

Thermal stress opening of closed cracks with local cooling on the cracked surface

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Abstract: Ultrasonic measurements are commonly used for defect sizing, but because of potential partial crack closure, the ultrasonic signal can behave differently, and as a result, the crack depth can be underestimated. Ultrasonic methods dedicated to the improvement of the measurement of this kind of defect like non-linear acoustics have then been developed. In parallel to this, another way to improve the crack sizing performance of both conventional and non-linear acoustics methods is to mechanically open the investigated crack using the material thermal dilatation. By cooling the opposite side of the crack, it bends the sample which creates an opening constraint on the investigated crack. The crack closure importance is then reduced and the sizing improved. However, due to the sample geometry, the opposite side of the sample may not always be accessible. To solve this problem, the crack opening by cooling the cracked surface is necessary. In this paper, this opening mechanism is explained, and experimental proof is given. Furthermore, the protocol repeatability is shown and the significant impact on the crack closure is demonstrated. Highlighting the crack size underestimation, this method could be of importance with a view to predicting the remaining service life of parts in an industrial context.



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Thermal stress opening of closed cracks with local cooling on the cracked surface

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Naval Group: Construction and maintenance of ships and submarines

Cracks: Observed on tubular industrial parts (Ferritic steel)

Accessibility:

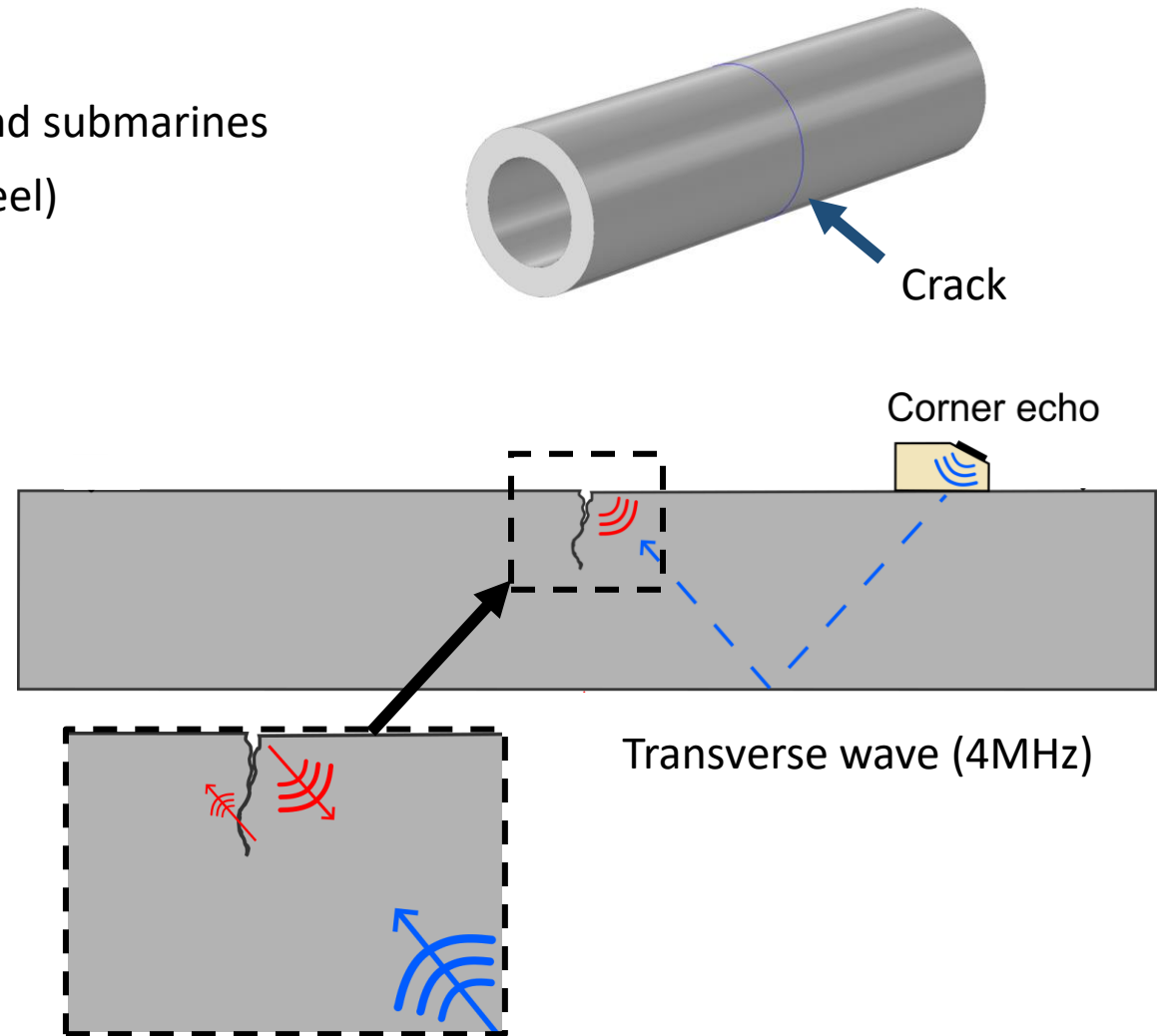
- Only the upper surface
→ Rebound
- Only one side of the crack
→ No transmission measurement

Performed control: **Observation of the reflected ultrasound signal** (Single element transducer, TFM, ...)

In the case of our closed crack:

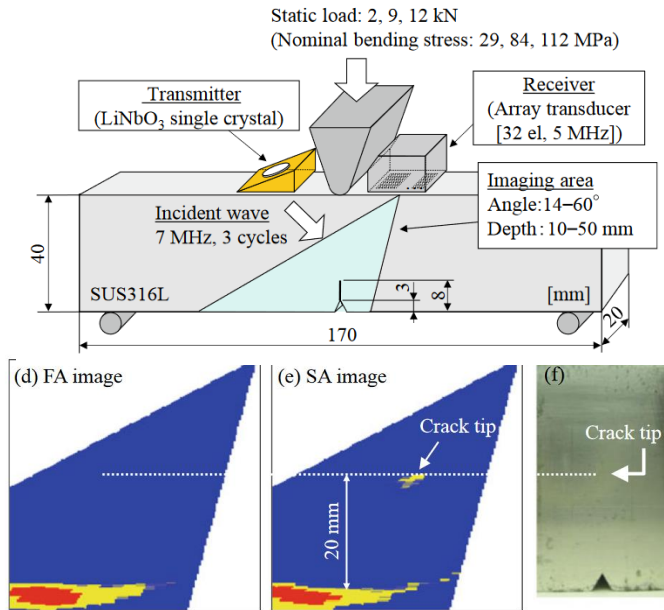
- **No tip diffraction echo**
- **Reduced corner echo**

