Acta Materialia 117 (2016) 81–90

Contents lists available at ScienceDirect

Acta Materialia

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

Full length article

Integrated modelling of a 6061-T6 weld joint: From microstructure to mechanical properties

D. Bardel [a, b, c], M. Fontaine [d], T. Chaise [a], M. Perez [b, *], D. Nelias [a], F. Bourlier [c], J. Garnier [e]

[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, 69456 LYON Cedex 06, France
[d] ESI Group Le Récamier 70, Rue Robert 69458, Lyon Cedex 06, France
[e] CEA, DEN, DMN, SRMA, F-91191 Gif-sur-Yvette, France

A R T I C L E I N F O

Article history:
Received 1 February 2016
Received in revised form
2 June 2016
Accepted 7 June 2016

Keywords:
Welding
Age hardening
Aluminium alloy
Finite element analysis
Digital image correlation

A B S T R A C T

Welding can highly modify the mechanical properties of materials due to the extreme thermal solicitations applied. For precipitation hardened materials, such as aluminium alloy 6xxx, a welding operation implies a modification of the microstructural state and, consequently, of the mechanical properties, both phenomena being highly nonlinear. The purpose of this paper is to propose a methodology to predict the post-welding mechanical properties of a welded joint. For this, three models are coupled: (i) a thermal finite element model of the welded structure that allows the prediction of the material's thermal history at every point; (ii) a precipitation model to predict the microstructural state in the joint using the thermal history; and (iii) a mechanical model to link the microstructural state to the mechanical properties, i.e. hardness, yield limit and hardening. A coupling between these models and a finite element commercial code is then performed to predict the precipitation state and mechanical properties of a 6xxx-T6 aluminium alloy after welding. To validate this methodology a tensile test is performed on a specimen extracted from a 6061-T6 welded plate. Using Digital Image Correlation, the in-plane strain fields across the weld are measured and compared with the finite element simulation of the tensile test, thereby providing good prediction.

© 2016 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

1. Introduction

6xxx series aluminium alloys are widely used (especially in the T6 state) for several applications, thanks to their good combination of formability, damage tolerance and specific strength [1,2] due to a large density of β'' hardening precipitates [3]. However, to assemble parts to produce industrial structures, welding is often used. Welded joint properties are strongly dependent on the post-welding microstructural state [4–7]. This high temperature heat treatment leads to very significant changes in the microstructural state of the material within the Molten Zone (MZ) and the Heat Affected Zone (HAZ): precipitates may grow, shrink, dissolve and/or coarsen, and the mechanical properties of the initial T6 state are lost [7–9].

The integrated modelling of heterogeneous structures has greatly progressed within the last decade (see *e.g.* the review of Simar et al. [7]). To account for the heterogeneous aspect of the weld, Nielsen et al. [6] and later Puydt et al. [10] machined microtensile samples at various positions around the melted zone. Local mechanical properties were later introduced within a Finite Element (FE) framework and compared successfully to the local deformation field obtained by Digital Image Correlation (DIC). However, this approach requires an accurate identification of the position of the weld and each FE calculation is therefore dependant on the welding conditions (geometry, welding energy, steady-state profile, boundary conditions, *etc.*), restraining the predictive ability of the whole method.

To overcome these limitations, one has to predict the material's microstructural evolution (*e.g.* precipitation state) at each FE integration point, for which a coupling between FE and the microstructural model is needed. The first coupling approach, which can provide microstructural information in each integration point, consists of using phenomenological microstructural approaches, such as the so-called isokinetic model proposed by Myhr et al. [11].

* Corresponding author.
E-mail addresses: Didier.Bardel@insa-lyon.fr (D. Bardel), michel.perez@insa-lyon.fr (M. Perez).

http://dx.doi.org/10.1016/j.actamat.2016.06.017
1359-6454/© 2016 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

This method was later used and coupled with mechanical models to provide a good evaluation of hardness profiles (see Hirose et al. [12]) or residual deformations after welding [13]. Nevertheless, these models oversimplify the physical mechanisms (nucleation/growth-dissolution and coarsening) [5] and avoid the extension to more complex microstructural-mechanical studies that require the knowledge of precipitate size distribution [7,14]. Hence, to get a complete distribution of precipitates but also to capture it in an adequate manner, even for rapid temperature fluctuations [15], a KWN-type (Kampmann-Wagner-Numerical [16]) model has to be coupled with finite element simulations.

In a previous work [13], an instrumented fusion line experiment was performed by Electron Beam Welding (EBW) in order to calibrate a thermal FE model using the equivalent source approach [17,18]. Conversely the recent studies in literature, a full coupling between FE simulations and the microstructural model is employed to offer a continuum of material properties across the weld, adapted to any kind of 3D transient thermal process. In this paper, an integrated approach, composed of a physical microstructural yield stress and a semi-phenomenologic work hardening model calibrated on anisothermal treatments, is proposed and coupled with the commercial FE software SYSWELD® [19]. This permits the mechanical behaviour of a heterogeneous weld (in terms of the precipitation state) to be addressed. Its goal is to accurately describe fields of the precipitation state, the yield strength and the work hardening resulting from highly non-isothermal treatments. Afterwards, a numerical tensile test is performed on a transverse section extracted from the FE plate where the thermal history is known at each point. The numerical results obtained from this integrated approach will be compared with to the experimental strain fields provided by the DIC method on the heterogeneous structure.

