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TFM-IMAGING OF SIDE DRILLED HOLES CLUSTERS: STUDY OF MULTIPLE SCATTERING EFFECTS TO IMPROVE THE CHARACTERIZATION OF FATIGUE FAILURE CRITERIA

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ABSTRACT

The objective of the proposed work deals with the ultrasonic analysis of local porosity clusters in order to correlate the ultrasonic indications to fatigue failure criteria. The aim is to study multiple scattering effects and to quantify the differences in comparison with simple scattering considerations. In order to simulate a set of porosities, we have considered equivalent voids in 2D such as cylindrical Side Drilled Holes (SDH).

In a first part, the modeling of multiple scattering phenomena is presented using an exact formulation based on a *formal solution in terms of cylindrical wave functions satisfying free space boundary conditions simultaneously at the surface of each cylinder. For both multiple and simple scattering assumptions, directivity diagrams are proposed in order to quantify the influence of the multiple interactions. Illustrations of the displacement potential are also shown for this goal. Then FMC acquisitions have been performed using simple or multiple scattering assumptions to estimate effects on TFM imaging technique. Finally, these simulations are compared with experimental FMC-TFM results. The simulations give realistic imaging and should permit to determine precise information to predict lifetime of the structure in fatigue.*

Keywords: Phased array ultrasound, multiple scattering, TFM imaging, lifetime prediction

NOMENCLATURE

J_n	Bessel function,
$H_n^{(1)}$	Hankel function of first type and n^{th}order
k	Wave number
σ	Stress field
$\vec{u}$	Displacement field

1. INTRODUCTION

The context of this work is to detect and characterize porosity in aluminum alloy to estimate a lifetime of a porous structure under a fatigue loading. The originality of the present work lies in the coupling between the phased array ultrasonic NDT and fatigue performance prediction. The motivation is to gain a better understanding of ultrasound interaction with a localized cluster of porosities to improve imaging analysis and correctly assess fatigue criteria. In practice, we are looking for a correlation criterion between a set of porosities and the corresponding FMC-TFM reconstruction. An observable parameter in this reconstruction is searched to be a fatigue-criticality criterion. Here, a set of parallel SDH clusters was chosen to represent porosities, because all its parameters are manageable.

The theory of the scattering matrix was developed in the 70's [1] in order to describe the scattering waves, in a fluid as in a solid medium. For a solid medium, we can find amount of literature dealing with the problem of a unique cylindrical defect ([2] for example). When there are two defects at least, it often focuses on the resonance around the defects varying as a function of their distance [3]. In such a study case, there are interactions between the defects, and in the case of a solid medium, mode conversions occur. The method often employed is the multiple scattering model method and the calculation of a scattering matrix [4]. In our case we have used the same formalism defined by [5] to evaluate multiple scattering of a complex set of SDH. Thanks to directivity diagrams, we compare simple and multiple scattering hypotheses. Then, imaging based on the multiple scattering model method will be shown.

2. MATERIALS AND METHODS

The material used is the aluminum 7075-T6. The samples are dog bone shaped and the SDH are machined by electro-erosion. Their disposition respects equilateral triangles, in order

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to have each SDH at equal distance of all its closest neighbors. The samples are shown on the following figure:

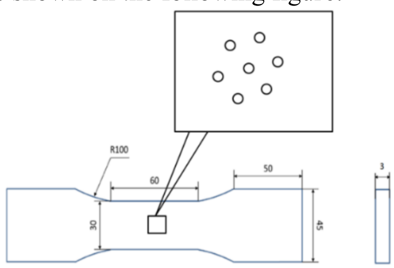

Figure 1 : Dimensions of the samples used

The aluminum 7075-T6 used has the following mechanical properties: $c_L = 6.37\ mm/\mu s$, $c_T = 3.16\ mm/\mu s$,$\rho = 2770\ kg/m^3$. Some characteristics of cluster of porosities were studied in our work (elementary size of each porosity, size of the global shape of the cluster, gradation in the sizes of the porosities, density of porosities). Here, only one will be presented. Its configuration and placement in the center of the sample (15 mm depth) is shown in Figure 1. It consists in a hexagon rotated of 15° to avoid particular alignments in fatigue loading.

