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Strain signatures associated to the formation of hot cracks during laser beam welding of aluminum alloys

Christian Hagenlocher [a,b,*], Peter Stritt [a,b], Rudolf Weber [a,b], Thomas Graf [a,b]

[a] Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Pfaffenwaldring 43, Stuttgart 70569, Germany
[b] Stuttgart Center of Photonic Engineering (SCoPE), University of Stuttgart, Pfaffenwaldring 43, Stuttgart 70569, Germany

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ABSTRACT

The local surface displacement during the laser beam welding process of MgSi alloyed aluminum sheets (AA6014) in overlap configuration was optically determined near the weld seam by means of digital correlation of images recorded with a high-speed video camera. The analysis allowed the time- and space-resolved determination of the plane strain in the immediate vicinity of the solidification zone behind the weld pool. The observations revealed characteristic signatures in the temporal evolution of the strain that are related to the formation of centerline cracks in laser beam welding.

1. Introduction

During the solidification process of alloys within the range between liquidus- and solidus temperature single grains are formed and grow in the liquid matrix. The solid fraction of the semisolid material increases while the liquid fraction diminishes [1,2]. When the semisolid material is subjected to (thermo-) mechanical load, the liquid melt film on the grain boundaries may tear. The surface of the resulting crack therefore shows a characteristic, freely solidified structure. In correspondence to the related formation temperature these cracks are commonly referred to as hot cracks [1–3].

As the grains grow in the direction of the temperature gradient, weld seams exhibit a continuous grain boundary along their longitudinal axis of symmetry [4]. After the first initiation of a hot crack, its propagation may follow the progressing melt pool along that grain boundary as shown in Fig. 1. This leads to the characteristic centerline cracks seen e.g. in close-edge welds of high-strength aluminum [5–7].

In case of a high liquid fraction, volume changes or displacements between the growing grains can be compensated by backfilling of liquid [8]. Once a high solid fraction is reached, only a thin coating of melt remains at the grain boundaries. In these conditions the solidifying melt is very sensitive to mechanical load. The semisolid material has a low ductility and a backfilling effect is not possible anymore. This phase of the solidification is associated to the so called brittle temperature range (*BTR*) [3,9]. Different theories exist on which kind of load on the solidification zone is responsible for the initiation and propagation of hot cracks. In most cases strain-based approaches are followed [2,3,10]. Rappaz [11] takes the strain rate into consideration. According to the acting stress is also responsible at its own [12] or in combination with the strain [5].

When welding in close-edge position, a small part of sheet metal is left between the weld and the edge of the sheet. The distance between the weld and the edge of the sheet influences the thermomechanical conditions for the weld. For small edge distances (2 mm to 6 mm) the heat accumulates during the process in the remaining sheet edge (*RSE*) [13,14], resulting in high thermomechanical loads [14]. It results in high transverse strains, which lead to high crack susceptibility of welds in close edge position [5–7].

In order to complement investigations based on simulation [5,12,15], an experimental determination of the strain which acts on the solidification zone, is also of major interest to better describe and understand the mechanisms that leads to the formation of hot cracks and to calibrate the simulation models. The present paper reports on experimental investigations to study the relation between the strain and the occurrence of hot cracks during laser welding. The strain was determined by means of digital image correlation applied to high-speed videos, since conventional strain measurement equipment such as strain gauges or tactile systems are limited in their application to welding processes [16]. They are not able to resist the high temperatures near the weld pool and are limited to the determination of the strain at one single point. Optical measurement techniques have the advantage that the measurement equipment is separated from the heated sample. Digital-image-correlation enables the determination of all local displacements in the observed area of a welding process [16–19]. To this end, videos of the affected areas are recorded and image-correlation algorithms track

* Corresponding author at: Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Pfaffenwaldring 43, Stuttgart 70569, Germany.
E-mail address: christian.hagenlocher@ifsw.uni-stuttgart.de (C. Hagenlocher).

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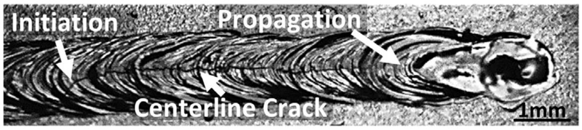

Fig. 1. Initiation and propagation of a centerline crack during welding of AlMgSi-alloy in close-edge position.

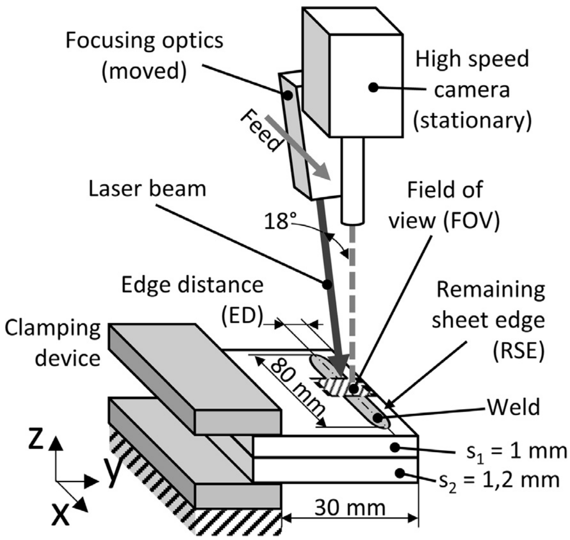

Fig. 2. Experimental setup.

the displacement of the grey scale gradient of significant surface structures between single frames. A detailed descriptions of digital-image-correlation can be found in [20–22]. For the results presented in the following the Software GOM-Correlate [23] was used to identify and measure the local displacements from the recorded high-speed-videos.

