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# MODELING ULTRASONIC NOISE AND ATTENUATION IN ELONGATED DUPLEX POLYCRYSTALLINE MATERIALS

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**ABSTRACT.** The interaction between ultrasonic waves and the polycrystalline microstructure of metals leads to structural noise and attenuation, which can cause significant losses in detection performances. Taking these phenomena into account in UT simulation can help designing suitable inspection procedures. It is possible to model them based on the intrinsic scattering coefficients of a material. Expressions of this coefficient valid for duplex elongated materials and for any mode and scattering direction are given in this communication. Structural noise from a titanium alloy was computed based on these expressions and is compared to measurement.

**Keywords:** Ultrasonic, Polycrystalline Material, Grain Noise, Attenuation

**PACS:** 43.20.Fn, 43.35.Cg, 43.35.Zc, 43.50.Ed

## INTRODUCTION

Structural noise and attenuation can be limiting factors in the ultrasonic non destructive testing of metallic parts. Modeling these phenomena can help designing inspection procedures. Among the possible approaches proposed in the literature, we can mention the computation of structural noise signals by [1] and the modeling of statistical properties of signals by [2]. A method similar to the one of [1] was developed at CEA LIST [3]. In subsequent works, it was modified [4] so that the statistical properties of the generated signals match the outputs of a scattering model. This model described the microstructure as a single phase and equiaxed polycrystal. In this communication, we present an extension of the simulation method and of the underlying model to the case of more complex microstructures such as duplex and elongated materials. First, we describe the simulation method. Then, we detail the application of the underlying scattering model for different microstructures. Finally, we compare outputs of the model to experimental results.

## SIMULATION OF ULTRASONIC INSPECTIONS WITH ULTRASONIC NOISE AND ATTENUATION

A method [4] previously developed at CEA LIST simulates ultrasonic testing with structural noise. It is based on the following assumptions: multiple scattering can be

neglected and the noise is a fully developed speckle (which means that the noise is due to a large number of subresolved scatterers). The fully developed speckle assumption is adequate as long as the grains in the material are small compared to the resolution capabilities of the probe. In this assumption, the actual number of scatterers has no impact on the statistical properties of the noise and we can describe the scattering by a volumic coefficient  $\eta$ .  $\eta$  is the same as the one studied by [5]. We define it as the fraction of the incident intensity that is scattered on average by a unit volume of the structure. It depends on the modes and the directions of the incident and scattered waves.

To use this coefficient to simulate structural noise, we generate a random distribution of scatterers. We choose a number  $N$  of scatterers per unit volume high enough to obtain fully developed speckle. The  $\eta$  of that distribution of scatterer is related to the mean of the square of their scattering amplitudes  $A$  and to the ratio of the velocity of the scattered and incident waves [5]:

$$\eta = N \langle |A|^2 \rangle \frac{v_{scat}}{v_{inc}}. \quad (1)$$

The distribution of the scattering amplitudes  $A$  is set in order to verify the above equation for the theoretical  $\eta$  of the simulated microstructure. That way, we ensure that the distribution of scatterers produces the same structural noise as the theoretical microstructure.

$\eta$  can also be used to obtain attenuation coefficients, by relating the energy lost due to attenuation to the energy scattered in every direction. These coefficients are used in the simulation for the computation of both structural noise and defect echoes. In the case of longitudinal waves, we obtain the following relation between the attenuation coefficient  $\alpha_L$  and the integrals over every direction of the scattered energy:

$$2\alpha_L = \int_{\Omega_{Total}} \eta_{L \rightarrow L}(\Omega) d\Omega + \int_{\Omega_{Total}} \eta_{L \rightarrow TH}(\Omega) d\Omega + \int_{\Omega_{Total}} \eta_{L \rightarrow TV}(\Omega) d\Omega \quad (2)$$

where the three coefficients  $\eta_{L \rightarrow \dots}$  are the scattering coefficients from L waves to each possible wave. Similar equations can be obtained for transverse waves. A detailed development that leads to equivalent expressions is given in [6].

$\eta$  is given by the scattering model described in the next section.

