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Surface acoustic wave suppression for ultrasonic imaging of near-surface defects using laser induced phased arrays

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Laser ultrasound (LU) offers a remote and non-contact mode of operation that makes it deployable for complex geometries, hostile environments, and places of restricted access. The disadvantage of LU is that it generates ultrasound with a low signal-to-noise ratio (SNR). To overcome the disadvantage of the low SNR, laser induced phased arrays (LIPAs) have been developed. Contrary to conventional transducer-based arrays, LIPAs use one laser for generation and a second laser for detection. A signal is captured for each combination of generation and detection laser position by scanning the generation and detection laser, following the paradigm of the Full Matrix Capture (FMC). In this work, LIPAs are synthesized in the non-destructive thermoelastic regime using a 7 ns pulsed 1064 nm laser and a 532 nm continuous wave laser to image side-drilled holes inside a metal sample. The acquired FMC data is post-processed using an imaging algorithm known as the Total Focusing Method (TFM). TFM is implemented by targeting one or more wave modes (i.e., longitudinal or transverse). However, the images generated contain a contribution from another wave mode called the surface acoustic wave (SAW). In LU, SAW is the strongest wave mode generated, and as a consequence, a region of the image generated is saturated by the SAW arrival (SAW crosstalk). The SAW crosstalk region extends into the sample starting at the scan surface and hence masks any features/defects within this region. It is crucial to detect defects closer to the scan surface for applications such as additive manufacturing and welding, where the manufacturing process is monitored to identify and then rectify the defects formed on the surface or near the surface. This study explores various signal processing techniques to suppress/remove the SAW wave mode from the ultrasonic data captured using LIPA for successful imaging of subsurface defects. The mode suppression is achieved by targeting the unique characteristics of the SAW, such as its velocity, amplitude, and phase. Different methods of wave suppression are compared, and relative merits are discussed.

Determining Elastic Properties of a Single Metallic Nanoparticle using Time-Resolved Ultrafast Spectroscopy

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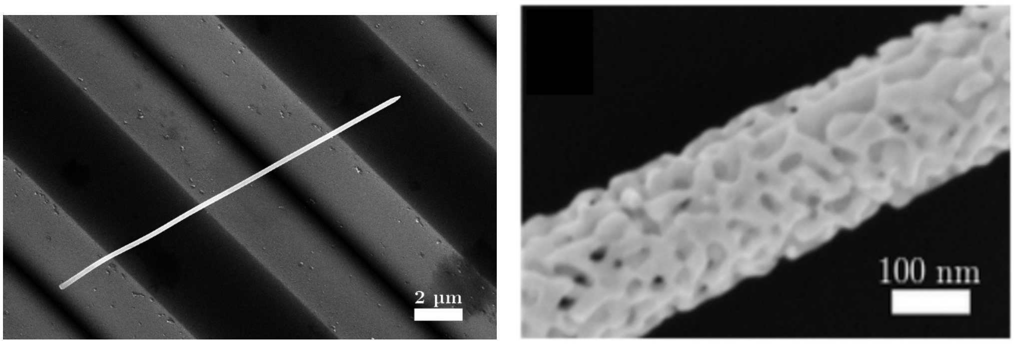
Metallic nanoparticles are the key elements for numerous applications. This is partially due to confinement which deeply modifies the properties of a nano-object compared to its bulk counterpart. In particular, thermal as well as elasticity properties and phenomena at the nanoscale can be deduced from their vibrational properties. That's the reason why they're extensively investigated. Picosecond ultrasonics have proven to be a very efficient way to investigate both ensemble and single metallic nanoparticle. It has been used to study the vibrational response of nanoparticles displaying a large diversity of shape, material and size.



Scanning Electron Microscopy images of a single Au nanowire standing over a pre-structured substrates and of a single porous gold nanowire

Among this diversity, one may distinguish nanowires. Taking advantage of their high aspect ratio and pre-structured substrate, such nanoparticle can be investigated experimentally as a free standing nano-object allowing to study its eigen modes freely from any environment coupling [1]. Thereby, the resonant frequency of its radial modes, especially its breathing modes, can be measured using time-resolved ultrafast spectroscopy. Those modes can also be expressed analytically via the PochHammer-Chree equation which displaying those frequencies dependence on both size and elastic properties (Young's modulus and Poisson's ratio) of the media. Knowing both the size of the nanowire and several breathing mode frequencies, an inverse method allow to obtain the properties for a single nanowire.

This technique has been employed to obtain the elastic properties of nanowires made of a single metal (e.g. Au or Ag). It has also been used for nanowires displaying complex heterostructures, AuAg alloy in that case [2]. Finally, it can be used to monitored properties in various environment (e.g. as a function of temperature).

[1] Belliard, L., et al. *Journal of Applied Physics* 114.19 (2013): 193509

[2] Delalande, R., et al. *Applied Physics Letters* 115.8 (2019): 083103

SRAS++ for single-crystal elasticity measurements in polycrystalline materials

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The elastic constants (C_{ijkl}) provide vital insights into the behaviour of a material, allowing calculation of various critical mechanical properties, along with the ultrasonic velocities often necessary for inverse problems, and facilitating simulation of microstructure evolution during materials processing. However, elasticity measurements are challenging to undertake, usually requiring a single crystal of known crystallographic orientation. The bulk wave velocities or the resonant frequencies of the material are then used to determine the elastic constants inversely. Unfortunately, most engineering metals appear as polycrystalline aggregates, preventing the measurement of their elastic constants by these methods.

Spatially resolved acoustic spectroscopy (SRAS) is an acoustic microscopy technique, that can image the microstructure and measure the crystallographic orientation of grains or crystals in the material. It works by measuring the velocity of surface acoustic waves (SAWs) via the acoustic spectrum. In the usual configuration, the SAWs are generated by laser using a pattern of lines and detected by laser at a point close to this grating-like source. The use of the acoustic spectrum to measure the velocity has a number of practical advantages, which makes the technique robust and fast and gives an excellent spatial resolution. This makes the measurement suitable for imaging and gives it many advantages over traditional laser UT and microstructural measurement techniques.

In this talk, we will demonstrate that by combining the measurement of the acoustic velocity spectrums from multiple grains, as measured by SRAS, it is possible to determine both the elastic constants of the sample and the crystallographic orientation of each grain. This provides a viable method to measure the elastic constants in 'real-world' polycrystalline samples. The talk will review the experimental instrument, inversion procedure (for calculating both crystallographic orientation elastic constants), and present recent experimental results. The talk will conclude by outlining the ongoing challenges and contemporary developments to address them, both experimental and numerical, in the pursuit of extremely high precision elasticity measurements in near real-time.

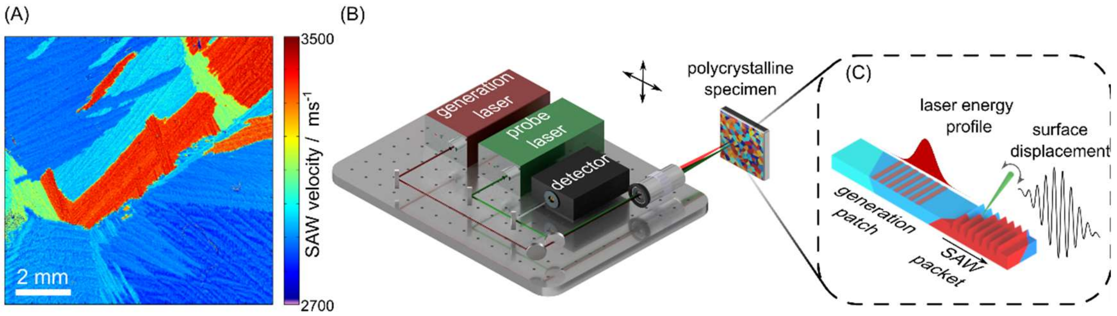

Figure 1: (A) SRAS SAW velocity map in polycrystalline titanium alloy. (B) basic SRAS system layout, and (C) working principle.

Laser ultrasonics in a multilayer structure: Semi-analytic model and different examples

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Laser-generated elastic waves have been the subject of numerous experimental, theoretical, and numerical studies to describe the opto-acoustic generation process, involving electromagnetic, thermal, and elastic fields and their couplings in matter. Among the numerical methods for solving this multiphysical problem, the semi-analytic approach is one of the most relevant for obtaining fast and accurate results, when analytical solutions exist.

First, we present a multilayer model to successively solve electromagnetic, thermal, and visco-elastodynamic problems. The optical penetration of the laser line source, as well as thermal conduction and convection, are accounted for. Complex thermal and mechanical coupling conditions are considered between the upper and lower media of the multilayer. [1]

Second, different illustrations of the model uses are proposed. On the first hand, it is used for the nondestructive evaluation of bonded assemblies thanks the analysis of elastic plane waves reflected from the bonding interface [2]. On the other hand, we use it to analyze picosecond ultrasonics experiments on single micrometric carbon fiber to infer their elastic properties. Finally, we present the interest of the model for generating significant database for machine learning investigations with laser ultrasonics.

[1] R. Hodé M. Ducousso, N. Cuvillier, V. Gusev, V. Tournat and S. Raetz, Laser ultrasonics in a multilayer structure: Semi-analytic model and simulated examples, J. Acoust. Soc. Am., vol. 150, p. 2065, 2021.

The developed PYTHON code is provided for free at https://doi.org/10.5281/zenodo.4301720.

[2] R. Hodé, S. Raetz, J. Blondeau, N. Cuvillier, V. Gusev, M. Ducousso and V. Tournat, Laser ultrasonics in a multilayer structure: Plane wave synthesis and inverse problem for nondestructive evaluation of adhesive bondings, J. Acoust. Soc. Am., vol. 150, p. 2076, 2021.

Ultrasonic bulk imaging of shock wave spatial distribution in opaque solids

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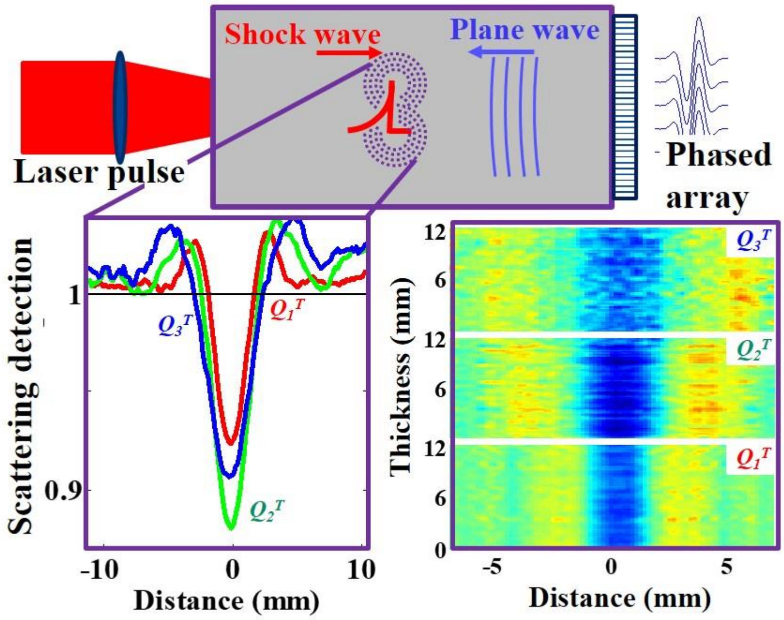
We present a method to image the bulk propagation of a laser-driven shock wave in a thick, opaque metallic plate by measuring the scattering of an elastic plane wave at one of its interfaces. The shock wave is generated by *ns* laser-loading and the elastic plane probe wave, contra-propagative with respect to the shock, is emitted by means of a phase-array device. The time-space detection of the probe wave allows building the movie of the shock propagation in the opaque structure. Applications range from fundamental wave science to laser-loading material science. [1]

[1] M. Ducousso, E. Cuenca, M. Marmonier, L. Videau, F. Coulouvrat and L. Berthe, *Bulk Probing of Shock Wave Spatial Distribution in Opaque Solids by Ultrasonic*, Phys. Rev. Applied, **15**, p. L051002 (2021).



Top : Principles of experiments ; Down-left : Space-resolved detection on the phase array of the scattering of the probe elastic plane wave on the shock ; Down-right : Shock propagation imaging in the bulk of a thick metallic plate.

