Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 94 (2020) 666–670

www.elsevier.com/locate/procedia

11th CIRP Conference on Photonic Technologies [LANE 2020] on September 7-10, 2020

In situ determination of the critical straining condition for solidification cracking during laser beam welding

Nasim Bakir[a,*], Andrey Gumenyuk[a], Vitaly Pavlov[b], Sergey Volvenko[b], Michael Rethmeier[c, a]

[a]*BAM - Bundesanstalt für Materialforschung und -prüfung, Unten den Eichen 187, Berlin 12205, Germany*
[b]*Peter the Great Saint-Petersburg Polytechnic University, Politekhnicheskaya Ulitsa 29, Saint-Pertersburg 195251, Russland*
[c]*Technische Universität Berlin, Straße des 17. Juni 135, Berlin 10623,Germany*

* Corresponding author. Tel.: +49-030-8104-4622; fax: +49-030-8104-1557. *E-mail address:* nasim.bakir@bam.de

Abstract

In recent years, laser beam welding has found wide applications in many industrial fields. Solidification cracks are one of the most frequently encountered welding defects that hinder obtaining a safe weld joint. Decades of research have shown that one of the main causes of such cracks is the strain and the strain rate. Obtaining meaningful measurements of these strains has always been a major challenge for scientists, because of the specific environment of the measurement range and the many obstacles, as well as the high temperature and the plasma plume. By applying novel metrology based on optical flow (OF) algorithm, the critical strain conditions for solidification crack formation for the stainless steel 1.4828 in the immediate vicinity of the solidification front was identified. The developed two-dimensional technique allows for obtaining full strain distribution in the hot cracking critical zone.

Keywords: Laser beam welding; Solidification cracking; Critical strain; Critical strain rate; Optical flow: Local measurment

1. Introduction

The prevention of hot cracks in the production and processing of metallic materials is an essential requirement for the safety of components or constructions. The topic of "solidification cracking" was a highly controversial issue for many years, especially in view of the reasons for the formation of hot cracks. The phenomenon of solidification cracking is complex because it is influenced by the interaction of mechanical, thermal and metallurgical factors [1].

Nomenclature

ε	strain
$\varepsilon_{critical}$	critical strain
$\dot{\varepsilon}_{Critical}$	critical strain rate
CTW	controlled tensile weldability
OF	optical flow
ROI	Region Of Interest
DIC	Digital Image Correlation

From a thermomechanical point of view, according to current theories, the critical strain as well as strain rate occurring during welding in the vicinity of the solidification front are the cause of solidification cracking. The theory of Prokhorov [2]–[5] which holds the critical strains within a material-specific "Brittleness Temperature Range" (BTR) as a responsible for the solidification cracking formation. Fig. 1. shows schematically the strain development within the BTR regarding to the theory of Prokhorov and the critical strain (CS) and critical strain rate (CST) required for the solidification cracking. The theory of Rappaz et al [6], shows even more direct connection between strain rate and hot crack formation.

While the theories deal with local thermomechanical and metallurgical processes, the hot cracking test methods used in

10.1016/j.procir.2020.09.104

practice are based on global concepts with measurable basic test criteria such as critical stress [7]–[9], strain [4], [10] and strain rate [11]–[13]. Recent studies have indicated that strain rates play a relatively direct role in hot crack initiation and propagation [6], [14]. The critical strain and the strain rate are used as a measure of weldability, with higher values indicating better solidification cracking resistance.

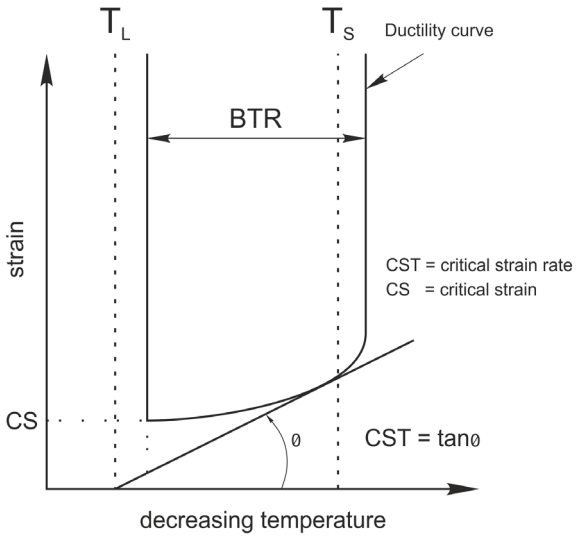

Fig. 1. The concept of the brittleness temperature range (BTR) during solidification of metals in the strain-temperature regime [5]

Because of the importance of the thermomechanical factors influencing the formation of solidification cracking, as mentioned, such as, the strain and strain rate, different measuring methods are developed to determine those critical values. However, the measurement or investigation techniques used until today cannot be realized directly from the process side without difficulties.