Concerning TFM experimental acquisitions, we used a linear phased array with a central frequency at 15 MHz, to have a wavelength of the order of the size of the defects (stochastic domain). The pitch is 0.12mm and 64 elements are used. The imaging is focused on the center of the sample, at a depth of 15mm. The imaging process is performed in a 4x4 mm window centered on the defects.

3. MULTIPLE SCATTERING MODEL METHOD

We searched to model the wave interactions between the SDH, to be more precise than a classical simple scattering model. Here, we explain the SOV method [6], and then we detail the multiple scattering model method, which is the resolution of a coupled system, depending on the simple scattering coefficients. Let us note $\vec{u}$ the vectorial displacement field such as:

$$\vec{u} = \overrightarrow{\mathrm{grad}}\phi + \overrightarrow{\mathrm{rot}}(\psi.\overrightarrow{e_z}) \qquad (1)$$

with Φ the scalar potential displacement of the longitudinal wave and $\vec{\psi} = \psi.\overrightarrow{e_z}$ the vectorial displacement potential of the transversal wave in a 2D case where the SDH axis is $\overrightarrow{e_z}$. Considering an incident longitudinal plane wave with an incident angle θ_0 at a point P located by $(r;\theta)$ in the cylindrical coordinates, we can defined the incident displacement potential Φ_{inc} as follows [2]:

$$\Phi_{inc}(\mathrm{P},\theta_0) = \Phi_0.e^{i\omega t}.\sum_{n=-\infty}^{+\infty} \alpha_n.J_n(k_L.r).e^{in\theta} \qquad (2)$$

with $\alpha_n = i^n e^{-in\theta_0}$ and k_L the wavenumber of the considered longitudinal wave. For an incident displacement potential of T polarity, replace Φ by ψ and k_L by k_T. Considering a unitary incident wave, i.e. $\Phi_0 = 1$, and implicit time dependency, the scattered potential displacement must respect the Sommerfeld conditions and can therefore be expressed as a composition of Hankel functions such as:

$$\Phi_S(\mathrm{P},\theta_0) = \sum_{n=-\infty}^{+\infty} \alpha_n.\mathrm{T}_n^{XY}.\mathrm{H}_n^{(1)}(k_L.r).e^{in\theta} \qquad (3)$$

where T_n^{XY} is the scattering coefficient of the cylindrical wave of n^{th} order of incident polarity X = (L or T) converted in the polarity Y=L. For ψ scattering field, set Y=T.

Since we considered voids in our study, boundary conditions are the cancellation of the normal and tangential stress on each interface of all cylinders. The matrix system to solve the problem of the multiple scattering can then be written as expressed in [5] (see equations (8) and (9) of this article). It gives an infinite matrix system, which is reduced to a finite problem, by replacing infinite sums by sums from $-N_{max}$ to N_{max}, taking care to leave the system reversible with a correct condition number. Scattered field of displacement potential can again be expressed such as:

$$\phi^{\mathrm{diff}}(\mathrm{P},\theta_0) = \sum_{Z_i}\sum_{n=-\infty}^{+\infty} \mathrm{C}_n^{Z_i(Inc\ L)}.\mathrm{H}_n^{(1)}(k_L.r_{X_i}).e^{in\theta_{X_i}} \qquad (4)$$

$\psi^{\mathrm{diff}}(\mathrm{P})$ is obtained by replacing $\mathrm{C}_n^{Z_i(Inc\ L)}$ by $\mathrm{C}_n^{Z_i(Inc\ T)}$ and k_L by k_T in (4). The cancellation of the total stresses (radial and tangential) has been checked all around each cylinder in order to ensure that the results stay corrects. The originality of this work is the possibility to study any disposition of any SDH, with any incidence in an elastic matrix, with the multi-scattering taken into account. Here, we restrain the study to 7 SDH with equal radius.

4. SCATTERING MODELS COMPARISONS AND TFM IMAGING

In order to compare both hypotheses, some scattering diagrams were plotted. Figure 2 shows the intensity in the far field of the estimated scattering amplitudes for a given incidence w.r.t. the observation angle.

