ULTRASONIC MEASUREMENTS TO VALIDATE A NEW MODEL OF HETEROGENEOUS ANISOTROPY IN STAINLESS STEEL MULTI-PASS WELDS

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Abstract

Understanding non destructive testing by ultrasound of multi-pass austenitic stainless steel welds advances with the modelling of the anisotropic and heterogeneous structure and with that of the propagation of the elastic waves in this type of material. We show that the new MINA model multi-pass welds allows simulating the anisotropic heterogeneous structure in a more realistic manner from the information in the welding notebook, as for example the order of passes. We introduce the anisotropic structure simulated by MINA into a new ultrasonic propagation code called ATHENA. The coupling between the two models allows obtaining a simulation of the welds ultrasonic testing. We show in a quantitative and qualitative way that the modelling results are close to the experimental measurements. Coupling MINA with ATHENA marks notable progress in the interpretation of ultrasonic testing.

Introduction

Some austenitic stainless steel multi-pass welds show a very complex anisotropic and heterogeneous grain structure (fig. 1). The ultrasonic testing of these welds is difficult to interpret because of beam splitting and skewing caused by the changing direction of the grains in the weld. This structure varies enormously from one weld to the other namely in relation to the order of passes used by the welder.

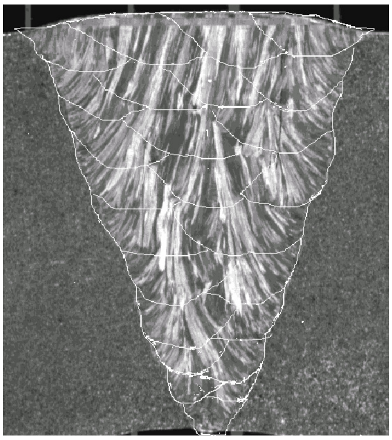


Figure 1: Macrography of weld D717D

The existing grain structure models are simplified as they do not take into account the variations of the order of passes. The MINA model (Modelling anIsotropy from Notebook of Arc welding) [1] allows calculating the grains local direction in a more realistic manner from the welding notebook: the chamfer geometry, number of passes and order, diameter of the electrodes used for each pass. This innovative model gives good results in grain structures in comparison with the real grain structures obtained by macrographic analysis of the corresponding weld.

We first describe the existing grain orientation and ultrasonic propagation models. In order to continue the validation of this model, we introduce a grain structure simulated by MINA in a new finite elements code of ultrasonic propagation called ATHENA. We compare these simulation results with the experimental measurements. We show that good correspondence between simulations and experimental results is obtained.

Models of grains orientation and modelling of the ultrasonic propagation

Several authors presented models to forecast the propagation of ultrasounds in an anisotropic medium. Some authors use propagation ray tracing codes, others finite element codes. For all mentioned codes the attenuation is not modelled, so there is no real information about the amplitude of the simulated waves. All the authors integrate simplified grain structures thanks to mathematical functions [2]. These describe structures are symmetrical (fig. 2) whereas most real grain structures are not symmetrical.

The MINA model allows simulating grain structures in a more realistic manner.

MINA model

The aim of the MINA model, detailed in reference [1], is to simulate a grain structure of a multi-pass weld in austenitic stainless steel, therefore predict the grains local orientation. We introduce in the ultrasonic propagation code (ATHENA) the grain structure of a weld in the form of local orientations modifying the coordinate systems of the elasticity coefficients that are used. This grain structure can arise from real orientation measured on a macrography or from the structure simulated by the MINA model.