THIN FILM CHARACTERIZATION BY PICOSECOND ULTRASONICS ON HIGH CURVATURE SURFACES

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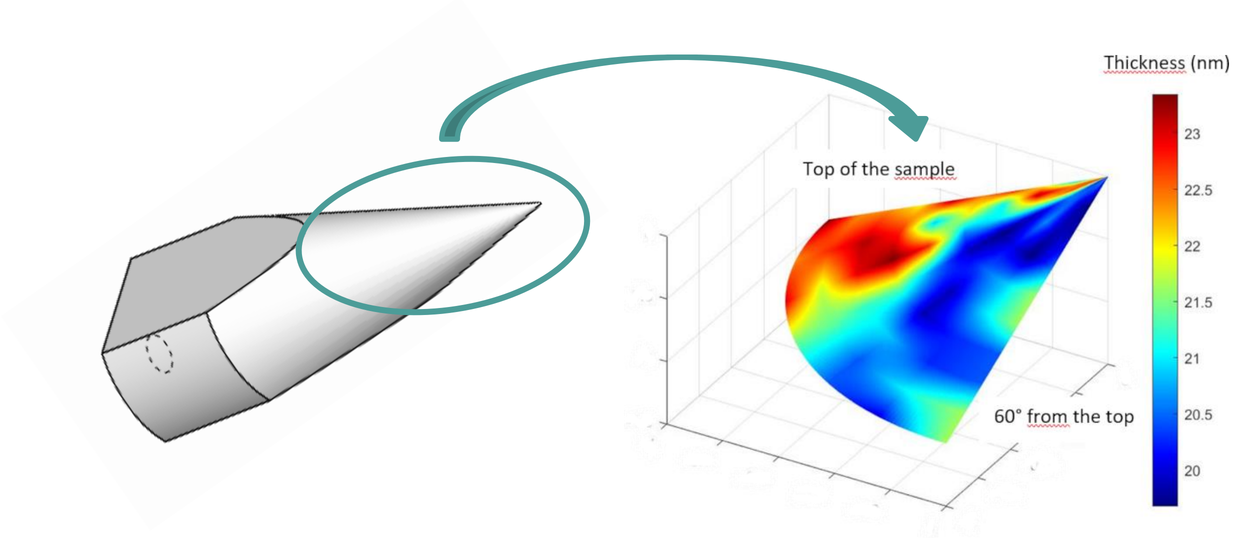
Compared to other techniques of thickness measurement such as ellipsometry or the Calo tester, picosecond ultrasonics presents the unique advantages to be contactless, nondestructive, and able to evaluate the properties of complex shape samples.

In this paper, results will be presented showing how accurately and fastly the thickness of a coating can be evaluated even in highly curved surfaces.

Moreover, this paper will also deal with the versatility offered by the picosecond ultrasonics technique. As soon as photo-generation and photo-detection are effective on the sample, many parameters can be studied. First, besides thickness measurement, picosecond ultrasonics also allows the elastic properties measurement of thin films, multilayers and nanostructures, and the evaluation of adhesion properties. Second, this technique proved to be efficient on a large diversity of materials of which some examples will be given. Third, it will be shown how our system is sufficiently flexible to ensure relevant results, even for traditionally tricky conditions such as high curvature surfaces.



Mapping of the thickness on the conical part of the sample

Keywords: picosecond ultrasonics, material characterization, non-destructive testing, highly curved surfaces

Grain-boundary Scattering of Surface Acoustic Waves: Experiment and Simulation

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Grain-boundary scattering is the major contribution to acoustic-wave attenuation in common polycrystalline materials at ultrasonic frequencies. A number of studies in the recent years showed that the two-point correlation function (TPCF) of the microstructure plays a vital role in the resulting frequency-dependent attenuation of bulk waves.[1] However, the topic of surface acoustic waves (SAWs) remained more or less untouched.

This contribution aims to fill this gap and shows a comprehensive study of the SAW behavior in polycrystals: First, the frequency-dispersion of the SAW attenuation in a polycrystalline aluminum sample was studied experimentally using a frequency-domain laser-ultrasonic setup.[2] Then, a statistical digital twin of the sample was created based on the TPCF similarity using a Laguerre tessellation. Such a digital twin was then used for a time-domain FEM simulation of SAW propagation.[3] The results of such a virtual experiment are in good agreement with the experiment itself in a broad range of frequencies in the stochastic regime of scattering, showing a large potential of the concept of virtual experiment with TPCF-based digital twin. The results also suggest that the power-law exponent of $\alpha \propto f^n$ in the stochastic regime is lower for SAW than it is for bulk waves.

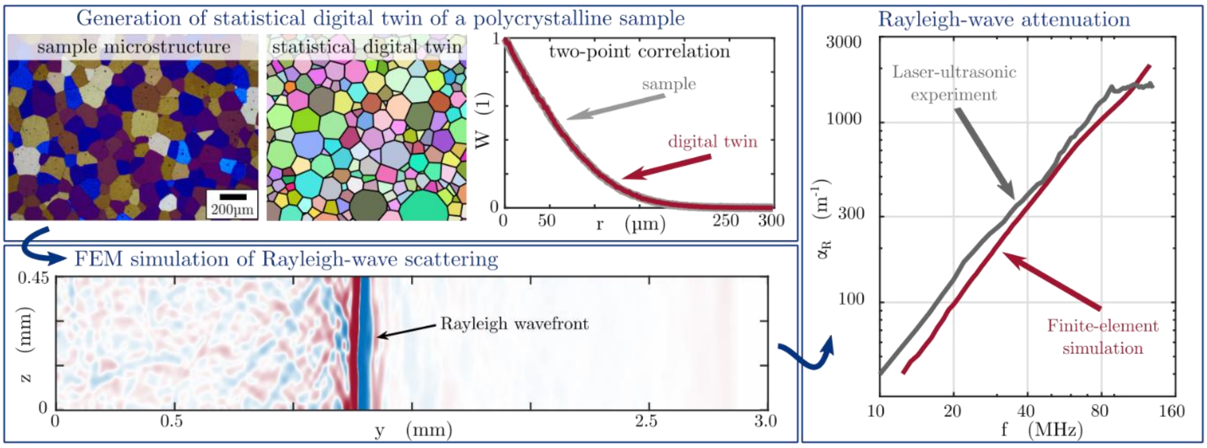

Figure: The relation of the sample and its statistical digital twin (top left), the out-of-plane displacement in the FEM simulation of SAW propagation through the digital twin (bottom left), comparison of resulting frequency-dependent attenuation in the simulation and experiment discussed in [1]. [3]

References

[1] M. Ryzy, T. Grabec, P. Sedlák, I.A. Veres, *Influence of grain morphology on ultrasonic wave attenuation in polycrystalline media with statistically equiaxed grains,* JASA 143 (2018), pp. 219-229

[2] M. Ryzy, T. Grabec, J. Oesterreicher, M. Hettich, I.A. Veres, *Measurement of coherent surface acoustic wave attenuation in polycrystalline aluminum*, AIP Advances 8 (2018), 125019

[3] T. Grabec, I.A. Veres, M. Ryzy, *Surface acoustic wave attenuation in polycrystals: Numerical modeling using a statistical digital twin of an actual sample,* Ultrasonics 119 (2022), 106585

High precision measurement of elastic anisotropy in metals

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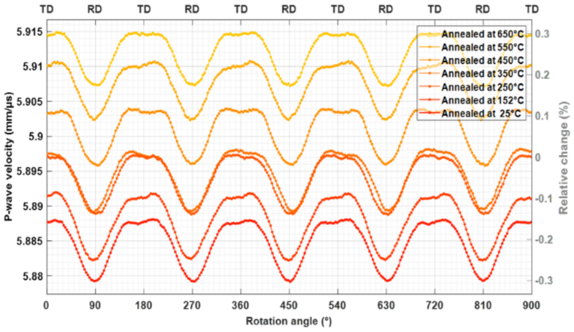
[1]*Swerim AB, Stockholm, Sweden.*

Anisotropy of elastic wave propagation in metals is controlled by texture together with crystalline anisotropy, so laser-ultrasonic measurements can provide valuable information about a material's underlying elastic phenomena. Evidently, anisotropy cannot be deduced from a single measurement and various approaches have been used to detect and quantify this which are reviewed briefly in the introduction. These include:

- Measurements of velocity by rotating the material with respect to the instrument. This is seldom feasible in an industrial environment but we demonstrate how high precision can be achieved this way in laboratory experiments.
- Changing the wave path using a masked axicon lens or by deflecting the generating laser using galvano-mirror optics. This latter approach is well suited to industrial application such as in steel processing. Examples of this method will be presented.
- Combining different wave types having the same direction of propagation such as S_0 and S_{H0} or S_0, S_{H0} and P waves.
- Using P-waves arrivals measured after different numbers of reflections through the thickness of the plate. Although the same fixed positions are used for generation and detection, the successive pulses pass along different directions in the material.

The largest uncertainty in LUS generally comes from the measurement of distance between the two laser points. By machining the material into a cylinder using a lathe, the diameter is extremely constant as the specimen is rotated. This has allowed velocities to be measured with a precision of better than 1 part in 10,000. Results on stainless steels show excellent agreement between measured wave velocities and values calculated from the texture. Another application to quenched and tempered martensite is shown below. Tempering between 20°C and 650°C causes reduction in hardness and leads to increases in stiffness and wave velocity but the anisotropy is almost unchanged.



The Galvano mirror technique is demonstrated in application to hot rolled steels where many path directions in the material can be rapidly scanned.

Finally, we discuss some limitations of texture measurements from ultrasonic measurements.

Laser utrasonics for quality control of resistance spot welding

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In the automotive industry spot welds are used for joining structural components and parts of the vehicle chassis together, and a car typically contains thousands of spot welds. Today the quality of the spot welds is mainly controlled by manual destructive testing (microscopy) and conventional ultrasonic transducers with coupling. This results in a high uncertainty due to operator dependency and the limitation of only testing a small fraction of all the spot welds. By using laser ultrasonics (LUS) for quality control of spot welds it is believed that the quality of all spot welds can be controlled in an automated and non-destructive way.

We will present a comparative study where the spotweld diameter on a total of over 220 spot welds is determined and compared by using three different methods, (1) LUS, (2) destructive testing and (3) the commercially available Tessonic resistance spot weld analyzer (RSWA).

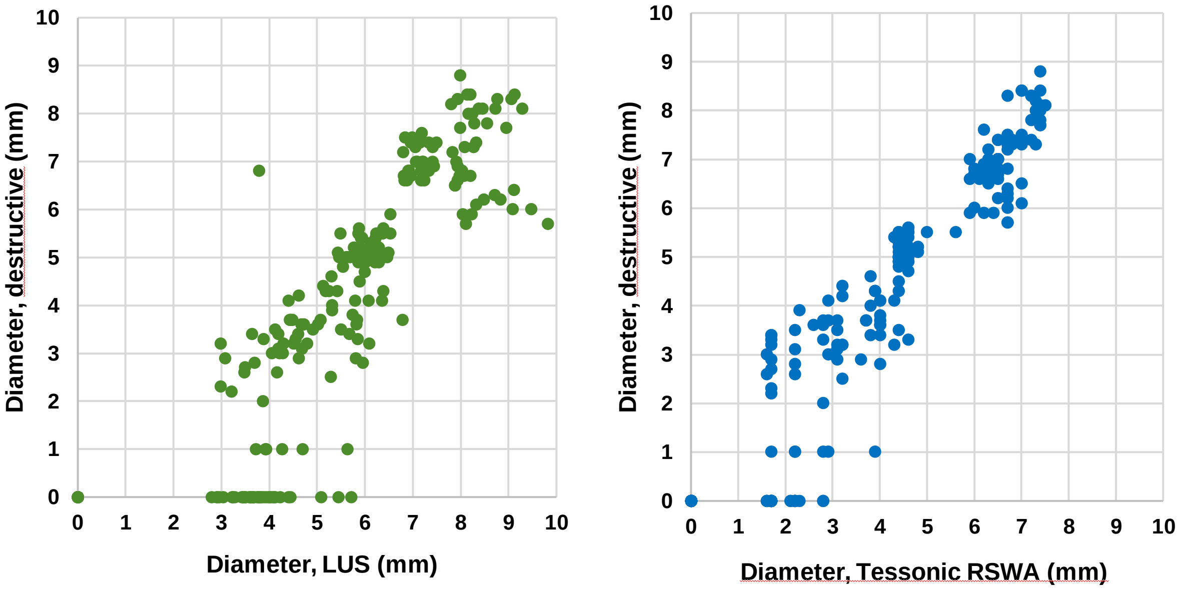

Figure 1 Graph showing the spot weld diameter determined by LUS (left) and Tessonic RSWA (right) plotted against the diameter measured by destructive testing.

