Available online at www.sciencedirect.com

ScienceDirect

Scripta Materialia 59 (2008) 324–327

Scripta MATERIALIA

www.elsevier.com/locate/scriptamat

Two- and three-dimensional characterizations of hot tears in a Al–Mg–Si alloy laser weld

D. Fabrègue,[a,*] A. Deschamps,[b] M. Suéry[b] and H. Proudhon[a]

[a] *Université de Lyon, INSA-Lyon, MATEIS, CNRS UMR5510, 7 Avenue Jean Capelle, F-69621 Villeurbanne, France*
[b] *SIMAP, Grenoble-INP, CNRS-UJF, BP 75, 38402 St Martin d'Hères Cedex, France*

Received 1 February 2008; revised 26 March 2008; accepted 28 March 2008
Available online 9 April 2008

Hot tears in 6xxx aluminium alloy laser welds are characterized. They are shown to be intergranular, originating from fracture of liquid films without plasticity of the surrounding grains. The hot tear initiates on both sides of the fusion zone, follows the liquid films between the columnar grains of the weld line and then propagates around the equiaxed grains of the fusion zone centre. By using three-dimensional X-ray tomography, the exact shape of the hot tears has been visualized.

Keywords: X-ray tomography; Hot tearing; Laser welding; Aluminium alloy

Laser welding has great potential as a joining method due to gains in productivity and weight saving as compared to other processes such as riveting. However, the use of laser welding is still limited owing to the loss of mechanical properties or to the presence of defects. Thus, research efforts are required to increase the weld performance (high joint coefficient, high-strength, low distortions and residual stresses, good fatigue and stress corrosion properties, etc.) [1], and to improve the quality of the weld, especially in terms of defect control [2]. In order to obtain a weld joint free of defects such as porosity or hot tears, the welding parameters (such as the laser power, the welding speed and the quantity of filler wire) need to be optimized and the phenomena responsible for the defect formation need to be better understood if one wants to control it.

Unlike much-studied classical welding processes such as arc welding, very few studies concentrating on the microstructure of laser welds have been reported [3–5]. Usually these studies deal with high-strength alloys for aerospace applications such as the 2xxx or the 7xxx series [6]. Most of the published work on laser welding is dedicated to parameter optimization, especially reducing the porosity level in the weld [7], but the literature on hot tearing during laser welding is quite limited. The present paper is concerned with observing the characteristics of hot tears and the propagation path of this defect during laser welding. The detailed microstructure of such welds has been already described in a previous paper [8]. This study will concentrate on the observation of hot tears, using standard micrography techniques in different planes of the laser weld, followed by synchrotron X-ray tomography to obtain three-dimensional (3-D) information on the defect.

The base material used in this work is the aluminum alloy AA6056, the chemical composition of which is given in Table 1. Sheets 1.6 mm thick were butt welded in the T4 state (i.e. after a solution treatment, water quench and several months of natural ageing). Welding was carried out along the rolling direction, on 400 mm × 150 mm samples, after degreasing. Butt joints were produced with a Nd:YAG laser operating at 3 kW. The focal point of the laser beam was set at the surface of the sheets.

A 1 mm diameter filler wire of AA4047 (12 wt.% Si, see Table 1 for exact composition) was employed and helium was used as shielding gas at a flow rate of $20\,\mathrm{l\,min^{-1}}$. This particular filler wire is usually chosen owing to its ability to prevent the formation of hot tears [9]. The welding speed and the filler wire speed were set, however, to obtain numerous hot tears in the weld. The number of hot tears was determined by X-ray radiography to be about 70 over the 400 mm weld length. Optical observations have been carried out in the rolling plane. Samples for optical observations were polished and etched for 20 s with a Flick solution (10 ml HF, 20 ml

* Corresponding author. Tel.: +33 4 72 43 81 79; e-mail: damien.fabregue@insa-lyon.fr

1359-6462/$ - see front matter © 2008 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.scriptamat.2008.03.039

Table 1. Composition of the 6056 and AS12 alloys (wt.%)

Alloy	Mg	Si	Cu	Mn	Fe
6056	0.86	0.92	0.87	0.55	0.19
AS12 (4047) (4047)	0.1	12	0.3	0.15	0.8

HNO_3 and 95 ml water). Specimens for electron backscatter diffraction (EBSD) characterization were obtained, after mechanical polishing, by electropolishing with a solution of 330 ml HNO_3 and 660 ml methanol. Samples for X-ray tomography have been machined to obtain a bar about 10 cm long, 2 mm wide and 2 mm thick. It is constituted of the fusion zone and some base material on the sides. X-ray tomography was carried out at the ESRF (European Synchrotron Radiation Facility, Grenoble) on the ID19 beam line. The specimen was imaged at 70 keV using 900 projections at different angular positions. The 3-D volume was then reconstructed via a filtered back-projection algorithm and further analyzed with the commercial software VGStudioMax (http://www.volumegraphics.com/products/vgstudiomax/). More details about this technique can be found in Ref. [10].