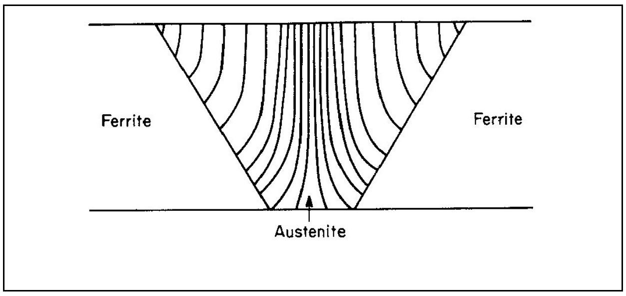


Figure 2: Model of grain structure used by Ogilvy

The MINA model is based on the one hand on information such as the order of passes, the chamfer geometry, the diameter of the electrodes, and on the other hand on variable parameters such as the lateral and vertical remelting rates (R_L and R_V) between passes and the incline angles of passes (θ_B and θ_C). The temperature gradient is simulated for each pass by MINA.

MINA is a phenomenological model to calculate the grains direction at the scale of grain size (macroscopic scale). The physical phenomena taken into account are the epitaxic growth, influenced by the direction of the local temperature gradient and the competition between grains. The advantage of this model is to take into account the parameters linked with the multi-pass technique that the classical crystalline growth models ignore. MINA is also quite simple as it is dedicated to only one type of steel (316 L) and to the shielded electrode welding.

In order to calculate the error made by the model, the directions of the real grains (fig. 1) are compared with the directions of the grains simulated by MINA (fig. 3) by local superimposition and subtraction. The mean value of the error on the whole weld $\Delta\theta$ is 10.27° and the standard deviation σ is 8.37°. This good result marks important progress in the field, as no model simulating a realistic grain structure for a multi-pass weld is available in the literature. Several other welds were simulated by MINA with a very different order of passes. Therefore different grains directions are obtained. The mean error $\Delta\theta$ is each time comprised between 10° and 15° [1].

This first validation of the MINA model is very encouraging. The aim is also to validate the model as regards the ultrasounds. We therefore try to know, if for example on weld D717D, a mean error of direction of only 10.27° will yield a good or bad simulation of ultrasonic waves propagation.

Simulation of ultrasonic propagation in transmission. ATHENA code

ATHENA is an ultrasonic propagation code in finite elements based on the research by Tsogka and al. and developed by EDF (Electricité de France) and INRIA (Institut National de Recherche en Informatique et en Automatique) [3]. The problem is to solve the elastodynamics equations in transitory regime in heterogeneous and anisotropic media. In order to build a numerical method that adds to the efficiency of the finite elements the geometric adaptability of the irregular meshes, Tsogka and al. use the fictitious domains method. The advantage of the latter is to combine a regular mesh of the calculation domain with an irregular mesh of the obstacle. The method combines the rapidity of regular meshes calculation with a fair approximation of the obstacle geometry. The space discretization is performed with mixed finite elements which allow mass condensation. That solution, together with an explicit time method, makes an almost explicit solving procedure possible. ATHENA uses the perfectly adapted absorbing layers (PML) to define the calculation domain boundaries without creating reflections on the domain limits. Simulations will be performed using a transmission technique to simplify the testing modelling. A heterogeneous anisotropic structure is defined by entering a mesh containing the grains directions. This permits calculation of the coordinate systems of the elasticity coefficients at any point of the weld. In figure 4a, a grain structure was simulated by MINA for weld D717D and integrated to ATHENA. A 2 mm square mesh is chosen, which corresponds to an accurate description of the structure at the scale of the wavelength. The position and the incline of the emitter on the upper surface of the weld are adjustable. In figure 4a, the emitter sends longitudinal waves with normal incidence and its position is noted 'P-12' as the middle of the emitter is located at x = -12 mm. ATHENA enables to visualize the ultrasonic beam propagation in the structure (fig. 4a). We obtain maximum values reached by the particles displacement velocity noted v at each point of the mesh.

