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 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.

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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...
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 $\theta_b$ of a pass next to the weld boundary, the inclination angle $\theta_c$ 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 center 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) $\theta_b$ and $\theta_c$ are angles of inclination of the electrode when a weld pass was laid down, see text for details.](image-url)
scale of the spatial variation of the material properties in the weld was reasonably represented by the granularity of the simplified maps.

Based on the results obtained from this study, the assumptions used in simplified weld maps can be verified. This opens the possibility of improving the generation of weld maps for advanced inspection procedures, which is discussed in a separate paper [8].

2. Experimental method

2.1. Specimen

The weld specimen, provided by our industrial collaborator (E.ON), was a section cut from a circumferential, multi-pass, MMA weld joining two sections of P91 pipe. The pipe was 285 mm in diameter (OD) and 35 mm thick. The weld had an initial root weld, done using TIG welding. High nickel content weld filler wires (TIG) and electrodes (MMA) were used [9]. The specimen for microstructural analysis was provided as a slice 5 mm thick; this was cut in half, see Fig. 2. Each half was ground and polished, finishing with 0.06 μm colloidal silica.

After polishing, the specimen was etched with 2% Nital and photographed using a Nikon D1X digital SLR camera with a Nikkor 105 mm macro lens.

2.2. Orientation measurements

Crystal orientation maps were measured by EBSD [16–18] in a Camscan FEGSEM. Individual areas (0.9 by 1.2 mm²) were measured as automated maps. As many as 100 of these were measured for each section of weld and these areas were then stitched together to make a map of the entire weld. This was a time-consuming process; each area took about 2 min to measure. It was also a labour-intensive process as the specimen had to be manually moved to measure each new area and each time the focus had to be adjusted to maintain the best measurement conditions. Automated stage-scanning processes are available but in this case, with such a large sample, the process did not give acceptable focus quality. Fig. 3 shows a schematic of the EBSD measurement process.

3. Results

3.1. Macrograph image

A macrograph of the weld is shown in Fig. 4. The boundary between the parent plate material and the weld is sharp. The areas of the root weld and the main weld can be distinguished, as can the individual beads laid down during welding. The solidification pattern of the grains seems to be visible in the dark–light contrast and the re-melting of the passes can be visualized from the figure. The solidification pattern is continuous across many of the bead boundaries, indicating that epitaxial solidification from one bead to the next does occur. The growth direction is generally perpendicular to the weld boundary and then curving up towards the surface of the weld in the material nearer the centre. This generally matches the pattern predicted in the simplified maps.

3.2. EBSD map

The orientation map from the EBSD measurements is shown in Fig. 5. It is evident that, while the individual grains are clearly seen, in contrast to the macro image, the individual weld beads are not easily discerned. The pattern quality map was also examined and it too does not show the individual weld beads. The different weld areas are distinguishable by smaller grains in the root weld area. The growth directions are clearly discernible and match those suggested by the macro image. The grain size varies across the weld; the grains are generally smaller at the edges and larger in the centre. There are some exceptions; there are fine grains that seem to be at the bases of some weld passes. This suggests some inconsistency in the rate at which the passes were laid down.

Comparing Figs. 4 and 5 reveals that the growth directions (general ‘flow lines’ in the former) are in agreement but that feature sizes differ between the macro image and the EBSD map. The dark–light contrast features are generally finer in the macro images than the grains in the EBSD map. The EBSD map, however, shows much better detail of the fine grain structure.

4. Analysis

4.1. Pole figures

The best way to investigate the assumption of transversely isotropic material in the weld is to look at pole figures representing the texture of the material in each EBSD scan area, expecting in this case a <100>-principal direction. The pole figure for a transversely isotropic material with a <100>-principal axis would have a single intense pole, representing the principal direction [100], together with a band of intensity in the perpendicular directions, representing an isotropic distribution of the [010] and [001] directions. Representative pole figures calculated from the EBSD data are shown in Fig. 6.

Qualitatively, the pole figures show that the transversely isotropic texture is dominant, with a <100>-principal axis. Also, since the X–Y plane in the pole figures corresponds to the plane of the cross-section of the weld, it can be seen that the principal direction lies very close to the plane of the weld cross-section. The pole figures generally show
an intensity peak in-plane and a band of intensity distributed about the perpendicular directions (e.g. Fig. 6a). The median angle out-of-plane of the pole of maximum intensity from approximately 30 representative

Fig. 4. Macrograph of the weld.

Fig. 5. EBSD map of the grain orientations in the weld. The colours represent the Euler angles of the crystals, following formulae that calculate the RGB number based on the measured angles [20].
The symmetry of each single crystal grain is cubic, but when many grains are considered within a polycrystal sampling area the symmetry is unlikely to be the same. If the grains are randomly oriented the polycrystal symmetry will be fully isotropic but in other cases the ensemble of grains in the sampling area is likely to have a lower symmetry than that of a single grain. The triclinic system is the most general case with 21 different components and it was chosen to represent the grains in each area sampled (polycrystal). In practice the polycrystal regions mostly have a roughly transversely isotropic symmetry because of the local crystal growth direction and the approximately random orientation normal to it, but for the stiffness tensor calculations the most general symmetry was used. HKL software [21] was used to capture the EBSD orientation data representing each area, as a list of x,y position and three Euler angles for each location. This data was then an input for the BEARTEX [22] programme, which calculated an orientation distribution function (ODF) from the individual orientation measurements.

