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Taguchi optimization and ultrasonic measurement of residual stresses in the friction stir welding

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ABSTRACT

The main goal of this study is optimization of residual stresses produced by friction stir welding (FSW) of 5086 aluminum plates. Taguchi method is employed as statistical design of experiment (DOE) to optimize welding parameters including feed rate, rotational speed, pin diameter and shoulder diameter. The optimization process depends on effect of the welding parameters on longitudinal residual stress, which is measured by employing ultrasonic technique. The ultrasonic measurement method is based on acoustoelasticity law, which describes the relation between acoustic waves and internal stresses of the material. In this study, the ultrasonic stress measurement is fulfilled by using longitudinal critically refracted (L_{CR}) waves which are longitudinal ultrasonic waves propagated parallel to the surface within an effective depth. The ultrasonic stress measurement results are also verified by employing the hole-drilling standard technique. By using statistical analysis of variance (ANOVA), it has been concluded that the most significant effect on the longitudinal residual stress peak is related to the feed rate while the pin and shoulder diameter have no dominant effect. The rotational speed variation leads to changing the welding heat input which affects on the residual stress considerably.

1. Introduction

1.1. Welding residual stress

Residual stresses are known as remaining stresses inside the material after manufacturing process, in the absence of any external loads or thermal gradients. The engineering properties of industrial equipment particularly fatigue life, dimensional stability, corrosion resistance, and brittle fracture can be considerably influenced by residual stresses. Welding processes, as essential production processes in the industry, produces residual stresses at a significant level. Welding residual stresses are the results of non-uniform thermal expansions and solidifications caused by the welding processes.

1.2. Residual stress measurement

Residual stresses measurement is a critical stage in the structures design and also in the reliability estimation of mechanical equipment under real service conditions. There are various methods available for stress measurement including three main categories: destructive, semi-destructive and non-destructive methods [1]. The destructive and semi destructive techniques, also called as mechanical method, rely on measuring the deformations produced by releasing residual stresses upon material removal from the specimen. Sectioning and contour method are principal destructive techniques which completely destruct the specimen to evaluate the residual stresses while hole-drilling, ring-core and deep-hole-drilling are semi-destructive techniques leave small holes on the material surface. Among them, the hole-drilling method is one of the most popular methods providing the stress measurement with good accuracy and reliability. Since the hole-drilling method is standardized by ASTM: E837, it is used by the majority of studies as a verification of other stress measurement methods [2–6]. Non-destructive methods including X-ray diffraction, neutron diffraction, ultrasonic and magnetic methods usually measure some parameter that is related to the stress. The non-destructive evaluation of stress becomes increasingly important since many structural components, e.g. bridges, aircraft structures or offshore platforms, need to be inspected periodically to avoid major damage or even failure.

1.3. Ultrasonic stress measurement

Ultrasonic stress measurement is founded on the linear relation between velocity of the ultrasonic wave and the material stress. This correlation, within the elastic limit, is known as the

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acoustoelastic effect, which says that flight time of the ultrasonic wave changes with the stress. In 1967, Crecraft [7] showed that the acoustoelastic law could be employed for stress measurement of engineering materials. The longitudinal critically refracted (L_{CR}) wave is a longitudinal ultrasonic wave propagated parallel to the surface. It has been proved by Egle and Bray [8] that the L_{CR} wave sensitivity to the stress is highest among the other types of ultrasonic waves. Tang and Bray [9] utilized the L_{CR} waves to measure the stresses and also studied effect of plastic deformation on the wave velocity variations. The L_{CR} waves were employed to evaluate bending stress in steel plates and bars by Bray and Tang [10]. They used two different testing frequencies (2.25 MHz and 5 MHz) and compared the results. They tried to confirm a unique capability of the ultrasonic method, which is penetrating in different depth (by changing the frequency of transducers) and measuring bulk stress in different depths. It means that the ultrasonic stress measurement could be used to measure through-thickness stresses while the aforementioned capability was also confirmed by Javadi et al. [11] and Sadeghi et al. [12] in the stainless steel and aluminum plates, respectively. By employing the L_{CR} waves produced by four different frequencies (1 MHz, 2 MHz, 4 MHz and 5 MHz) of ultrasonic transducers, Sadeghi et al. [12] determined distribution of longitudinal residual stress through the thickness of aluminum plates joined by friction stir welding. Javadi et al. [13] employed the L_{CR} method to measure through-thickness distribution of hoop and axial residual stresses in stainless steel pipes. However, they recommended using another stress measurement method (like hole-drilling method) to be used as verification of the L_{CR} measurement method.

