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Mechanical Characterization of Laser Welded Materials using Laser Interferometry

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ABSTRACT

Stainless steel Ph13-8 has yield stress much higher than 304L. These two materials are joined together by laser welding. It is important to study the mechanical properties of the laser welded area. The laser welded spot is only at submillimeter size. Traditional strain measurement method using the strain gage is impossible. In this paper, the strain is measured using non-contact laser interferometry method. Two markers are placed on the LIGA specimens along the loading direction to reflect the laser beams to generate the interferometric fringe patterns. The markers are generated using micro-hardness indentation in the welded area. A pair of CCD cameras is used to capture the interferometric fringes during each step of the loading along the longitudinal direction. Fast Fourier Transform (FFT) is then applied to calculate the frequency and phase shift of the fringes. The displacement and strain can be obtained from the phase shift of the fringe pattern. This ISDG strain measurement technique is further developed by using multi markers to study the mechanical properties variation across the welded area.

KEYWORDS

Laser welding, ISDG, FFT, multi-marker,

INTRODUCTION

The mechanical properties in the heat-affected zone (HAZ) have critical effects on the mechanical performance of the welded components. It is important to assess the mechanical properties in the welded area. Laser welding process has high power density, small heat-affected zone and it has been widely used in various industries. It is not easy to characterize the mechanical properties of these small zones using traditional strain measurement methods such as strain gauge.

Sharpe *et al* has demonstrated the direct strain measurement on small gage length using the laser interferometric strain/displacement gage (ISDG) [1-5]. Two markers were placed on the specimen for the laser reflection. The motion of these two markers can then be calculated from the fringe motion generated by the reflected laser. Zupan *et al* improved the ISDG technique by applying Fourier analysis to the fringe pattern [6].

In our experiment, a standard dog-bone tensile testing design was used for the characterization purpose. The tensile specimens were extracted so that the gage sections were located in the welded area. A loading stage which is capable of tension, compression and bending is used to load the welded specimen. Load is acquired by the load-cell during the test. Instead, the displacement and strain were measured directly by using laser interferometric strain/displacement gage (IDSG). The two indent markers on the specimen define the gage section. The indentation markers were located directly over the welded area.

THE OPTICAL BASICS OF ISDG

The principle of ISDG is similar to Young's double slit experiment as shown in *Figure 1*, but laser reflection is used instead of laser transmission. The relation between the fringe pattern and the space of reflection markers can be expressed as following equation:

$$m\lambda = d\sin(\theta) \tag{1}$$

Where m is the order of fringe, λ is the wavelength, d is the space between the two markers, θ is the incident laser light angle. According to this equation, the change of the space of the markers Δd can be measured by the change of the fringe location and the strain can be calculated from the displacement of markers:

$$\Delta m\lambda = \Delta d \sin(\theta) \quad (2)$$

$$\Delta \mathrm{d} = \frac{\Delta m\lambda}{\sin\theta} \quad (3)$$

$$\varepsilon = \frac{\Delta d}{d_0} = \frac{\Delta m \lambda}{d_0 \sin\theta} \quad (4)$$

The location of the fringe can be decided by the phase of the fringe pattern. Therefore the motion of the fringe, as well the displacement and strain can be measured from the phase shift of the fringe patterns:

$$\Delta m = \frac{\Delta \Phi}{2\pi} \quad (5)$$

$$\varepsilon = \frac{\left(\frac{\Delta \Phi}{2\pi}\right)\lambda}{d \sin(\theta)} \quad (6)$$

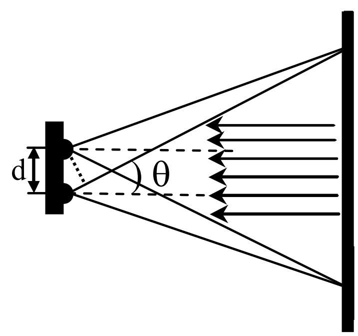


Figure 1: The principle of ISDG

LASER WELDED SPECIMENS

Stainless steel Ph13-8 and 304L is joined by the laser welding. The thickness of the metal sheet is 2.28 mm (0.090”). The welding process has partial penetration depth of 1.52 mm (0.060”). An SEM image of the cross section of the laser welded zone is shown in *Figure 2*. It can be seen that the welded zone has width in the submillimeter range, varying from top to bottom of the welded zone.