Figure 1 shows the EBSD mapping of the fusion zone perpendicular to the welding direction. A hot tear is observed in black. On this figure the grain colour is randomly chosen and does not correspond to a preferential crystallographic direction. In fact, no preferential texture has been observed in the fusion zone. However, the EBSD picture confirms that the phenomenon of hot tearing is intergranular as already mentioned in the literature [11].

Figure 2 shows the fracture surface characteristic of the phenomenon of hot tearing in laser welding. Solidification dendrites can be observed on this surface. Moreover, this dendritic surface is smooth, indicating that no plasticity took place during the fracture process. This leads to the conclusion that hot tearing during laser welding has the same origin as hot tearing during casting, i.e. fracture of liquid films [9]. Solidification stresses/strains pull apart the dendrites until a cavitation pressure is reached in the liquid and fracture takes place

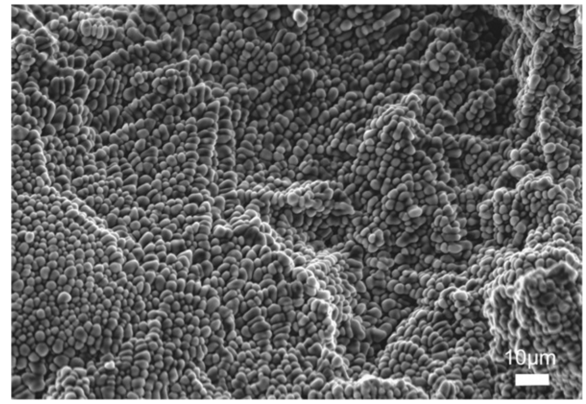

Figure 2. Scanning electron microscopy observation of the hot tearing surface.

[12]. Note that the secondary arm spacing of the dendrites observed in Figure 3 is about 5 μm. Using the relation given in Ref. [13], and considering the solidification interval of this alloy, leads to a calculated cooling rate of about 400 K s^{-1}. Such a high cooling rate is characteristic of the laser welding process.

The hot tearing defect occurs at the very end of the solidification process [12], usually for solid fractions higher than 0.9. During laser welding, solidification firstly takes place on the side of the fusion zone due to heat extraction by conduction from the base material [14]. Figure 3 shows the micrograph in the rolling plane of a laser weld containing hot tears.

From Figure 3, and based on mechanical and thermal considerations, the initiation site of the hot tear as well as its growth path can be determined.

The initiation site of the hot tear must be on the side of the fusion zone where the liquid fraction is small (whereas the centre of the weld still has a high proportion of liquid at this time). Because of the thermal gradients, this zone undergoes large strains due both to the solidification shrinkage (perpendicular to the welding direction) and to the large thermal contraction of

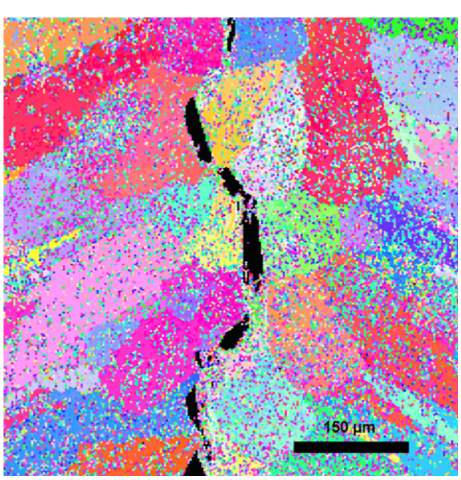

Figure 1. EBSD map of the fusion zone perpendicular to the welding direction. Black zones correspond to the hot tear.

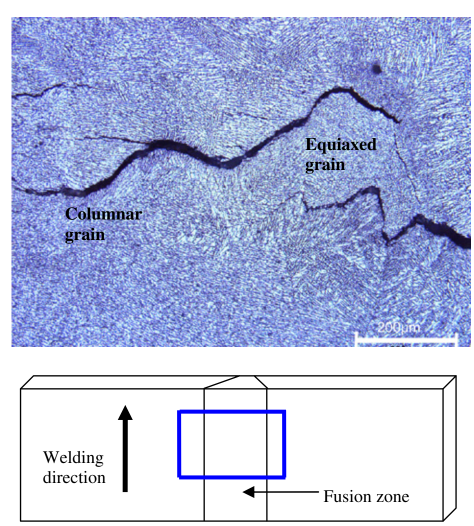

Figure 3. Optical micrograph of the fusion zone seen from the top surface of the plate.