Pearlite Monitoring in Steel Sheets by Laser UltraSonic Technique

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Short Summary: A new laser-ultrasonic technique based on the cementite (Fe3C) magnetic transition was developed to monitor the presence of pearlite in steel sheets. In contrast to off-line and destructive metallography techniques, this non-destructive technique determines in real time during cooling in which proportion austenite was decomposed in pearlite. The technique is therefore complementary to other non-destructive techniques such as the laser ultrasonic velocity technique or the magnetic techniques that monitor austenite decomposition during cooling of steel plates but that do not give any information on the new phases formation.

PEARLITE MONITORING PRINCIPLE

UltraSonic (US) velocity measurements conducted during cooling on pure Cementite (Fe3C) show a clear and strong velocity drop around 200 Celcius (fig. 1). This velocity change is attributed to the magnetic transition of Cementite when crossing its 200 C Curie temperature T_c: above 200 C, Cementite is no longer magnetic while below 200 C it is ferro-magnetic. Moreover, measurements show also that the Cementite Curie temperature and velocity change both decrease with Mn alloying elements. As pure pearlite is composed by 89% of ferrite and 11% of Cementite, this magnetic transition of Cementite may be detected and monitored during cooling in steel sheets containing even a small amount of pearlite.

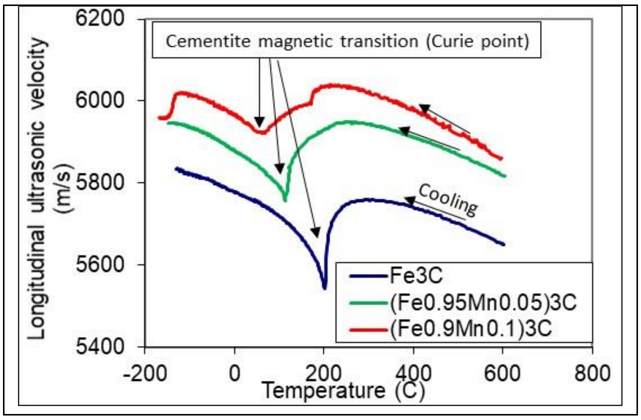


Fig.1: Measurement of ultrasonic velocity in pure Cementite (Fe3C) with different Manganese addition as a function of temperature during cooling.

To monitor pearlite fraction in the steel sheet material, a law of mixture combining pure ferrite and pure pearlite ultrasonic velocities is used:

$$V = V_{ferrite}.(1 - X_{pearlite}) + V_{pearlite}.X_{pearlite} \qquad \text{equation (1)}$$

V: US velocity measured on material (mixture of pearlite and ferrite).

$V_{ferrite}$ $V_{pearlite}$: US velocity measured respectively on pure ferrite and pure pearlite

$X_{pearlite}$: pearlite fraction.

The pearlite fraction is obtained by reversing the above equation.

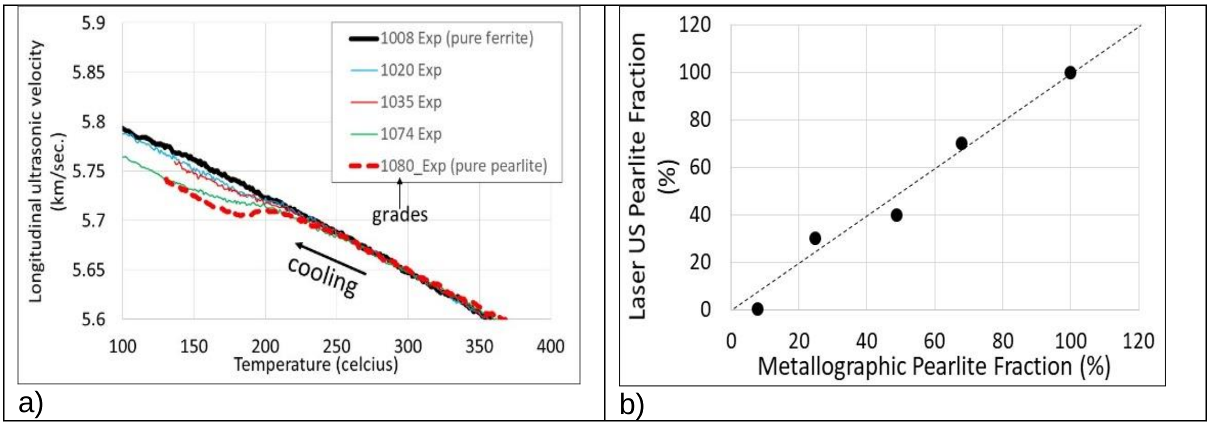
PEARLITE MONITORING VALIDATION

To validate the above technique, ultrasonic velocity was measured during dilatometric tests at a 1 celcius/sec. cooling rate on steel grades with different Carbon contents. The chemistry of the different grades shown on table 1 produces different amounts of pearlite in the final material after cooling: from pure pearlite (100% pearlite – grade 1080) to almost pure ferrite (~0% of pearlite – grade 1008).

Table 1: Steel grades for technique validation/calibration

	C	Mn	Si	Cr	Mo	Al	% pearlite measured by metallography
1008	0.1	0.4	0	0	0	0	8%
1020	0.2	0.45	0	0	0	0	25%
1035	0.35	0.75	0	0	0	0	49%
1074	0.75	0.65	0	0	0	0	68%
1080	0.787	0.693	0.197	0.027	0.002	0.031	100%

For each grade, a clear deviation of velocity is observed during cooling when crossing the 200 C Cementite Curie temperature (fig.2-a): the higher the amount of pearlite is, the stronger the deviation is. For grades 1020, 1035 and 1074, pearlite fraction is determined by adjusting its value so that calculated and measured velocities match; grades 1008 and 1080 are used as reference for pure ferrite and pure pearlite respectively. With these adjustments, pearlite fraction obtained by the present laser ultrasonic technique is in good agreement with pearlite fraction from metallography (fig. 2-b), validating the technique. Figure 3 shows the velocity fittings for grades 1020 and 1074.



a) b)

Fig.2: a) Measurement of laser ultrasonic velocity in different steel grades containing various amounts of pearlite. b) Pearlite fraction deduced from laser ultrasonic measurements (present method) versus pearlite fraction obtained by metallography.

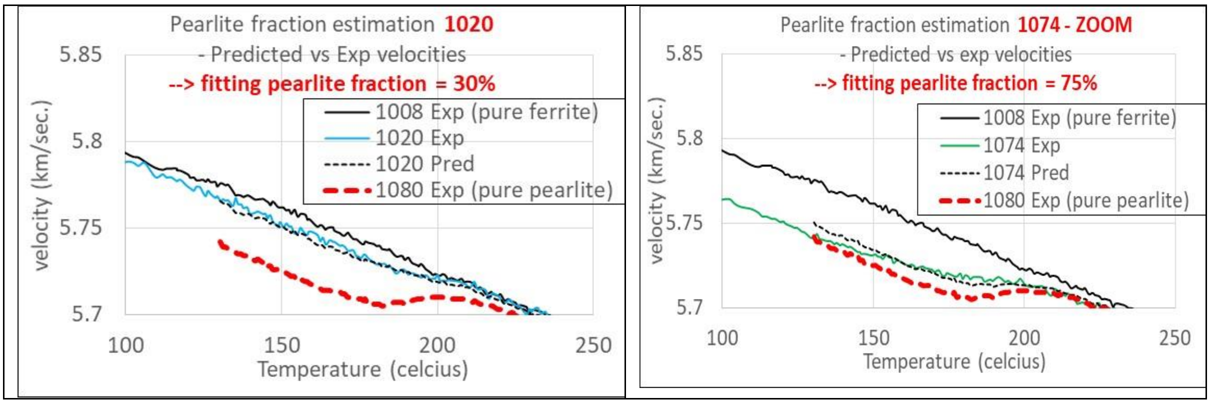


Fig.3: Measured versus predicted velocity (eq.1) for grades 1020 and 1074 using reference pure ferrite (1008) and pure pearlite (1080) velocities (grade 1035 prediction not shown)

Phase Transformation Monitoring by Dilatometry and by Laser-Ultrasonic Velocity techniques on grades DP780 and QP

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Short Summary: Phase transformation during cooling is evaluated on two industrial steel grades, a DP780 and a QP, using two different techniques: the laser-ultrasonic velocity technique and the dilatometry technique. Results analysis for the DP780 grade show that the lever rule method used with the dilatometry technique needs to be corrected to consider two metallurgical phenomena to agree with laser-ultrasonic velocity results: the austenite enrichment in Carbon during austenite to ferrite transformation and the difference of volume between ferrite and pearlite. Results analysis for the QP grade show that the laser-ultrasonic velocity technique, in contrast to the lever rule method for dilatometry, detects some austenite transformation in ferrite at high temperature, prior to martensite transformation, which is confirmed by metallographic observations. Then the massive martensite transformation of QP at lower temperatures is detected correctly by both techniques, with no need of correction for the lever rule method for dilatometry. This is because martensite transformation does not involve any Carbon enrichment in austenite during transformation.

EXPERIMENTAL PROCEDURE

Steel grades:

Phase transformation during cooling has been monitored on two different steel grades using dilatometry and laser-ultrasonic velocity techniques. Chemical compositions are in Table 1.

Table 1: Steel grades chemical composition in major elements (weight %)

Grade	C	Mn	Si	Cr	Al	Mo	B
DP780 grade	0.136	2.09	0.208	0	0.027	0	0
QP grade	0.37	1.95	1 .95	0.35	0	0.12	0

DP780 produces mainly ferrite, pearlite and martensite phases, while the QP grade is expected to produce mainly martensite. As a result, the two techniques of transformation monitoring can be evaluated against this wide range of transformations with these two grades.

Dilatometric tests:

A Bahr dilatometer DIL805L was used for dilatometric tests with four different cooling rates: 0.1, 1, 5 and 10ºC./sec. after an austenitization of 950ºC during 300 sec. After the trials, microstructures of samples were analyzed by metallography. To evaluate the transformation kinetics with the dilatometry technique, the classic lever rule method is used**:** on the dilatometric curve, the experimental slopes for the austenite and austenite transformed phases are used for the lever rule formula.

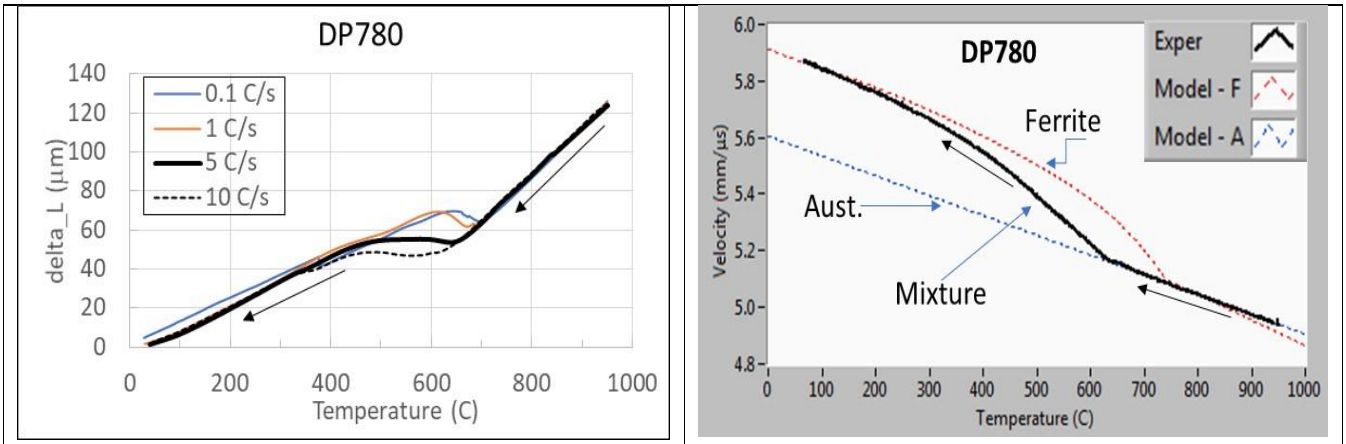
Laser-ultrasonic velocity tests:

Ultrasonic velocity measurements were performed during cooling tests conducted on a Gleeble-3500 machine on samples of same grade as dilatometric tests. The ultrasonic velocity method detailed in **[1]** was used to deduce the transformed austenite.