The experimental determination of local critical strains and strain rates in the high temperature range, which are relevant for hot crack formation, is generally difficult with the usual measuring methods, such as inductive displacement sensors or strain gauges (SG). These methods cannot be used to determine values in the immediate vicinity of a molten bath because of the high temperature conditions that occur.

The contactless measuring techniques and especially those based on image processing are appropriate for this task. However, the strain measurement is often carried out from the back of the weld seam in order to exclude the influence of laser light and possibly resulting plasma on the image quality.

Quiroz et al. [15] used the Digital Image Correlation (DIC) technique to measure the strain distributions on the bottom of the specimen surface during bead-on-plate partial penetration welding conducted in the Controlled Tensile Weldability (CTW) test facility but circumventing the influence of laser light and plasma on the image quality. Bakir et al. [16], [17] used 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.

A suitable optical measurement technique for determining local critical straining condition for solidification cracking is the so-called MISO (Measurement by Means of In-Situ Observation) technique which was developed from Matsuda et al. [18], [19]. In this method, a high-speed camera in combination with an optical magnification is used to record the formation of hot cracks. However, the MISO method leads to generally increased measuring errors due to the difficult light-optical conditions in the vicinity of the weld pool and the high magnifications. With the help of the MISO method, strains can only be measured at points, whereby it must be noted that the critical strain is location dependent.

2. Experimental setup

The tests were carried out on austenitic steel grade 1.4828 (AISI 309) plates having a thickness of 1.5 mm. The chemical composition of the tested alloy is given in Table 1.

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

C	Cr	Ni	Mn	Mo	Si	P	S	Fe
0.05	19.32	11.06	0.97	0.11	2.07	0.027	0.004	Bal.

Free edge test was used for the welding experiments. The specimen with the dimension of 90 mm x 45 mm was fixed from one side and then welded 4mm parallel to the free edge as shown in Fig. 2 schematically. A high-power Yb:YAG disk laser TruDisk 16002 with a maximum output power of 16 kW was used as laser source with a wavelength of 1030 nm and a beam parameter product of 8 mm x mrad. The laser radiation was transmitted with an optical fibre with a core diameter of 200 µm.

Determination of the local strain conditions were normally carried out in combination with an externally loaded hot cracking test [20], [21]. The use of self-loaded hot crack test is employed usually for the classification of various materials to their hot cracking susceptibility. However, the utilisation of the self-loaded hot cracking test for local determination reduces the time and effort required for such measurements.

The welding parameters were chosen so that a fully

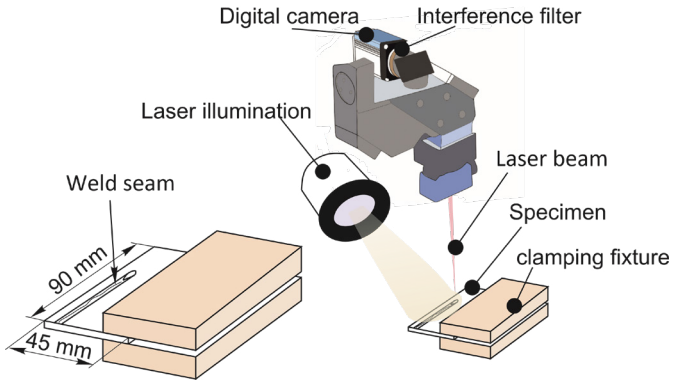

Fig. 2. Schematic representation of the experimental setup with the free edge test using the digital camera and the laser illumination

penetrated weld was produced. Here, 1.8 kW laser power and a constant welding speed of 1.2 m/min were applied. Argon was used as shielding gas. The measurement of the local strains was carried out with the usage of a digital camera and

external laser illumination (diode laser 808 nm) and appropriate filtering (interference filter).

