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Laser ultrasound and simulated time reversal on bulk waves for non destructive control

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Abstract. Laser welding of aluminium generally creates embedded welding defects, such as porosities or cracks. Non Destructive Inspection (NDI) after processing may ensure an acceptable weld quality by defect detection. Nowadays, NDI techniques used to control the inside of a weld are mainly limited to X-Rays or ultrasonics. The current paper describes the use of a Laser Ultrasound (LU) technique to inspect porosities in 2 and 4-mm thick sheet lap welds. First experimentations resulted in the detection of 0.5-mm drilled holes in bulk aluminium sheets. The measurement of the depth of these defects is demonstrated too. Further experimentations shows the applicability of the LU technique to detect porosities in aluminium laser welds. However, as the interpretation of raw measures is limiting the detection capacity of this technique, we developed a signal processing using Time-Reversal capabilities to enhance detection capacities. Furthermore, the signal processing output is a geometrical image of the material's inner state, increasing the ease of interpretation. It is based on a mass-spring simulation which enables the back-propagation of the acquired ultrasound signal. The spring-mass simulation allows the natural generation of all the different sound waves and thus enables the back-propagation of a raw signal without any need of filtering or wave identification and extraction. Therefore the signal processing uses the information contained in the compression wave as well as in the shear wave.

1. Introduction

Assembling aluminium alloy can be achieved through various techniques. The absence of non-destructive control methods to quantify the assemblies' quality, can become a factor in choosing one or another technique. Laser welding in particular can generate different kinds of defects such as cracks or porosities, depending on which aluminium alloy is welded. The goal of our study is to explore different non-destructive controls so as to propose a novel method of inspection, which will be capable to detect on-line inner defects in an industrial context. For this purpose, we chose the ultrasound principle coupled with the laser ultrasound technique. This system has already shown capabilities of inner defects detection in surface treated aluminium alloys [1]. Detecting defects and assessing their sizes can also be improved by the use of signal processing techniques such as SAFT (Synthetic Aperture Focalisation Technique) [2]. To obtain a geometric image of the material's inner state through ultrasound measures, we chose to use Time-Reversal



properties. These will determine the regions of interest within the measure. To perform this, the simulation tool seems to be quite adequate [3].

2. Simulation

The system we simulate is a possible description of a solid material expressed as a coupled mass-spring network [4]. We define $u_a = p_{a,b} - p_{0a,b}$ with p the position for a mass a and k the springs constant. We can write the following relationship in the case of mass-spring interaction:

$$\begin{aligned} F_a &= k[(u_{a+1} - u_a) - (u_a - u_{a-1})] \\ &= kl \left[\frac{(u_{a+1} - u_a)}{l} - \frac{(u_a - u_{a-1})}{l} \right] \end{aligned} \quad (1)$$

The notations can be found on figure 1.

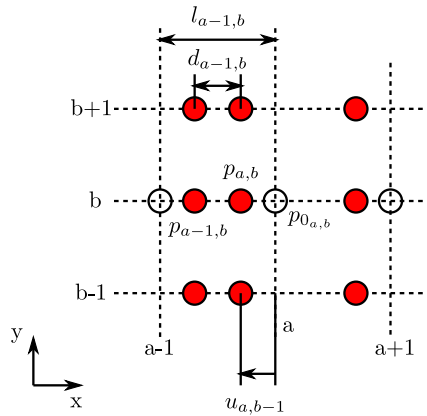


Figure 1: Initial state of the model's grid

When taking into account the limit on l and therefore consider a large amount of mass-spring systems connected to one another and then express the equation in the continuous domain and by defining $c^2 = (k/m) \times l^2$ as the wave's celerity to obtain the wave propagation equation [5]:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \quad (2)$$

The relation between k , m , l , c and physical variables is:

$$c^2 = \frac{k}{m} l^2 = \frac{E}{\rho} \quad (3)$$

with E Young's modulus and ρ the volumetric mass of the considered material. It is so established that a mass-spring description can lead to the same well-known wave-propagation equation.

3. Experimental set-up

Ultrasonic measurements were performed with a pulsed laser to generate the soundwave and an interferometer to record the surface displacement induced by this soundwave. The pulsed laser interacts with the surface to produce ultrasonic surface and bulk waves. The interferometer measures the out-of-plane surface displacement. Each experiment was done in ablation mode so as to obtain a sufficient Signal-to-Noise Ratio (SNR) and an appropriate soundwave directivity.

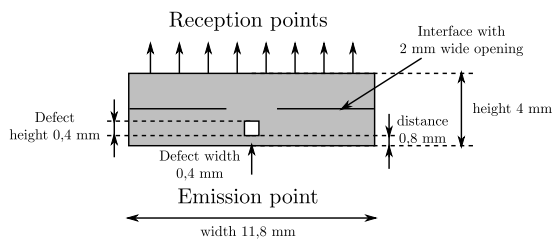


Figure 2: Configuration of the simulated plate with included defect

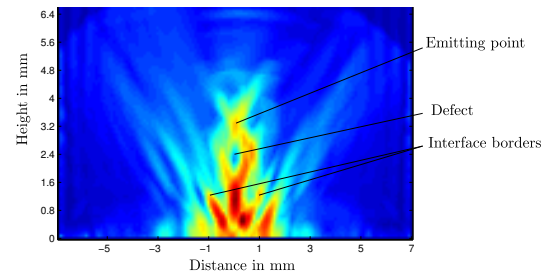


Figure 3: Extraction of the maximum energy for each point over the whole propagation duration

The impact can be approximated as a punctual point, thus defining the direction of the different waves. The pulsed laser is a Nd:YAG laser of wavelength $\lambda = 1064$ nm. The pulse length is 10 ns and therefore, the generated ultrasonic wave has a maximum frequency at -3 dB of 20 MHz. The interferometer uses a frequency doubled Nd:YAG laser at $\lambda = 532$ nm. Its frequency range of detection is: 20 kHz to 45 MHz. The measurement were performed with the excitation on the weld and the interferometer on the opposite surface. This configuration allow the detection of defect, but does not allow to precisely identify each porosity nor its size [6].

