Evaluation of Friction Stir Spot Welding Process by Laser Ultrasonic Method with Synthetic Aperture Focusing Technique

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Abstract. The application of laser ultrasonic technique is developed for evaluation of friction stir spot welding (FSSW) quality. The features of laser-generated ultrasonic waves in good welding and incomplete fusion area are simulated by finite element method (FEM). The non-contact laser ultrasonic inspection system (LUIS) was established to verify the numerical results. The interaction of laser ultrasound with the welding joint has been investigated. Laser ultrasonic reflected waves in good welding and incomplete fusion area can be distinguished according to some signatures. The shear waves may be more sensitive to incomplete fusion defects than the longitudinal waves in testing the welding joint. The C-scan results can sufficiently evaluate the intrinsic characters of welding area by time-domain synthetic aperture focusing technique (T-SAFT) processing. The research results show that the laser ultrasonics would be an effective method to realize detection of FSSW defects.

1. Introduction

Friction stir welding (FSW), a highly effective solid-state welding technique, has been applied to aerospace, automobile and railway industries for the recent years[1-3]. Stronger and lighter friction stir welding joints are excellent candidates to replace bonding and riveting in the manufacture of large fuselage and other components[1]. Some 7xxx and 2xxx series aluminum alloys can be made use of this advanced welding technique to achieve high quality of welding joints[3]. However, considering the changes in material conditions or welding parameters, typical defects are incomplete fusion, lack of penetration, wormholes and kissing bonds (vertical) in butt joints, and hooking, wormholes and kissing bonds (horizontal) in lap joints[3-8]. They are known as the most challenging problem for inspection of FSW joints. Friction stir spot welding (FSSW) is a relatively new solid-state welding variant of FSW that possesses the high quality of welding joints, few defects and little distortion. Ultrasonic method has been applied to evaluating the welding quality because of its high sensitivity and resolution[7]. Considering the special application of FSSW joints, the inspection of welding joints needs the non-contact ultrasonic method to avoid the pollution of couplant. The air coupled ultrasonic method has no effect in detecting the defects in metal owing to the large impedance difference between air and metal material. The electromagnetic ultrasound is able to perform the non-contact measurement, but the stand-off distance is very small to restrict its application.
Laser ultrasonics uses one laser with short pulse for the generation of ultrasonic waves and another laser, with long pulse or continuous laser, coupled to an optical interferometer for the detection of ultrasonic displacements\cite{9-12}. Laser ultrasonic method, possessing the features of non-contact and broadband, with advantage of high speed scanning in complex structures inspection and testing in special conditions, has found application in many occasions\cite{13-14}. Hedin et al investigated the FSW with butt joints and identified the defect positions by laser ultrasonics based on the thermal ablation regime with time of flight diffraction (TOFD)\cite{15}. Mandache et al concentrated on the comparative investigation of different non-destructive inspection (NDI) techniques for detecting the lack of penetration discontinuities in butt joint friction stir welds and they used laser ultrasonic method based on the thermal ablation regime with frequency-domain synthetic aperture focusing technique (F-SAFT) to detect the defects\cite{16}. Lévesque et al utilized laser ultrasonics based on the thermal ablation regime with F-SAFT for defect detection and residual stress measurement of butt joint friction stir welds\cite{17}. Therefore, laser ultrasonics has been proven a potential NDT method for monitoring of FSSW process. However, the thermal ablation regime of laser ultrasonics would damage the material surface, which restricts its application in aerospace industries. At the same time, the F-SAFT would not be used by misalignment of generation-detection position with the small depth of detection\cite{18}. Therefore, the T-SAFT was utilized to improve the detectability and signal to noise ratio (SNR) of laser ultrasound. The testing results show that laser ultrasonics would be an effective method to achieve evaluation of the quality of lap joint.

2. **Principle of T-SAFT**

The T-SAFT has been used in the traditional ultrasonic imaging systems mainly due to its benefits that it would improve the lateral resolution in a broad focal zone and is capable of improving contrast in ultrasonic images by reducing backscattering effects\cite{18}. As shown in Fig. 1, a flaw located at point C within the material will reradiate the acoustic field from many measurement points onto the surface. The T-SAFT implementation is to directly perform the summation of $N$ signals shifted in time and taken from the measurement grid within a given aperture. Thus, it can be described as follows:

$$S_{\text{DAS}}(t) = \sum_i a_i S_i(t + \Delta t_i), \quad i = 1, 2, 3, \ldots N,$$

where $S_{\text{DAS}}$ is the synthetic signal, $S_i$ is the signal at some point, $a_i$ is the weighting coefficient calculated by the apodized function, and $\Delta t_i$ denotes the delay time of echo signals and its formula is listed:

$$\Delta t_i = \frac{2z}{c} \left( \sqrt{1 + \left( \frac{id}{x^2} \right)^2} - 1 \right),$$

where $c$ is the ultrasound velocity in the medium, $z$ is the vertical distance between the flaw and detection point, $d$ is the scanning step. The appropriate time shift of successive signals forming a locus curve is a function of the point where the signals are collected.

