MAY 22-23 2024
Kista, Sweden

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The 6^{th} International Workshop on LUS for Metals

Welcome to the the 6^{th} International Workshop on Laser-Ultrasound for Metals (LUS4Metals) at Swerim in Stockholm, Sweden May 22 to 23 2024.

This event will once again unite parties from academia and industry in a workshop with dynamic and fruitful exchanges between the attending researchers and industrial partners from all over the world around topics of Laser-ultrasonics.

This workshop is continuing from previous workshops held at the University of British Columbia (Canada, 1^{st} and 2^{nd}), the metals research institute Swerim (former Swerea Kimab, Sweden, 3^{rd}), RECENDT (Austria, 4^{th}), and Centrale Supélec (France, 5^{th}).

We would like to extend our gratitude to the sponsors Jernkontoret, Tecnar, EMG, Sound&Bright and Swerim, who makes the workshop possible.

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PROGRAM

Day 1 - May 22

08:30	**Registration and welcome reception**
09:00	**Opening and introduction**
	Session 1
09:20	Insights from the online LUS grain size gauge and the potential for future process control, **Dietmar Hoppe**, SMS Group GmbH (*Invited speaker*)
10:00	Measurement and calculation of sound velocities of steel during recrystallisation, **Clemens Grünsteidl**, RECENDT GmbH
10:20	**Coffee break**
	Session 2
10:50	Identification of steel grade and predicting mechanical properties using machine learning for laser ultrasonic data, **Krister Ekström,** Swerim AB
11:10	Laser Induced Phased Array Element Localisation for Accurate 2D and 3D Ultrasonic Imaging **Geo Davis**, University of Strathclyde
11:30	Laser-ultrasonic characterization of anisotropic elasticity of shape memory alloys using surface acoustic waves, **Pavla Stoklasová**, Institute of Thermomechanics, Czech Academy of Sciences
11:50	**Tecnar,** Tecnar Automation Ltée (*Sponsor presentation*)
12:00	**Lunch**
	Session 3
13:00	Zero-Group-Velocity Lamb modes in Anisotropic Plates, **Claire Prada**, Institut Langevin, ESPCI Paris
13:20	Ultrasonic scattering of elastic waves in polycrystalline materials with elongated grains: theoretical models and numerical simulation, Juan Camilo **Victoria Giraldo**, CentraleSupélec, ENS Paris-Saclay, CNRS
13:40	Guided waves in chromium coated zirconium cladding tubes, **Diboune Hafsa**, Institut Langevin, ESPCI Paris
14:00	Deep-learning-based surrogate model of laser-induced elastic wave propagation in metallic microstructures with elongated grain, **Frédéric Allaire**, CEA List
14:20	**Coffee break**
	Session 4
14:50	In situ measurement of microstructure evolution using laser ultrasonics, **Matthias Militzer**, The University of British Columbia (*Invited speaker*)
15:30	Application of Laser Ultrasonics in Detecting Unusual Austenite Grain Growth Behavior, **Minghui Lin**, The University of British Columbia
15:50	An experimental study of elasticity in polycrystalline iron using laser-ultrasonics, **Bevis Hutchinson**, Swerim AB
16:10	Austenite grain growth in as-cast and as-hot rolled steels, **Sabyasachi Roy**, The University of British Columbia
16:30	In-Situ Grain Size Measurement During Dynamic Recrystallization And Hot Rolling Simulations By Laser Ultrasonics, **Mikael Malmström**, Swerim AB
16:50	**Group Photo**
18:20	**Subway** (Blue Line 11) - from Kista C to Kungsträdgården
19:00	**Dinner at Jernkontoret**, Kungsträdgårdsgatan 10, 111 47 Stockholm

PROGRAM

Day 2 - May 23

Session 1

08:30 Laser ultrasonics for monitoring of metal additive manufacturing, **C.J. Lissenden**, The Pennsylvania State University (*Invited speaker*)

09:10 Harnessing Spatially Resolved Acoustic Spectroscopy (SRAS) ++ for Elasticity Imaging of Materials, **Wenqi Li**, University of Nottingham