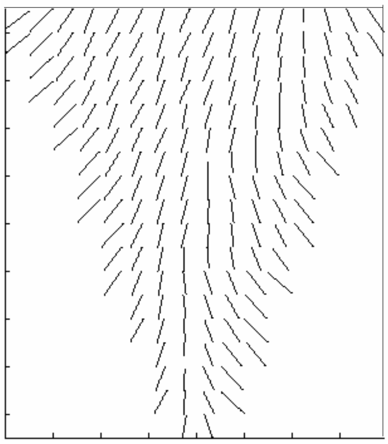
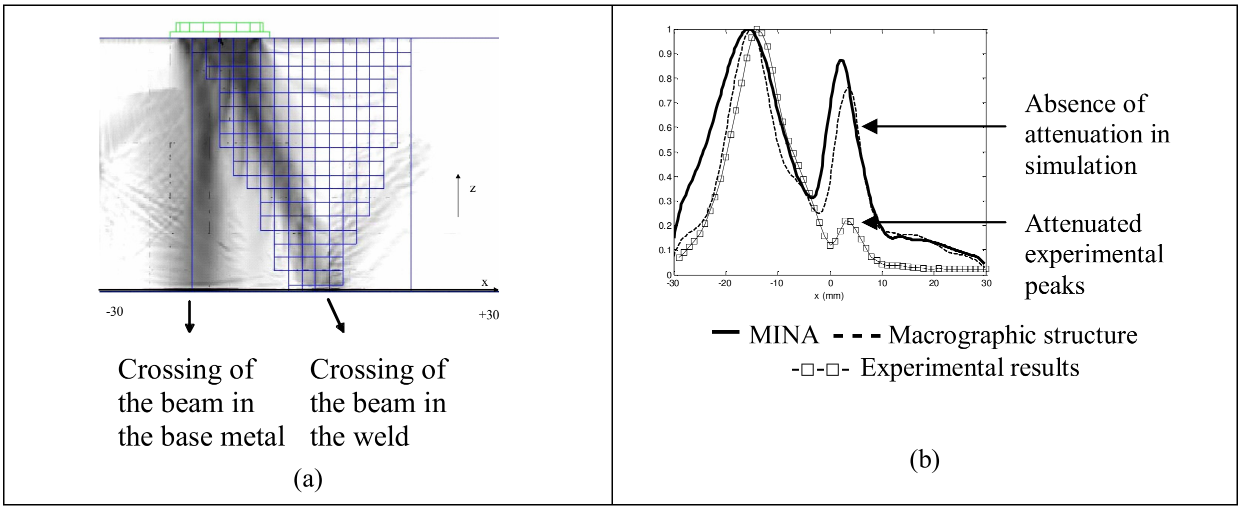


Figure 3: Orientations modelled by MINA for weld D717D



Crossing of the beam in the base metal

Crossing of the beam in the weld

(a)

Absence of attenuation in simulation

Attenuated experimental peaks

(b)

Fig. 4: Beam skewing and splitting in heterogeneous anisotropic structure: (a) Simulation of ultrasonic propagation by Athena (location P-12) in the MINA grain structure, (b) Simulated echodynamics with MINA grain structure and real grain structure and experimental echodynamics.

It is thus possible to deduce the corresponding echodynamic curves in transmission at the bottom of the weld (fig. 4b, curve «MINA »). The points which make the curve are in fact punctual velocity values obtained on axis Ox at the bottom of the weld. The echodynamic curves supplied by the code are proportional to the amplitude delivered by the transducer. We convolve these echodynamics with a Bessel's function that reproduces the sensibility of a plane receiver. The time of flight at each point is also simulated. The advantage of ATHENA is that it allows visualization of the whole beam. We can perfectly visualize in figure 4a the beam splitting and skewing because of the heterogeneous anisotropic structure. Two peaks resulting from the beam splitting are seen on the echodynamics (fig. 4b).

Attenuation of the ultrasonic wave is not taken into account by ATHENA: the relative amplitudes of the peaks simulated by ATHENA and those of the experimental peaks can thus notably vary (fig. 4b). For such columnar grains structures the attenuation can reach 0.3 dB.mm^{-1} according to Seldis [4]. It varies in relation to the angle between the beam and the axis of the grain. We therefore chose to allow for the location of the peaks and not their amplitude. To make use of the experimental results in a more accurate way, further research must take attenuation into account.