EXPERIMENTAL RESULTS and DISCUSSION

Grade DP780:

Figure 1 shows the measured sample length variations (dilatometry) and the measured ultrasonic velocity for DP780 grade: a large amount of ferrite, pearlite and possibly martensite is formed at all cooling rates.



a) dilatometric test results

b) ultra-sonic test results (5ºC./sec.)

Fig.1: DP780 grade during cooling

Using these measurements, the austenite phase fraction evolution has been estimated during cooling respectively by the lever rule method and by the ultrasonic velocity method **[1]**. Results on Figure 2 show a discrepancy between phase transformation kinetics obtained by dilatometry and by laser-ultrasonic velocity methods for the 4 cooling rates: the dilatometry tends to <u>over-estimates</u> the transformation kinetics compared to the laser-ultrasonics.

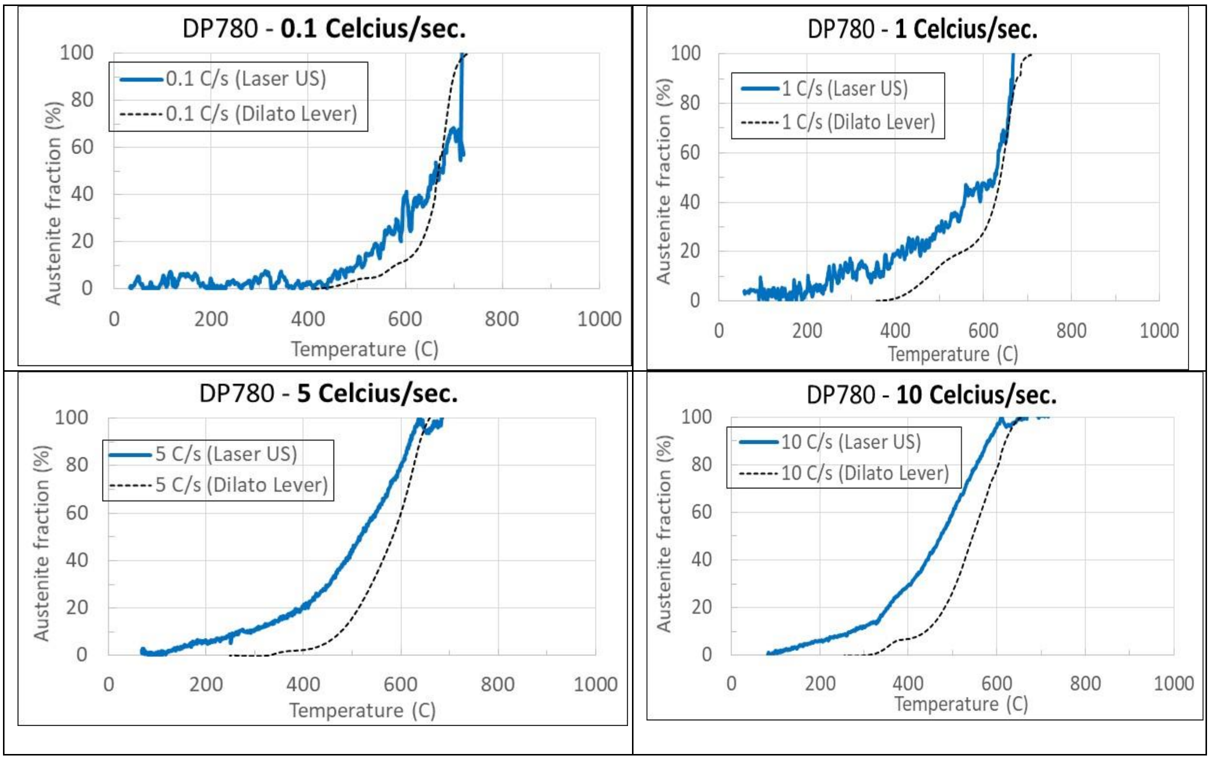


Fig.2: Transformation kinetics of DP780 obtained by classic dilatometry analysis **(lever rule method)** and by laser ultra-sonic analysis for different cooling rates

These discrepancies are believed to be due to the lever rule method used for dilatometry that does not consider Carbon enrichment in austenite during ferrite formation and that does not consider the significant difference of volume between ferrite and pearlite. Therefore, these two mechanisms have been introduced in the lever rule analysis using the following equations **[2]** to correct the dilatometric curves (lever rule corrected).

Lattice parameters equations for ferrite, austenite and pearlite used to correct lever rule **[2]**

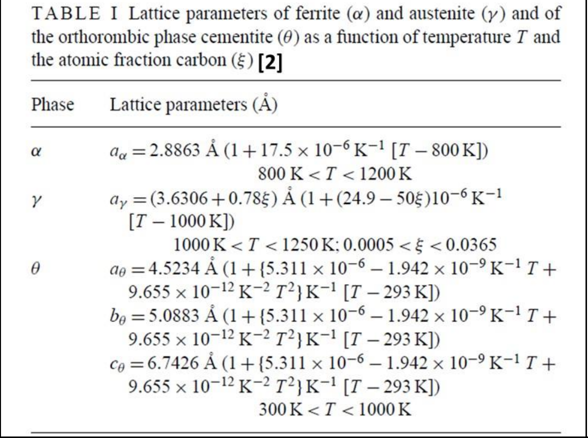


TABLE I Lattice parameters of ferrite (α) and austenite (γ) and of the orthorombic phase cementite (θ) as a function of temperature T and the atomic fraction carbon (ξ) **[2]**

Phase	Lattice parameters (Å)
α	$a_\alpha = 2.8863\ \text{Å}\ (1 + 17.5 \times 10^{-6}\ \text{K}^{-1}\ [T - 800\ \text{K}])$ $800\ \text{K} < T < 1200\ \text{K}$
γ	$a_\gamma = (3.6306 + 0.78\xi)\ \text{Å}\ (1 + (24.9 - 50\xi)10^{-6}\ \text{K}^{-1}\ [T - 1000\ \text{K}])$ $1000\ \text{K} < T < 1250\ \text{K};\ 0.0005 < \xi < 0.0365$
θ	$a_\theta = 4.5234\ \text{Å}\ (1 + \{5.311 \times 10^{-6} - 1.942 \times 10^{-9}\ \text{K}^{-1}\ T + 9.655 \times 10^{-12}\ \text{K}^{-2}\ T^2\}\text{K}^{-1}\ [T - 293\ \text{K}])$ $b_\theta = 5.0883\ \text{Å}\ (1 + \{5.311 \times 10^{-6} - 1.942 \times 10^{-9}\ \text{K}^{-1}\ T + 9.655 \times 10^{-12}\ \text{K}^{-2}\ T^2\}\text{K}^{-1}\ [T - 293\ \text{K}])$ $c_\theta = 6.7426\ \text{Å}\ (1 + \{5.311 \times 10^{-6} - 1.942 \times 10^{-9}\ \text{K}^{-1}\ T + 9.655 \times 10^{-12}\ \text{K}^{-2}\ T^2\}\text{K}^{-1}\ [T - 293\ \text{K}])$ $300\ \text{K} < T < 1000\ \text{K}$

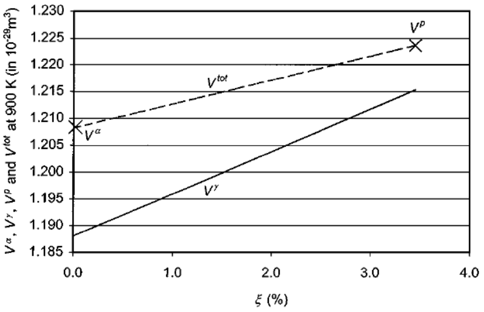


Figure 1 The atomic volumes of austenite, V^γ, and of a system composed of equilibrium fractions ferrite and pearlite, V^{tot}, depending on the carbon concentration at a temperature of 900 K. The atomic volumes of ferrite, V^α, and pearlite, V^{p}, are depicted as well.

Results on Figure 3 show that after correction, dilatometry and laser ultrasound are in very good agreement, except for the cooling rate 0.1 °C./sec. The reason for this remains unknown.

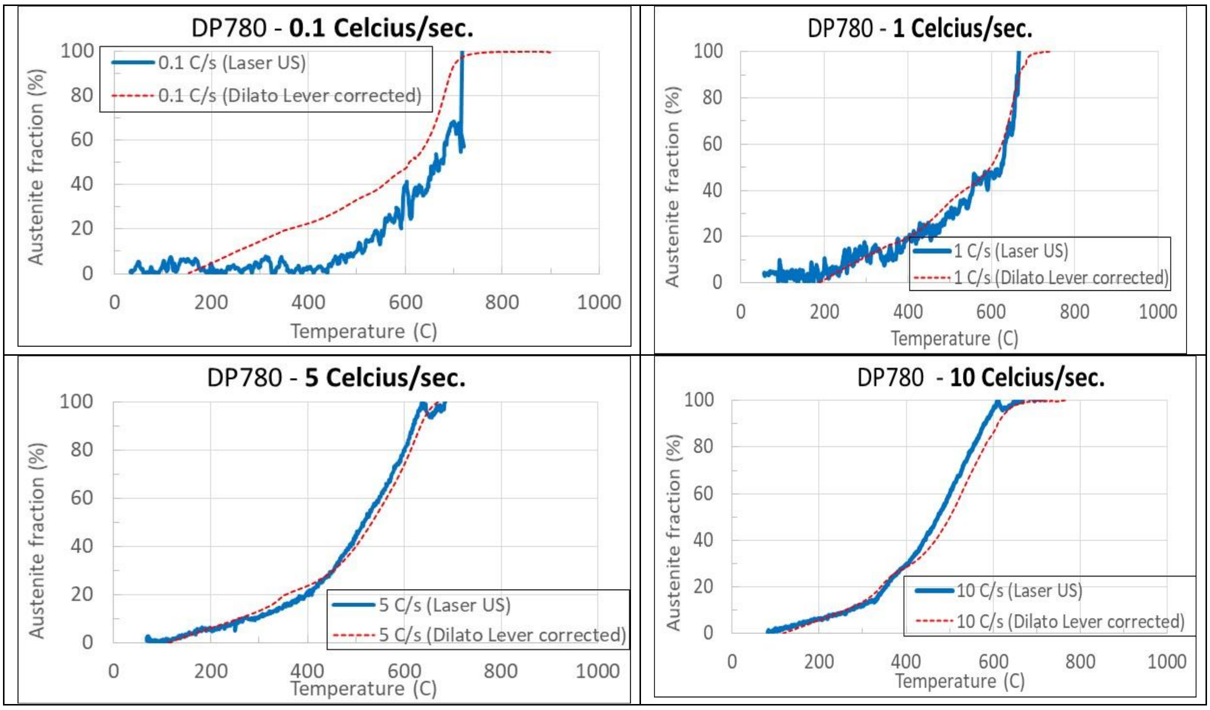


Fig.3: Transformation kinetics of DP780 obtained by modified dilatometry analysis **(lever rule method corrected [2]**) and by laser-ultrasonic analysis for different cooling rates

Grade QP:

Figure 4 shows the measured sample length variation (dilatometry) for the QP grade: at low cooling rate (0.1°C./sec.), a large amount of ferrite (upper temperatures) and of bainite (lower temperatures) is formed. At higher cooling rates (1 and 5°C./sec.), only martensite seems to form at ~300°C.