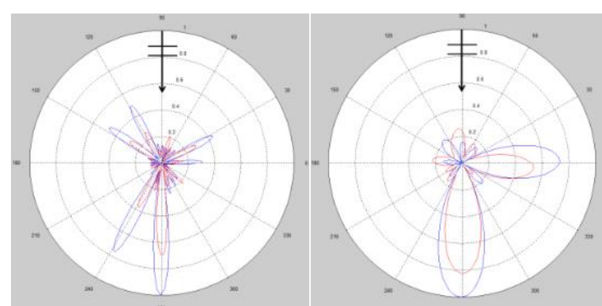

Figure 2: Scattering diagrams without interactions between defects (blue); with interactions (red); Incidence and scattered waves are L-polarized; 15 MHz incidence (left) / 5 MHz incidence (right);

On the Figure 2, the simple scattering model does not consider the geometrical shadowing between cylinders, unlike CIVA where geometrical shadowing is included. Some differences are notable, particularly in the side of the incidence. The same diagrams were plotted at a lower frequency (5 MHz).

As expected, the multiple scattering effects are more visible at lower frequency. In the considered case, we have used the CIVA software to simulate the corresponding FMC-TFM reconstruction.

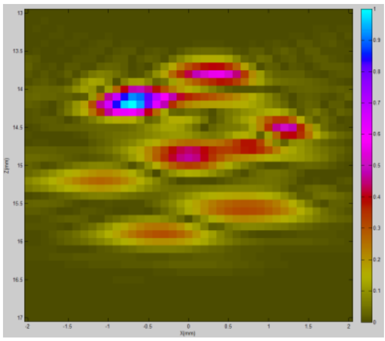

Figure 3: CIVA FMC-TFM reconstructions with 64 elements; (normalized scale, 40x40 pixels);

As shown in figure 3, the top defects are clearly visible, and bottom ones are always distinguishable which seems somewhat erroneous.

The cartography of the diffracted displacement potential field of the configuration was then studied as shown on Figure 4.

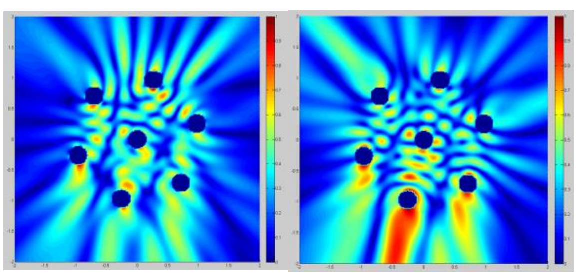

Figure 4 : Displacement potential fields with (left) and without (right) interactions;

Shadowing effects are clearly visible when interactions are considered. It let guess that a TFM reconstruction taking into account multi-scattering will be more realistic.

For comparison, an experimental reconstruction was made (see Figure 5). Some phantom-echoes are visible (due to the depth), but work is currently being done to reduce it.

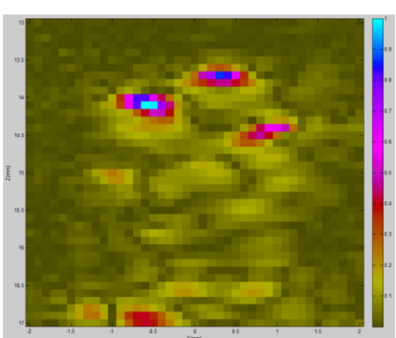

Figure 5: Experimental FMC-TFM reconstructions with 64 elements (normalized scale, 40x40 pixels);

On the experimental reconstruction, we can indeed observe that central and bottom defects are virtually not visible, cause of their interaction with the top defects.

5. CONCLUSION AND PERSPECTIVES

Considering multiple scattering effects, temporal reconstructions of the SDH shall be more realistic than the classical ones, computed by a ray method combined with a simple scattering hypothesis. Temporal reconstructions with 64 elements are ongoing, therefore not shown here. Results of controls from the top and from the bottom will be concatenated to have an entire imaging of the defects. These defects will be detected and characterized as accurately as possible to simulate the samples with SDH in fatigue tensile and determine a realistic lifetime.

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