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Investigation of solidification cracking susceptibility of type 316L stainless steel during laser beam welding using an in-situ observation technique

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Abstract

Laser welding is a widely established manufacturing process in many industry sectors. Solidification cracking as well as the weldability of materials is still since many years a highly contentious issue, particularly regarding the causes of the hot crack formation. Many of studies have been conducted to determine the critical conditions of occurrence of the solidification cracking. In this study a 2D in-situ observation technique in conjunction with laser diodes as the illuminating source has been employed to measure the arising strain field during the laser beam welding process. For the first time the employed technique enabled the in-situ measurement of the transient strain field at the surface of the workpiece directed to the laser beam in the critical range, where the solidification cracking normally occurs. Thus the critical threshold strain values at high temperatures characterizing transition from crack free to crack concomitant welding process could be deduced.

Keywords:optical measurment technique ;critical strain;solidification cracking: Laser beam Welding

1. Introduction

Solidification crack formation is a complex phenomenon because it is influenced by the interplay of mechanical, thermal, and metallurgical factors. Early studies by Prokhorov [1], [2] proposed that solidification cracks form in the last stages of crystallization when liquid is still present around the growing dendritic network, and that the primary factor of such cracks is the strain. He found that such cracks occur within a specified temperature range between the solidus temperature (TS) and the liquidus temperature (TL). This range is known as the brittle temperature range (BTR). In the BTR, the hot ductility of the material is very low and the brittleness is high. The solidification cracks occur only when the strain exceeds the

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ductility curve (Figure 1). This defined strain value is known as the minimum critical strain. The minimum critical strain and the BTR are specific and dependent on the chemical composition of the material, welding conditions, and the grain size, as well as its mechanical properties. As reported by Prokhorov, a minimum critical strain and strain rate (ε_{min},$d\varepsilon/(dT)$) are necessary for the formation of a hot crack.

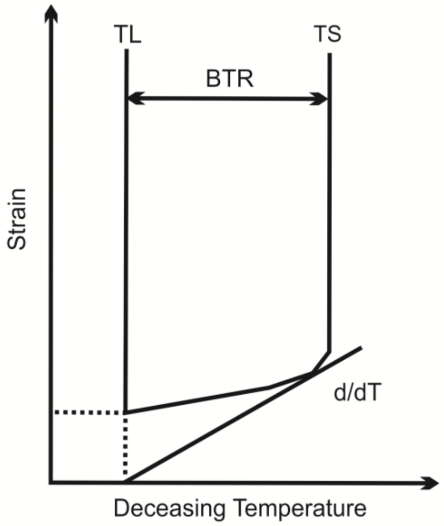

Fig. 1. The concept of the brittleness temperature range (BTR) during solidification of metals in the strain-temperature regime [3]

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. De Strycker et al. designed the Digital Image Correlation technique (DIC technique) to record strain development during stainless steel tube welding [4]. Quiroz et al. [5] 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. [6], [7] 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. [8] 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. [9] also utilized the DIC technique and the CTW test to analyse 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. The application of a special illumination system and corresponding filter technology can improve the quality of the video recording. But there is still the need to develop a measurement technique to determine the time resolved strain distribution in the crack-sensitive region in order to analyse the critical conditions responsible for solidification cracking phenomena.

Optical measurements are capable of capturing even complex deformation until the ultimate material failure. Today a concept of term “optical flow” has received a widespread recognition. The term „optical flow” means seeming movement of the brightness picture, observed at movement of objects in front of a camera or at movement of the camera in unmoved environment. The method involving optical flow algorithms are widely used in objects tracing, pattern recognition and recently for optical metrology tasks [10]. In this study, a digital camera that was inserted with a laser head, was used to film the moment of formation of the solidification crack. The aim was, developing a novel 2D optical measurement technique to determine the state of strain in the immediate vicinity of the solidification front. For the first it became possible to determine the real critical strain required for solidification crack formation during in situ observation of the laser welding process.

2. Experimental setup

A CTW-test (shown in Fig. 2) was performed to investigate the materials’ susceptibility to hot cracking. The CTW-test is a test method developed by 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 to 2.66s to reach maximal global strain 7% under a strain rate of 6%/s.