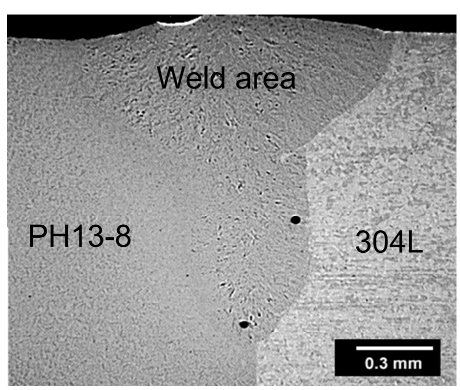


Figure 2: SEM image showing the cross section of laser welded zone

Dog-bone tensile specimens were extracted from the laser welded zone. The welded metal sheet was grounded flat on the top surface. The tensile specimens were then extracted across the penetration depth, with gage section mostly located in the HAZ. The specimen has thickness of 0.2mm (0.008”). The width of the gage section is 0.2mm (0.008"). The length of the gage section is 0.813mm (0.032"). The tensile specimen is shown in *Figure 3(a).*

The tensile specimens were mechanically polished to 1 micron finish to show nice reflection surface. The specimens were then slightly etched to show the edge of the welded zone. The Vickers indents used as reflection markers were carefully placed over the welded zone. The SEM image in *Figure 3(b)* clearly shows the welded area and the edge of the welded zone and the original material.

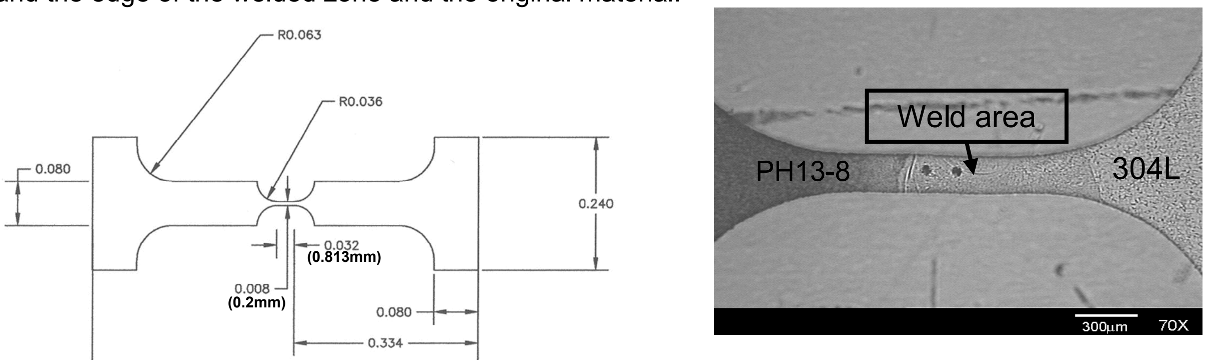


Figure 3: (a) Tensile specimen extracted from the welded area; (b) SEM image of the gage section

UNIAXIAL STRAIN MEASUREMENT

The experimental configuration for uniaxial strain measurement is shown in *Figure 4*. He-Ne red laser with wavelength $\lambda = 633nm$ is shined onto the two indentation reflection markers on the specimen surface. The two markers for laser reflection are Vickers micro-hardness indents, with half-angle of 68^o. The fringes are located at 45^o angle relative to the specimen surface. The fringes were captured by a pair of CCD cameras aligned along the two reflection markers. The CCD cameras have resolution of 1024x1280 pixels.

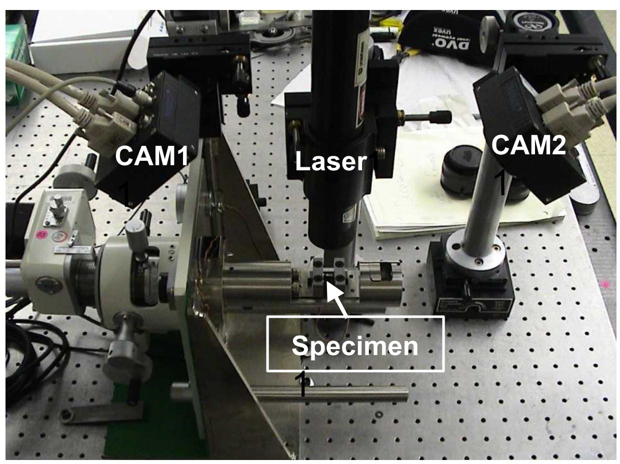


Figure 4: Experimental configuration for uniaxial strain measurement

DATA ACQUISITION AND REDUCTION

In this testing system, the load was induced by the loading stage and recorded by the load cell attached to the fixture of the specimen. The fringes were recorded by the CCD cameras during each step of the loading. A typical fringe pattern is shown in *Figure 5.*

