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Investigation of the elastic/crystallographic anisotropy of welds for improved ultrasonic inspections

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ABSTRACT

Ultrasonic inspection is an effective way of ensuring the initial and continued integrity of welded joints non-destructively. The accuracy of the technique can be compromised due to spatial variations in the anisotropy of the material stiffness in the weld region. Predicted in-plane weld stiffness maps can be used to correct the ultrasound paths for improved results, but these are based on several assumptions about the weld material. This study has examined the validity of these assumptions and provided detailed weld metal grain orientation maps from which a stiffness map has been calculated for an Inconel 600 weld. Good agreement was found except near the boundaries of the weld. Further it was found that the crystal growth (most compliant) direction was typically oriented around 14.5° out of plane towards the welding direction. Having validated the model, a comparison of predicted and calculated stiffness maps was made. The predicted map was found to be satisfactory over the majority of the weld area.

1. Introduction

As an effective method of creating a sealed joint, welding is widely used in pressure vessels and other critical thick-walled components requiring high levels of structural integrity. Often the welded materials are resistant to high-temperatures and corrosive environments. Some of these materials can be difficult to weld. Inconel, for example, is an excellent candidate for extreme pressures and environments but can be prone to fissures in welded areas. Therefore non-destructive inspection of the weld during the production and also during maintenance is vital to ensure the safety of the joint.

1.1. Ultrasonic defect detection

Ultrasonic inspection is useful for the detection and sizing of possible defects non-destructively. The equipment is portable, and the technique is sensitive to small defects, has good penetration depth and only needs to access one side of the weld. However, the accuracy of ultrasonic inspection in welds can be compromised by any, unaccounted for, anisotropy in the stiffness of the material. This causes deviation of the ultrasonic beam and results in errors in the interpretation of the signals and incorrect defect sizing. Research works, e.g. [1–3], have been carried out to understand this behaviour using simplified weld stiffness maps. These exploit the relationship between the stiffness tensor and crystallographic orientation, and rely on a few simplifying assumptions.

1.2. Stiffness maps

To predict the stiffness maps, it is assumed that the material properties of the multi-pass welds are transversely isotropic, with the unique principal axis lying in the plane of the cross-section. It is assumed that the grain growth direction corresponds to the local principal direction and that the plane perpendicular to the grain growth direction can be considered to be isotropic. It is known that these assumptions are strictly incorrect, because the welding wire moves along the weldline, so that the heat flow and solidification directions are tilted somewhat out of this plane.

It is also assumed that the material is single phase and that one crystal stiffness tensor can be used for all the material across the weld. It is assumed that the magnitude of the principal stiffness will be constant and its direction will vary, with the direction of grain growth. The angle of this principal direction to the plate normal, in the plane of the cross-section, is the only parameter characterised by the simplified stiffness map.

It is thus possible to use a simple model with a small number of parameters to describe the weld stiffness map, and such maps have been proposed for more than 20 years [4]. Early stiffness maps were based on a continuous expression relating the angle of the principal direction

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to a small number of geometric parameters of the weld [4]. A set of discrete data points for a visual map could be calculated at the required density. A review of available models for description of these maps can be found in Ref. [5]. More recently, a model named Modelling of anIsotropy based on Notebook of Arc welding (MINA) has been developed [6]. It is based on information about the welding procedure that is normally documented by the welder, and considers rules for crystal growth so as to predict the grain orientations in a multi-pass weld.

Fig. 1(a) shows a schematic of MINA modelling. The model uses geometric information on the welding pool, the dimensions of the electrode and the order of the sequence of passes for each layer, as well as four physical parameters related directly to the process, which are the inclination angle θ_B of a pass next to the weld boundary, the inclination angle θ_C of a pass next to a previous weld pass, and the relative lateral and vertical re-melting rates, R_l and R_v, respectively [7]. The stiffness orientation map is calculated using an algorithm that simulates the three physical phenomena during grain growth: epitaxial growth, the influence of the temperature gradient, and the competition between the grains (selective growth). Fig. 1(b) shows an example of a weld stiffness map made using recorded welding procedures and MINA parameters obtained from the macrograph of the weld [8].

1.3. Weld microstructure

In this study we are concerned with the microstructure of the fusion zone of a weld, where molten weld filler metal has cooled to room temperature with a particular cooling rate and thermal gradient geometry. The temperature and cooling rate influence the final grain size and the thermal gradient influences the direction of grain growth.

