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Abstract. Welding distortion is an important engineering topic for simulation and modeling, and there is a need for experimental verification of such models by experimental studies. High-speed pulsed digital holography is proposed as a measurement technique for out-of-plane welding distortion. To demonstrate the capability of this technique, measurements from a laser spot weld are presented. A complete two-dimensional deformation map with submicrometer accuracy was acquired at a rate of 1000 measurements per second. From this map, particular points of interest can be extracted for analysis of the temporal development of the final distortion geometry. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.OE.51.3.030501]

Subject terms: laser welding; deformation; high-speed holography; thermal distortion.

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1 Introduction

The thermal cycle associated with any welding process induces stresses and associated strains within the structure. Welding involves high temperatures (leading to a reduction in yield strength) combined with melting of the material, and thus generally results in plastic deformation, which permanently changes the shape of the structure. This is a well-known problem and has been a frequent subject of FEM-simulations.¹ (Laser bending² is an example of a process that actually utilizes the deformation that takes place.) Although there has been a lot of simulation work carried out on welding-related thermal distortion, there is a need for experimental validation of the results. This is usually done by careful measurement of the shape before and after welding.³ One problem with this type of measurement is that no information is given regarding the history of deformation occurring during the welding process. To address this problem, the deformation can be measured with interferometric measurement methods⁴ that give temporal resolution, but this technique will only give information over a very small area. There are, however, some methods that measure the complete deformation field, including the use of stereo cameras^{5,6} to track the movement of points/speckles. Another optical technique is digital holographic interferometry,⁷ which measures out-of-plane deformation with an accuracy better than the wavelength of the laser used for illumination and produces a deformation map over a relatively large area. In order to capture continuous motion, it is possible to

use high-speed holography,^{8–10} as we did in this work. In our case the high-speed measurements were enabled by a high-speed camera in combination with a high-power Q-switched intercavity frequency doubled Nd:YAG laser that was used for illumination.

2 Experimental Work

The experimental setup is sketched in Fig. 1. The experiment involved a standard setup¹¹ for digital holography where the reference light was taken from the back reflection of a plano-concave lens. The illumination laser used for the holography was a ROFIN-SINAR RSM 200D/SHG, a Q-switched intercavity frequency doubled (532 nm) Nd:YAG laser, capable of 80 W output power. To optimize the beam quality, a small aperture (1.4 mm diameter) was inserted into the laser cavity, and the laser was tuned to a mode that was as close as possible to TEM₀₀. In the configuration used for the experiment, the laser delivered 1.85 W at 1000 Hz (1.85 mJ pulse energy). The pulse length was estimated as approximately 200 ns, thus the peak power for the illumination laser was in the order of 9 kW. The high-speed camera used was a Redlake Motionpro X3 with a frame rate of 1000 Hz. Temporal sampling was controlled by the short illumination laser pulses. The exposure time of the camera, 997 μs, was sufficient to position the images on separate frames without having to synchronize the camera with the illumination laser. An area of 24 × 32 mm on the plate surface was imaged with a resolution of 600 × 800 pixels. The specimen to be welded was a 2.4 mm thick stainless steel 304 L plate. To reduce the influence of residual stresses, the plate was annealed at 1100 °C. Then it was stress relief heat treated at 300 °C for 6 h. On the opposite surface from the measuring system, a laser spot weld was created using a welding laser (HAAS 3006D Nd:YAG laser with a 600 μm fibre diameter). At a peak power of 1000 W, a 100 ms long pulse (100 J) produced a small spot weld (approx 1 mm diameter and 1 mm deep) on the plate surface. The sampling interval was 1 ms, and information on the phase of the object light was encoded using the spatial carrier method.¹² Using an inclined reference wave, the complex amplitude of the object wave appears as a high frequency lobe in the spatial Fourier plane of the encoded image. Windowing out this lobe and performing an inverse Fourier transform, each pixel has a complex value, where the phase is the phase difference between the object light and the reference light. The phase change of the object light can be calculated by the complex conjugate multiplication of two consecutive frames. The phase difference obtained represents the out-of-plane (Z) movement of the plate, and if this movement is larger than $\lambda/2$ (266 nm) the phase will wrap. This can be seen as an abrupt step in the phase image from $-\pi$ to $+\pi$. The wrapping can be compensated for by a 2D-unwrapping algorithm.¹³ To decrease computation time for the unwrapping algorithm, the phase image was down-sampled to 60 × 80 pixels before unwrapping. Before this down-sampling the image was low pass filtered by 20 × 20 averaging. By doing this on the complex values, the phase information is weighted by the intensity, and the noise level is reduced significantly. The phase shift was measured over time and converted to physical deformation measurements in μm. This gave a two-dimensional map of deformation over time during welding, with a time increment of 1 ms.

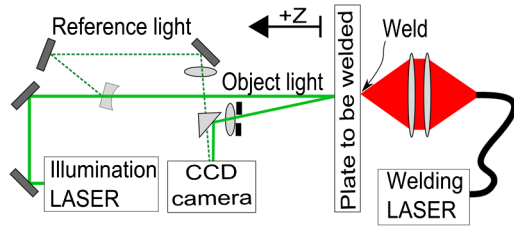


Fig. 1 Measurement setup for pulsed digital holography.