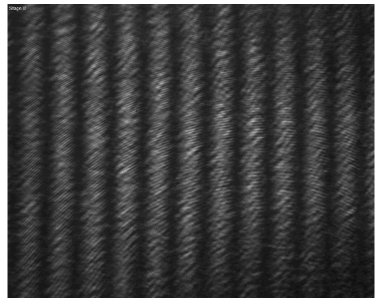
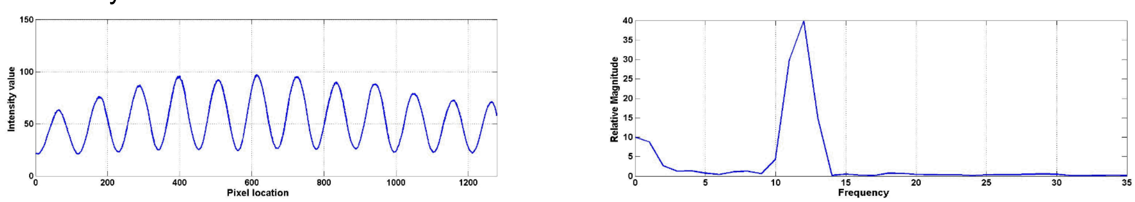


Figure 5: A typical fringe pattern from the uniaxial testing captured by CCD cameras

As discussed in the optical basics of ISDG, the displacement and strain of the specimen can be calculated from the motion of the fringe pattern, i.e. the phase shift of the fringe. The motion in each fringe pattern is the sum of both rigid body motion and strain of the specimen. The rigid body motion of the specimen will cause the fringe patterns in both cameras to move in the same direction, while the strain will cause the fringe patterns to move in the opposite direction. Therefore, in order to obtain the strain, a pair of cameras is needed to capture the fringe patterns on both sides of the incident laser beams. The strain is calculated by subtracting the motion of these two fringe patterns:

$$\Delta\Phi = \Delta\Phi_{1\,\mathrm{total}} - \Delta\Phi_{2\,\mathrm{total}} = \Delta\Phi_{1\,\mathrm{RBM}} + \Delta\Phi_{1\,\mathrm{strain}} - (\Delta\Phi_{2\,RBM} + \Delta\Phi_{2\,\mathrm{strain}}) \tag{7}$$

In Sharpe's work, the fringe is captured using a linear diode array, which can only capture one dimensional information of the fringe. In this work, two dimensional information of the fringe pattern was recorded using CCD cameras, as shown in Figure 4. The values along each column are added and averaged to remove noise. The averaged intensity value versus the row pixel location shows nice sinusoidal curve. By applying FFT, the frequency, as well as the amplitude and phase shift can be calculated for the fringe pattern of each step. The intensity curve and the converted frequency curve are shown in *Figure 6(a) and (b)* for the fringe pattern in Figure 5. Using the load recorded by load cell and the strain obtained from the fringe pattern for each step during the loading, the stress and strain curves can be obtained. *Figure 7* shows stress-strain curves obtained using ISDG method and strain gauge. It is clearly shown that the stress versus strain curves of 304L obtained using both methods match very well.



(a) (b)

Figure 6: (a) Intensity curve and (b) the FFT result of the intensity curve for the fringe pattern in Figure 5