## SCATTERING MODEL

We use a scattering model to establish a relation between the properties of the microstructure and the coefficient  $\eta$ . This model is based on the approach proposed by [7]. The microstructure is described as an assembly of randomly oriented crystallites. As the crystallites are anisotropic, differences in orientation translate into elastic contrasts that cause scattering. The Born and single scattering approximation are used to derive expressions of  $\eta$ . Assuming that the density of the material is homogeneous, the following expression can be obtained:

$$\eta = \frac{1}{v_{inc} v_{scat}^3 (4\pi\rho^2)} p_i^{scat} k_j^{scat} p_k^{inc} k_l^{inc} p_m^{scat} k_n^{scat} p_p^{inc} k_q^{inc} \cdot \int \langle \delta C_{ijkl}(\vec{x}) \delta C_{mnpq}(\vec{x} + \vec{s}) \rangle_{\vec{x}} \exp[i(\vec{k}^{inc} - \vec{k}^{scat}) \cdot \vec{s}] dV \quad (3)$$

where the indices *inc* and *scat* refer to incident and scattering waves.  $k$  is the wave vector,  $p$  the polarization vector and  $v$  the velocity.  $\rho$  is the density of the material.  $\delta C$  is the variation of elastic constants compared to their average:

$$\delta C_{ijkl} = C_{ijkl} - \langle C_{ijkl} \rangle_{\vec{x}} \quad (4)$$

where  $\langle \rangle_x$  denotes an average over the positions  $\vec{x}$  in the material. It is equivalent to an average over the possible realizations of the microstructure.

The spatial correlation of elastic constants  $\langle \delta C_{ijkl}(\vec{x}) \delta C_{mnpq}(\vec{x} + \vec{s}) \rangle_{\vec{x}}$  depends on the geometrical and elastic properties of the microstructure. The adaptation of the model to different types of microstructures comes down to the development of that particular term.

### Single phase equiaxed microstructure

Expressions of this scattering coefficient for any mode and any scattering direction are given in [5] in the case of an equiaxed single phase material. The geometry of the microstructure is described in a statistical manner, by using a spatial correlation function. This function, noted  $W(\vec{s})$ , is defined as the probability that two points separated by  $\vec{s}$  are located in the same grains. An exponential form is usually assumed for this function,  $D$  being a characteristic grain size:

$$W(\vec{s}) = \exp\left(-\frac{2|\vec{s}|}{D}\right). \quad (5)$$

For a single phase microstructure with this correlation function, equation (3) simplifies to:

$$\eta = \frac{1}{v_{inc} v_{scat}^3 (4\pi\rho^2)} p_i^{scat} k_j^{scat} p_k^{inc} k_l^{inc} p_m^{scat} k_n^{scat} p_p^{inc} k_q^{inc} \cdot \langle \delta C_{ijkl} \delta C_{mnpq} \rangle \frac{\pi D^3}{\left(1 + \frac{\Delta k^2 D^2}{4}\right)^2} \quad (6)$$

where  $\Delta k$  is the difference between incident and scattered wave vectors.  $\langle \delta C_{ijkl} \delta C_{mnpq} \rangle$  is an average in a single crystallite over all its possible orientations. The indices of that covariance that need to be considered depend on the modes and directions of the incident and scattered waves. For example, in the case of the backscattering of L waves propagating along the  $z$  axis, only  $\langle \delta C_{3333} \delta C_{3333} \rangle$  needs to be considered. For a material with cubic symmetry, it is equal to:

$$\langle \delta C_{3333} \delta C_{3333} \rangle = \frac{16(C_{1111} - C_{1122} - 2C_{1212})^2}{525}. \quad (7)$$

For a material with hexagonal symmetry, it is equal to:

$$\langle \delta C_{3333} \delta C_{3333} \rangle = \frac{16(4C_{1111} - C_{1133} - 3C_{3333} - 2C_{1212})^2}{2205} + \frac{64(C_{1111} - 2C_{1133} + C_{3333} - 4C_{1212})^2}{11025}. \quad (8)$$

Expressions for other modes and directions are given in [5].