→ Undersizing issue with conventional ultrasound methods

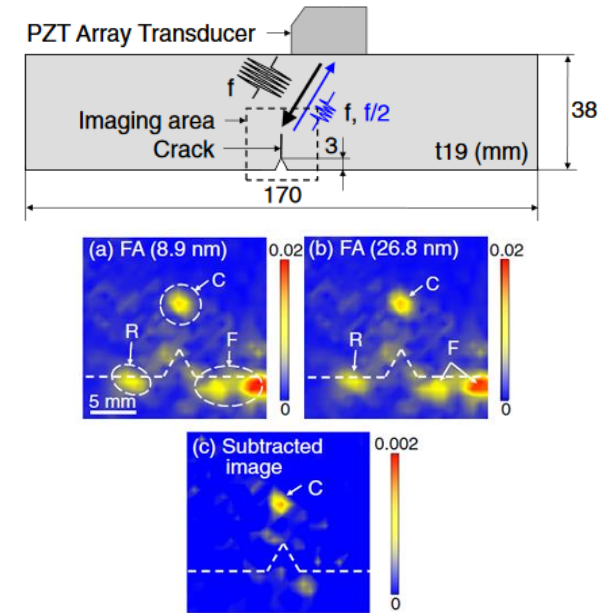


Solution: Non-linear acoustic methods

- Appearance of the diffraction echo on subharmonic images
- Increased signal/noise ratio with more complex methods (FAD, ...)



Sub-harmonics [Ohara, 2007]



FAD method [Ikeushi, 2013]

For accessibility reasons + Reliability: **Still difficult in an industrial context**

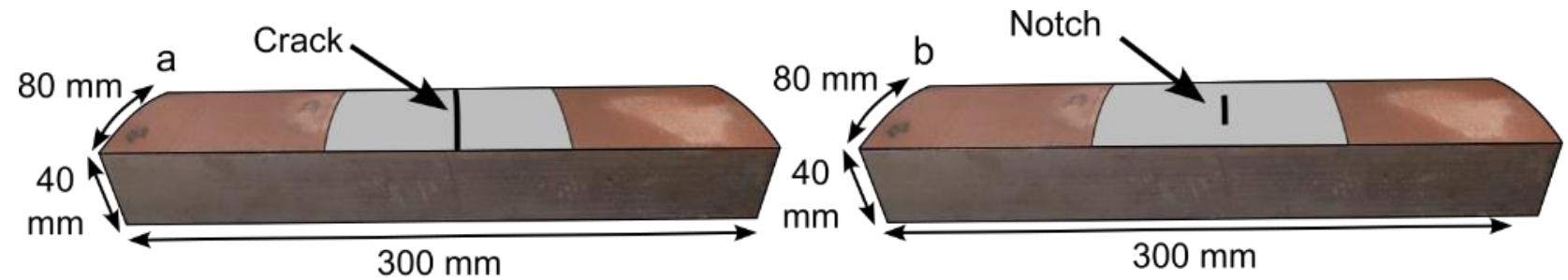
→ External load to temporarily open closed cracks?

1. Sample and crack description
2. Thermal pump principal
3. Cooling description
4. Experimental result
5. Wave propagation modeling
6. Opening capacity
7. Conclusion



Samples and cracks

Extracted samples:



To highlight the **impact of the closure** on the corner echo → Bending test + corner echo measurement

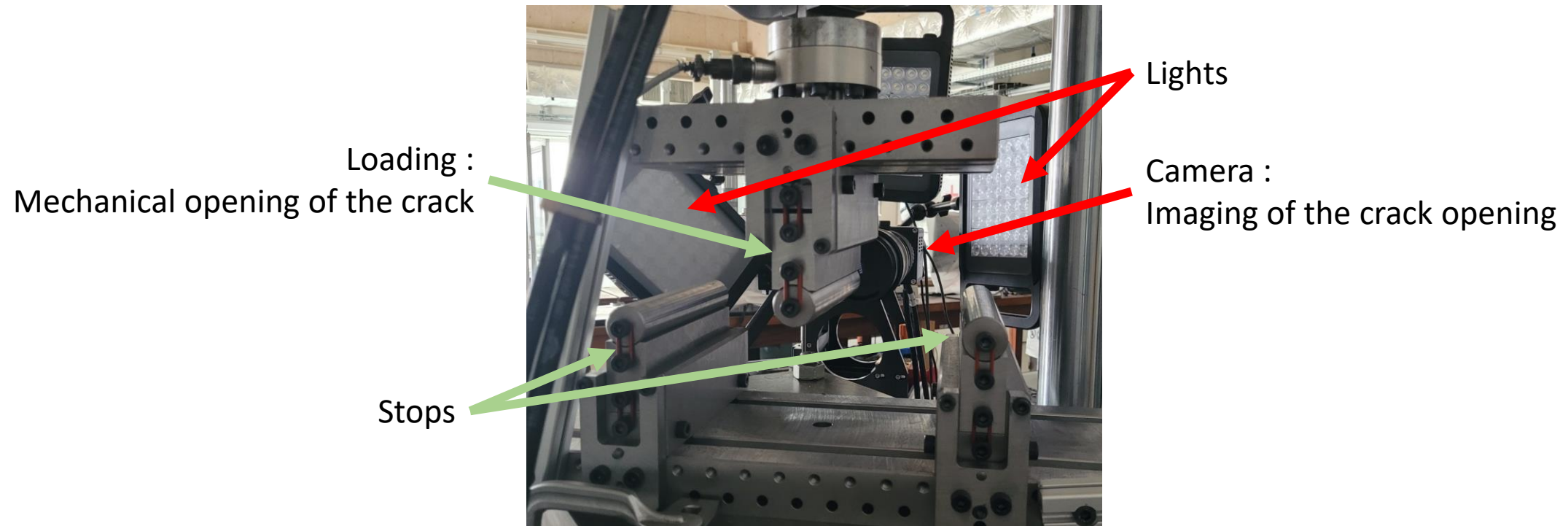
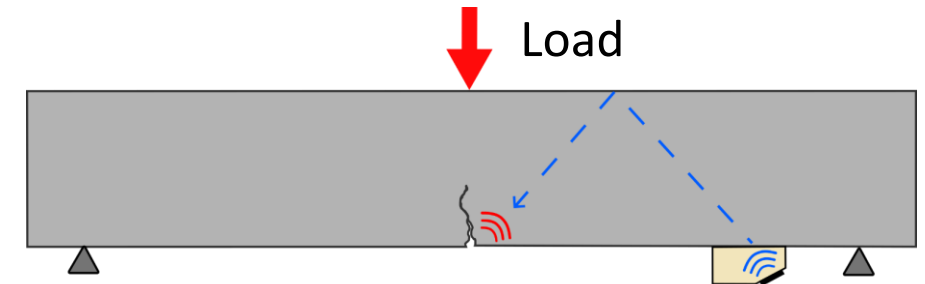
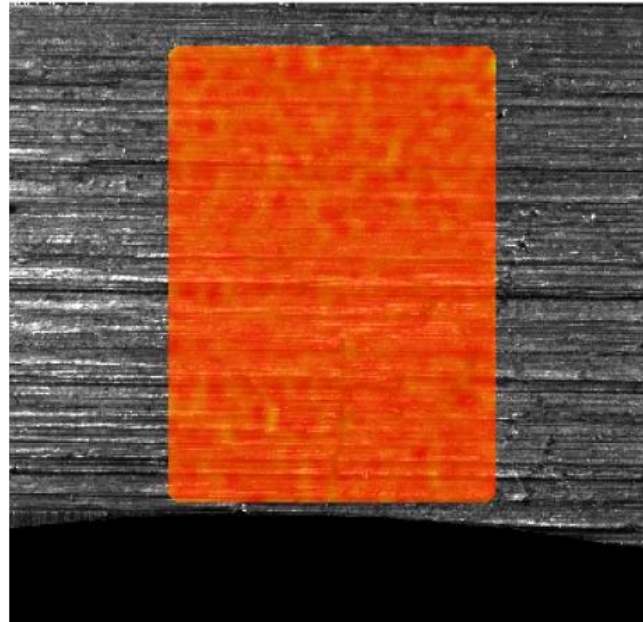


