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Determination of local constitutive properties of aluminium friction stir welds using digital image correlation

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ABSTRACT

In this paper a simple procedure for the characterization of the constitutive behaviour of welds is presented. Digital Image Correlation (DIC) is used for accessing local strain fields in transverse weld tensile samples and the stress distribution is calculated taking into account local strain data and thickness variation across the samples. The constitutive behaviour of the welds is assessed from local tensile stress–strain curves, plotted up to moderate values of plastic deformation, by fitting an appropriate work-hardening model to the experimental results and the ultimate tensile strength of the welds is estimated using the Considère criterion. Based on this information it is possible to assess the constitutive behaviour of different weld sub-zones, which cannot be derived from the hardness measurements, as well as evaluating the mis-match in yield stress and plastic properties across the welds. The proposed methodology is validated by comparing local stress–strain curves obtained by testing transverse weld samples of friction stir welds in very thin plates with those obtained by testing longitudinal samples of the same welds.

1. Introduction

It is well known that the global strength of any weld depends on the distribution of properties across the zones affected by the welding operation. Consequently, it is important to determine the local mechanical properties of different weld sub-zones in order to understand the global strength and ductility of the bonding. Mechanical characterization has traditionally been addressed by performing hardness tests across the welds, by testing miniature samples from each region of the weld or samples obtained by weld thermal simulation, and more recently, by using digital image correlation to obtain local stress–strain curves across transverse weld samples [1,2].

Hardness testing is the most well-known and widely used technique for the mechanical characterization of welds. However, no precise relations have yet been established to determine important constitutive relations, which enable the plastic behaviour of the welds to be described, from hardness data. Testing of miniature samples, from different weld sub-regions, allows constitutive properties to be determined [3–6]. However, the production and testing of such miniature specimens is very complicated. If steep gradients in material properties exist within the welds, then even very small specimens may exhibit non-homogeneous properties. This problem can be avoided by using bulk material samples from weld thermal simulation, which allows full-size specimens to be tested and properties from yield to fracture to be determined [7,8]. However, the highly transient thermal histories experienced by the welded joints are difficult to characterize accurately and to reproduce, which makes the use of thermal simulation samples simultaneously expensive and imprecise.

One important step towards the immediate characterization of the mechanical behaviour of different weld sub-zones and of the global response of the welds is the use of digital image correlation to obtain local and global stress–strain curves. Reynolds and Duvall [9] were pioneers in applying this technique to determine the constitutive behaviour of both weld and base metal constitutive behaviour. These authors, as well as all the others who have used this technique for the mechanical characterization of friction stir welds [10–12] and laser welds [13,14], assumed iso-stress conditions during transverse tensile weld sample loading. Using this assumption, the local stress–strain curves are determined by mapping the global applied stress to the corresponding local strain fields captured using DIC. Lockwood et al. [4] analysed the viability of the iso-stress assumption by performing numerical simulations of tensile tests, using a FE model replicating experimental welds with local material properties assessed by DIC. Full correspondence between predicted and measured global weld behaviour was not achieved, which was attributed to the possible limitations of the iso-stress load assumption in mechanical characterization.

Actually, assuming iso-stress conditions implies that the various weld regions are arranged in series and the cross-section at

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any location in the specimen is homogeneous [15]. However, this is not the case in welded samples for which, depending on the welding technology in use, steep microstructural gradients and thickness variations can be registered across the samples. In friction stir welding (FSW), for example, the forging action of the tool induces a significant thickness reduction in the weld relative to parent plate [16]. In the present study, the mechanical characterization of friction stir welds was performed using a very simple procedure which enabled local stress fields to be determined, by taking into account local thickness variations in the regions under evaluation and the local strain fields acquired by DIC. Since the stress and strain ranges in different sample regions are limited by the strength of the weakest region, the constitutive behaviour of the harder sample regions was assessed by fitting an appropriate hardening model to the "incomplete" stress–strain curves. This procedure enabled the local constitutive behaviour in different sample regions to be modelled as well as allowing the maximum strength in each weld region to be estimated using the Considère criterion.

2. Computation of local stress–strain curves from local strain fields

The methodology presented in this section enables local tensile stress–strain curves to be calculated from local strain fields registered using DIC during tensile tests of transverse weld specimens. Fig. 1a shows a schematic of a full-size transverse tensile specimen, with the weld centred in the gauge section and the loading axis normal to the welding direction. In this Fig. 1 indicates the weld, 2 the heat affected zone and 3 the base material. Fig. 1b shows an image of the major logarithmic strain (ε_1) distribution after maximum load, acquired using DIC, in a tensile sample. This clearly demonstrates the non-uniform strain distribution across the sample and the occurrence of rupture in the weld, where the largest strain values were registered.