## **Description of a duplex microstructure**

This scattering model has been applied in literature to compute backscattering coefficient for L wave in the case of duplex titanium [8]. We describe here a way to obtain scattering coefficients of any wave in any direction and for more types of duplex metals.

An experimental micrographic picture where a duplex structure appears clearly is given by [9]. For modeling purposes, we describe that structure as a mix of primary and secondary phase in a manner similar to [8]. The primary phase is the first to appear during the solidification. It arranges itself in randomly orientated crystallites called macrograins. Later during the solidification, a secondary phase appears. It arranges itself in a set of colonies in each macrograin. The orientation of a colony is influenced by the orientation of the macrograin. A colony is composed of parallel needle-like crystallites that all have the same crystalline orientation. We assume that these crystallites are too small to individually affect ultrasonic scattering and we model a colony as a homogeneous mix of secondary and residual primary phases. We assume that the orientation of the secondary phase is related to the orientation of the surrounding primary phase by an alignment of dense planes and directions. Such alignment has consequences on the elastic constants on the materials.

We developed expressions of elastic constants for two types of metal. In the first one, the crystallographic lattices of the primary and secondary phases are respectively body-centered cubic (bcc) and hexagonal and the relation between the two phases is the same as given by [8]. It can be used to describe a titanium alloy with beta and alpha titanium as primary and secondary phases. In the second type, the crystallographic lattices of the primary and secondary phases are respectively body-centered cubic (bcc) and face-centered cubic (fcc) and they are related by the Kurdjumov-Sachs relationships. It can be used to describe a steel with ferrite and austenite as primary and secondary phases. The orientation relationships of the two types are given in Table 1.

**TABLE 1.** Orientation relationships between primary and secondary phases.

bcc to hexagonal	$\{110\}_{bcc} \parallel (0002)_{hex}$	$\langle 111 \rangle_{bcc} \parallel \langle 11\bar{2}0 \rangle_{hex}$
bcc to fcc	$\{110\}_{bcc} \parallel \{111\}_{fcc}$	$\langle 111 \rangle_{bcc} \parallel \langle 110 \rangle_{fcc}$

These orientation relationships imply that 6 orientations are possible for the hexagonal secondary phase and 24 orientations are possible for the fcc secondary phase. A possible orientation is called a variant. We assume that each of the variant has the same probability of appearing. We obtained analytical expressions for Euler angles that describe all these possible orientations. Listing of all these expressions takes several pages, so they are not given here. However, averages of the elastic constants over these variants are given later, as they are the quantities needed to calculate scattering coefficients.

## **Scattering coefficients for a duplex microstructure**

Based on the description of the microstructure, we obtain this expression for the covariance of elastic constants that appears in the expression of the scattering coefficient:

$$\begin{aligned}
& \langle \delta C_{ijkl}(\vec{x}) \delta C_{mnpq}(\vec{x} + \vec{s}) \rangle_{\vec{x}} \\
& = \langle (p_P \delta C_{ijkl}^P + p_S \delta C_{ijkl}^{SAV}) (p_P \delta C_{mnpq}^P + p_S \delta C_{mnpq}^{SAV}) \rangle W_M(\vec{s}) \\
& + \langle p_S \delta C_{ijkl}^S p_S \delta C_{mnpq}^S \rangle W_C(\vec{s}) W_M(\vec{s}) \\
& - \langle p_S \delta C_{ijkl}^{SAV} p_S \delta C_{mnpq}^{SAV} \rangle W_C(\vec{s}) W_M(\vec{s})
\end{aligned} \tag{9}$$

where  $p_P$  and  $p_S$  are the proportions of the primary and secondary phases.  $W_M(\vec{s})$  is the probability that two point separated by  $\vec{s}$  are located in the same macrograin.  $W_C(\vec{s})$  is the conditional probability that two point separated by  $\vec{s}$  and located in the same macrograin are located in the same colony.  $C^P$  and  $C^S$  are the elastic constants of the primary and secondary phases.  $C^{SAV}$  is the elastic constants of the secondary phase averaged over the variants, and is expressed:

$$C_{ijkl}^{SAV} = \sum_{a=1..N} C_{ijkl}^{SVa} \tag{10}$$

where  $N$  is the number of variants and  $C^{SVa}$  is the elastic constants of variant  $a$ .