Image correlation during loading (PIV) : Measurement of strains around the observed crack
→ Observation of the **crack opening**

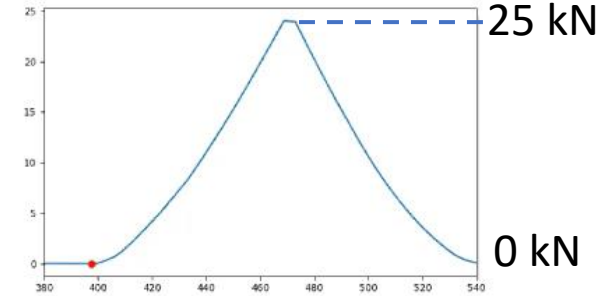


Corner echo
SW45 - 4 MHz

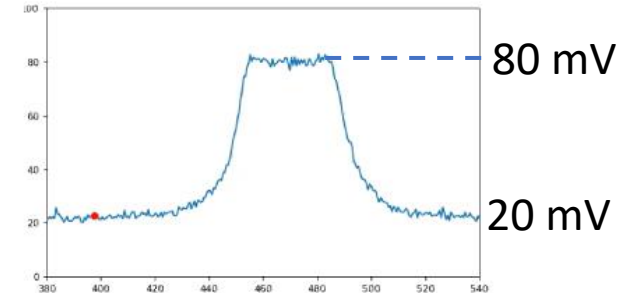
Strains



Loading



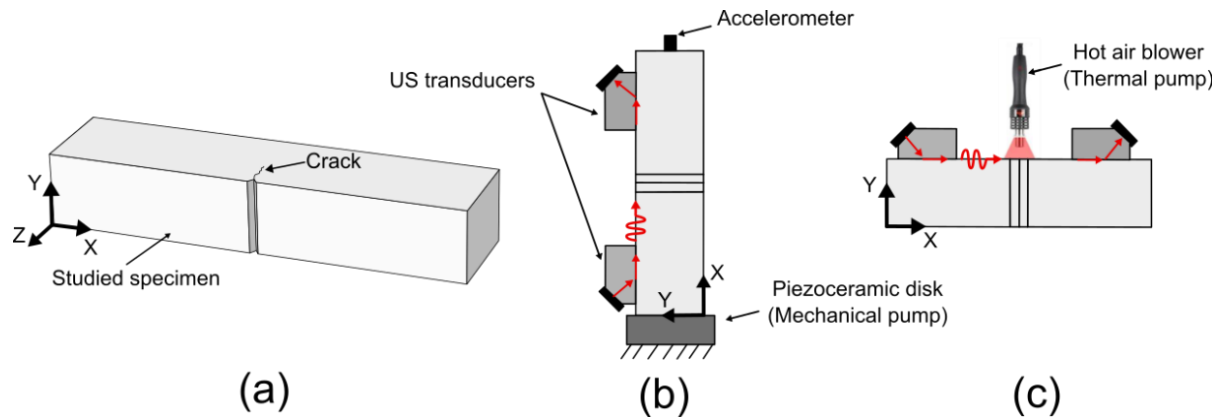
Corner echo



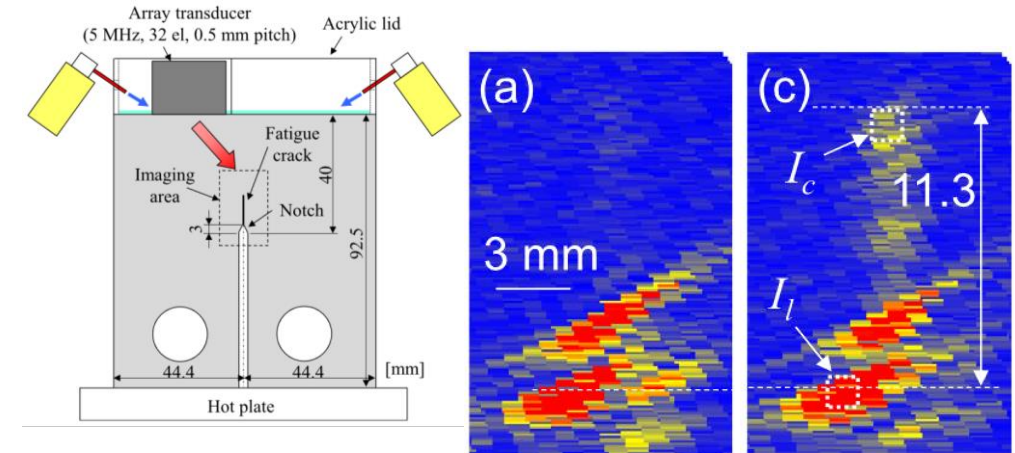
Cracks are totally opened
How can such an opening constraint be replaced?