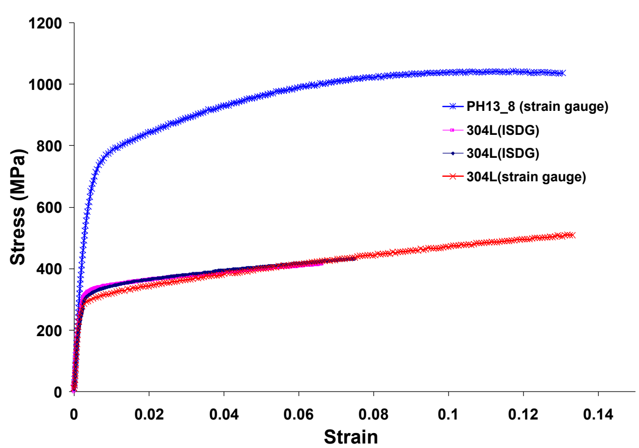
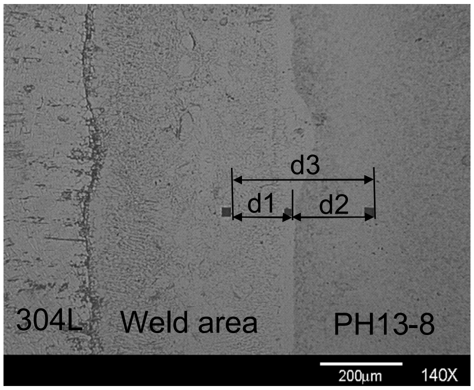


Figure 7: Comparison of stress-strain curves of 304L obtained using ISDG and strain gauge

MULTI-MARKER ISDG MEASUREMENT

Multi-marker ISDG can be applied to measure the non-uniform strain over the specimen for inhomogeneous materials. The markers at different location can measure the local strain at that location. Two pairs of reflections were places over the tensile gage section so that one is located in the welded zone and the other pair is located in the Ph13-8, as shown in *Figure 8(a)*. Therefore, the deformation in the welded area can be obtained from gage 1 and the deformation in Ph13-8 can be obtained from gage 2. Gage 3 will represent the total deformation across the welded area and ph13-8. A typical fringe pattern from three-marker interference is shown in *Figure 8(b)*.



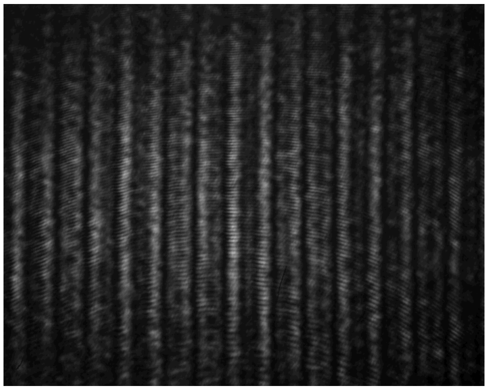


Figure 8: (a) Multi markers on the specimen; (b) The fringes from the multi-marker interference

The stress-strain curves obtained from these three markers are shown in *Figure 9*. It can be seen the stress strain curve from gage 2 is matching well with Ph13-8. The stress-strain obtained from gage 1 represents the laser welded zone. The stress strain curve from gage 3 is the effective property from the welded area and ph13-8.

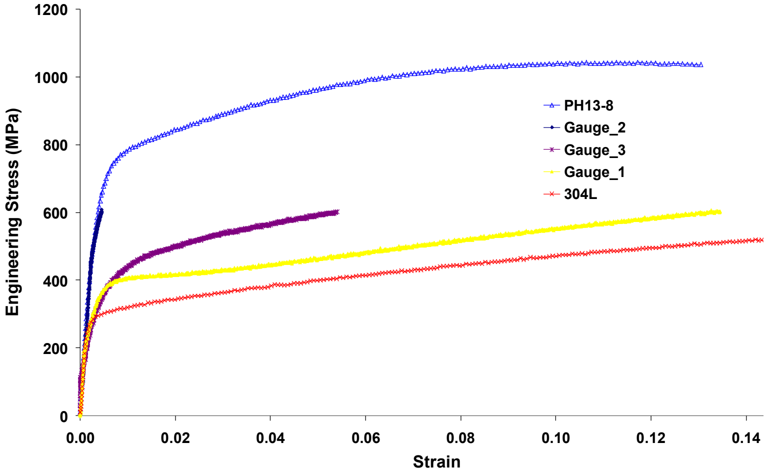


Figure 9: Stress-strain curves from multi markers ISDG

CONCLUSIONS

The non-contact laser interferometry strain/displacement gage technique can be successfully applied to measure the material properties of laser welded material. The micro-hardness indents generate reflection markers on the tensile specimen surface for strain measurement. CCD cameras enable to capture two dimensional information of the fringe pattern. By applying the FFT to the fringe pattern, the frequency and phase shift can be calculated for each step of the loading. The multi-marker ISDG can be applied to measure the variation of the mechanical properties for inhomogeneous material.

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