![Fig. 1. Schematic diagram of a 2-D array of ultrasonic signals at the sample surface for its use with T-SAFT](image)

2
The coherent summation increases the SNR for defect detection by the factor $\sqrt{N}$. While maintaining the depth resolution $\Delta z$, the T-SAFT processing improves the lateral resolution $\Delta x$. It can be shown the depth and lateral resolutions for defect sizing are given by

$$\Delta x = \frac{z}{a} \Delta t, \Delta z = \frac{1}{2} v \Delta t,$$

where $v$ is the ultrasonic wave velocity, $\Delta t$ is the ultrasonic pulse duration and $a$ is the dimension of the synthetic aperture. In practice, the strength of the ultrasonic wave and the detection sensitivity both decrease as the lateral distance between the sampling and the observation point at the depth $z$ increases. Hence, the total opening angle of the synthetic aperture is expected to be limited to roughly $60^\circ$, which means $a \sim z$.

## 3. Specimen and experimental setup

### 3.1 Specimen

The specimen is composed of two 7xxx series aluminum alloy plates processed by the FSSW technology shown in Fig. 2. The dimensions of plates are 140×50×2 and 140×50×1mm, respectively, located in the first and second layer. The dimensions of overlap region are 42×50mm and the radius of welding area is about 6mm. After the faying surfaces and the surrounding of the workpiece were carefully cleaned, the specimen was attached to the backing plate of a MTS ISTIR FSSW equipment. In the welding process, the tool rotation speed was set to 1000rpm and its side tilt angle was about 0.5°. The tool (i.e. pin and shoulder) penetration increased to 2.5mm at the end of the weld. The adjustable welding tool had a scrolled shoulder with a diameter of 9.5mm and a right hand threaded pin with a diameter of 3.175mm.

![Fig. 2. The specimen with lap joint structure manufactured by the FSSW technology](image)

### 3.2 Experimental setup

In order to verify the theoretical analysis, an experimental setup was constructed for investigating the interaction of laser-generated ultrasonic waves with the welding region. Fig. 3 shows the schematic diagram of the experimental system. A Nd:YAG pulsed laser with wavelength of 1064nm, pulse duration of 10ns, and energy range of 0~20mJ was used to induce ultrasonic waves. A laser measurement system that is sensitive to the out of plane displacement was utilized to measure ultrasonic displacements, and the system was equipped with a continuous laser with wavelength of 1550nm and power range of 0~2W, optical splitter and two-wave mixing (TWM) interferometer. The received voltage signals from the laser interferometer were processed by the signal processing unit, and then recorded by a digital oscilloscope (Tektronix DPO7254C) and DAQ card (NI-5112). A trigger signal from the pulsed laser source was used to trigger the digital oscilloscope and the DAQ card. The pose of laser probes can be adjusted by the mechanisms with four degrees of freedom (X, Y and Z translation, and Z rotation). The trajectory of specimen rested on a precise motion platform was accurately controlled by a program.
4. Results and discussion

4.1 Characteristics of laser-generated ultrasonic waves in good welding and incomplete fusion area based on FEM

To compare the characteristics of laser-generated ultrasonic waves in good welding and incomplete fusion area, FEM, due to its flexibility in modeling complicated geometry and its capability in obtaining full field numerical solutions, has been used to deal with the process of ultrasonic waves induced by a pulsed laser. Fig. 4 shows the waveforms of laser ultrasound measured at the 1.5mm distance from generation point in the surface of specimen. Because the velocities of Rayleigh, longitudinal and shear waves in aluminum are assumed to be 2940, 6300 and 3100m/s, respectively, the first to arrive at the detection position is Rayleigh waves (R) and followed by reflected longitudinal waves (rL), mode conversion waves (SL/LS) and reflected shear waves (rS) according to the time difference of wave reaching detection position. As it can be seen from Fig. 4, the R waves have a large time width and their energy mainly distributes in the low frequency (below 1MHz). Therefore, eliminating the interference of R waves by high-pass filtering is significantly useful for obtaining the signals of rL and rS to monitor the quality of welding process. The arrival time of rL, SL/LS and rS waves in Fig. 4(a) and (b) is evidently discrepancy resulting from the difference of propagation paths displayed, so making the most of this difference would be able to distinguish the good welding and incomplete fusion area.
4.2 Experimental results of laser ultrasonic waves in welding specimen