Thermal pump : Principle

Local cooling → Local material contraction → Opening of cracks



Replacement of DAET mechanical pump wave (hot air)
[Manogharan, 2023]



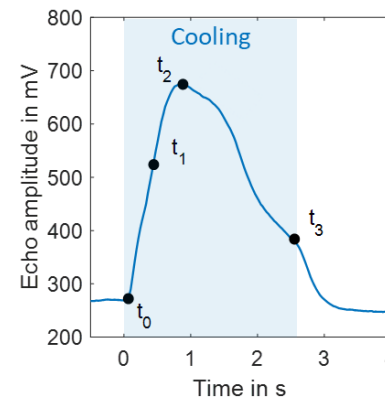
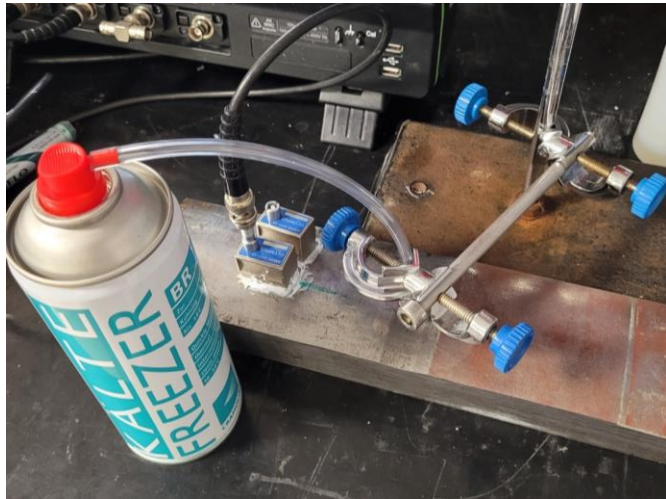
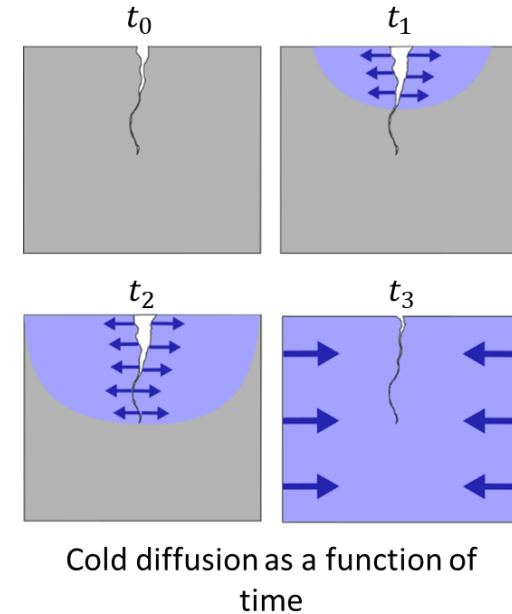
Global preheating local cooling [Ohara, 2013]
Apparition of the diffraction echo

A local change in temperature can have a significant impact on crack closure
How can it be implemented?

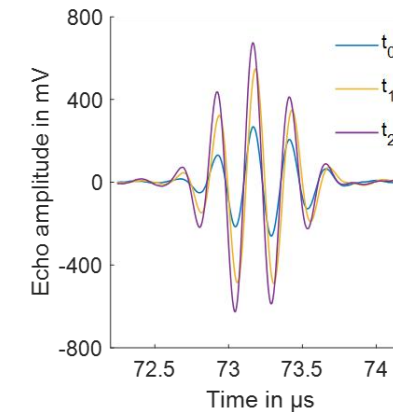
Direct cooling of the assessed crack
No pre-heating

At the beginning of the crack cooling ($t_0 \rightarrow t_2$):
High $\Delta T \rightarrow$ Opening

After ≈ 1 second ($t_2 \rightarrow t_3$):
Temperature homogenization \rightarrow Closure



Evolution of the corner echo

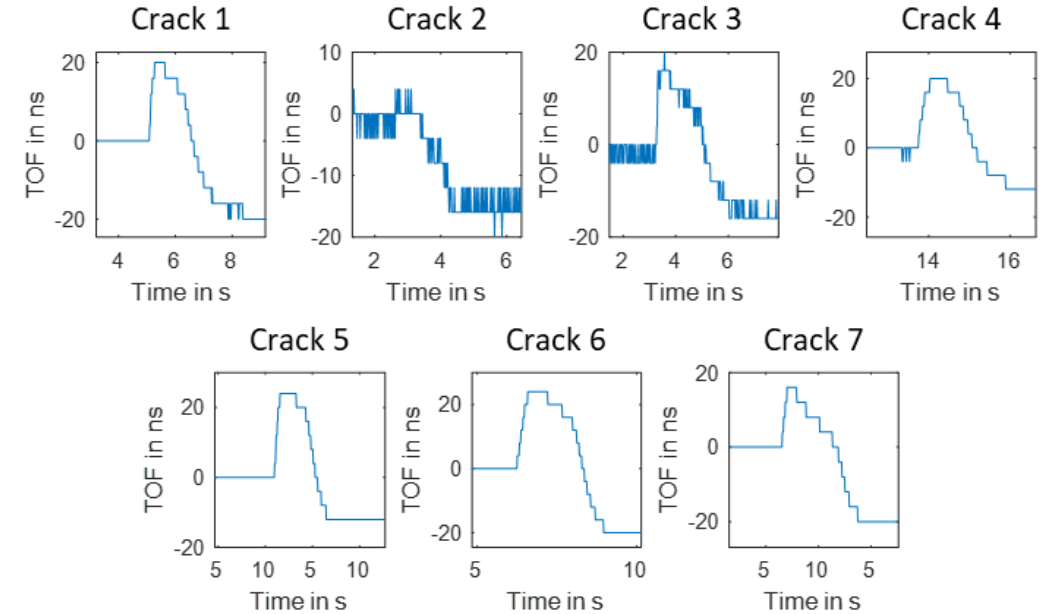
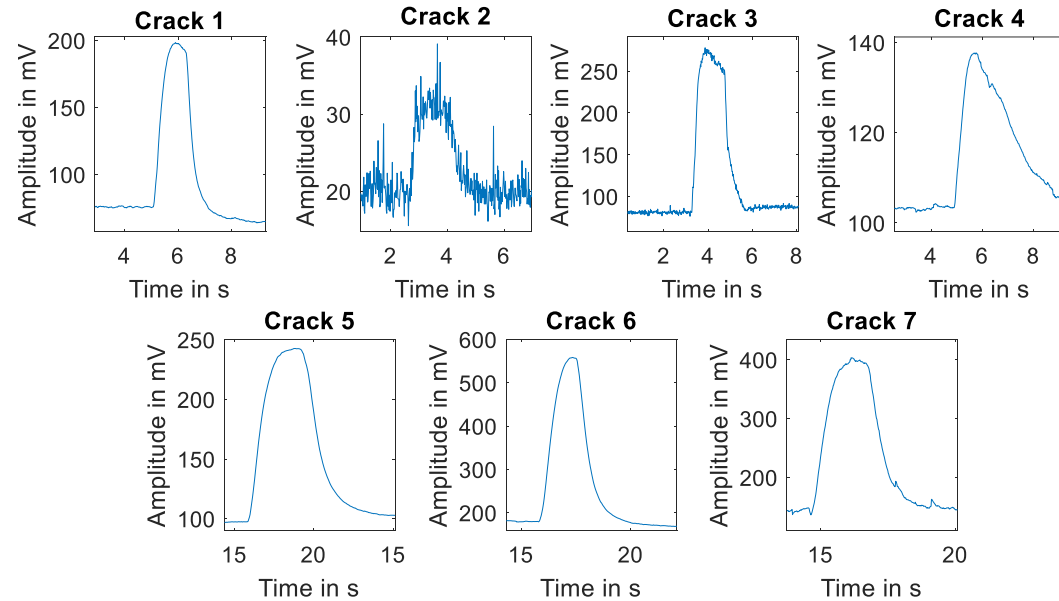