3. The optical measurement technique

The optical measuring technique is based mainly on image processing algorithm. During the welding process, the installed camera records the molten pool area and its surroundings. An optical flow (OF) algorithm based on Lucas-Kanade (LK) [22] was used to calculate the optical OF and then the displacements. The displacements were estimated for Region Of Interest (ROI) behind the weld pool and covered the hot cracking critical zone. Normally during welding, the workpiece is fixed, and the laser head moves over or vice versa. Therefore, the evaluation technique was also adapted and improved to determine the displacements for moving images. The selected ROI consists of inlet and outlet (see Fig. 3). Just after solidification and behind the solidification front, the inlet receives the new pixels (solidified material) and they take the displacement value of 0. The new pixels were tracked as long as they are located within the ROI. Based on the determined full-field displacement, the full-field strains were calculated.

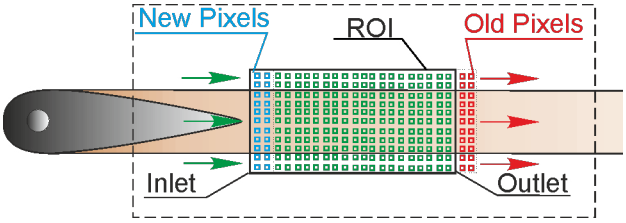

Fig. 3. Schematic representation of the static ROI concept during the welding process, adapted from [23], [24]

4. Results and discussion

Because of the speckle effect provided from the effect of the coherent laser illumination on a rough surface, a special preparation of the measured object, as is the case of DIC, is not required (see Fig. 4). The Speckle effect creates a speckle pattern with good contrast. This speckle pattern remains constant over several consecutive image sequences which allows the calculation of the optical flow.

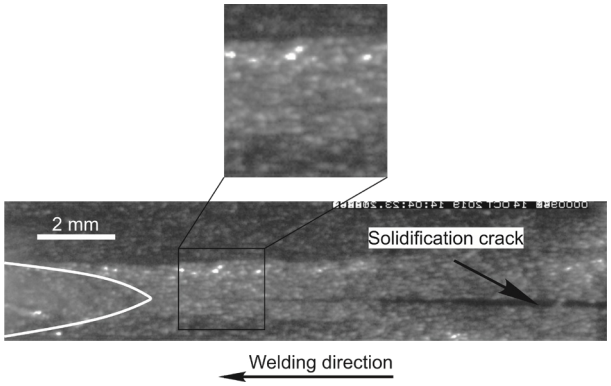

Fig. 4. A sequence from the recorded video shows the solidification crack and the speckle effect on a specimen during the welding process

Fig. 5 shows the calculated full-field displacement and full-field strain for a sequence during the welding process. By using the free edge test, a crack along and parallel to the free edge is expected as shown in Fig. 4 and Fig. 5. Since a crack has formed, the narrow sheet metal part moves away from the specimen. That can be observed clearly in the Fig. 5 as the displacement increases linearly starting from the solidification front. The calculated strains which based on the estimated displacements can also be seen in the Fig. 5.

The strain distribution corresponds to the displacement distribution as a strain concentration in the transition region of the displacement, in other words, along the crack. The strain distribution shows a concentration directly behind the weld pool tail, which also increases moving away from the weld pool. However, the strain development from the solidification front till the crack tip will be considered, since the strains after that are not relevant.

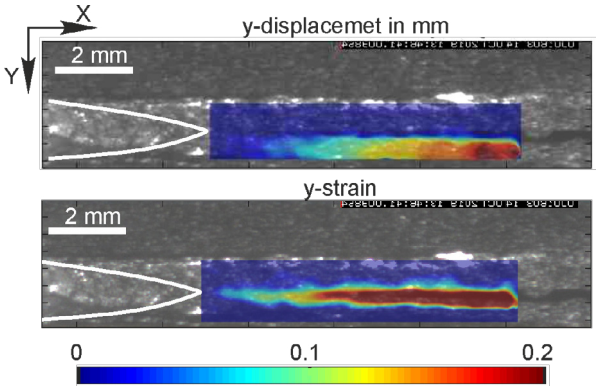

Fig. 5. The obtained full-field strain and full-field displacement distribution using the OF in immediate vicinity of the solidification front

For better determination of the critical strain ($\varepsilon_{critical}$) that causes solidification cracking for the tested steel grade, the strain development along a line AB for four measurements on four specimens are shown in the Fig. 6. Since the point A are