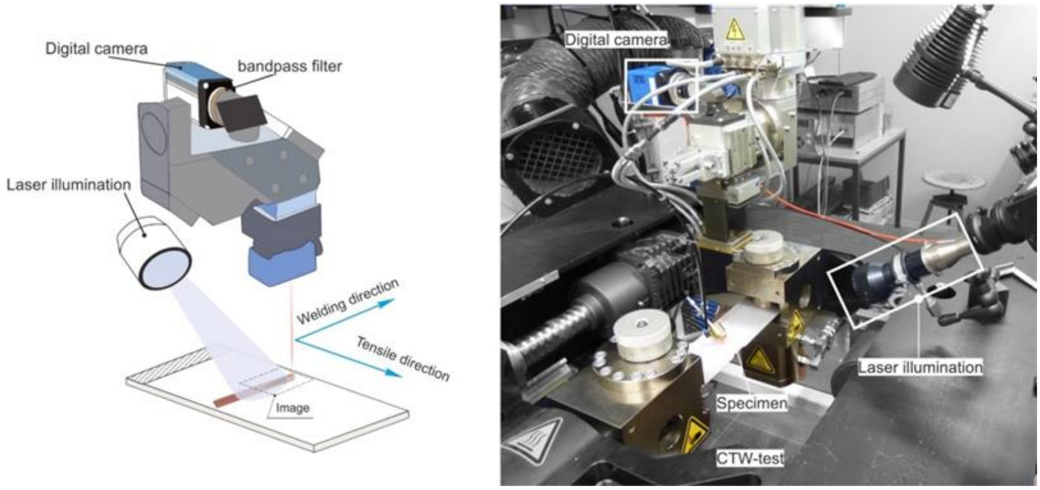

Fig. 2. CTW test facility used in conjunction with laser welding

A coaxial sCMOS camera integrated into the optical path of the welding laser is illustrated in Fig. 2. 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. The chemical analysis of the alloy is provided in Table 1.

Table 1. Chemical composition (wt-%) of the investigated material

C	Cr	Ni	Mn	Si	P	S	N	Fe
0.03	16.95	10.57	1.36	0.39	0.04	0.004	0.019	Bal.

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 illuminating 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 visualised in a single image.

3. The optical evaluation

The optical flow technique was employed to calculate the displacement field in-situ using the Lucas-Kanade (LK) algorithm [11], [12].

To compute the optical flow between two images, must solve the following optical flow constraint equation need to be solved:

$$I_x u + I_y v + I_t = 0 \tag{1}$$

I_x, I_y, and $I_t$are the spatial and temporal image brightness derivatives. $u\ and\ v$ is the horizontal and vertical components of the two dimensional optical flow vector, corresponding to the displacements in each direction respectively.

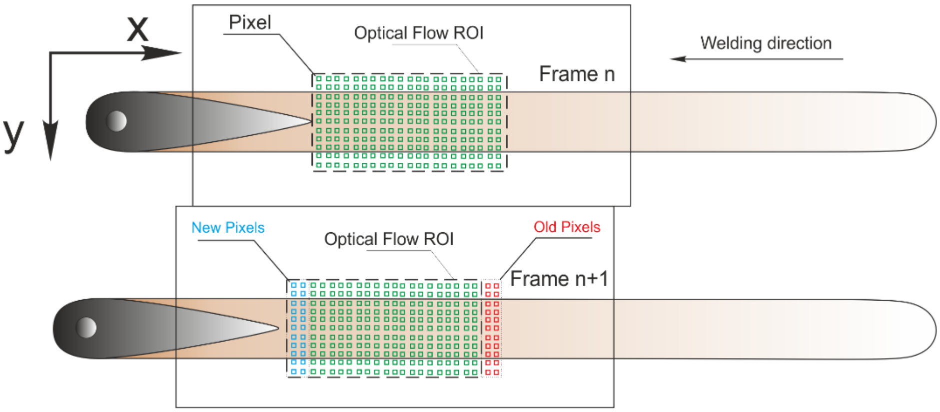

Fig. 3. Schematic representation of the course of the ROI placement during the welding process

Based on the supposition of the equivalence of the optical flow in vicinity of every point it is possible to formulate the main equation of the optical flow for all the pixels near those points and solve the equation system by least square method according to the well known Lucas Kanade algorithm [12].

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 and was linked to the rear part of the weld pool where a solidification crack was expected (See Fig. 3). The velocity of the ROI's movement corresponded to the welding speed. The 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 (see Fig. 3). 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.

Based on the estimated displacements the Green-Lagrangian strain has been calculated for each frame and added for the strain of the previous frame.

The great advantage for this technique compared to the DIC algorithm is that the new objects can be considered in the ROI. In the case of DIC, the objects that must be traced should exist in the reference image. Morever, LK method possesses higher spatial resolution compared to digital image correlation[13].