Shape of the corner echo

Ajouter t3

Experimental results

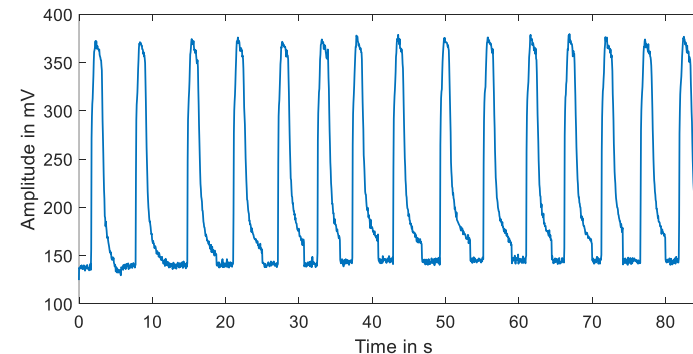
On 7 different cracks with **different mechanical behavior**:



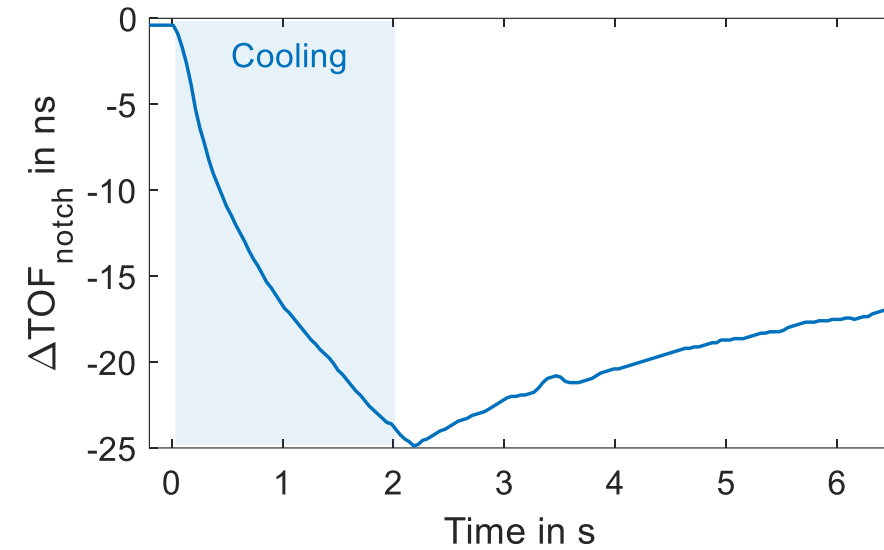
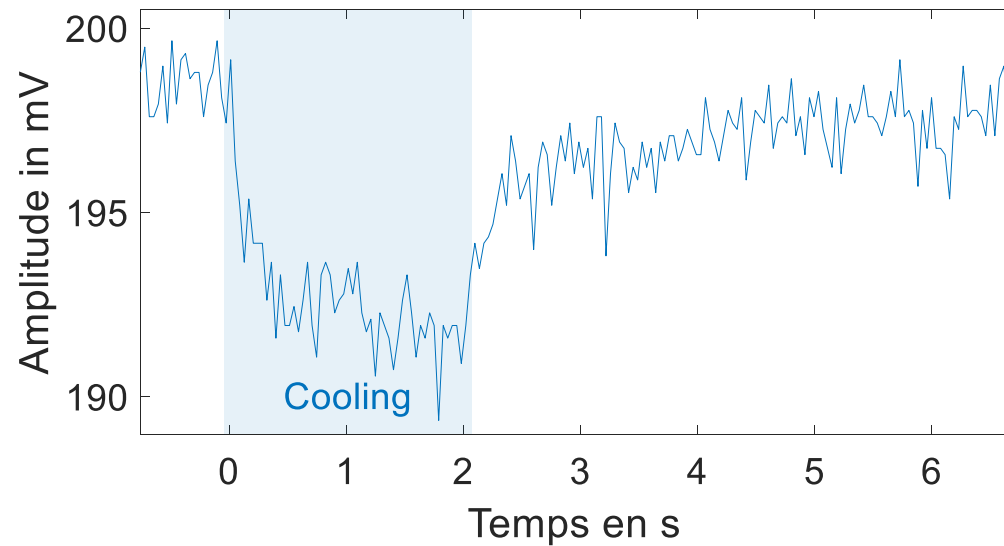
Huge sensitivity of the corner echo amplitude to thermal pump (between 30% and 200% increase)