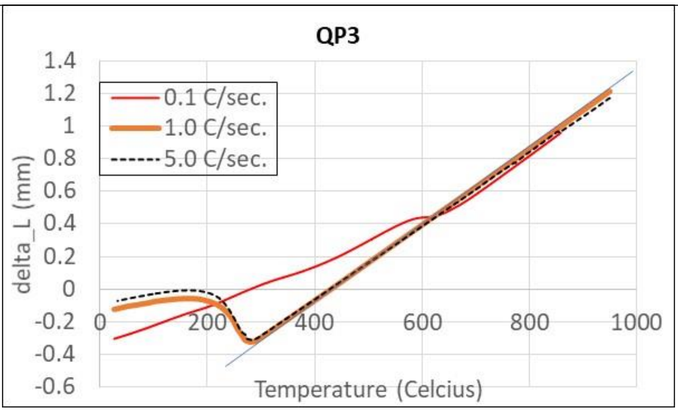


Fig.4: Dilatometric tests on QP grade during cooling at different cooling rates.

As for DP780 grade, the same comparison of transformation kinetics obtained by dilatometry and by laser-ultrasonic techniques has been made for the QP grade, as shown on Figure 5.

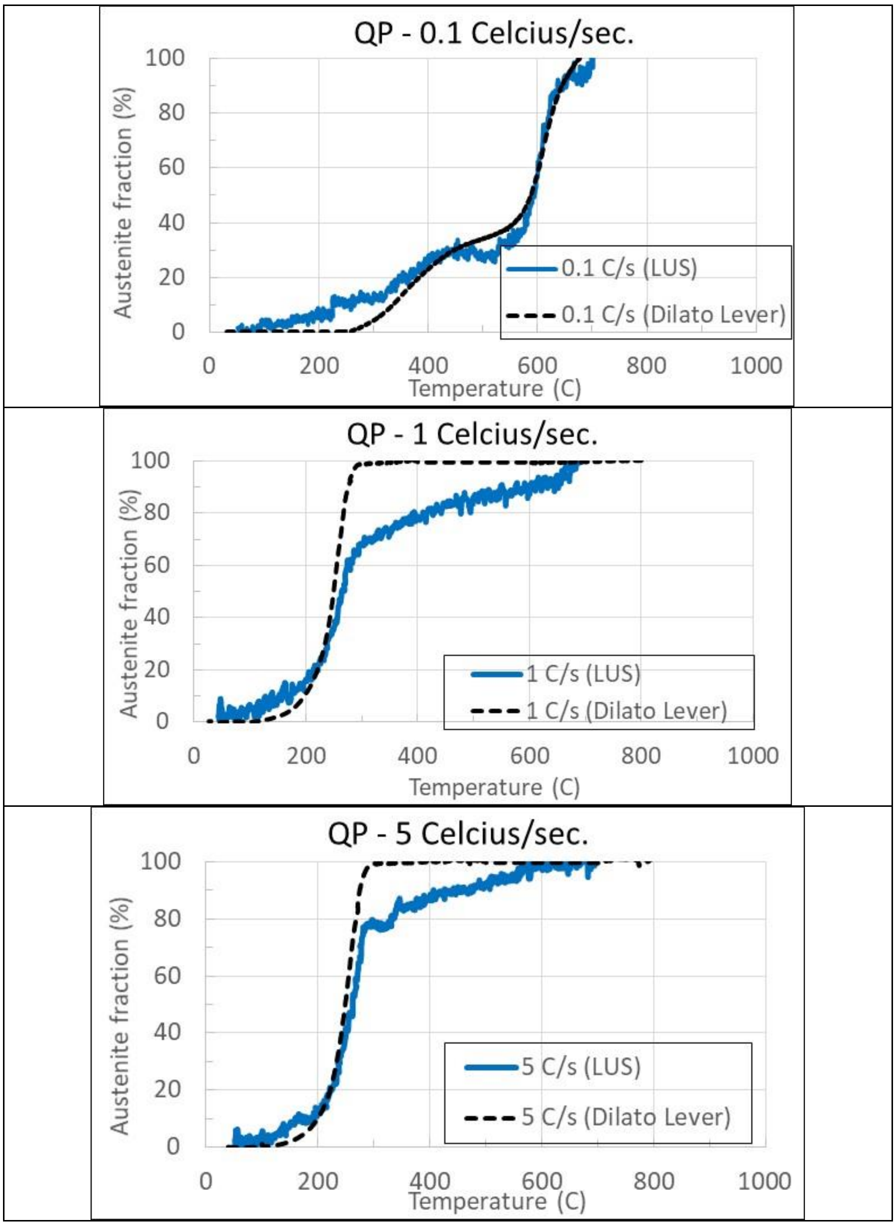
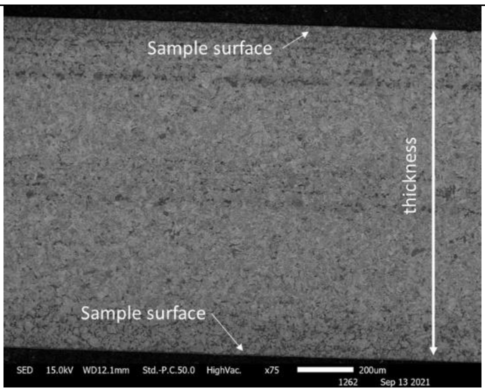


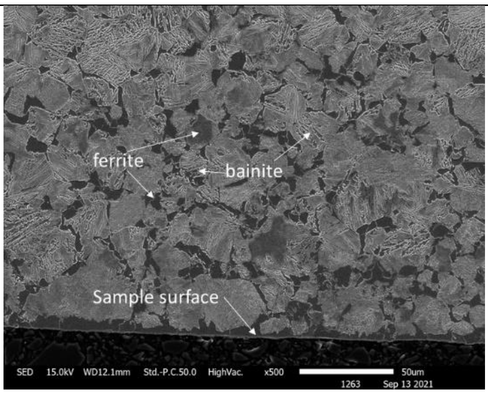
Fig.5: Transformation kinetics of QP grade obtained by classic dilatometry analysis **(lever rule)** and by laser ultra-sonic methods for different cooling rates

Here the massive transformation of martensite at ~300°C. for cooling rates 1 and 5°C./sec. is correctly monitored by the two techniques: the lever rule method seems to work relatively well here without any correction. This is because during austenite to martensite transformation, in contrast to DP780 (Figure 2), there is no Carbon enrichment in austenite so no need for correction. However, for 0.1°C./sec., a correction of carbon enrichment should be needed because of the important amount of ferrite formed at ~ 600°C. The reason for this remains unclear.

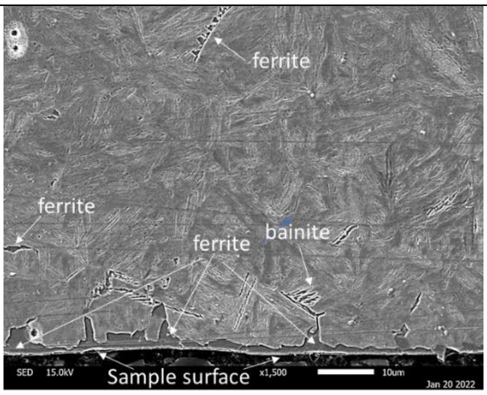
Also, Figure 5 shows an important difference between laser-ultrasonic and dilatometry analysis for high cooling rates (1 and 5°C./sec.): the lever rule method indicates no other phase formation except martensite, while the ultrasonic velocity technique clearly indicates a certain amount of austenite has been transformed (probably to ferrite), prior to martensite transformation.



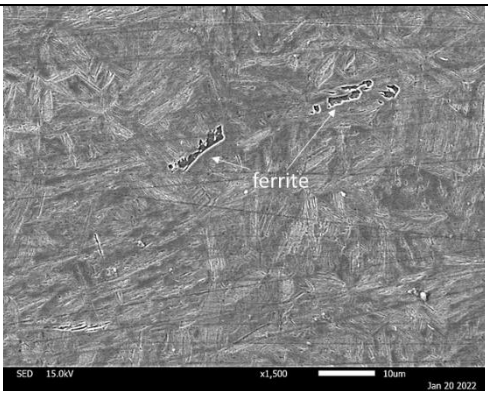
0.1°C./sec. - **full thickness**



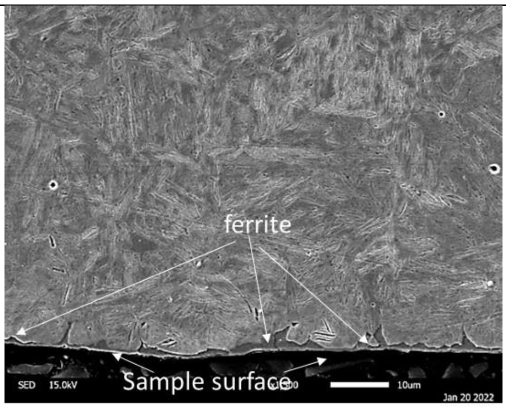
0.1°C./sec. – **zoom near surface**



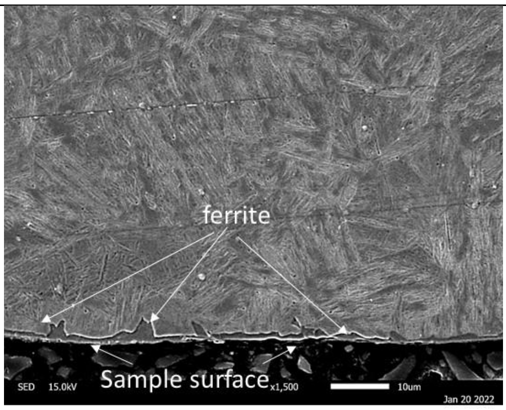
1°C./sec. – **near surface**



1°C./sec. – **in bulk material**



5°C./sec. **- near surface**



5°C./sec. **- near surface**

Fig.6: Microstructure obtained by metallography on QP grade after 3 different cooling rates (0.1, 1, 5°C./sec.)

To verify this, metallography was conducted on the dilatometric samples: metallographic analysis is shown in figure 6.
At 0.1°C./sec. (figure 6 top): a large amount of ferrite, bainite is observed, which confirms the indication of dilatometric curves of no martensite formation (Figure 4).
At 1°C./sec. (Figure 6 middle): the presence of some islands of ferrite and bainite microstructures among a large amount of martensite microstructure is observed. These ferrite islands are also clearly seen near sample surfaces: this is probably due to a decarbonization of layer that promotes ferrite formation near the surfaces during cooling.
At 5°C./sec. (Figure 6 bottom): ferrite seems present only near sample surfaces (decarbonization layer), while the bulk material seems exclusively martensite.

These results perfectly confirm the results of laser ultrasonic technique (Figure 5) that indicate a certain amount of ferrite and possibly bainite formation prior to martensite formation. Note that the laser-ultrasonic technique indicates that this amount of ferrite (prior to martensite) is higher at 1°C./sec. than at 5°C./sec. This is confirmed by metallography (Figure 6) which indicates a larger amount of ferrite/bainite islands in the bulk material at 1 °C./sec. while at 5°C./sec. ferrite/bainite islands are only at surfaces.

Therefore, the ferrite formation in the QP grade clearly detected by the laser-ultrasonic technique shows the superiority of this technique in the present conditions over dilatometry. The reason why dilatometry does not detect ferrite transformation at 1 and 5°C./sec. for the QP grade is due to the remarkable linear behavior of the curve down to 300 °C. (Figure 4) that is attributed to pure austenite before the martensite transformation around 300°C.

CONCLUSION

Two different techniques have been evaluated and compared to monitor phase transformation on two different steel grades: the laser ultrasonic and the dilatometric techniques. The analysis reveals that the classic lever rule method used for dilatometry needs to be corrected to consider the enrichment in Carbon during phase transformation in DP780 from austenite to ferrite and to consider the difference of volume between ferrite and pearlite. The analysis of QP grade reveals that the laser ultrasonic technique, in contrast to dilatometry, detects the formation of ferrite at high temperature prior to martensite formation, which is in agreement with metallography. The massive phase transformation in martensite at lower temperatures is detected similarly by both techniques without any need of correction of dilatometry for this QP grade. This is because of the absence of Carbon enrichment in austenite during the transformation in martensite. It is concluded that the correction of lever rule method proposed by **[2]** for austenite to ferrite-pearlite seems useful for usual cooling rates (1 to 10 °C./sec.). Also the method proposed by **[2]** based on volume difference between the phases could certainly be applied to the lever rule method of dilatometry to detect ferrite formation on QP grade (Figure 4). However, for very low cooling rates (0.1°C./sec.), the need of this correction could not be evidenced by our experiments and further investigations are needed to understand why.