Validation of MINA by ultrasonic simulation

We can integrate in ATHENA the real grain structure, that is the structure obtained by image analysis of weld D717D (fig. 1). Simulated propagation of ultrasounds is obtained in the optimal structure coming from the macrography analysis. A first comparison can then be made with the simulated propagation in the grain structure calculated by the MINA model. In figure 4b, the two corresponding echodynamic curves at the bottom of the weld are shown superimposed, in order to compare the positions of the peaks obtained on axis x (curves « MINA » and « Macrographic structure »). We can so estimate that there is good modelling of the heterogeneous anisotropic structure when the locations of the peaks are in agreement. The same simulation and comparison work was performed for nine different locations of emitter on the surface of the weld, each location being separated by 4 mm. The comparison between the ultrasonic propagation in the structure simulated by MINA and the exact structure gave very good results: the beam skewings are in agreement, so are the beam splittings (two peaks on the echodynamics). The mean value of gaps between x_{real} and x_{MINA} (location of the peaks) is 2.48 mm with a 1.73 mm standard deviation. These values are satisfactory in the case of a 40 mm thick austenitic weld testing. They confirm that the grain structure simulated by MINA allowed obtaining good ultrasonic simulation.

This first validation stage is positive and allowed selecting the experimental ultrasonic tests that will conclude the validation of MINA.

Validation of MINA by experimentation

Confronting the results of ultrasonic simulations with experimental measurements is necessary. Indeed the previous comparison does not take into account all the parameters which exist during the experimental measurements. A transverse plane of the weld was chosen as plane of incidence. The receiver measured a BSCAN at the bottom of the weld (the receiver displacement step is 1 mm along axis Ox). The echodynamics at the bottom of the weld could then be deduced from these experimental

BSCAN as well as the times of flight in the weld. It was thus possible to compare these averaged experimental measurements with those previously simulated by ATHENA. A particular example is given in figure 4b for the emitter location P-12. The echodynamics simulated by ATHENA with real grain structure and the echodynamics simulated by ATHENA with grain structure calculated by MINA are superimposed to the experimental echodynamics. Good agreement is observed in relation to the location of the peaks. The performance of the simulations can therefore be observed qualitatively with MINA grain structure. The same procedure was applied for all locations of the emitter. The locations of the peaks were read on these experimental and simulated echodynamics so that they can be compared quantitatively. The average of the gaps is 3.18 mm and is satisfactory and conclusive. The grain structure simulated by MINA really allowed finding again in a satisfactory way the beam skewings and splittings that were experimentally detected for the studied weld D717D. The weak gaps between simulations and experiments in comparison with the formulated precisions for the testing of high thickness welds thus validate the MINA model from an ultrasonic point of view.

Conclusion and perspectives

The propagation of ultrasounds in anisotropic and heterogeneous structures is complex to model and appeals to a coupling between a model of the material and a model of ultrasonic propagation. We adapted and developed two simulation tools to achieve that modelling: the MINA model which allows simulation of the grain structure of a weld only from the information in the welding notebook, and the ATHENA model, a finite elements ultrasonic propagation code which can be applied to such heterogeneous and anisotropic structures.

The results of ultrasonic simulations and those of the experiments allowed validation of the MINA model. The MINA model coupled with the ATHENA model allows simulations of numerous types of very different grain structures and also allows multiplication of the ultrasonic simulations. This means notable progress in understanding and analyzing ultrasonic testing of stainless steel welds. This better understanding of ultrasonic testing of austenitic steel multi-pass welds also allows progress in reliability of non destructive testing with a view to improving evaluation of the mechanical integrity of structures. There is still important work to do to model the attenuation in heterogeneous anisotropic structures. The LCND intends to start research with EDF and INSA in Lyon (CCNDM) on this theme.

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