One ODF was calculated for each area scanned by EBSD. Then, also using BEARTEX, the ODFs and the single crystal stiffness tensor were used to calculate a stiffness tensor representing each polycrystalline area, using the Voigt–Reuss–Hill approximations, following the method of Bunge [23]. This is because each grain is constrained by its neighbours and so the stiffness tensor representative of the polycrystal is not simply the average of the constituent single crystal values.

To map the results, the Young’s Modulus as a function of direction for each polycrystal (each area) was calculated, following Nye [13], using the relations for the triclinic (lowest symmetry) crystal system. Fig. 7 shows a visual representation of the results of the Young’s Modulus calculations. Minimum values of E in the plane of the surface are represented by arrays of arrows located at the centres of the EBSD areas; each arrow represents the magnitude and direction of Emin. Although it is not easily determined from the map, the magnitude of Emin was reasonably consistent, as was that of Emax, which was also calculated for comparison. The standard deviation in Emin was 10% and only 5% for the magnitude of Emax. This low level of variation corroborates the use of a constant level of modulus anisotropy with only its direction varying across the weld as assumed by the model.

An important feature of this material can now be commented on. Because the principal axis of the transversely isotropic material is a \(<100>\) direction, and because the \(<100>\) directions are minimum stiffness directions in this material, the Emin directions line up with the
directions of the principal axis. This can be seen in Fig. 6 where the principal directions in the pole figures line up with the $E_{\text{min}}$ arrows. This means that the $E_{\text{min}}$ map can be used for comparison with the MINA predicted map. (In situations where $E_{\text{min}}$ did not line up, the principal directions could be mapped from the pole figure data, or the ODFs.)

4.3. Predicting the stiffness map using MINA

The MINA model was used to predict the simple stiffness map of the weld, for comparison with the measured results. The four MINA parameters used in this model, $\theta_B = 30^\circ$, $\theta_C = 0$, $R_v = 0.1$, and $R_l = 0.5$, are the optimized values from comparing the weld map with the one obtained from the macrograph shown in Fig. 4, and the resulting map is shown in Fig. 8.

The comparison between the MINA map and the map of $E_{\text{min}}$ calculated from the EBSD measurements is shown in Fig. 9.

The agreement is acceptable in the centre of the weld but less good near the weld boundary. The weakest agreement between the two maps is at the root of the weld where the grains are small (see Fig. 5) and the calculated orientation changes quite abruptly over short distances (see Fig. 7).

5. Discussion

The aim of this study was to use measured material property data to verify the assumptions used in predicting simple stiffness maps, and to determine the ‘goodness’ of the predicted maps. Three major assumptions were examined and are discussed in turn below.

5.1. Assumption 1: The weld material is transversely isotropic

The pole figures in Fig. 6 show that the material has a transversely isotropic texture, with the principal direction approximately in the plane of the pole figure, which corresponds to the plane of the weld cross-section.

5.2. Assumption 2: The growth direction corresponds to the principal direction

For this crystal system, the $<100>$ growth direction is crystallographically the least stiff. From Fig. 6 we can see that the $<100>$ direction is generally only slightly inclined (median angle 14.5°) to the cross section, because of the forward movement of the welding torch along the weld line. Despite the slight inclination, the direction of minimum in-plane stiffness ($E_{\text{min}}$) in the stiffness map of Fig. 7 corresponds to the lines of crystal growth in the cross section of Fig. 4.

5.3. Assumption 3: The properties can reasonably be averaged over a certain area

This assumption is linked to the occurrence of variation in direction but not magnitude of the stiffness over the map. This is confirmed by the low variation in the magnitudes of $E_{\text{max}}$ and $E_{\text{min}}$.
calculated for the scanned areas. They have standard deviations of 5% and 10%, respectively.

The consistency among the scanned areas is also supported by the generally consistent variation of intensity about the principal direction shown in the pole figures (Fig. 6).

5.4. Comparison of MINA predicted map to calculated map

The agreement between predicted and calculated stiffness maps (Fig. 9) is reasonably good. The predicted angle is within 25° of the calculated angle over 60% of the weld area. There is, however, room for improvement, particularly in the root area of the weld and at the boundary between the parent plate and the weld metal. These are also the areas where the texture is least pronounced. A new method was thus developed to refine the MINA predicted map inputs using ultrasonic phased array measurements. This procedure is described in a separate publication [8]. The refining method is robust enough not to need an accurate starting map, so it is useful for predicting a weld map even in cases when the weld notebook information is not known.

6. Conclusions

In this study the following main points were determined:

1. For the purpose of creating a simple stiffness map the material in the weld can be assumed to be transversely isotropic with the principal direction corresponding to the [100] growth direction of the grains. This growth direction can be assumed to lie in the plane of the weld cross-section. Our results have confirmed that the average angle out-of-plane is approximately 14.5°.

2. The averaging of properties over a certain area to represent the continuum of the weld with a set of discrete data points at a granularity suitable for correction of an ultrasonic signal is reasonable and does not introduce uncertainties larger than 10%.

3. The predicted simple stiffness map, using the MINA model, matches the measured stiffness variation quite well, with some improvement desirable. A process to refine the MINA map was thus developed, which is discussed in [8].

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