Repeatability :

$$A_{max} = 376 \text{ mV and } \sigma = 3 \text{ mV}$$



Same measure on a 3mm-deep notch :



With a notch : no opening

→ Variations = Impact of the cooling on ultrasound signal

Amplitude : Small variation (5% decrease)

TOF : No increase

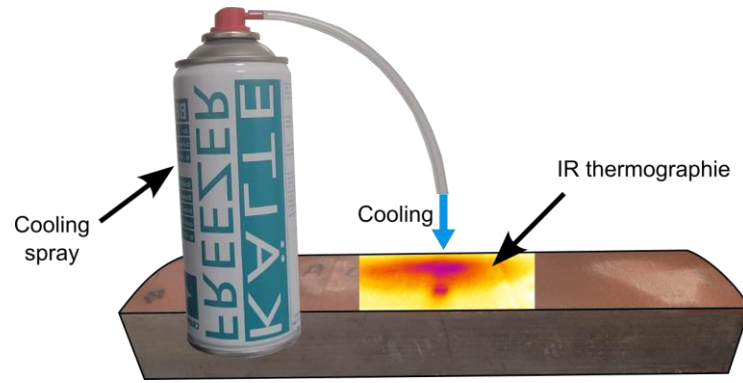
→ The amplitude increase on closed cracks = opening

How can the variations on the notch be interpreted?

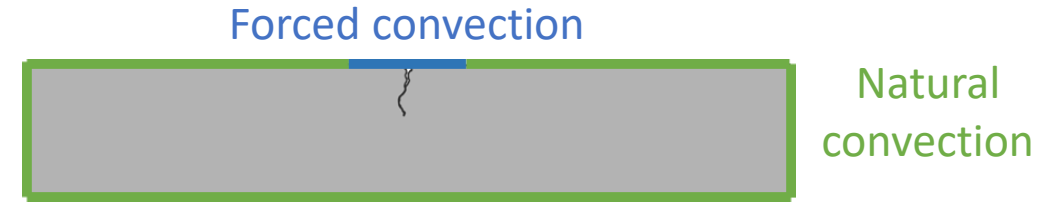


Modelling

Cooling modeling to assess the various phenomena associated with temperature variation



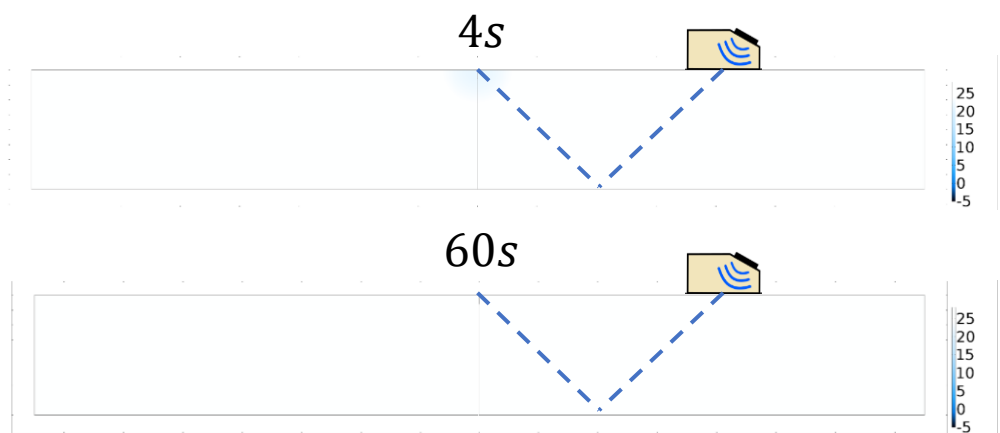
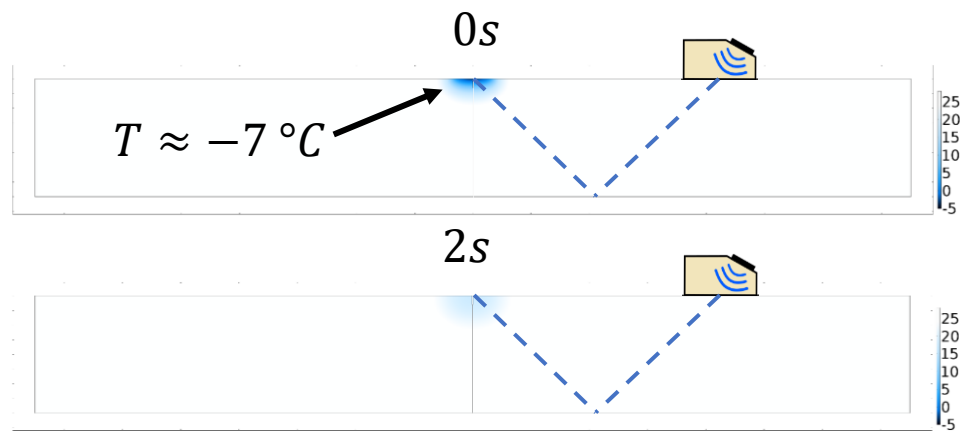
Experimental measurement for time up to 30s



Comsol simulation (thermo-mechanical)

Convection motions :

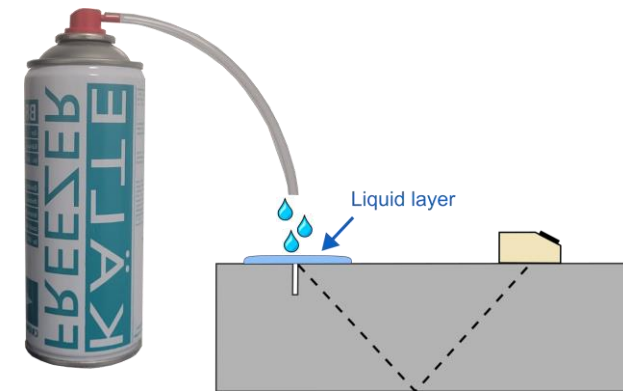
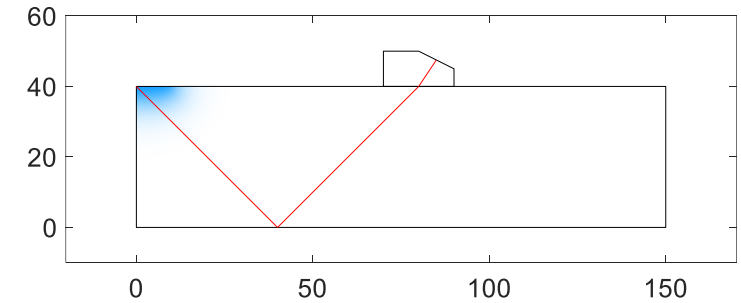
- Cool air
- Ambient air