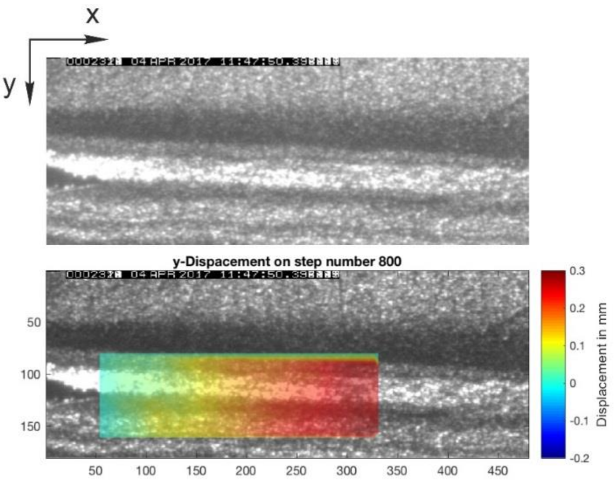

Fig. 4. Video recording image during welding and the estimated displacement distribution

4. 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. Fig. 4 shows the estimated displacement distribution for a video image during the welding.

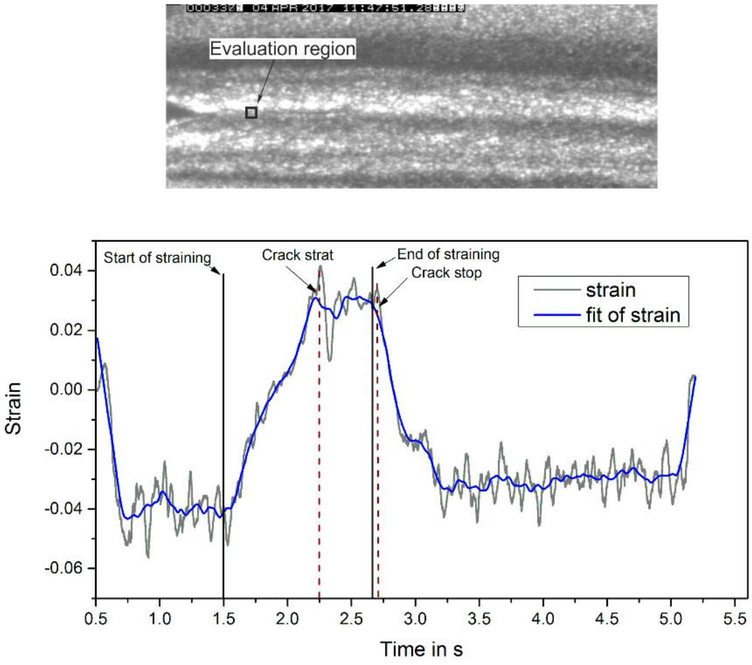

Fig. 6. The strain history over the time in the vicinity of the solidification front

Fig. 6. shows the transverse strain at the moment of crack formation. In this case, where the solidification crack occurred, a concentration of transverse strain was observed immediately behind the weld pool tail. The maximum value of strain in this region was considered as a critical strain required for solidification cracking formation. To analyse the results more closely, Fig. 5 plots the median strain evaluation over time near the solidification front (i.e., behind the weld pool for a box of 6x6 pixels).

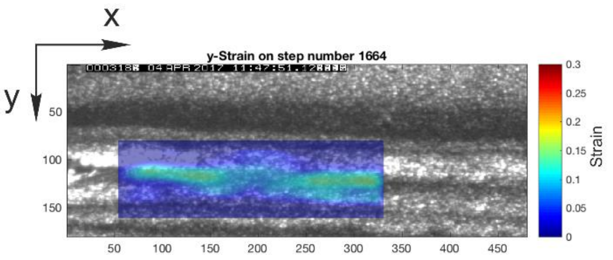

Fig. 5. Transverse strain at the moment of formation of the crack formation

As Fig. 5 implies, the strain curve initially shows that compressive strain (approx. -4%) 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. The strain increases with the increase in external strain and changes from compressive to tensile strain. At a certain point in time (*t* = ~2.25s), a crack was observed on the surface. The corresponding strain value at this moment represents the critical strain value required for solidification crack formation. The estimated critical strain for this welding condition is 3.2%. After the crack forms, and as long as the strain reaches the critical value, the crack propagates through the material and follows the solidification front. This explains why the strain remains fairly stable between the dashed lines (crack start and stop). When the external strain ceases (*t* = 2.66s), the local strain begins to fall. After a short time, the strain decreases below the critical threshold and stops the crack growth. After that point, the strain quickly dwindles into a compressive strain, similar to the situation before the application of the external strain. The solidification crack is no longer expected.

5. Conclusion

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 characterising the transition to hot cracking during laser welding processes to be determined.

The critical strain required for solidification crack formation for stainless steel type 316L was determined in situ to be between 3.2 and 3.5%.

Moreover, this technique allows an automatic identification of the cases that can be critical for the solidification crack formation by monitoring the state of strain on the crack-sensitive region within the Mushy Zone.

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