2. Experiment

The displacements and the strain occurring during laser welding of AA6014 sheets with a size of $100 \times 40\,mm^2$ were investigated by digital image correlation. Fig. 2 sketches the experimental setup. It depicts the position of the focusing optics and the high-speed camera as well as the clamping of the samples. In each experiment, two sheets were joined in overlap configuration by full penetration welding. The upper one had a thickness of $s_1 = 1$ mm and the lower one a thickness of $s_2 = 1.2$ mm. The length of the welds was 80 mm. The thermomechanical conditions were varied by changing the edge distance *ED* of the welds in the range between 3 and 12 mm.

The welds were performed with a 16 kW TruDisk 16002 laser from TRUMPF. The beam delivery through a fiber with a core diameter of 200 µm and a numerical aperture of 0.1 rad yielded a beam quality of $M^2 \approx 30.5$. The magnification of the processing optics was 2.8, resulting in a focal diameter of 560 µm and a Rayleigh length of $z_R = 7.84$ mm. The moving beam was inclined opposite to feed direction by 18° with respect to the normal of the sample surface and focused onto the surface of the samples (Fig. 2). A laser power of 4700 W at a feed rate of 6 m/min was applied to achieve full penetration welds. The process parameters were kept constant for all welds presented in this paper.

To enable digital image correlation a pattern which is rich in contrast is needed as shown in Fig. 3. The picture is a photography of a sample with applied stochastic pattern. These pattern were created by first applying a white paint for the background on the surface of the samples. This background paint was based on calcium carbonate with a decomposition temperature > 800 °C. The required stochastic pattern of black dots was generated by spraying a graphite-based paint, which

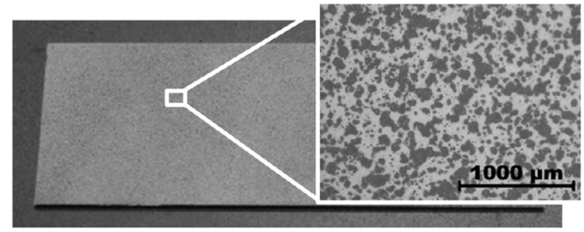

Fig. 3. Sample with applied stochastic dot pattern.

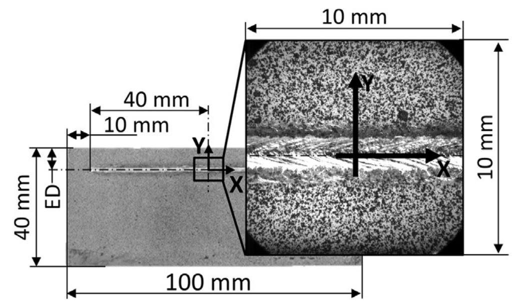

Fig. 4. Field of view (magnified) and its location on the sample.

sublimates at a temperature > 3000 °C, on the white background in a second step. Due to the low melting temperature of aluminum alloys of $T_{melt} < 660$ °C the paints were not affected by the heat of the welding process. This allows to determine the deformations next to the fusion line of the weld during melting and solidifying processes. The particles contained in the paint may contaminate the weld pool and influence the weld pool behavior as well as the solidification. However, for the present investigations, this effect was neglected.

The spatial resolution of the displacement measurement depends mainly on the spatial resolution of the imaging system and the size of the black dots. The high optical magnification used in the experiments led to a projected scale of 100 px/mm resulting in an accuracy of the displacement measurement of ±10 µm. The dot size of <100 µm of the stochastic pattern yielded a spatial resolution of better than 100 µm. The frame rate of 1000 fps of the high-speed camera resulted in a temporal resolution of 1 ms. With the feed rate set to 6 m/min, the camera recorded 10 frames per mm of the welding seam. This allowed to identify the dynamic changes of the thermomechanical effects during laser beam welding.

Two-dimensional image correlations can be calculated from pictures of a single camera. The high-speed camera was orientated perpendicular to the surface of the samples to avoid geometrical distortions caused by the angle of view. It is important to observe a fixed surface pattern to ensure that a displacement of the pattern results from a deformation of the samples. The field of view (*FOV*) of the camera was stationary to analyze the temporal development of the strain during the complete welding process.

The position and the size of the observed *FOV* and the coordinate system are shown in Fig. 4 where a welded sample and its significant geometric scales are depicted. The magnified inset shows the *FOV* which measured $10 \times 10\,mm^2$ and was located at a distance ranging from 35 to 45 mm from the start of a welded seam. The *x*-axis points in the direction of the feed (movement of the laser beam). The origin of the *x*-axis was set in the center of the field of view located at a distance of 40 mm from the start of the weld seam. The time is set to $t = 0$ ms at the moment where the laser beam passes the origin $x = 0$ mm of the coordinate system (Fig. 5(a)). The entire welding process started at $t = -400$ ms and ended at $t = +400$ ms. The *y*-axis was orientated transverse to the feed direction and $y = 0$ mm was set at the centerline of the resulting weld seam. The edge of the sheet metal was located in positive *y*-direction.