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Modeling method for the simulation of austenitic weld ultrasonic inspection - realistic prediction of echoes and structural noise in weld inspection

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In-service Non-Destructive examination of welds encountered in the primary circuit of nuclear power plants is a major issue for the safety of the installation. When inspected with ultrasound, the welds exhibit highly anisotropic and complex microstructures which induce beam perturbations and structural noise. The numerical modeling is then a preferred tool for the prediction of the performance of ultrasonic nondestructive examination of the weld and for the analysis of complex data obtained from weld inspection.

The simulation approach developed by EDF R&D is based on the modeling of the microstructure of a weld in association with a finite element solving of the ultrasonic propagation. Firstly, a virtual synthetic model of anisotropic and textured structure with homogeneous columnar grain orientation has been used to quantify the ultrasonic attenuation as a function of the grain to ultrasonic beam angle. The quantification of the attenuation is compared with experimental data and reveals a very good agreement.

Secondly, a similar method has been applied to compute the ultrasonic propagation into a synthetic realistic (2D) weld microstructure. The grain size, grain orientation map and crystallographic texture are obtained from Electron BackScatter Diffraction (EBSD) measurements. Voronoi tessellation is used to create an artificial weld microstructure. This approach enables to reproduce the main phenomena which degrade the inspection of welds - attenuation, beam perturbation and structural noise – and allows to obtain an accurate description of ultrasonic echoes.

Finally, in the frame of the NEMESIS project, in collaboration with CEMEF, the approach has been extended with the use of a weld microstructure obtained from a Cellular Automaton – Finite Element (CAFE) simulation predicting the solidification structure. A virtual microstructure corresponding to a Gas Tungsten Arc Welding multi-pass process has been injected as the propagation media of the 3D Finite Element solver of the ultrasonic propagation: A3D. Qualitative results are presented, and the perspectives opened by this proof of concept will be discussed.

Laser Ultrasonic Tomography using Deep Neural Networks

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Estimation of material characteristics through acoustic velocity mapping and reconstruction of the grain structure is necessary to provide detailed information about the quality of metal components. Ultrasonic tomography methods perform this characterization by measuring acoustic travel times through the test object, using numerous paths at varying angles. Consequently, this information is processed using an algorithm solving for the inverse problem. Performing these algorithms is hardware and time demanding, hence limiting real-time use of the technique.[1] This limitation compromises the use of tomography for applications where rapid evaluation is required, such as in-process inspection of manufacturing or welding.

A novel, real time tomography technique has been proposed based on Deep Neural Networks which can achieve high resolution velocity maps of anisotropic materials using computational resources of an ordinary desktop computer, using pre-trained networks.[2] In this paper, we demonstrate this technique for the first time, on experimentally acquired signals, for metallurgy. The technique is demonstrated using laser ultrasonics. In this way, the generation and detection of ultrasound were performed using lasers, leading to a completely non-contact tomography system. By applying this technique for laser ultrasonics, the tomography capabilities are expanded for use in extreme environments, on complex shapes and in places of limited access, without the requirement of any couplant.

The sample used in this study consisted of multiple, bonded metals with varying acoustic properties and velocities. Using this technique, we were able to produce velocity maps of the sample, showing the change in velocity and location of different materials within the sample.

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Assessment of Grain Size on Moving Steel Strips during Hot Rolling with Laser Ultrasonics

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Laser ultrasonics (LUS) has demonstrated, through numerous in-situ laboratory experiments, its ability to monitor microstructural features and metallurgical transformations which occur in steel strips during thermal cycles with temperatures reaching 1250°C. Within an original work supported by the European Commission, a consortium including ArcelorMittal, Imagine Optic and IMI-NRC integrated several LUS components (Generation and Detection Lasers, Two-Wave Mixing Interferometer, Dedicated Fibered Optical Head) in a transportable trolley in order to run investigations on moving strips during normal production in a hot rolling mill, at three different locations :

- the exits of stands 1 and 5 in order to evaluate the austenite grain size on steel products at temperatures between 850°C and 1050°C,
- the run-out table to estimate the ferrite grain size and austenite phase fraction on strips at temperatures.

Trials were carried out on classic low carbon grades, allowing to record signals which, with the development of a specific data processing tool, allowed calculating the grain size. Such results were then compared to predictions from metallurgical models, finding reasonably close values.

This work received financial support from the European Commission under Grant Agreement number RFSR-CT-2015-00007 “MicroControl-PLUS”.

Recrystallization kinetics of Fe-30Ni alloy with 0.008-0.083% Nb

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Niobium is added to many steel grades as a 'microalloying element' in small quantities of around 0.05% for significantly improving their user properties of strength and toughness by refinement of the final grain structure. This is notably the case in high strength low alloy (HSLA) steels which are processed by low temperature controlled rolling. The intention is to produce a deformed grain structure in the austenite with a high density of grain boundaries where ferrite grain nucleation can take place during quenching. Niobium plays a vital role since it retards recrystallization of the austenite and raises the recrystallization temperature. Despite many investigations into this phenomenon, it is far from clear how this mechanism operates and how to optimize it.

The GLUS® testbed at Swerim which is the combination of the thermo-mechanical simulator GLEEBLE and laser ultrasonics (LUS) provides a unique possibility to explore and validate alloying concepts to increase the understanding of how material properties evolve during the process. Especially the GLUS® technique is useful for the materials where the prior austenite grain is impossible to reconstruct. We will present results of model alloys similar to that of Ji et al [1] with various amount of Nb that has been evaluated in order to increase the understanding of the influence of Nb on the recrystallization behavior. The model alloys were soaked for 3 min at 1100 °C after which they were deformed at 850, 900, or 950 °C with two hits with an engineering strain of 20 % each. Below in Fig. 1 the measured longitudinal wave velocity of one of the model alloys shown as a function of temperature, which displays a parabolic shape due to the particular thermo-elastic behavior of Ni. The measured grain size as a function of time post compression is also shown in Fig. 1 for the two hits of the 0.083 % Nb at 950 °C which displays 50% the recrystallization at around 4 seconds post compression.

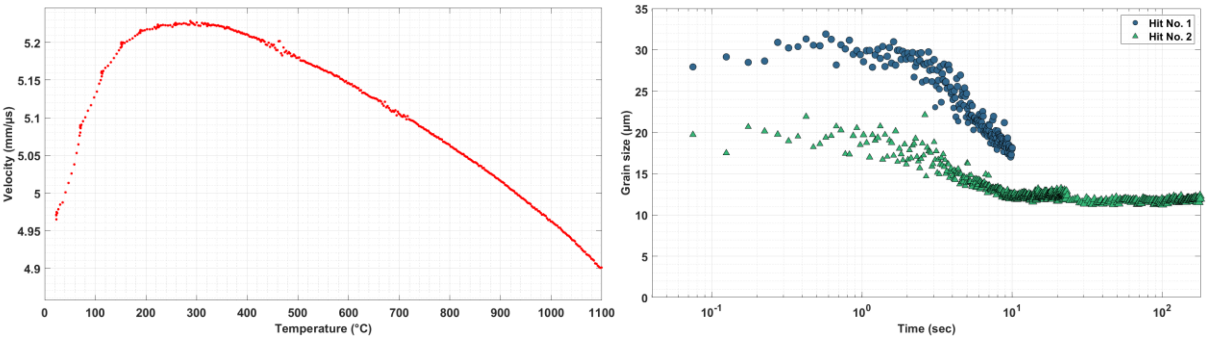

Fig. 1 (left) P-wave velocity versus temperature during heating for the Ni 30 % model alloy with Nb 330 ppm. (right) The measured grain size vs time post compression of 20 % + 20 % (engineering strain), with a speed of 10 ps and an inter-pass-time of 10 seconds between the two hits.

This work was partially financed by the strategic innovation program for Metallic material, by Vinnova, the Swedish Energy Agency, and Formas as well as the European Union's Research Fund for Coal and Steel (RFCS) research program under grant agreement nr. RFCS-2018-847296.

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On-line grain size gauge for the hot strip mill based on laser ultrasonics

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The properties of high strength steels depend to a large extent on the austenite grain size prior to quenching. It is, therefore, very desirable to be able to characterize the austenite microstructure during the hot rolling process. However, the temperatures of the material of interest in the hot strip mill (HSM) range between 800-1200 °C, and move at 1-10 m/s, therefore the only method capable of measuring the microstructure in the bulk with these prerequisites is laser ultrasonics (LUS). It has previously been shown that it is possible to reliably measure the grain size in the HSM [1,2]. This project intends to realize an installation of a permanent LUS grain size gauge after the last stand, and before the run-out table, in the HSM and to monitor the microstructure.

In order to realize a robust LUS-gauge a grain size calculation model has been developed which is both temperature corrected and does not require a reference sample [3]. Additionally, the LUS-gauge has been equipped with optics for a long working distance of ~600 mm and suitable harsh environment protections. The installation of the gauge is intended to be finished in Q1 of 2022.

We will present some of the laser ultrasonic measurement results from this world first permanent installation of an on-line grain size gauge in a hot strip mill.

This work was partially financed by the strategic innovation program for Metallic material, by Vinnova, the Swedish Energy Agency, and Formas as well as the European Union's Research Fund for Coal and Steel (RFCS) research program under grant agreement nr. RFCS-2018-847296.

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[Poster] Acoustic velocity mapping of multi-metallic components using laser-induced ultrasonic time-of-flight tomography and neural data interpretation

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Multi-metallic components are designed to harness the differing mechanical, thermal, chemical, or electromagnetic properties of two or more metals within a continuous solid structure to achieve higher performance than is possible when a single material is used. Depending on the requirements of the component, dissimilar metal parts may be joined using a wide variety of fusion, flow, or solid-state welding techniques. The acoustic transmissivity of these joints makes such components theoretically suitable for ultrasonic testing (UT). However, many established UT inspection methods require an acoustic velocity map of the component as a separate corrective input in order to return accurate results. Such velocity maps may be acquired with destructive methods, which are not suitable for *in situ* deployment, e.g. during manufacturing or welding. This study presents the results of applying non-destructive, laser-ultrasonic time-of-flight tomography to the challenge of mapping acoustic velocity in several different multi-metallic samples. The technique is deployed using laser-induced ultrasonic arrays, and the data obtained is rapidly interpreted using a pre-trained neural network that outputs velocity maps in real time [1]. The velocity maps obtained from the technique are shown to be sufficiently accurate for use as stand-alone inspection data, and are also highly valuable as corrective inputs to other UT techniques or imaging algorithms. Combining the flexibility innate to laser ultrasonic transduction with the reconstruction speed of neural networks enables robust acoustic velocity mapping for a variety of multi-metallic structures and component geometries with high potential for *in situ* deployment during manufacturing. The results motivate further development of the technique toward the mapping of finer-scale acoustic inhomogeneity in metals such as that caused by polycrystalline texture.

