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To cite this article: N Bakir et al 2018 J. Phys.: Conf. Ser. 1109 012047

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Novel metrology to determine the critical strain conditions required for solidification cracking during laser welding of thin sheets

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Abstract. The weldability of materials is still for many years a highly contentious issue, particularly regarding the causes of the hot crack formation. Because of the process-related temperature and emissions, direct measurement for the arising strain in the close vicinity of the welding process is challenged. Therefore, the externally loaded hot cracking tests remain for decades the only way to determine the critical straining conditions for solidification cracking. In this study, a novel optical two-dimensional in situ observation technique has been developed to allow the strain evaluation during the welding process in the moment of crack formation. Additionally, the Controlled Tensile Weldability (CTW) test was used to generate the hot crack under different global straining conditions. To record the welding process and the moment of the solidification crack initiation a HDR-CMOS camera was used together with an 808 nm diode laser as an illumination source, so that the melt pool and the re-solidifying metal could be visualized in a single image. In order to obtain good temporal resolution, the frame rate of the camera was set to 1100 frame per second. The contrast in images obtained using this unique setup allows to apply the optical flow technique based on Lucas-Kanade (LK) algorithm to follow the pixels in each image sequence and then to calculate the displacement field. The strains were calculated based on the estimated displacements. Using this technique, the local strains under different global strain rate conditions has been determined and analysed. Moreover, the described procedure of the optical measurement allows to determine the real material dependent values of critical strain characterizing transition to the hot cracking during laser welding processes. The experiments as well as the measurement has been performed on the stainless steel 316L (1.4404)

1. Introduction

Control over the strain and strain rates development is an important issue in welding of hot crack susceptible materials. Different experimental methods have been applied in the past to observe and estimate critical strain responsible for solidification cracking [1].

With the conventional measuring methods, such as inductive displacement transducers and strain gauge, experimental determination of local strain causing hot cracks in the high temperature range is generally difficult. These techniques do not allow measurements near a weld pool due to the resulting high temperature. As alternative optical measurement techniques, based on the image processing has
been applied for strain and strain rate measurement related to welding processes. One of the obstacles is an existence of high process related emissions typical for nearly all welding processes, preventing measurement of in plane strain distribution with required accuracy in the interesting high temperature region during welding.

In the field of experimental solid mechanics Digital Image Correlation (DIC) method has significantly evolved due to its numerous advantages [2]. This non-contact optical method allows calculating the fields of displacement and deformation on the surface of objects and parts of constructions and is based on comparison of digital images of an object taken during its deformation. Typically the DIC based methods are used in experimental mechanics applications, where accuracy is a crucial requirement.

De Strycker et al. designed the DIC technique to record strain development during stainless steel tube welding [3]. Quiroz et al. [4] applied this technique to measure the strain distributions on the bottom of the specimen surface during bead-on-plate partial penetration welding conducted in the CTW test facility, but circumventing the influence of laser light and plasma on the image quality. Bakir et al. [5,6] employed the digital image correlation technique to conduct in-situ measurements of strains during the formation of solidification cracks. The experimental setups used allow measurements of the displacement and the strain approximately 2 mm from the fusion line. Chen et al. [7] have developed the high-temperature DIC to measure the strain during GTAW process. This technique does not allow measurements in the immediate vicinity of the solidification front. Gollnow et al. [8] also utilized the DIC technique and the CTW test to analyze the weld pool near transverse displacements and the influence of this displacement on hot crack formation. In all the above introduced studies, the measurement has been carried out either near the weld seam or in the welding seam but at certain points i.e. at pre-determined locations.

Today a concept of optical flow has received a wide recognition. The term „optical flow” means seeming movement of the brightness picture, observed when objects move in front of a camera or a camera itself is moved. Based on presumption that in normal situation the optical flow deviates from the movement field insignificantly, it is possible to estimate displacement in a set of images changing with time. The algorithms of optical flow calculation are used in various scientific fields and practical applications, particularly, for estimation of velocity fields of fluid flow, tracking objects in video sequences, image compression etc., where convenience and speed are required.

In present work an attempt to apply this novel method for evaluation of critical strain responsible for hot crack formation during laser beam welding of thin sheet materials has been undertaken. For the first time it becomes possible to measure a transient strain field in immediate vicinity of solidification front, directly in the zone where the hot crack is initiated. In the first part of the paper the experimental method is validated on simple tensile specimens and results are compared with those obtained with commercial DIC-measurement system. The second part represents results of the strain measurement obtained for real welding trials made under conditions of application of tensile load to the welding specimens during control tensile weldability (CTW) test.

