress of aluminum alloy sheet is simplified to plane stress state. The pre-stress loading method is proposed and the acoustoelastic constants are obtained. With the known acoustoelastic constants, the longitudinal and transverse FSW residual stresses are measured with the laser ultrasonic. The result shows that the residual stress distribution is obviously asymmetrical and the residual stress on the advancing side is greater than that on the retreating side. The transverse residual stress is smaller than the longitudinal residual stress. Then, the influence of welding speed, rotational speed, tool tilts angle and plunge depth on residual stress is discussed. The results show that the welding speed has great influence on the residual stress, while the influence of the rotational speed on the residual stress is relatively small. When the welding speed is low, the influence of the rotational speed on the stress is more obvious than when the welding speed is higher. For the appropriate range which is determined according to the engineering experience, the effect of tool tilt angle and plunge depth on maximum longitudinal residual stress can be ignored. The research of this paper is of great significance to the application of laser ultrasonic technology in the quality inspection of welded parts and the optimization of FSW process.

1. Introduction

7075 aluminum alloy is widely used in aerospace industry because of its high strength, good plasticity and so on. It is easy to produce porosity, hot crack and softening of heat affected zone when welded with traditional welding methods [1,2]. FSW is a new solid state joining technology invented by the Welding Research Institute of Britain. Compared with the traditional welding method, it has the characteristics of high quality, high efficiency, low consumption and low welding deformation. It is especially suitable for welding of 7075 aluminum alloy [3,4]. The formation mechanism of the residual stress in FSW and traditional welding method is different, and during the welding process, a strong rigid restraint and a large pressure on the welded joint part must be imposed. Therefore, the distribution of residual stress field in FSW is bound to show different characteristics. However, due to the limitations of test methods and techniques, the characterization and regulation of the residual stress in FSW is still not effectively solved. The conventional methods of measuring residual stress include hole-drilling method, cutting groove method and X-ray method, etc. [5–7]. However, mechanical method is complicated, time consuming, and will induce damages to the material. X-ray method has the disadvantage of damaging human health and being sensitive to the direction of detection. Laser ultrasonic technique has several advantages such as: non-contact, high-precision, non-destructive, high adaptability. In recent years, laser ultrasonic has been widely used in defect detection [8,9], elastic constant measurement [10–13] and residual stress measurement application [14–17].

The research of laser ultrasonic measurement of residual stress has attracted a great deal of attention of researchers. Doxbeck [14] used the creeping longitudinal waves generated by laser to determine residual stress of autofrettaged steel specimen. Duquennoy [15] measured surface residual stress in steel rods with different heat treatments by laser induced surface wave. Ruiz [16] discusses

* Corresponding author.
E-mail address: csliu@mail.neu.edu.cn (C. Liu).

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the dispersion of laser induced surface waves due to stress. The results suggest that a diffraction correction may be introduced to increase the accuracy of surface wave dispersion measurements. Bescond [17] measured residual stress using laser-generated surface skimming longitudinal waves based on the laser ablation mechanism. Although the method was destructive to the surface of the sample, the measurement accuracy was very high. Karabutov [18] designed a special optoacoustic transducer which was used both for the excitation and detecting of the ultrasonic pulses. This technique was used for measurement of residual stress in electronic welding stainless steel specimen. The results are in good agreement with the traditional method. Sanderson [19] used the simplified finite element modelling to determine the capability and sensitivity of the technique for residual stress measurement. A clear correlation between the magnitude of the residual stress and the surface wave behavior was presented. Moreau [20] used laser ultrasonic measurements of residual stress in a 7075-T651 aluminum sample surface-treated with low plasticity burnishing. Dong [21] used the laser-generated surface acoustic wave to determine the velocity distribution around the joint, from which the distribution of main residual stress are calculated according to acoustoelastic theory.

In this paper, laser ultrasonic, a non-contact method using laser for the generation and detection of ultrasonic, is applied to measure residual stress of 7075 aluminum alloy FSW. The method is based on monitoring the small velocity change produced by the stress of the laser-generated surface wave. The residual stress of aluminum alloy sheet is simplified to plane stress state. The pre-stress loading method is proposed and the acoustoelastic constants are obtained. The residual stress profile measured is compared with the results from strain gauge measurements. Then, the influence of welding speed, rotational speed, tool tilts angle and plunge depth on residual stress is discussed respectively. The results show that the welding speed is the main factor affecting the residual stress. When the welding speed is low, the influence of the rotational speed on the residual stress is more obvious than when the welding speed is higher. The tool tilt angle and plunge depth have little influence on maximum longitudinal residual stress. The research of this paper is of great significance to the optimization of FSW parameters and the evaluation of residual stress.