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In-situ laser ultrasonic measurements of phase transformation kinetics in lean Ti-Mo alloys

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Molybdenum (Mo) is one of the most common β-stabilizing elements used in commercial titanium alloys. As compared with other conventional β-stabilizers, such as vanadium and chromium, molybdenum possesses the lowest diffusion rate in the β phase[1] and a rather low diffusivity in the α phase[2], thus playing an important role in controlling the rates of diffusional α/β phase transformations. While most of earlier studies focused on complex multicomponent Ti-systems, here we investigate quasi-binary Ti-Mo model alloys with systematically varied Mo content up to 6 wt.% (i.e., the typical content range used in commercial Ti-alloys) to elucidate in detail the effect of Mo on the phase transformation kinetics. Thermodynamics aspects of Ti-Mo systems have been well established, but much less quantitative information is available in terms of kinetics, particularly for lean Ti-Mo alloys. In this study, phase transformations were measured during continuous heat treatments at varying rates using a Gleeble thermo-mechanical simulator coupled with a Laser Ultrasonics for Metallurgy (LUMet) sensor. The measurably different mass densities and elastic constants of the parent and product phases result in variation in the ultrasound longitudinal velocity, which can be correlated to the volume fractions transformed. The transformation kinetics for a given alloy was seen to be more sensitive to cooling rate as compared to heating rate. As expected, increasing the Mo content delays the phase transformations. The results obtained during continuous heating were compared with thermodynamic calculations, while those obtained during cooling were modelled using the additivity concept applied to the Johnson-Mehl-Avrami-Kolmogorov (JMAK) theory. The present study further established laser ultrasonics as a non-contact, *in-situ* and real time characterization technique for phase transformations in Ti-alloys. Thus, laser ultrasonic studies have the potential to significantly contribute to knowledge-based design of optimized Ti-alloys and their heat treatments.

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Analysis of the effect of inline laser-induced ultrasonic waves on the microstructure of materials processed in laser powder bed fusion conditions

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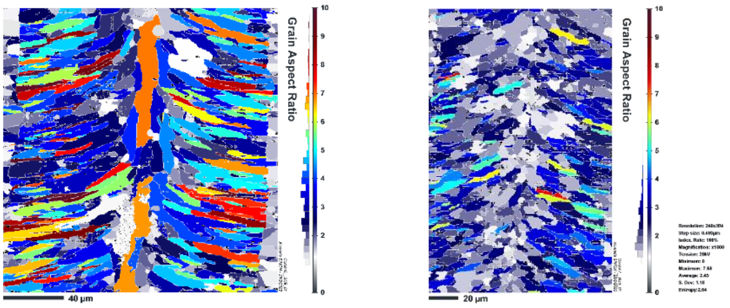
Metallic Laser Additive Manufacturing Processes and, particularly, the Laser Powder Bed Fusion Process, demonstrate a strong and ever-growing potential in a very varied field of applications. However, standard LPBF generally produces anisotropic columnar microstructure [1], induced by solidification conditions, which is unlikely desired. Different approaches have been proposed to produce an equiaxed grain refinement through adaptations of process parameters or a modification of the composition of the alloys that cannot be generalized. Recent publications [2] proposed to extend the well-known grain refinement by ultrasonic waves in casting processes. This has been successfully demonstrated in laser cladding conditions.

This study aims to explore the possibility of generating an equiaxed microstructure for LPBF using online laser-induced ultrasonic waves. This first experimental approach will be carried out on a simplified experimental setup representative of the laser fusion conditions, mainly on stainless steel material. In an initial experiment, the material is initially solicited by an external shear ultrasound transducer during the fusion process. Microstructural analysis demonstrates that this type of solicitation has a clear effect on the final microstructure. Then, new experiments including inline laser-induced ultrasonic waves is made by modulating the processing laser. The influence of process parameters (mainly process speed and laser power) and the ultrasonic signal (frequency, amplitude) is investigated. The microstructures are analyzed by EBSD and clearly evidence that the elongated grains normally generated by solidification conditions are fragmented into smaller grains for a range of frequencies.



(a) (b)

Figure 1: Microstructures analyzed by EBSD (a) without and (b) with laser modulation.

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Laser-Ultrasonic Characterization of Omega Particles in Ti15Mo

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The elasticity of single crystals of metastable beta-phase of the Ti15Mo alloy with particles of both isothermal and athermal omega phase was studied by the Transient grating spectroscopy. This laser-ultrasonic method utilizes a pulse infrared laser for thermoelastic generation of high-frequency surface acoustic waves (SAWs) in an examined material and a 532nm-continuous laser beam for their contactless heterodyne detection [1]. By attaching a sample to a rotational stage, an angular dispersion of SAWs can be measured. Since the hexagonal isothermal omega-phase forms from the bcc beta-phase as a result of low-temperature aging, the measurement was performed both on a sample in the solution-treated state [2] and on samples that were aged after solution treatment at different ageing temperatures (300°C, 350°C, 400°C) and durations (4h, 6h, 16h, 32h). A 360deg-angular scan of SAWs over examined samples showed that the ageing conditions affect the amount of isothermal omega particles whose presence leads to stiffening and isotropization of shear elasticity of the aged samples. All samples were measured at room temperature, the solution-treated single crystal was afterwards measured in-situ between room temperature and 83K. The effect of athermal omega phase particles on elasticity was comparable to that caused by isothermal omega particles.

Acknowledgment: This work has been financially supported by the Czech Science Foundation (project No. 22-13462S).

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[2] Nejezchlebová, J., Janovská, M., Sedlák, P., Šmilauerová, J., Stráský, J., Janeček, M., Seiner, H., Elastic constants of β-Ti15Mo, J. Alloys Compd. 792, (2019), 960-967.

Numerical Investigation of Ultrasonic Scattering Phenomena at the Grain-Scale in Polycrystalline Materials

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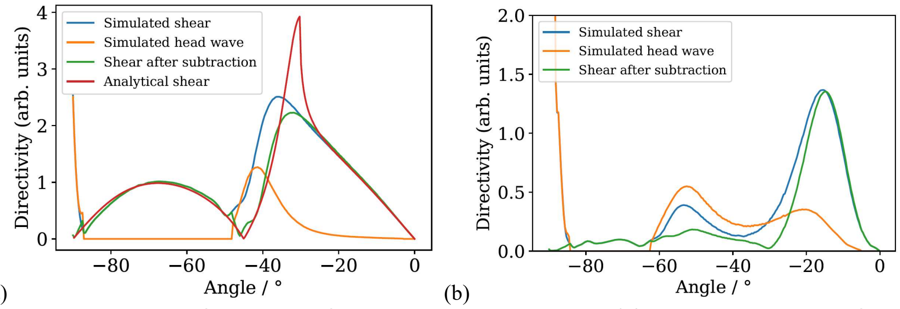
In polycrystalline materials, elastic waves strongly interact with grain boundaries and their propagation generates complex ultrasonic scattering phenomena. The recorded signals are generally difficult to interpret but contain rich information useful for characterizing the polycrystalline microstructure. Mastering the correlation between the ultrasonic grain scattering and the crystallographic and morphological characteristics of the microstructure is therefore essential. It is now widely recognized that grain-scale finite element (FE) modeling enables us to properly investigate grain-scale scattering mechanisms by fully grasping the multiple scattering phenomena. It allows to simulate synthetic microstructures and to analyze the influence of specific grain arrangements on the wave scattering. It is also a way to investigate the response of real microstructures, obtained, for instance, from EBSD maps and for which no explicit analytical model is available.

This contribution presents recent modeling and simulation results obtained using a space discontinuous Galerkin (dG) FE solver. First, the advantages of the space dG method and aspects for an appropriate numerical setting in the context of ultrasound scattering modeling are discussed. Second, the coherent wavefronts are analyzed by means of the attenuation coefficient, allowing the quantification of average microstructural characteristics. Among these, the grain-size distribution is mainly investigated here. For example, a recent method proposed for identifying bimodal grain-size distributions in 2D microstructures is extended to the 3D case, and the dimensionality of the grain scattering phenomena is discussed. Third, the structural noise due to incoherent waves is studied in 2D and 3D. The scattering coefficient is evaluated numerically and compared to analytical models. Some numerical “experiments” are carried out to discuss, confirm or refute theoretical hypotheses.

Radial position independent directivity for laser generated ultrasonic shear waves in thermoelastic regime

Xin L. Tu [1], Paul D. Wilcox [1], Alberto M. Gambaruto[1], Jie Zhang[1]
[1]*University of Bristol, Bristol, UK*

The shear waves generated by pulsed laser in the non-destructive thermoelastic regime, are commonly used for defect detection. The shear wave propagates inside the material with a strong angular-dependency, termed directivity. An accurate, consistent measure of shear directivity at all radial position is required to design inspections and maximise the signal-to-noise ratio (SNR). However, head waves, which travel on the free surface with longitudinal velocity and inside the material with shear velocity, interfere with the shear wave in certain regions. Due to the head wave having a different ray path, wavefront, and attenuation from the shear wave [1], the measured shear directivity varies with the radial distance from the source. This makes it challenging to extract the true shear wave directivity from finite element (FE) simulations without using very large spatial domains. A method is proposed to avoid this problem by removing the contribution from the head wave. This work uses FE simulations to show that a wavefield dominated by the head wave can be obtained by running a second simulation, which takes the displacements of the original simulation (simulating the physics of the laser ultrasonic wave generation mechanism) as boundary conditions, with damped initial pulses. This wavefield is subtracted from the original wavefield, leaving pure shear waves. This method is first benchmarked with the analytical shear wave directivity for a force dipole on the free surface of a homogeneous, isotropic half space [2]. The subtraction removes head wave interference in the region 30˚-51.6˚, and the Rayleigh wave near surface, as shown in Figure 1a. The directivity from 25˚-30˚ is difficult to fully reconcile with the analytical solution. This is because in FE simulations, the force dipole must be implemented as opposing point forces applied to adjacent nodes, which hence have a finite (as opposed to infinitesimal) separation. This method is then applied to an anisotropic material similar to that found, for example, in austenitic welds [3], to obtain a shear directivity independent of radial positions, as shown in Figure 1b, for which there is no analytical solution.



(a) (b)

Figure 1: subtraction of head wave from shear wave directivity in (a) an isotropic material, fitted with analytical solution, and (b) a transversely isotropic material.

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Grain structure modeling in fusion welding processes using a coupled CAFE approach - Application in NDT methods

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Fusion welding processes aim at joining parts of different compositions, geometries or functionalities by the development of a common melted zone. However, during the solidification stage and join formation, several defects such as hot crackings may develop, leading to a decrease of the weld quality. Non Destructive Testing (NDT) methods are used by industries to detect such defects using ultrasound (US) technics. However, the microstructure encountered during wave propagation in particular in the welded domain influences the efficiency of these methods. The morphology and size of grains lead to a scattering of US signal influencing defects detection, localization and sizing. Consequently, virtual grain microstructure would provide valuable information to enhance NDT technics and defect detection methods as a material of interest to analyze wave propagation.

Among approaches of interest, the Cellular Automaton – Finite Element (CAFE) method aims at simulating grain structure evolution during solidification processes. This method is based on the use of regular grid of cubic cell superimposed onto a finite element mesh. This latter enables to follow macroscopic field evolution at the scale of the domain of interest. Temperature are thereafter interpolated at cell scale in order to estimate the growth of solidification envelopes. In this work, a CAFE method simulates the grain structure formation during Gas Tungsten Arc Welding (GTAW) process applied in a chamfer configuration with added metal on a 316L stainless steel grade (Fig. 1 a). The simulated microstructure is compared with experiments developed in a partnership (NEMESIS project). A good coherence is found regarding the grain texture (EBSD map and pole figures) (Fig. 1 b) once valuable thermal conditions (e.g. melt pool shape) are obtained, using an original heat source model. Some early results associated to US method are presented based on the virtual microstructure to analyze and improve the performance of future software. Discussions are thereafter proposed for these activities as well as for the enhancement of hot cracking criterion.

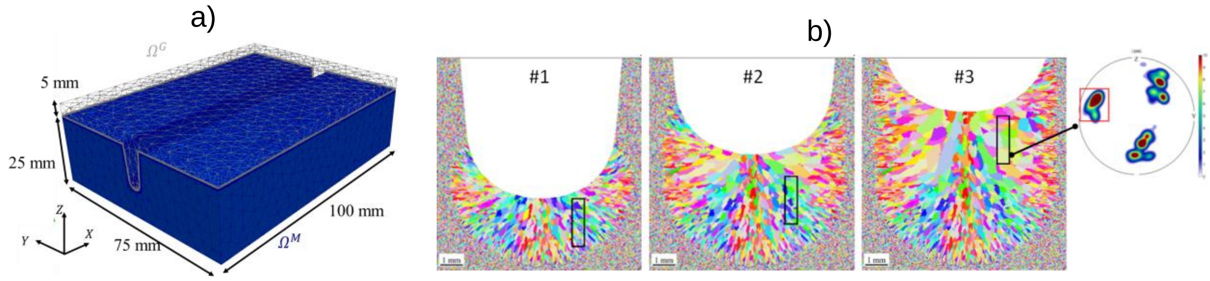

Fig. 1: a) Welding configuration, b) Simulated microstructure - three passes (CAFE) with pole figure.