3 Results

Figure 2 shows deformation as a function of time at different positions on the plate. This sort of 1D information can also be measured with ordinary interferometers, but with the holography method, an arbitrary point in the measurement field can be chosen for subsequent analysis after the measurements are finished. It can be seen that the plate bends toward the heat source (welding laser beam) until the pulse ends at 0.1 s. The displacement spreads a considerable distance from the weld area and can be easily measured even 10 mm from the weld (bearing in mind that the weld diameter is only ~ 1 mm). Due to plastic deformation in the weld zone there is, eventually, a permanent deformation in the opposite direction to the initial bending. What would not be noticeable in a 1D measurement is that this deformation starts immediately during the cooling phase. In Fig. 3 the deformation in a line crossing the center of the weld is plotted for different time steps. The shape difference during the heating phase ($t < 100$ ms) and the cooling phase ($t > 100$ ms) reveals the development of a clear deformation in the center of the weld. It is seen that maximum deformation appears at the end of the heating process and is approximately Gaussian shaped with a maximum deformation of $40 \mu\text{m}$ and a width of 30 mm. After cooling, the maximum deformation is approximately $18 \mu\text{m}$. One of the advantages of the holographic method is that it gives a complete 2D deformation map, which can be plotted as a 3D surface (see Fig. 4). In this case the Z-axis is magnified 1000 times, and the residual maximum deformation was measured to $18.3 \mu\text{m}$.

4 Discussion

This work demonstrates a new tool for the monitoring of weld distortion. The holographic method gives the accuracy of an interferometer but measures over a wide area. Two-dimensional information is very useful when trying to understand a process, and the high-speed digital holography interferometer acts as a quantitative displacement camera.

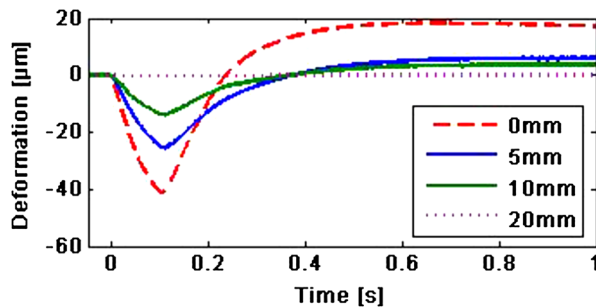


Fig. 2 Deformation over time at different distances from the weld center.

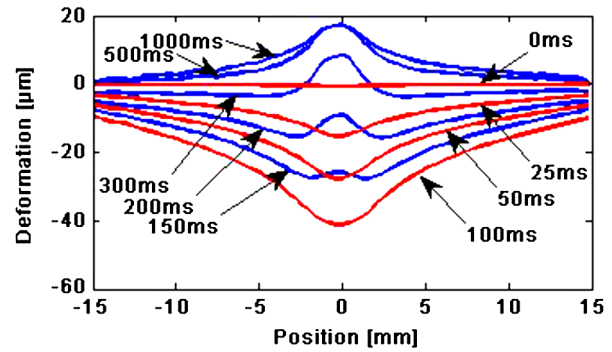


Fig. 3 Deformation over distance at different time steps.

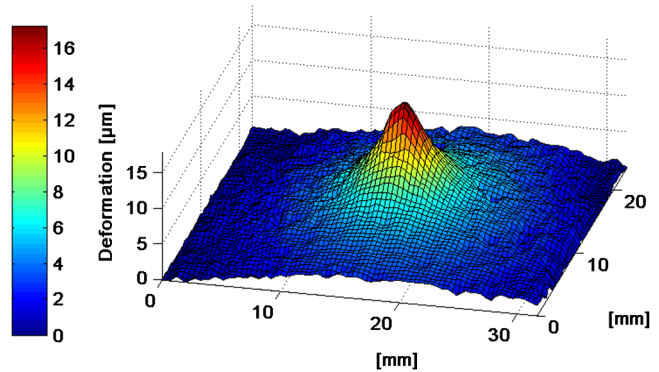


Fig. 4 Shape of deformation at $t = 1000$ ms.

The key feature enabling the application of high-speed holography in this work was the use of an illumination laser with both high pulse energy and high frequency together with a good beam quality. To be able to unwrap the phase sequence over a temporal series of interferograms one has to make sure not to violate the sampling limits. In practice this means that the variation in displacement between successive frames has to be less than $\lambda/4$. In our case, this means a maximum deformation of 133 nm , and with a frame rate of 1 kHz , this gives a maximum allowed deformation speed of $133 \mu\text{m/s}$, which is less than the 0.5 mm/s registered during these experiments. To circumvent this limitation, the phase was unwrapped spatially at each temporal step and added together after the unwrapping to get the temporal evolution for each pixel. With this approach we are only limited by the condition that the deformation speed must be below $133 \mu\text{m/s}$ somewhere on the image to allow the stitching of the phases together. The displacement of a plate during welding is much greater than the eventual final deformation and is in the opposite direction (as seen in Fig. 3). The type of displacement history maps created by pulsed digital holographic interferometry will be a powerful tool in the investigation of this type of phenomenon—particularly when verifying FEM-models. The technique could also be used in combination with thermal cameras to analyze the interaction between thermal gradients and stress/strain phenomena.

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