2. Acoustoelastic theory

The ultrasonic evaluation of the residual stress is based on the acoustoelastic theory. This effect results in the change of the ultrasonic wave propagating velocity according to the material strain state. The theory of the acoustoelastic effect for surface waves was reviewed in reference [22]. Here, only the final result is given. Considering the research for the FSW residual stress of the uniform and isotropic thin plate, the stress in the thickness direction is very small compared to the other two directions, we can approximate $\sigma_z = 0$ and the problem is simplified into plane stress state. Surface wave propagation on the free surface of an elastic isotropic solid defined by normal plane coordinates (x, y) is considered in this paper. According to the discussion about the surface wave acoustoelastic effect conducted by Husson [23], variations of the propagation velocity can be expressed as a function of two nonzero surface stresses σ_x and σ_y as follows:

$$\frac{\Delta v_x}{v_0} = \frac{v_x - v_0}{v_0} = A_x\sigma_x + A_y\sigma_y \tag{1}$$

$$\frac{\Delta v_y}{v_0} = \frac{v_y - v_0}{v_0} = A_x\sigma_y + A_y\sigma_x \tag{2}$$

where v_0 is the surface wave velocity in an unstressed medium; v_x and v_y are the surface wave velocities in the presence of (σ_x, σ_y) in the x and y directions, respectively; σ_x and σ_y are the principal stress; $A_x$andA_y are the acoustoelastic coefficients of the surface wave which depend not only on the propagation directions of the wave but also on the stress direction. These acoustoelastic coefficients can be estimated theoretically according to physical parameters of the material [24]. Considering the difference between the theory and the experiment, in order to improve the measurement accuracy, we use the pre-stress loading method to measure the acoustoelastic constants in the experiment.

In order to obtain the stress using Eqs. (1) and (2), the constants A_x and A_y must be determined in advance. For a uniaxial stress field, only the pre-stress σ_x is applied, the constants A_x and A_y can be determined by the calibration experiment. When the specimen is in the state of uniaxial stress, the Eqs. (1) and (2) can be simplified as:

$$\frac{\Delta v_x}{v_0} = \frac{v_x - v_0}{v_0} = A_x\sigma_x \tag{3}$$

$$\frac{\Delta v_y}{v_0} = \frac{v_y - v_0}{v_0} = A_y\sigma_x \tag{4}$$

Obviously from Eqs. (3) and (4), it is known that for a certain pre-stress if the surface wave propagation velocity along the stress direction and vertical stress direction is measured respectively, we can get the acoustoelastic constants.

3. Experiment procedure

The experiment is divided into three steps, including preparation of the experimental samples, laser ultrasonic for measurement of the FSW residual stress, verification of the experimental results by hole-drilling method.

3.1. Preparation of the experimental samples

A number of parameter settings can be varied during FSW such as welding speed, rotational speed, tool tilt angle, tool design and plunge depth, but their individual influence on the residual stress remains unclear in most cases. In this study welding speed, rotational speed, tool tilts angle and plunge depth are altered. The test material is a 7075 aluminum alloy plate with thickness of 5 mm (supply state: T6). The mechanical parameters of the material are shown in Table 1. The nominal chemical composition of the alloy is 5.6 Zn, 2.5 Mg, 0.5 Fe, 0.16 Cu, 0.23 Cr, 0.3 Mn, and 0.2 Ti with a balance of Al. An H13 steel FSW tool with a 15 mm diameter shoulder and a cylindrical, 5 mm in diameter, threaded pin was used. The welding way is butt welding and the size of the weldment is 250 mm $\times$ 40 mm $\times$ 5mm. The range selected for welding speed and rotational speed was chosen experimentally to be as wide as possible whilst retaining production of reasonably sound welds. Table 2 lists the different combinations of tool rotational speed and welding speed used in this study, where parameter f is defined as welding speed/rotational speed. 16 weldments can be obtained by matching the welding speed and rotational speed in each FSW.

3.2. Laser ultrasonic for measurement of the FSW residual stress

3.2.1. Experimental setup

The laser ultrasonic system includes three parts: the Nd:YAG laser (for ultrasonic generation), the laser Doppler vibrometer (for ultrasonic detection) and the pre-stress loading device (for acoustoelastic constant measurement). The experimental system is shown in Fig. 1. A laser pulse (pulse width$\tau = 8$ns, wavelength $\lambda = 1064$nm, repetition frequency $f = 20$Hz, single pulse energy