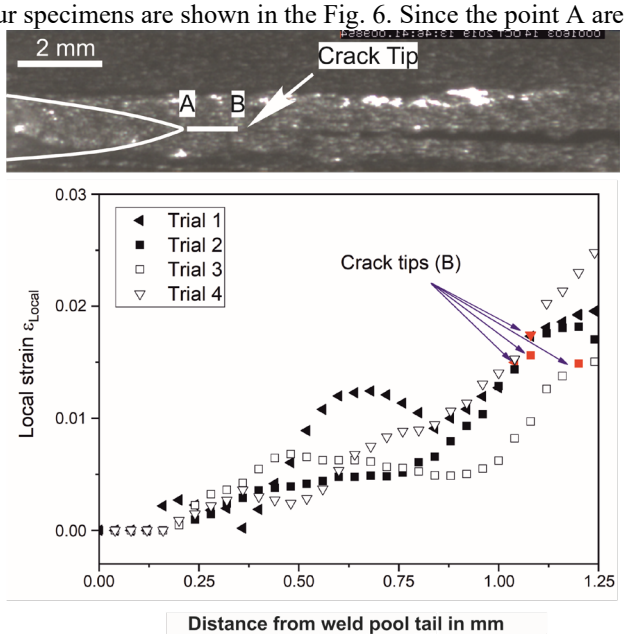

Fig. 6. The strain development from the solidification front (weld pool tail) till the crack tip (along the line AB) for four trials.

located on the weld pool tail and B on the crack tip.

The strain development corresponds to the strain distribution as the strains increase after solidification till the crack tip. The crack tip's locations are in red point in the diagram indicated. These points indicate also the critical local strain required for solidification cracking. The determination of critical strains at four specimens shows very high repeatability as listed in Table 2. The critical Strain ($\varepsilon_{critical}$) for hot crack initiation for this steel grade is 0.0157±0.00118. This critical strain values have been reached after 1.1±0.07 mm from the weld pool tail. Based on the two determined values, the critical strain and the crack tip location, and considering the welding speed, the critical strain rate can be also calculated.

Table 2. The critical strain for four trials and the distance of the crack tip from the weld pool tail.

	Critical strain $\varepsilon_{critical}$	Distance of crack tips in mm
Trial 1	0.0150	1.04
Trial 2	0.0155	1.08
Trial 3	0.0148	1.2
Trial 4	0.0174	1.08
Average	0.0157	1.1
Standard deviation	±0.00118	±0.07

Assuming that the strain increases from 0 to 0.0157 over 1.1 mm which corresponds to 0.055 s, the critical strain rate ($\dot{\varepsilon}_{Critical}$) is equal to 0.28 s^{-1}.

5. Conclusion

A self-restraint hot cracking test (free edge test) was used in combination with a novel optical measurement technique to determine the critical straining conditions for solidification cracking for the stainless steel grade 1.4828 (AISI 309).

The Lucas-Kanade algorithm for the optical flow (OF) calculation was implemented to obtain the full-field displacement and then the full-field strain.

The use of external laser illumination with appropriate filters allows to obtain good image quality with good contrast.

The critical straining conditions required for solidification cracking can be obtained by means the proposed technique in the immediate vicinity of the solidification front.

A very good repeatability was demonstrated for the used measurement technique. The critical straining conditions for solidification cracking for the tested steel und under this welding conditions has been detected ($\varepsilon_{critical} = 0.0157, \dot{\varepsilon}_{Critical} = 0.28\ s^{-1}$).

Acknowledgements

The authors would like to thank the Technische Universität Berlin (TU Berlin) for the financial support for the establishment of contacts with the Peter the Great Saint-Petersburg Polytechnic University.