The energy of pulsed laser was 10mJ and its spot radius was about 2mm, thus the power density of laser pulse was about $8 \times 10^6 \text{W/cm}^2$ lower than the ablation threshold of material to guarantee thermoelastic generation of ultrasonic waves. The output power of continuous laser was 0.3W, which is sufficient to keep the high detection sensitivity because the specimen surface is quite smooth. The distance between generation and detection point was about 1.5mm to receive the reflected waves. To obtain a good SNR, reducing the signal bandwidth would be an effective method. Therefore, the acquired original signal was processed by a high-pass filter at 1MHz and signal averaging of twenty times. Fig. 5 and 6 show the time-domain signals and corresponding frequency spectrums of reflected longitudinal and shear waves in incomplete fusion and good welding area. The low frequency contents (below 5MHz) of ultrasonic waves dominate a very large percent in the total energy, but the decrease of amplitude would be insignificant with the increase of frequency above 5MHz. Thus, the wideband ultrasound will be useful for recognizing material defects. As shown in Fig. 5 and 6, the R and SL/LS waves disappear because of the filtering and distribution of acoustic field. Moreover, the time-domain amplitudes of rL and rS in the incomplete fusion area obviously higher than those in good welding area, and the arriving time of rL and rS in good welding and incomplete fusion area has a slight difference. These results agree well with the theoretical analysis and simulation data.

![Fig. 5](image1.png) Features of reflected waves in incomplete fusion area by high-pass filtering of 1MHz: (a) time-domain signal, and (b) corresponding frequency spectrum

![Fig. 6](image2.png) Features of reflected waves in good welding area by high-pass filtering of 1MHz: (a) time-domain signal, and (b) corresponding frequency spectrum
4.3 C-scan results based on laser ultrasonic longitudinal and shear waves

In C-scan tests, the energy of incident laser was set to 10mJ and its spot radius was about 2mm, which can guarantee the nondestructive generation of ultrasound. The output power of continuous laser was 0.3W to keep the high sensitivity of detection. The acquired A-scans were processed by the average of twenty signals to reduce random noise in the scanning process, which has no effect on the scanning speed. The scanning step was set to 0.2mm to achieve the precise tests. Fig. 7(a) shows the C-scan image that was formed according to the features of reflected longitudinal waves based on the configuration of pulse-echo method. At the same time, the C-scan image was generated by the reflected shear waves based on the pulse-echo method shown in Fig. 7(b). The C-scan results obviously reflect the basic characters of welding area. Some heterogeneous weld locations have been found in the C-scan images. Therefore, the reflected shear waves may be more sensitive to incomplete fusion defects than the reflected longitudinal waves by contrasting Fig. 7(a) with (b).

Fig. 7. C-scan images from the test specimen by laser ultrasonics: (a) rL and (b) rS waves

4.4 Improvement of C-scan image by T-SAFT

To improve the lateral resolution of the incomplete fusion defects and SNR of C-scan image, the T-SAFT was utilized to process the reflected laser ultrasonic shear waves. The number of apertures was set to nine and the weighting coefficients were calculated by window function using Hanning according to the above analysis. At the same time, the delay time of every echo signal was obtained based on the formula (2). Then, the C-scan data were reconstructed by the T-SAFT. Compared with the Fig. 7, the SNR and resolution of C-scan image was evidently improved by the algorithm shown in Fig. 8. Therefore, laser ultrasonic method combined with T-SAFT would successfully apply to testing the FSSW defects.

Fig. 8. C-scan image processed by T-SAFT
5. Conclusions

Laser ultrasonic method using laser thermoelastic generation and TWM interferometer detection is an optimum choice for detecting the quality of FSSW joints. The features of laser-generated ultrasonic waves in the welding joint were investigated by FEM, which can provide effective guidance for the experiment. The reflected longitudinal and shear waves in good welding and incomplete fusion waves can be distinguished by time difference of arriving at the detection point. The C-scan results, based on pulse-echo method, are able to evaluate the FSSW technology from different aspects. Laser ultrasonic shear waves may be more sensitive to the incomplete fusion defects than the longitudinal waves. The resolution and SNR of laser ultrasonics to detect small defects can be greatly enhanced by using T-SAFT. As a result, laser ultrasonics associated with T-SAFT processing would be an effective method to realize the characterization of FSSW defects.

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References