2. Validation of the method
The experiments on determination of two-dimensional in-plane displacements and strains were conducted with test specimens using equipment shown in Figure 1. This equipment is a testing machine that allows applying maximal tensile load of 200 kN to planar specimens. The edges of the test specimens are fixed by means of two hydraulic clamps, one of which is unmovable and the other moves relative to the machine frame with a constant velocity. The velocity is programmed and controlled by the numerical control unit of the equipment during an experiment. In order to concentrate the applied stress, the round hole with the diameter of about 2/5 of the specimen’s width was made in the middle of the specimen (Figure 1 (b)). The surface of the specimens was covered with stochastic pattern using white (aluminum oxide) and black (iron oxide) paints for better recognition of the texture during the following processing of the video. The video sequences of a specimen under tension were obtained using a CMOS-camera installed on a focusing optical head of a laser, perpendicular to the specimen’s surface. Technical specifications of the camera are given in Table 1.
Table 1. Technical specifications of the CMOS camera.

| Name                     | Max resolution (pixel) | Max. frames/second |
|--------------------------|------------------------|--------------------|
| pco.edge 5.5 (S-CMOS)    | 2560x2160              | 200                |

During the experiment the specimen was subjected to tensile load for 10 seconds and elongated by 10 mm, which corresponded to a relative elongation of 2.86%. The videos were taken by the camera with the frame rate of 20 fps.

The comparison between two approaches, the DIC method and optical flow Lucas-Kanade method was made. For this purpose, the two-dimensional fields of displacements and strains on the surface of the specimen at different times have been calculated. Figure 2 (a) and (b) shows the results for the longitudinal component of the displacement vector corresponding to the highest elongation for the DIC and LK methods respectively and Figure 3 shows time dependent displacement in three selected points for the both methods. The results are qualitatively and quantitatively very similar.

Figure 1. (a) Equipment for tensile tests and video recording (b) schematic illustration of the camera installation.
Figure 2. Vertical displacement contours for the open hole tensile test obtained via (a) DIC (b) LK.

As the DIC algorithm exhibits very high accuracy, its results were used as the reference values to calculate the absolute error for the displacement obtained using LK.

Figure 3. Comparison between DIC and LK estimates of v-displacement for points (P1, P2 and P3).

Figure 4 shows the absolute error over all frames using the DIC results as the reference values. The highest error is seen at point P3 and is less than 0.065 mm, which corresponds to a relative error of 0.8%.
Figure 4. Estimated absolute error for points P1, P2, and P3.

Strain was calculated based on the estimated displacement from both methods. Figure 5 shows the $\varepsilon_{yy}$ fields thus obtained. Figure 6 plots strain estimated from both algorithms along the lines AB and CD.

Figure 5. Comparison of $\varepsilon_{yy}$ for open hole tensile test obtained using DIC (a) and LK technique (b).

The results show a qualitative correlation between the estimated results of the DIC and LK methods. For the DIC method, the displacement data for the subset was fitted using the least squares plane fit algorithm, which was not used for the displacement obtained using the LK method. However, a Gaussian fitting algorithm was used to smooth the displacement gradients before calculating the strains in this case. It should be noted that the local strain estimation can be improved by using the same technique [9].
3. Welding tests

3.1. Experimental setup

A CTW-test (shown in Figure 8) was performed to investigate the materials’ susceptibility to hot cracking. The CTW-test is a test method developed by the BAM for investigation of the hot cracking susceptibility of laser welded joins in which the specimen can be subjected to defined strain during welding at a defined speed. The straining speed is either constant or increases linearly. Welding was performed with a disk laser at a focal position of +5 mm and a welding speed of 20 mm/s. The travel path of the laser was 100 mm.

The specimen was deformed between the welding time of 1.5s and 2.66s to reach maximal global strain of 7% under the three strain rates of 4%/s, 6%/s and 8%/s.

A coaxial sCMOS camera integrated into the optical path of the welding laser is illustrated in Figure 8. The frame rate of the camera was set to 1170 fps.

For the hot cracking tests, 316L (1.4404) stainless steel alloy was selected. The plate thickness of the material was 2 mm. Because homogeneous illumination must be ensured, a diode laser with a wavelength of 808 nm and a maximum power of 100 W was used as an illumination source. A bandpass
filter was placed on the camera lens, allowing only the illumination wavelength to pass through and suppressing all other wavelengths. The laser light was collimated to a spot size of about 60 mm on the measuring region, so that the melt pool and the re-solidifying metal could be visualized in a single image.