Result: Access to the **estimated temperature/strain field as a function of time**

Notch case (modelling of the following phenomena):

- Attenuation variation : $\alpha(T)$
- Ultrasound deviation : $\frac{\partial v(x,y)}{\partial y} \neq 0$ and $\frac{\partial v(x,y)}{\partial x} \neq 0$
- Variation of material properties: $v_T = \sqrt{\frac{E(T)}{2\rho(T)(1+\nu(T))}}$
- Material acoustoelastic : $\frac{dv_T/v_T^0}{d\epsilon_{th}} = -8.27$
- Liquid layer applied by the cooling spray : liquid/solid interface



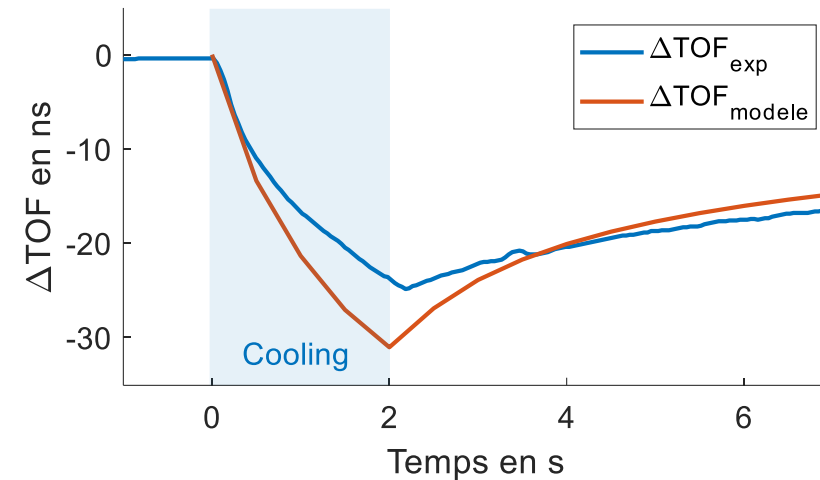
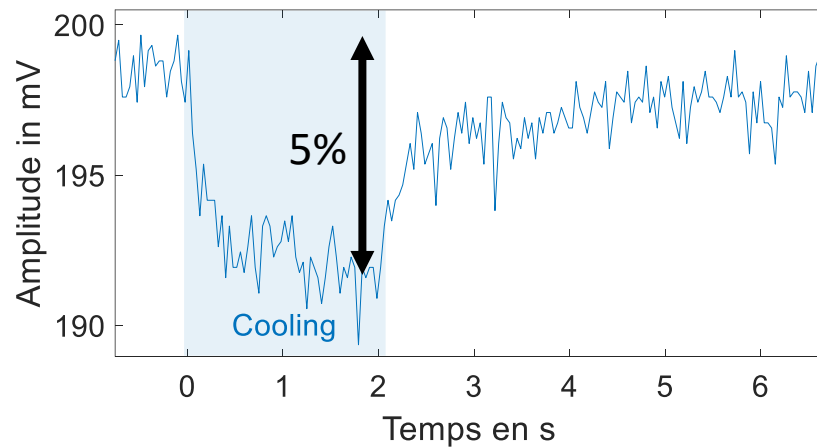
Based on the simulation results: evaluation of every listed phenomena

Attenuation variation and beam deviation : Negligeable

Liquid layer : Amplitude ↘ 10%

Material properties variation : TOF ↘ 10 ns

Material acousto-elasticity : TOF ↘ 20 ns



Amplitude drop = Loss in liquid layer

→ Temperature influence on the echo amplitude = negligible

→ For cracks : Amplitude increase = opening (underestimation due to the liquid layer)

TOF drop = Impact of the temperature on the material

→ For cracks: TOF increase at the beginning = Crack acousto-elasticity/ Crack opening

Thermal pump: Opening capacity

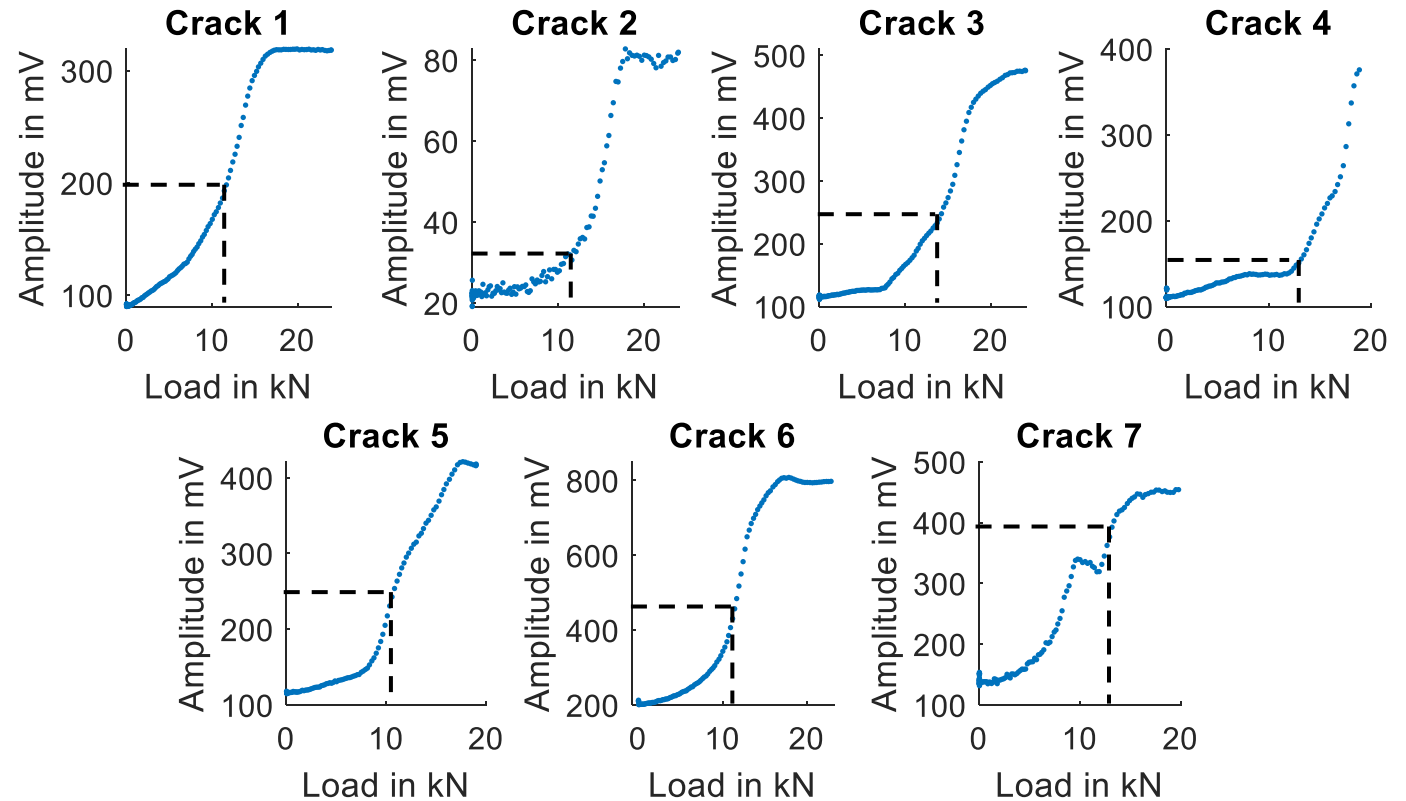
Comparison to the bending test opening
(7 different cracks):