The L_{CR} measurement was developed in immersion mode by Belahcene and Lu [14] to measure welding residual stresses of S355 steel plate. They used hole-drilling method to verify the ultrasonic stress measurements. Palanichamy et al. [15] measured the residual stresses in austenitic stainless steel weld joints using ultrasonic technique. Javadi et al. [16] presented a comparison between using contact and immersion transducers in ultrasonic stress measurement of dissimilar plates and pipes. In another work, they also compared contact and immersion mode in ultrasonic stress measurement of stainless steels plates [17]. Comparing the results obtained from aforementioned works ([16] and [17]) shows that there is no considerable difference between using the contact and immersion technique, hence the contact transducers are employed in this study.

Recently, employing the L_{CR} waves is more popular in the ultrasonic stress measurement and the majority of studies consider the longitudinal waves more than the ultrasonic shear waves [18–24]. Hence, the L_{CR} waves are used in this study to measure the residual stresses of the aluminum plates joined by friction stir welding.

1.4. Friction stir welding (FSW)

The welding residual stresses may be produced after all of the welding processes including both fusion and solid state welding processes. Solid-state welding processes do not involve the melting of the structures being joined; instead, the weld is created by producing coalescence at temperatures below the melting point of the base metals, without addition of the filler metal. Friction stir welding (FSW) is a solid state welding process patented by TWI [25], in which a rotating tool (with a pre-determined tilt angle) is embedded into the adjoining edges of the plates to be welded, and then moved all along the welded joint. As the tool moves, the material is forced to flow around the tool in a complex flow pattern, which has been described in several literatures [26–28]. The result would be producing frictional heating along with plastic deformation in the welding zone while no material melting is created.

Bussu and Irving [29] showed that the fatigue life is improved by presence of the residual stresses; however they considered distortions caused by the residual stresses that restrict application of the FSW process in manufacturing production. Peel et al. [30] employed the X-ray diffraction method to evaluate distribution of residual stresses caused by the friction stir welding of 5083 aluminum plates. Similar studies were developed by Staron et al. [31] and Prevéy and Mahoney [32] on the friction stir welding of aluminum.

1.5. Design of experiment (DOE)

Due to that residual stresses produced by the FSW process plays an important role in designing the industrial equipment, optimization of the FSW process parameters which could influence on the residual stresses are very essential. Design of experiment (DOE) and statistical techniques are extensively used to optimize process parameters. Taguchi method is one of popular optimization techniques that could be used to optimize welding parameters. Optimization of process parameters is a key step in the Taguchi technique to reach high quality without increasing the cost. This is because optimization of FSW process parameters can decrease the residual stress, which leads to improvement of performance characteristics. The optimum process parameters obtained from the Taguchi method are not sensitive to the variation of environmental conditions and other noise factors [33]. Generally, classical process parameter design is complex and not easy to solve. This is mainly true when the number of the process parameters increases, leading to a large number of experiments have to be carried out. To solve this problem, the Taguchi method with a special design of orthogonal arrays can be employed to study the entire process parameter space with a small number of experiments only [34]. The optimum combination of the process parameters can then be predicted [35].

1.6. Goals and objectives of this study

The main goal of this study is optimization of residual stresses produced by the FSW process on aluminum plates. By using the Taguchi method, the DOE is employed to optimize welding parameters including feed rate, rotational speed, pin diameter and shoulder diameter. The optimization process leads to residual stress minimization while the longitudinal residual stresses are measured by utilizing the L_{CR} waves. The ultrasonic stress measurement results are also verified by employing the hole-drilling standard technique. By using statistical analysis of variance (ANOVA), it has been concluded that the most significant effect on the longitudinal residual stress peak is related to the feed rate while the pin and shoulder diameter have no dominant effect. In addition to the feed rate effect, the rotational speed variation also leads to changing the welding heat input which affect on the residual stress considerably.

2. Theoretical background

2.1. L_{CR} method

Different experimental setups can be used for residual stresses measurements fulfilled by the L_{CR} waves. As a common configuration, three ultrasonic transducers with same frequency are used. The longitudinal waves are produced at the first critical angle by a transmitter (sender) transducer, then propagate parallel to the surface of tested material and finally are detected by two receiver transducers assembled in different distance from the sender. The reason of using two receiver transducers is decreasing the environmental effects, like ambient temperature, on the wave velocity.