Journal of Materials Processing Technology 235 (2016) 1–12

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Residual stresses induced by electron beam welding in a 6061 aluminium alloy

D. Bardel[a,b,c,*], D. Nelias[a], V. Robin[c], T. Pirling[d], X. Boulnat[b], M. Perez[b]

[a] Université de Lyon, INSA-Lyon, LaMCoS UMR CNRS 5259, F69621 Villeurbanne, France
[b] Université de Lyon, INSA-Lyon, MATEIS UMR CNRS 5510, F69621 Villeurbanne, France
[c] AREVA NP, Departement d'ingenierie mecanique, Lyon, France
[d] Institut Laue Langevin, ILL-Grenoble, F 38042 Grenoble, France

ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form 8 April 2016
Accepted 9 April 2016
Available online 11 April 2016

PACS:
81.40.Gh
81.05.Bx
61.05.fm
02.70.Dh
81.05.Rm
81.40.–z

Keywords:
Thermo-metallurgical analysis
6061 Aluminium alloy
Neutron diffraction
Finite elements
Residual stresses
EBSD

ABSTRACT

Electron beam welding fusion line was performed on 6061-T6 aluminium plates. The thermal histories encountered in the heat affected zone were measured to calibrate a thermal finite elements model. This model has been used as entry parameter of a metallurgical model that predicts the precipitation dissolution induced softening, as well as residual elastic strains. Local deformations measured with a neutron diffraction experiment show a good agreement with the coupled modelling approach for all strain components and the "M" shaped residual strain curves, characteristic of age hardening alloys weld joints, is well reproduced.

1. Introduction

The modelling of welding processes is complex because it involves many coupled phenomena at various scales as described in Debroy and David (1995) work (fluid dynamics, heat transfer, solidification, precipitation, *etc*). Not only the molten zone (MZ) is affected by the welding process, but also many microstructural transformations may occur in the so-called heat affected zone (HAZ) inducing important consequences on the final properties of the welded parts. Among all these properties, residual stresses strongly affect the distortion and fatigue life of structures (Costa et al., 2010), the toughness and the corrosion resistance in welds (Deplus et al., 2011). The prediction of residual stresses involves a fine coupling of all these approaches.

The simulation of the dynamics of the MZ uses various physical fields such as fluid dynamics (Traidia and Roger, 2011), heat transfer, chemistry and electromagnetism (Traidia et al., 2013) to predict the shape of the MZ and the amount of energy absorbed by the sample to consequently estimate the size of the HAZ.

Microstructural models (*i.e.* solidification Rappaz and Gandin, 1993 or precipitation Perez et al., 2008) can be used to predict the solidification patterns Mokadem et al. (2007), Wang et al. (2004) and also the precipitation state Simar et al. (2012) within the MZ and the HAZ.

To the best of authors knowledge, despite their fine description of microstructural features, multi-physical models do not go so far as to predict residual stresses. This is due to high computational cost and/or wide range of experimental data needed to validate their consistency.

---

* Corresponding author.
E-mail addresses: didier.bardel@insa-lyon.fr (D. Bardel), daniel.nelias@insa-lyon.fr (D. Nelias).

http://dx.doi.org/10.1016/j.jmatprotec.2016.04.013

Table 1
Chemical composition of the 6061 aluminium alloy used for the welding experiments.

	Mg	Si	Cu	Fe	Cr	Mn	Oth.
wt%	1.02	0.75	0.25	0.45	0.05	0.06	0.09
at%	1.14	0.72	0.11	0.22	0.03	0.03	0.04

At the other hand, mechanical approaches are based on the estimation of local constitutive laws by reproducing the thermal cycle of a given region on a macroscopic sample (*e.g.* using thermomechanical simulator). Finite element codes interpolate the experimentally characterised constitutive laws to predict residual stresses (see the recent contribution of Chobaut et al., 2015). However, these approaches depend on the geometry of the parts: a new geometry would require new set of mechanical characterisation.

To by-pass this difficulty, a simple thermo-metallurgical approach is proposed in this paper: a thermal model based on the equivalent heat source Goldak et al. (1984) is first used to reproduce the size of the MZ/HAZ and the evolution of the thermal field. From this field, a microstructural model predicts the proportion of hard and soft phases that is, itself implemented in a FE software that predict residual stresses.

2. Electron beam welding experiments

2.1. Materials and treatments

6061 Alloy is a high strength aluminium alloy thanks to a specific heat treatment (presented for example in Bardel et al., 2014) to obtain the largest density of hardening β'' precipitates (*i.e.* T6 state). The composition of the alloy, where several thermocouples are fixed, is given in Table 1. In order to mimic real welding experiment and also get reproductible results, a fusion line was performed on two 6061-T6 plates: the first one was used for microstructure analysis and the second one for residual stress analysis.