An Inconel 600 weld filler was laid down by manual metal arc (MMA) welding to join P91 ferritic steel plates. Inconel [9,10] has the austenitic face-centred cubic (FCC) structure, and can be considered to be single phase [11]. The preferential growth direction in FCC metals is with a <100> direction parallel to the steepest thermal gradient [12]. The <100> direction corresponds to the least stiff direction in this crystal [13]. Since the metal making up the parent plate has the BCC structure it should not be assumed that epitaxial growth occurs at the weld-parent plate boundary [11].

Due to the, generally elliptical, shape of the weld pool, and the fact that it moves through the material, the thermal gradients that influence the grain growth direction vary across the weld. At the boundaries with the parent metal the thermal gradient tends to be steep [14] and oriented perpendicularly to the parent metal boundary [12]. At the centerline of the weld the gradient tends to be lower [14] and the orientation depends on the speed of the weld bead (pass). With slow welding speeds the grain growth direction at the centre of the weld can tend to follow the direction of bead movement [12]. The temperature and grain growth rate also vary across the weld. The growth rate is slowest at the boundary and is higher at the weld centerline, where the temperature is highest.

This results in an overall pattern of nucleation of new grains immediately at the fusion boundary, some of which remain small. Grains oriented with a <100> direction parallel to the thermal gradient experience preferential growth, leading to columnar grains growing towards the centre of the fusion zone. In the centre region of the weld, the relatively slow weld speed of the MMA welding method used here would be expected to promote some growth in the direction of the weld bead movement. However the higher growth rate and small temperature gradient in the centre of the weld counteract the development of strong texture along the weld direction by promoting smaller, more equiaxed grains [12].

The use of multiple passes with a relatively small electrode, as was done in the weld studied here, tends to even out the differences in grain size between the edges and the centerline of the weld. Each pass is like a smaller scale version of the weld. With small beads the differences within each bead are less and the overall weld is more homogeneous [15]. Also, since for the inner weld beads the 'base metal' consists of previously laid weld metal, epitaxial growth does occur, which contributes to a smoothing of the overall weld texture pattern.

1.4. Aims of this study

The simplified maps of the stiffness variation in the weld are predicted based on only a few known parameters about the weld and rely on a number of assumptions. They provide stiffness direction data at a level of granularity that is suitable for correction of the ultrasonic signal. Given their importance in the interpretation of ultrasonic inspection data, it is important to do material studies to validate the underlying assumptions and predictive capability. This is timely because since these maps were developed it has become much easier to measure the stiffness variations directly, for example by electron back scatter diffraction (EBSD) in a scanning electron microscope [16–18] or by spatially resolved acoustic spectroscopy (SRAS) [19] using laser ultrasound. Here detailed EBSD measurements coupled with stiffness tensor calculations provide a map of the variations in stiffness across the weld, both in magnitude and direction, at a level of detail much higher than presented in the simple maps. The aim of this study was to use measured maps to determine the 'goodness' of the predicted maps. Specifically, with the measured data we investigated a) the reasonableness of the assumption of transverse isotropy in the weld material, b) whether the principal directions correspond to the visible growth pattern and c) whether the

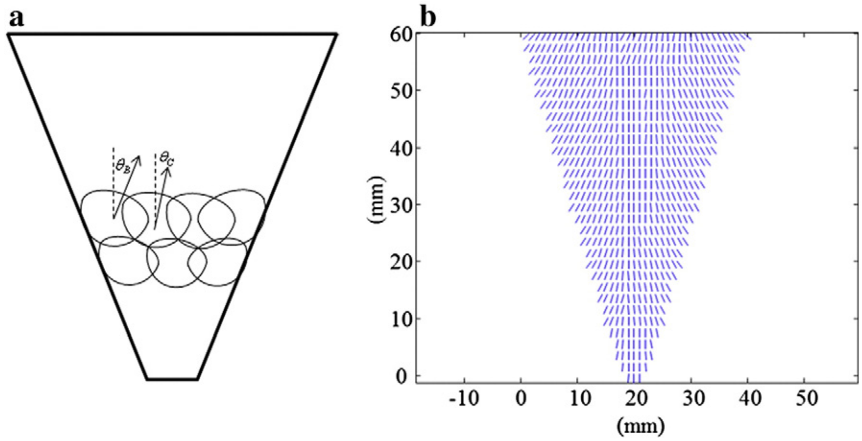

Fig. 1. Schematic of MINA modelling (a) and an example of a predicted weld stiffness map showing the direction of the principal axis (b). In (a) θ_B and θ_C are angles of inclination of the electrode when a weld pass was laid down, see text for details.