For both the bcc to hexagonal and the bcc to fcc cases, the averaged elastic constants  $C^{SAV}$  have a cubic symmetry. Three terms of  $C^{SAV}$  are given in table 2, the others can be obtained using cubic symmetry. In the bcc to hexagonal case,  $C^S$  is expressed in coordinates such that  $C_{1111}^S = C_{2222}^S \neq C_{3333}^S$ .

**TABLE 2.** Elastic constants averaged over variants.

	bcc to hexagonal	bcc to fcc
$C_{1111}^{SAV}$	$\frac{3C_{1111}^S + 2C_{1133}^S + C_{3333}^S + 4C_{1313}^S}{6}$	$\frac{23C_{1111}^S + 13C_{1122}^S + 26C_{1212}^S}{36}$
$C_{1122}^{SAV}$	$\frac{C_{1111}^S + 4C_{1122}^S + 6C_{1133}^S + C_{3333}^S - 4C_{1313}^S}{12}$	$\frac{13C_{1111}^S + 59C_{1122}^S - 26C_{1212}^S}{72}$
$C_{1212}^{SAV}$	$\frac{3C_{1111}^S - 2C_{1122}^S - 2C_{1133}^S + C_{3333}^S + 4C_{1313}^S}{12}$	$\frac{13C_{1111}^S - 13C_{1122}^S + 46C_{1212}^S}{72}$

By using equation (9) in equation (3), we can obtain a decomposition of the scattering coefficient of a duplex microstructure into three scattering coefficients.

$$\eta_{duplex} = \eta_{macrograin\_average} + \eta_{secondary} - \eta_{variant\_average} \tag{11}$$

**TABLE 3.** Parameters for calculating the scattering coefficient of the decomposition.

	Spatial correlation function	Elastic constants
$\eta_{macrograin\_average}$	$W_M(\vec{s})$	$p_P \delta C_{ijkl}^P + p_S \delta C_{ijkl}^{SAV}$
$\eta_{secondary}$	$W_C(\vec{s}) W_M(\vec{s})$	$p_S C^S$
$\eta_{variant\_average}$	$W_C(\vec{s}) W_M(\vec{s})$	$p_S C^{SAV}$

The three coefficients of this decomposition are the scattering coefficients of three fictitious materials characterized by spatial correlation functions and elastic constants given in table 3. Equations (3) to (8), as well as the equations in [5], can be used to calculate these three coefficients.

The three coefficients can be interpreted as follows:  $\eta_{macrograin\_average}$  is the contribution of the macrograins to the scattering,  $\eta_{secondary}$ -  $\eta_{variant\_average}$  is the contribution of the colonies ( $\eta_{secondary}$  being the contribution of individual colonies and  $\eta_{variant\_average}$  a reduction of the scattering due to orientation relationships).

### **Elongated material**

All the previous results were for the case of non-elongated grains. Taking into account an elongation of the grains means changing the spatial correlation function given in equation (5). Following [10], we generalize to elongated structures using the form:

$$W_{elongated}(\vec{s}) = \exp\left(-2\frac{s}{d}\sqrt{1 + \left(\frac{d^2}{h^2} - 1\right)\cos^2\theta}\right) \quad (12)$$

where  $h$  and  $d$  are the grain sizes respectively in the elongation direction and in the directions perpendicular to it.  $\theta$  is the angle between  $\vec{s}$  and the elongation direction. Using that new function implies modifying the term known as the form factor in equation (6). For an equiaxed material, it is equal to:

$$S_{equiaxed} = \frac{\pi D^3}{\left(1 + \frac{\Delta k^2 D^2}{4}\right)^2}. \quad (13)$$

For an elongated microstructure as defined above it becomes:

$$S_{elongated} = \frac{\pi d^2 h}{\left(1 + \frac{\Delta k_{perp}^2 d^2 + \Delta k_{elong}^2 h^2}{4}\right)^2}. \quad (14)$$