Amplitude with thermal pump \leftrightarrow 13 kN

Significant opening but **not total**:
(echo saturation between 16 kN to 22 kN)

Phased array measurements:
No diffraction echo during cooling process

→ Cooling optimization needed



Thermal pump: Conclusion

Closed cracks are still not completely opened

This method provides significant crack opening allowing a better sizing

The equipment necessary is simple and the measurement flexible

An optimization of the cooling could help reach the total opening (pre-heating, larger spray, colder spray)

Future work:

- Imaging of the crack during its opening
- Nonlinear imaging ( Cooling impact on the wave speed)

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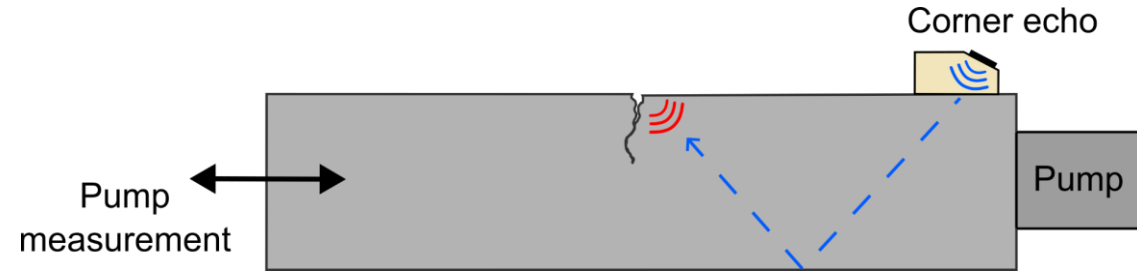
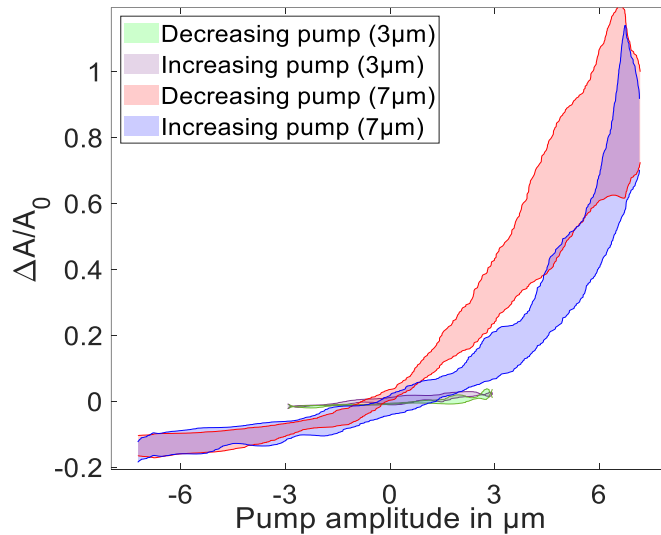
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Monitoring of the corner echo:

→ Relative variation $\frac{\Delta A}{A_0}$

Pump amplitude = displacement of the opposite lateral surface (laser vibrometer)



Large variations of the echo amplitude can be obtained

→ Significant crack opening

Very limited variation observed if low pump wave

→ Threshold phenomenon

→ Necessity of the clapping phenomenon

Limitations: “Large” amplitude pump wave necessary

On a real industrial NDT control : Resonance might not be easy to use

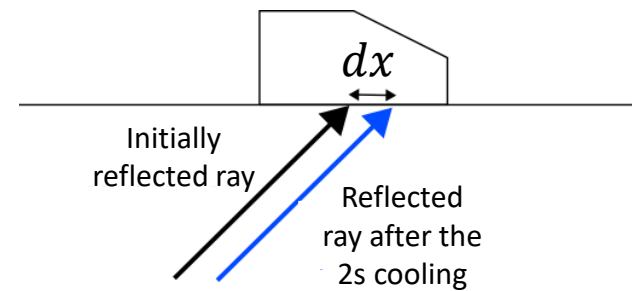
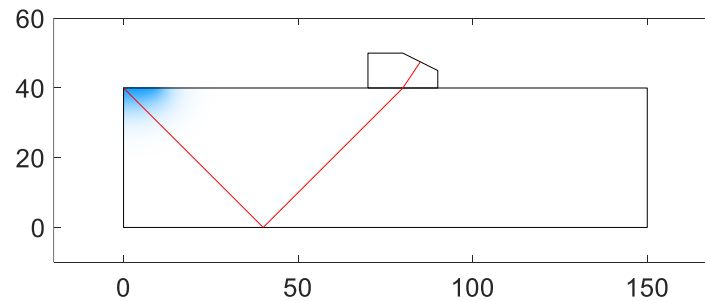
→ Pump amplitude = Limiting factor

Wave speed depends on T° : $v_T = \sqrt{\frac{E(T)}{2\rho(T)(1+\nu(T))}}$

With cooling : $\frac{\partial v(x,y)}{\partial x} \neq 0$ and $\frac{\partial v(x,y)}{\partial y} \neq 0$

→ Deviation of the ultrasonic beam

With a ray tracing algorithm in the simulated field temperature: $dx \approx 10^{-1}mm$



Order of magnitude confirmed experimentally (no deviation observed)