In contrast to the experiments with tensile specimens the camera field of view has been moved together with the laser beam relative to the specimen with a constant velocity. A region of interest (ROI) of 86x270 pixels moving together with a solidification front covered an area of 2.15x6.75 mm from the weld seam was linked to the rear part of the weld pool where a solidification crack was expected. The velocity of the ROI’s movement corresponded to the welding speed. New pixels, which exceed the edge of the ROI due to the material movement, take the displacement values 0 then they have been considered in the displacement calculation. After estimation of the displacement between two frames, the main displacement field has been warped according the new calculated displacement and then added the temporary displacement field.

3.2. Results and Discussion

Combining this technique with the external laser illumination allows local strain field measurements to be taken during the welding process, suppressing disturbances for the resulting plasma emission even in the region of the weld seam. Figure 9 shows the transverse displacement and strain distribution at different time upon application of tensile load. Whereas prior to the crack formation the strain distribution is even over entire ROI (note, that increased values of the strain values in the upper part can be explained by appearance of new pixels with assigned zero displacement in sequential frames connected to a vertical downward motion of the specimen due to the tensile load) in the moment immediately before the crack initiation the strain start to concentrate in the middle part of the weld corresponding to the further crack location. In this case, shortly before the solidification crack initiation i.e. ~ 2.5ms, a concentration of transverse strain was observed immediately behind the weld pool tail. The value of strain in this region was considered as the critical strain required for solidification cracking formation.

Figure 8. Transverse displacement and strain at different moments before (a), during (b) and after (c) formation of the crack, the numbers to the left and at the bottom of each picture represent a pixel scale of the correspondent picture.

At the moment some time after crack formation the strain further accumulates in the zone, where the crack originally occurred (which is now shifted to the right), but in the hot crack critical region...
a relaxation of strain values is observed. To analyze the results more closely, Figure 10 plots the median strain evaluation over the time near the solidification front for the trial that tested under a strain rate of 4%/s (i.e., behind the weld pool for a box of 6x6 pixels). This evaluation region has been chosen over the crack location.

Figure 9. The transverse strain history over the time close to the solidification front.

As Figure 10 implies, the strain curve initially shows that the strain fluctuates between 0.5% and 1% and was observed as a result of thermal expansion near the weld pool before the application of an external load. When an external load is applied (at \( t = 1.5s \)), the strain behaviour changes. Due to the accumulated external load and the thermal expansion, which interact in the same direction, the strain rapidly increases. At a certain point in time (\( t \approx 2.2s \)), a crack was noticed on the surface. The corresponding strain value at this moment represents the critical strain value required for solidification crack formation. The estimated critical strain under this welding test condition is 3.6%. After the crack formed, it propagates through the material and follows the solidification front. The strain required for this crack propagation is smaller than the one needed for crack formation, which explains why the strain falls after reaching the critical strain value. When the external strain is stopped (\( t = 3.24s \)), the local strain begins to fall. After a short time, the strain decreases below the critical threshold and fluctuates between 2% and 2.5%, consequently the crack growth stops. Additionally, it has been observed, that the first peak in the strain evaluation represents approximately the time of crack formation. Following test confirmed this hypothesis and a high level of repeatability of the obtained extreme (critical) values has been observed, as could be seen from the Table 2. The results demonstrate that the critical local strain is dependent on the applied external strain rate.
### Table 2. Results of critical strain estimation at different strain rates.

| External strain rate in %/s | 4   | 6   | 8   |
|-----------------------------|-----|-----|-----|
| Mean critical local strain in % | 3.65| 3.9 | 4.28|
| Standard deviation in %     | 0.070| 0.141| 0.106|

### 4. Conclusions

This paper represents the results for proposed optical flow method based on the Lucas-Kanade (LK) algorithm applied to two different problems. The following observations can be made:

- The estimated strain and displacement for conducted tensile test are generally very close to those measured with conventional DIC-technique.
- The LK technique allows measurement of strain or displacement without special selection of a region of interest.

Using a novel optical measurement technique together with the optical flow algorithm, a two-dimensional deformation analysis during welding was conducted. This technique is the first to provide a measurement of the full strain field locally in the immediate vicinity of the solidification front.

Additionally, the described procedure of the optical measurement allows the real material-dependent values of critical strain characterizing the transition to hot cracking during laser welding processes to be determined.

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