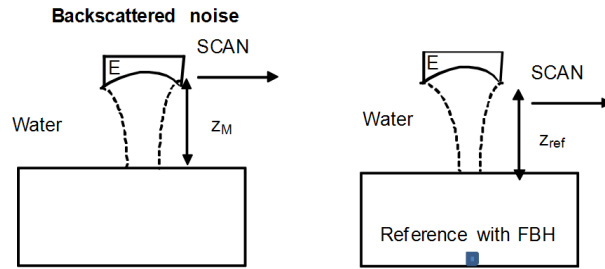
where  $\Delta k_{elong}$  and  $\Delta k_{perp}$  are the components of  $\vec{k}_{inc} - \vec{k}_{scat}$  respectively in the elongation direction and in the directions perpendicular to it.

This substitution yields expressions for the scattering coefficient of single phase elongated materials. By applying it to each term of the decomposition of equation (11), it is possible to obtain expressions for duplex elongated materials.

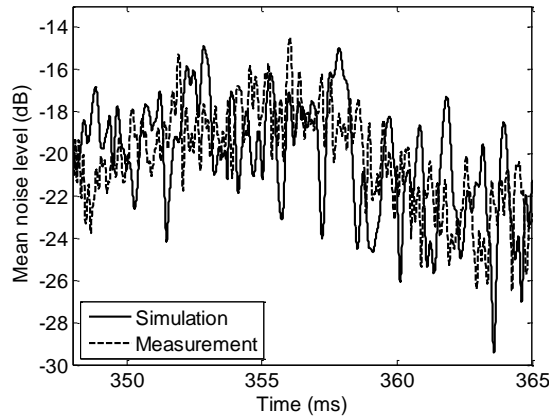
### **VALIDATION**

An experimental validation was performed using the measurement setups presented figure 1. The main characteristics of the transducer are a focal length  $F$  of 406.2mm, a diameter of 25.4mm and a center frequency  $f_0$  of 10MHz. Measurements were performed in immersion at normal incidence. Structural noise was measured in a sample of duplex titanium, and the echo of a Flat Bottom Hole in a reference block was measured using the same transducer. The waterpath  $z_M$  was chosen such that the beam was focused in the half depth of the block.

A micrographic study of the titanium alloy sample showed that the grains were elongated. It also allowed estimating the sizes of the macrograins and the colonies. The



**FIGURE 1.** Pulse/echo acquisition for structural noise and reference echo.



**FIGURE 2.** Measured and simulated averages of the envelopes of structural noise as a function of time.

elastic constants of each phase were assumed to be equal to data found in literature. All these parameters were used as an entry for a simulation of structural noise, though some adjustments were made concerning the size of colonies as they did not appear clearly enough on the micrographs.

The simulation method is based on the models described in this communication. It was integrated in a development version of the CIVA simulation platform [11].

Simulations were run for both the experiments of figure 1. In order to compare measured and simulated structural noise, the envelopes of the noise signal at each position of the probe were computed and averaged. The average structural noise as a function of time was obtained. It is plotted in figure 2, expressed in decibels compared to the echo of the reference defect.

This comparison shows a good agreement: the gap between the two results is smaller than the oscillations of the noise. Both the absolute value and the evolution of the noise are satisfactory. Other simulation results for this configuration, obtained without taking into account the grain elongation, had shown a disagreement of approximately seven decibels [12]. This illustrates that improving the description of the microstructure can help improving the simulation results.

## CONCLUSION

The structural noise that occurs in ultrasonic NDT can be simulated based on the coefficient  $\eta$  of the material. We presented a way to compute this coefficient for every mode and in every scattering direction for duplex and elongated materials. These computations are based on the Born and single scattering approximations. We propose decomposing the scattering coefficient of the duplex material into three terms. It leads to relatively simple expressions despite the complexity of the material.



Experimental validations on a duplex titanium alloy with elongated grains show a good agreement. It demonstrates the relevance of both the simulation method and the scattering model. However, they are not expected to be valid for every case of ultrasonic structural noise. It is known that in some cases multiple scattering dominates, and it is not taken into account by this method. In future works we aim at including multiple scattering contributions in this method.

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