Knowing the local strain values, the evolution of the cross sectional area of a specific part of the sample, A^i, can be determined using the following relationship

$$A^i = A_0^i \exp(-\varepsilon^i), \tag{1}$$

in which A_0^i is the initial cross-section of the specimen in the zone under study, calculated after evaluating specimen dimensions across the samples, and ε^i is the local axial strain registered using DIC.

The local stress in this area is obtained by dividing the applied load, F, by the actual cross sectional area, A^i, of the part of the sample under study:

$$\sigma^i = \frac{F}{A^i}. \tag{2}$$

Expressions (1) and (2) can be used as long as the sample part under analysis is subjected to uniaxial loading conditions. In order to evaluate if the local microstructural heterogeneities and geometric discontinuities across the transverse weld samples, such as thickness variations across the weld, had any influence on the local strain fields, the evolution of local principal logarithmic strains ε_1^i versus ε_2^i with plastic deformation should be analyzed before calculating the stress–strain curves. This analysis allows the occurrence of any local change of the deformation path during the tensile test to be determined. More precisely, it is possible to evaluate the existence of any local stress triaxiality and if it had any influence on the local stress–strain curves registered for each sample part.

3. Experimental procedure

Similar and dissimilar welds, obtained by friction stir welding of 1 mm thick aluminium sheets were tested in this study. The base materials were two very popular automotive aluminium alloys, AA5182-H111 (BM5) and AA6016-T4 (BM6) alloys. The welding conditions and results of the metallographic and mechanical analysis of the welds can be found in [17,18]. From these references it can be inferred that the AA5182 similar welds (S55) and the AA5182–AA6016 dissimilar welds (D56) were in over-match relative to the base material's hardness and yield stress, but the AA6016 similar welds (S66) were in under-match. Longitudinal and transverse samples were cut from all these welds, following the sampling scheme shown in Fig. 2.

In the present investigation, the tensile tests were performed in a 10 kN universal testing machine, operating at room temperature, with a nominal initial strain rate of $1.33 \times 10^{-3}\ \mathrm{s}^{-1}$, in accordance with the ISO6892-1 standard [19]. The global strain of the longitudinal specimens (Fig. 2) was evaluated using a 50 mm gauge length clip-on extensometer. For the transverse samples, the local strain fields were determined by DIC using Aramis 3D 5M optical system (GOM GmbH). Before testing, the specimens were prepared by applying a random black speckle pattern, over the previously mat white painted surface of the transverse samples, in order to enable data acquisition by DIC. It is also important to clarify that none of the transverse or longitudinal samples were subjected to surface smoothing in order to homogenise sample thickness across the gauge section or avoid any influence from surface roughness on plastic behaviour.

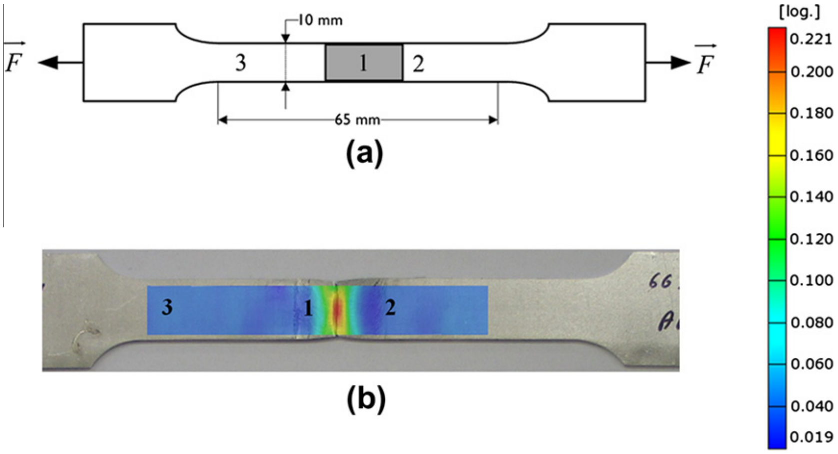

Fig. 1. Transverse tensile specimen: 1 – Weld; 2 – HAZ; 3 – BM.