Ref.: C. Xue *et al.*, Structure and texture simulations in fusion welding processes – comparison with experimental data, Materialia 21 (2022), 101305

Fake Anisotropy of Thermal Diffusivity from Transient Grating Spectroscopy Measurements

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Transient grating spectroscopy [1] is used for contactless nondestructive laser-ultrasonic characterization of thermal and acoustic properties [2]-[4] of a given material from measurements on a single free surface. A pattern of standing acoustic waves with fixed wavelength λ and wavevector k is photothermally generated by an interference of two pulsed laser beams on a sample surface (see Fig. 1). Detection of an out-of-plane displacement of the sample surface provides information about the acoustic behavior and thermal diffusion in the direction parallel to k. In the case of anisotropic physical properties, the sample might be rotated along the surface normal. We are, therefore, able to obtain the angular distributions of both the elastic and thermal properties on the sample surface.

Our research had aimed to measure the thermal diffusivity of various cubic, single-crystalline metallic samples. Surprisingly, we observed anisotropic angular distribution of the thermal diffusion coefficient. To find the source of this physics-defying result, a numerical finite element method study of the transient grating spectroscopy method was carried out in Comsol (see Fig 2). It was found out that when elastically anisotropic materials absorb heat from the excitation laser in different crystallographic directions, they might produce slightly different out-of-plane displacement of the surface, despite having isotropic thermal diffusivity. This effect, even though seemingly insignificant, strongly influenced the calculation of thermal properties. Thus, it was shown that transient grating spectroscopy measurements might indicate fake anisotropy of thermal diffusivity for elastically anisotropic samples.

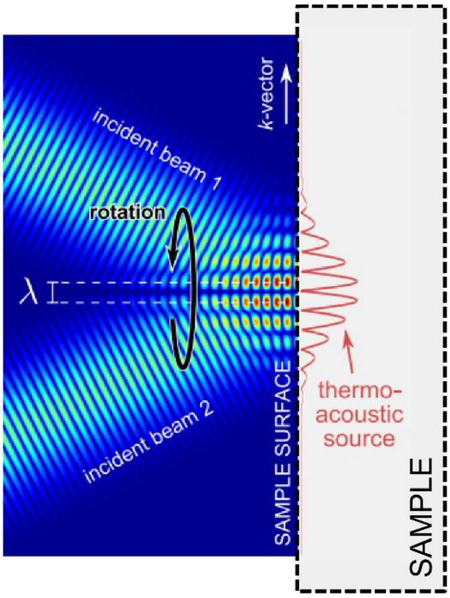

Fig. 1: Schematic illustration of the transient grating spectroscopy method.

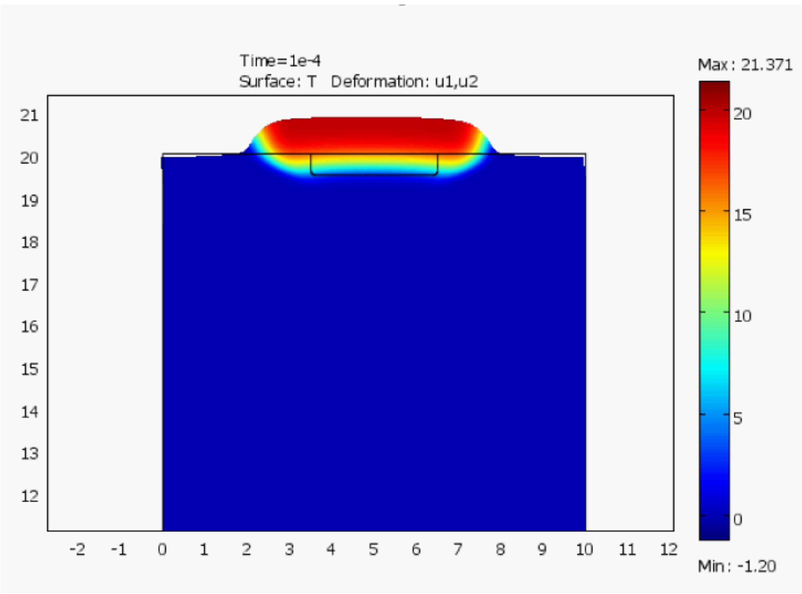

Fig. 2: A finite element method study of a single thermo-acoustic transient grating source in an elastically anisotropic metallic sample.

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The French Society of Metallurgy and Materials (SF2M), created in January 1945, is a non-profit scientific association, of general interest. It brings together around 1,000 individual members (from industry and academia) and 15 partners (industrial groups or federations). It is a place of meeting, training, and exchanges, a motor for the dissemination of information and innovations, and a point of convergence in a national and international network in the field of materials, their manufacture, and their usage. The SF2M contributes to the promotion of materials sciences and techniques, to the sharing of information on the progress of knowledge and innovations in the field of Metallurgy and Materials Science, by the organization of technical and scientific conferences. It promotes materials science and technology, particularly for young audiences. The SF2M represents its members with other scientific associations in France and abroad.

Author Index

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PROGRAM

5th International Workshop on Laser-Ultrasound for Metals

5-6 May, 2022, Gif-sur-Yvette, France

LUS4Metals

The 5th International Workshop on Laser-Ultrasound for Metals (LUS4Metals) will be held at CentraleSupélec (Paris-Saclay University, in the southern suburbs of Paris, France) from May 5 to 6, 2022, in following on from previous workshops held at the University of British Columbia (Canada, 1st and 2nd), the metals research institute Swerim AB (former Swerea Kimab, Sweden, 3rd), and Recendt in Linz (Austria, 4th).

This event will once again open to all interested parties from academia and industry. The small to medium size of the workshop will allow dynamic and fruitful exchanges between the attending researchers and industrial partners from all over the world around topics of Laser-Ultrasound Testing, modelling and simulation, from fundamental aspects to challenging

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Thursday, 5th May 2022

08 : 00 Registration and Welcome Reception

08 : 30 **Pierre-Alain Boucard**, Director of LMPS (CentraleSupélec, ENS Paris-Saclay), France
Opening

08 : 40 **Christophe Bescond,** Invited speaker, NRC Canada, Boucherville, Qc, Canada
Recent developments at NRC Canada for steel microstructure characterization and weld inspection

09 : 20 **Bevis Hutchinson**, Swerim AB, Stockholm, Sweden
High precision measurement of elastic anisotropy in metals

09 : 40 **Krister Ekström**, Swerim AB, Stockholm, Sweden
Recrystallization kinetics of Fe-30Ni alloy with 0.008-0.083% Nb

10 : 00 **Philip Meilland**, ArcelorMittal Maizieres Research, France
Assessment of grain size on moving steel strips during hot rolling with Laser ultrasonics

10 : 20 **Pavla Stoklasová**, Institute of Thermomechanics, Czech Academy of Sciences
Laser-Ultrasonic Characterization of Omega Particles in Ti15Mo

10 : 40 Coffee Break

11 : 00 **Paul Dryburgh**, OPG, University of Nottingham, UK
SRAS++ for single-crystal elasticity measurements in polycrystalline material

11 : 20 **Kristýna Zoubková**, Institute of Thermomechanics, Czech Academy of Sciences
Fake anisotropy of thermal diffusivity from transient grating spectroscopy measurements

11 : 40 **Xin Tu**, Dep. Mech. Engin., University of Bristol, UK
Radial position independent directivity for laser generated ultrasonic shear waves in thermoelastic regime

12 : 00 **Marc Choquet**, Sponsor Presentation, Tecnar Automation Ltée, Canada

12 : 15 **Bruno Pouet,** Sponsor Presentation, Sound & Bright, California, USA
Christelle Anceau, Opton Laser Int., France

12 : 30 Lunch Break

14 : 00 **Peter Huthwaite**, Invited speaker, Imperial College, London, UK
High speed modelling of waves with the finite element method

14 : 40 **Mathieu Ducousso**, SAFRAN Tech, France
Laser ultrasonics in a multilayer structure: semi-analytic model and different examples

15 : 00 **Tomáš Grabec**, Institute of Thermomechanics, Czech Academy of Sciences
Grain-boundary scattering of surface acoustic waves: experiment and simulati

15 : 20 **Bing Tie**, LMPS, CentraleSupélec, ENS Paris-Saclay, CNRS, France
Numerical Investigation of ultrasonic scattering phenomena at the grain-scale in polycrystalline materials

15 : 40 **Pierre-Emile Lhuillier**, EDF R&D, France
Modeling method for the simulation of austenitic weld ultrasonic inspection - realistic prediction of echoes and structural noise in weld inspection

16 : 00 Coffee Break

16 : 20 **Nicolas Legrand**, ArcelorMittal Global R&D, East Chicago, USA
1) Pearlite monitoring in steel Sheets by laser ultrasonic technique
2) Comparative Analysis of Phase Transformation Monitoring by Dilatometry and by Laser Ultrasound.

16 : 50 **Mariana Rodrigues**, University of British Columbia, Vancouver, Canada
In-situ laser ultrasonic measurements of phase transformation kinetics in lean Ti-Mo alloys

17 : 10 **Anton Jansson**, Swerim AB, Stockholm, Sweden
Laser ultrasonics for quality control of resistance spot welding

17 : 30 **Matthew Riding,** DEEE**,** University of Strathclyde, Glasgow, UK
[Poster] Acoustic velocity mapping of multi-metallic components using laser-induced ultrasonic time-of-flight tomography and neural data interpretation

17 : 40 **Edouard Demaldent**, Sponsor Presentation, CEA List, LSMA, France
Physic-based modelling for ultrasonic testing in complex materials at CEA List

18 : 10 Group Photo | 18 : 30 Bus Meeting
18 : 45 Bus Start | 19 : 00 Dinner

Friday, 6th May 2022

08 : 00	Welcome Reception
08 : 30	**Edgar Scherleitner**, Invited speaker, RECENDT, Linz, Austria The potential of laser ultrasound for sustainability in metal production and processing
09 : 10	**Mikael Malmström,** Swerim AB, Stockholm, Sweden On-line grain size gauge for the hot strip mill based on laser ultrasonics
09 : 30	**Mathieu Ducousso**, SAFRAN Tech, France Ultrasonic bulk imaging of shock wave spatial distribution in opaque solids
09 : 50	**Peter Lukacs**, University of Strathclyde, Glasgow, UK Laser Ultrasonic Tomography using Deep Neural Networks
10 : 10	**Panagiotis Kamintzis**, University of Strathclyde, Glasgow, UK Surface acoustic wave suppression for ultrasonic imaging of near-surface defects using laser induced phased arrays
10 : 30	Coffee Break
11 : 00	**Gildas Guillemot**, CEMEF, MINES ParisTech, PSL Research University, France Grain structure modeling in fusion welding processes using a coupled CAFE approach - Application in NDT methods
11 : 20	**Alverède Simon**, CEA List, LIC, France Analysis of the effect of inline laser-induced ultrasonic waves on the microstructure of materials processed in laser powder bed fusion conditions
11 : 40	**Ronan Delalande**, LAUM and INSP, France Determining elastic properties of a single metallic nanoparticle using time-resolved ultrafast spectroscopy
12:00	**Frédéric Faese**, NETA SAS, France Thin film characterization by picosecond ultrasonics on high curvatures surfaces
12 : 20	Closing Ceremony and LUS4Metal 2024 organization
	Bing Tie, LMPS, CentraleSupélec, ENS Paris-Saclay, CNRS, France **SWERIM AB** next LUS4Metals and MDPI Applied Sciences Special Issue
12 : 30	Lunch Break

There will be no call for papers at the workshop. Workshop participants interested in publishing a full-length paper may consider submitting it in the MDPI Applied Sciences Special Issue ``Application of Laser-Ultrasonics in Metal Processing”, edited by our colleagues at Swerim AB.
https://www.mdpi.com/journal/applsci/special_issues/Laser_ultrasonics_in_Metal_Processing

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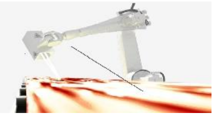

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