4. Time-Reversal

4.1. Time-Reversal Principle

The Time-Reversal principle has been established by Fink et al [7]. The ultrasound signal must be recorded by a receiver array. By sending the recorded ultrasonic signal backwards on the exact same position as the recording device's, the ultrasound signal will then use the path it took during the initial emission. Moreover, the backwards-emitted signals will also focus on the initial emitting point. In addition, the Huygens principle ensures that every interface can be considered as an emitter. The signal will not only naturally focus on the initial emitting point but also on every interfaces that stand on the wave's path. This property can then be used to detect defects.

4.2. Time-Reversal with numerical simulation input

We simulated the whole signal: both the initial emission and the time-reversed signal. The simulated configuration is two 2-mm thick, lap welded aluminium alloy plates with an included rectangular hole 0.4 mm wide and 0.8 mm deep (figure 2).

The displacement signal is only recorded out-of-plane on 120 points on the opposite side of the simulated plate, thus simulating a transmission configuration. Each recorded point is distant from the other by 0.1 mm. The recorded signal is then sent backwards on the same points, in a material with the same physical properties but without any prior geometrical information, neither on its size nor on the presence of a defect. The Time-Reversal is then performed. The signals are recorded on each point, for every iteration. The visualisation which is used consist in the extraction of the masses' kinetic and potential maximum energy ($\max(U = U_c + U_p)$), figure 3. The visualisation consists in storing the maximum value of the energy for each point over the whole back propagating duration. The results show the focus on the surface of the defect as well as on the emitting point. The maxima's extraction undoubtedly reveals the emitting point. Concerning the defect and the interfaces, the energy levels clearly shows the outline of the defect (figure 3) whereas for the interfaces, only the tips are being identified. Moreover one side does not show any potential identification ambiguity where the other can be misinterpreted because

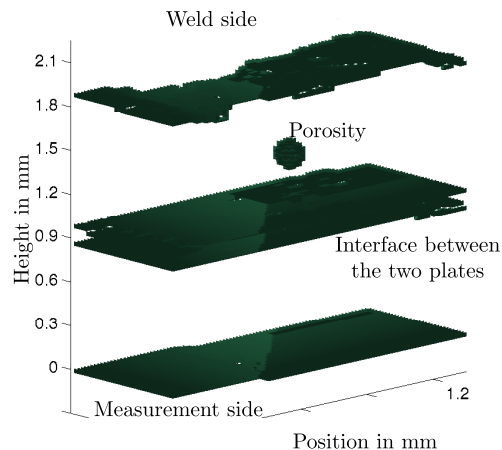


Figure 4: X-ray tomography of the tested lap-welded part

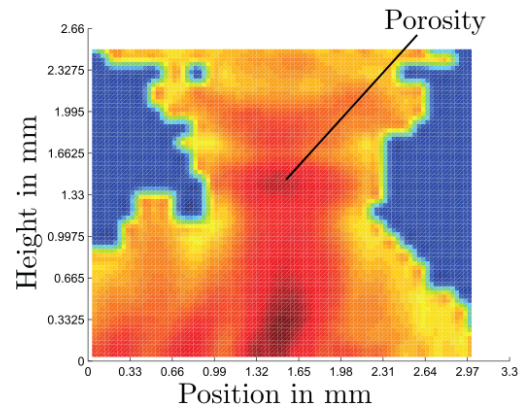


Figure 5: Maximum extraction after Time-Reversal with real data input

of an close energy peak. The Time-Reversal on simulated signals shows the effectiveness of this method even if some smearing signals can create false positive.

4.3. Time-Reversal with real data input

The next experiment uses real raw measurement data on lap-welded aluminium alloy plates. Only out-of-plane information was available and therefore sent backwards in the simulation. To compare the results, X-ray tomography has been used to characterise the tested part. The result is shown figure 4 and shows an included porosity in the upper plate.

The maximum extraction shows a maximum of energy where the porosity is. The porosity is smaller as the defect that has been simulated before therefore the porosity does not show the outline of the defect. Moreover some smearing is to be expected giving the high signal close to the emission points. This result is encouraging and more experiments should be conducted to confirm the method's effectiveness.

5. Conclusion

We hereby present a method that successfully reconstructed the internal status of lap-welded aluminium alloy plates. Furthermore, the prior knowledge about the inspected material to achieve such result is minimal. This method still needs improvement, the maximum energy extraction is sufficient in some cases but is not sensitive enough for the smallest defects. Nevertheless, simulated and experimental results show the effectiveness of this approach. Further development should include a computational optimisation to achieve a real-time analysis.

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