References

[1] C. E. Cross, Hot Cracking Phenomena in Welds, T. Böllinghaus and H. Herold, Eds. Springer Berlin Heidelberg, 2005, pp. 3–18.
[2] N. N. Prokhorov, The Technological Strength of Metals while Crystallising during Welding, Svar. Proiz., vol. 4, pp. 1–8, 1962.
[3] N.N. Prokhorov and B.F. Jakuschin, Theorie und Verfahren zum Bestimmen der technologischen Festigkeit von Metallen während des Kristallisationsprozesses beim Schweißen, Schweißtechnik, no. 18, pp. 8–11, 1968.
[4] N. N. Prokhorov and M. N. Gavrilyuk, Strain Behavior of Metals During Solidification After Welding, Svar. Proiz., vol. 18, no. 6, pp. 5–9, 1971.
[5] N. N. Prokhorov, The problem of the strength of metals while solidifying during welding," Svarochnoe Proizvodstvo, vol. 6, pp. 5–11, 1956.
[6] M. Rappaz, J.-M. Drezet, and M. Gremaud, A new hot-tearing criterion, Metallurgical and Materials Transactions A, vol. 30, no. 2, pp. 449–455, 1999.
[7] Z. Feng, S. A. David, T. Zacharia, and C. L. Tsai, Quantification of Thermomechanical Conditions for Weld Solidification Cracking, Science and Technology of Welding and Joining, vol. 2, no. 11, pp. 11–19, 1997.
[8] Z. Feng, T. Zacharia, and S. David, On the thermomechanical conditions for weld metal solidification cracking, in 77 th Annual AWS Convention, 1996.
[9] T. Zacharia and G. A. Aramayo, Modeling of Thermal Stresses in Welds, in Modeling and Control of Joining Process, 1993.
[10] W. R. Apblett and W. S. Pellini, Factors Which Influence Weld Hot Cacking, Welding Research Supplement, vol. Vol: 33, pp. 83–90, 1954.
[11] F. Matsuda, H. Nakagawa, S. Katayama, and Y. Arata, Solidification Crack Susceptibility in Weld Metals of Fully Austenitic Stainless Steels (Report VI) : Effect of La or REM Addition on Solidification Crack Resistance(Materials Metallurgy and Weldability), Transactions of JWRI, vol. 11, no. 1, pp. 79–94, Jun. 1982.
[12] F. Matsuda, H. Nakagawa, K. Nakata, and O. Hitoshi, The VDR Cracking Test for Solidification Crack Susceptibility on Weld Metals and Its Application to Aluminium Alloys, Transactions of JWRI, vol. 8, pp. 85–95, 1979.
[13] T. Senda, F. Matsuda, and G. Takano, Studies on solidification crack susceptibility for weld metals with trans-varestraint test, J Japan Weld Soc, vol. 42, pp. 48–56, 1973.
[14] C. E. Cross and N. Coniglio, Weld Solidification Cracking: Critical Conditions for Crack Initiation and Growth," in Hot Cracking Phenomena in Welds II, S. B. Heidelberg, Ed. 2008, pp. 39–57.
[15] V. Quiroz, a. Gumenyuk, and M. Rethmeier, Investigation of the hot cracking susceptibility of laser welds with the controlled tensile weldability test, The Journal of Strain Analysis for Engineering Design, 2012.
[16] N. Bakir, A. Gumenyuk, and M. Rethmeier, Numerical simulation of solidification crack formation during laser beam welding of austenitic stainless steels under external load, Welding in the World, vol. 60, no. 5, pp. 1001–1008, Sep. 2016.
[17] N. Bakir, A. Gumenyuk, and M. Rethmeier, Investigation of solidification cracking susceptibility in laser welded H400 austenitic stainless steel using digital image correlation technique, in SCT2014 - Future trends in steel development, processing technologies and applications - 4th International conference on steels in cars and trucks (Proceedings), 2014, pp. 299–307.
[18] F. Matsuda, H. Nakagawa, and S. Tomita, Quantitative Evaluation of Solidification Brittleness of Weld Metal during Solidification by In-Situ Observation and Measurement (Report IV), Transactions of JWRI, vol. 15, no. 2, pp. 85–95, 1986.
[19] F. Matsuda, H. Nakagawa, and K. Sorada, Dynamic Observation of Solidification and Solidification Cracking during Welding with Optical Microscope, Transactions of JWRI, vol. 11, no. 2, pp. 67–77, 1982.
[20] N. Bakir, A. Gumenyuk, and M. Rethmeier, Investigation of solidification cracking susceptibility during laser beam welding using an in-situ observation technique, Science and Technology of Welding and Joining, vol. 23, no. 3, pp. 234–240, 2018.
[21] F. Matsuda, H. Nakagawa, and S. Tomita, Quantitative Evaluation of Solidification Brittleness of Weld Metal during Solidification by In-Situ Observation and Measurement (Report IV), Transactions of JWRI, vol. 16, no. 2, pp. 85–95, 1987.

[22] B. D. Lucas and T. Kanade, An iterative image registration technique with an application to stereo vision, International Joint Conference on Artificial Intelligence. Vacouver, pp. 674–679, 1981.
[23] N. Bakir, V. Pavlov, S. Zavjalov, S. Volvenko, A. Gumenyuk, and M. Rethmeier, Development of a novel optical measurement technique to investigate the hot cracking susceptibility during laser beam welding, Welding in the World, vol. 63, no. 2, pp. 435–441, 2019.
[24] N. Bakir, V. Pavlov, S. Zavjalov, S. Volvenko, A. Gumenyuk, and M. Rethmeier, Novel metrology to determine the critical strain conditions required for solidification cracking during laser welding of thin sheets, in Journal of Physics: Conference Series, 2018, vol. 1109, no. 1.