The first objective of the modelling of the thermal field within the whole plate is the calibration of an equivalent heat source. The work of Zain-Ul-Abdein et al. (2010) has shown that only a limited number of well placed thermocouples are required for this calibration. Thus, 7 ThermoCouples (TC) (referred as TC1–TC7) were positioned in the lower and upper surface of the plate and 3 additional TC (referred as TC8–TC10) were used to check the reproducibility of the approach (see Fig. 1). K-type thermocouples (diameter 80 μm) are micro-welded on upper and lower surfaces. Then, varnish is filled on the contact area to protect the connection against mechanical stresses and to get more accurate thermal measurement by limiting radiation effects from the beam. The thermocouples are linked to a Nimtech FrontDAQ acquisition central thanks to air and electric-proof connections. To get accurate results, even for fast heating rates, the acquisition frequency is 200 Hz. The response time of the whole equipment have been measured and it is 15 ms for a simulated increment of temperature $\Delta T = 400\,^{\circ}$C.

These experiments were performed at the IUT of Creusot (France). The electron beam (EB) welding device has a power of 5.47 kW ($U = 55.9$ kV, $I = 97.8$ mA) with a vacuum pressure in the gun of about 10^{-5} hPa. The maximal dimensions for the welded plates in the chamber (where the vacuum pressure is 5×10^{-3} hPa) are $= 180 \times 200$ mm (length and width) and they are laid on rectangular parallelepipeds.

From 30 mm thickness cold rolled workpiece, upper and lower surfaces have been machined (well lubricated) in order to get a thickness of 20 mm and thus assure full penetration of the welds. This protocol has been set to eliminate the shear texture surface effect resulting from rolling as described in Delannay and Mishin (2013). Textured sample are indeed not well suited for residual stresses measurement by diffraction methods, since too few grains in the gauge volume (GV) may lead to no diffraction signal.

To evaluate the influence of the welding velocity V on residual stresses, several tests were performed with $V = 0.45$ m/min, $V = 0.72$ m/min and $V = 0.9$ m/min. For each velocity, one plate (the one used for diffraction) were instrumented with TC and the other (the one used for microstructure analysis) were welded in the exact same conditions.

In this paper, most of the experimental and numerical results are presented for the $V = 0.45$ m/min plate because this low velocity induces more drastic changes in the precipitation state.

The fusion line experiment is composed of four steps: (i) starting outside the specimen with low velocity until the plate border, (ii) fusion line in the plate with a constant velocity and extinction outside the sample, (iii) cooling in the vacuum chamber during ≈5 min and finally (iv) cooling in the lab environment.

2.2. Thermal results

The temperature profile of all TC is reported in Fig. 12. These results do not show the final cooling stage when vacuum is broken. Thermal profiles are in phase for the upper and lower surfaces except for TC9/TC10 thermocouples that have been fixed at a distance of 120 mm from the starting point unlike the others that are welded at a distance of 60 mm (*cf.* Fig. 1). Temperature profiles of TC9/TC10 are similar to TC6/TC7, which attests that steady state conditions are fulfilled during welding.

For a same transverse distance from the weld centre, the thermal gradients are more important in the upper surface. This demonstrates the energy gradient through the thickness and justify a conical repartition of the equivalent heat source.

Heating (HR) and cooling (CR) rates are defined as the time lap between 50 °C and the maximum temperature, and the maximum temperature and 150 °C, respectively. The highest gradient was measured by TC4 (HR = 158 °C/s, CR = 32.9 °C/s), which has been fixed at 3.5 mm from the weld centre (*cf.* Fig. 1).

After approximately one minute from the beginning of the process there is no more significant temperature gradient in the plate. At this stage the cooling rate is low in the vacuum chamber (CR ≈0.07 °C/s), then after opening the chamber CR increases by convection (CR ≈0.15°C/s) and this effect is amplified when the plate is put outside the welding instrument.

3. Experimental investigations

3.1. Macrographic analysis

To calibrate finite element (FE) thermal modelling (presented in the next section), the size of the molten zone (MZ) must be determined. Thus, to distinguish between the various zones in the welds, macrographic specimen were cut, polished and etched with Keller reagent and then observed with a LEICA M420 optical microscope (zoom ×3). A picture is provided for each welding velocity in Fig. 2 for samples collected in the central section of the plates.

On the cross sections shown in Fig. 2, the MZ is clearly distinguishable. Note that the transition between the HAZ and the BM cannot be distinguished in such macrographies; only a transmission electron microscopy (TEM) study could bring more information about the boundary of the HAZ from a precipitation point of view.

3.2. Scanning electron microscopy

To get more insight into the microstructural evolution in the welds, a scanning electron microscopy (SEM) study was performed. A Field Emission Gun SEM Zeiss Supra 55VP (diaphragm diameter