To present this coupling, this paper is divided into three parts:

- Experimental: To introduce (i) the welding device used to calibrate the FE model [13] and to provide the cross-weld specimens, (ii) the tensile tests performed after anisothermal representative heat treatments [9], and (iii) the DIC experiment performed on the heterogeneous structure.
- Modelling: A multiclass precipitation model [9] is presented as well as its coupling with a new semi-phenomenological elasto-plastic approach.
- Simulation: The thermal FE model is applied on a 6061-T6 blank which contains the mechanical specimen used for cross-weld mechanical simulation. Thus, the numerical Green-Lagrange strain fields will be compared with the experimental ones.

2. Experimental investigations

2.1. Fusion line treatment for thermal FE calibration

The first objective of these experiments is to get thermal histories to calibrate a FE thermal simulation of welding and to provide an heterogeneous sample, in terms of precipitation state, to perform a transverse-weld tensile test.

An instrumented Electron Beam (EB) fusion line was performed on a 6061-T6 plate where several K-type thermocouples were fixed. The EB welding device used in this study has a power of 5.47 kW and the relative velocity of the EB source is set to 0.45 m/min. To get a full penetration of the fusion line, a thickness of 20 mm (Z axis in Fig. 1) was chosen for the plate, the other dimensions being 180 × 200 mm (180 mm is in the fusion line direction, see X axis on the macrography in Fig. 1). This plate (its chemical composition is given in Table 1) has been extracted by machining (well lubricated and with low velocity to decrease heat generation [20] and thus the impact on the microstructure) of the upper and lower surfaces from a 30 mm thickness cold rolled aluminium plate, to minimise the potential surface texture due to the cold roll process [21].

To reproduce the thermal field encountered during the process, the thermocouple histories and macrographies of the molten zone were used to calibrate a conical volumetric moving heat source. This methodology will not be described (see Ref. [13]) here. Fig. 1 represents the result of the thermal FE simulation and the comparison with one macrography of the middle section of the plate.

2.2. Hardness measurements

To characterise the post-welding mechanical properties of the weld joint, the Vickers hardness was measured. A semiautomatic microhardness Buehler OmniMet HMS machine was used in the central layer of the welded plate. A 0.3 kg load (applied during 10 s) was chosen in order to obtain small footprints compared with the molten zone size: the diagonal of the footprint for the base material was of the order of 70 μm and spacing between measures of about 0.35 mm.

In order to have an accurate characterisation of the fusion line, it was decided to conduct 9 cross lines in the thickness with a step of 0.4 mm in the HAZ and 2 mm beyond. The measurements were performed on a welded plate which was kept cold (in a freezer) after fusion line and air cooling in order to minimise the natural ageing effects, which are not accounted for in this study.

The obtained hardness map and two 1D hardness profiles are presented in the next section and confronted with numerical ones.

2.3. Cross-weld tensile test and Digital Image Correlation

To improve the mechanical characterisation of our heterogeneous structure, a tensile test was performed on the weld joint and

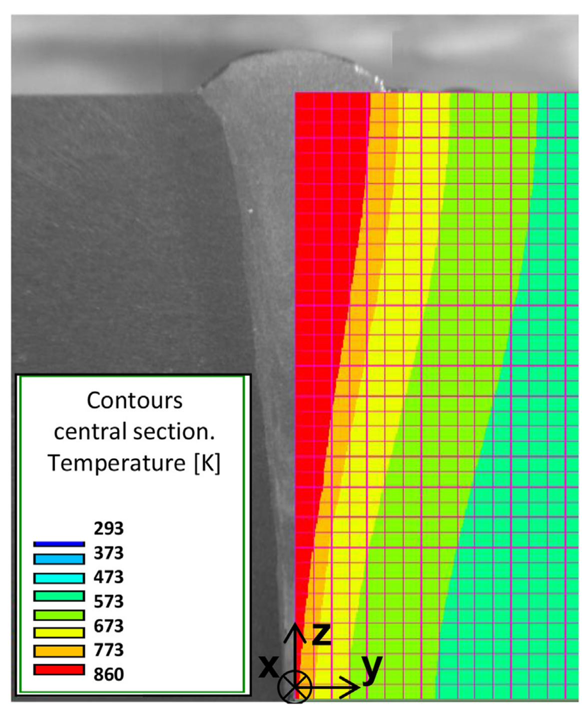

Fig. 1. Representation of the mid section of the plate and confrontation between the macrography (left) and numerical results from the calibration presented in Ref. [13]. These thermal results will be used as input for the metallurgical FE simulations.

Download English Version:

https://daneshyari.com/en/article/7877588

Download Persian Version:

https://daneshyari.com/article/7877588

Daneshyari.com