09:30 Unveiling the Mysteries of Material Recrystallization in-situ through Spatially Resolved Acoustic Spectroscopy, **Carolina Guerra**, University of Nottingham

09:50 **Coffee break**

Session 2

10:20 Induction hardening depth measurements by laser ultrasound for automotive industry, **Anton Jansson**, Swerim AB

10:40 Laser resonant ultrasound spectroscopy: analyzing materials with temperature, **Martin Ševčík**, Institute of Thermomechanics, Czech Academy of Sciences

11:00 Surface Breaking Crack Detection on Thin-walled Austenitic Stainless Steel Cylindrical Rods with Periodic Ribbed Structures Using Laser Ultrasonics, **Geo Davis**, University of Strathclyde

11:20 Thin Film Characterization by Transient Grating Spectroscopy, **David Mareš**, Institute of Thermomechanics, Czech Academy of Sciences

11:40 **Closing**

12:00 **Lunch**

13:00-14:00 Lab tour at Swerim, Isafjordsgatan 28A 164 40 Kista

ABSTRACTS

Insights from the online LUS grain size gauge and the potential for future process control

Dietmar Hoppe[1], Thomas Haschke[1], August Sprock[1], Christoph Hassel[1], Joachim Hafer[1]
Linda Bäcke[2], Jan-Erik Thorberg[2], Christer Jonsson[2],
Mikael Malmström[3], Franziska Kneisel[4], Matthias Bärwald[4]

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In a joint project, an innovative Laser UltraSonic (LUS) device was installed in the SSAB Hot Strip Mill in Borlänge. The measuring device, including the software for signal processing and signal evaluation, was developed, built and implemented in collaboration between SSAB, SWERIM, EMG and SMS group. It was installed after the last rolling stand and allows measurements of the austenite grain size immediately after rolling.

The LUS measurements were carried out on various grades with different dimensions and process parameters. The calculated process data of the tested strips were collected from the SMS process models (pass schedule model PSC® and cooling section model CSC) and subjected to a comprehensive analysis with the measured process data and the measured austenite grain size. The analysis starts with the discharge of the slabs from the reheating furnaces, followed by the roughing mill, the coil box, the finishing mill, the cooling section and finally the downcoiler. Extensive recalculations were done with the PSC® and CSC in order to quantify the correlation of the measured austenite grain size and the process conditions of the rolled strips.

The extensive recalculations show good agreement with the measured grain size. In principle, this can improve the setting accuracy in the finishing mill and in the cooling line and be a useful tool for optimizing the set-up for existing products.

In the near future, the LUS measurements could be integrated into the Level 2 automation system in order to use the austenite grain size in the pass schedule model PSC®, the cooling section model CSC and the microstructure property model MPM. Then the models can use the austenite grain size as a setpoint for direct process control in the hot rolling mill and thus improve control of product properties and minimizing downgrading.

Measurement and calculation of sound velocities of steel during recrystallisation

Clemens Grünsteidl[1], Christian Kerschbaummayr[1], Edgar Scherleitner[1], Matthias Militzer[2], Christian Hoflehner[3], Markus Sonnleitner[3]

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[3]voestalpine*, Linz, Austria*

The use of scrap as a raw material for secondary steel production has a major contribution to reducing negative environmental impacts of steel products. However, the varying content of trace elements in scrap affects their properties, and thus poses a challenge to manufacturers: Process parameters need to be adapted to the input composition, to maintain the quality of the product. This requires a large amount of characterization experiments, covering variations and combinations of trace metals. For this purpose, laser-ultrasound (LUS) offers a high-throughput alternative to state of the art methods, with the great potential to be applied as an in-line sensor.

We study the use of LUS to quantify the progress of recrystallisation in ultra-low-carbon steel sheets with different contents of trace elements after cold rolling. The change of texture during recrystallisation causes a change of sound velocities, which we detect in situ, with LUS coupled to thermal simulator. Measuring on 0.8 mm thick sheet samples, we exploit plate resonances for the determination of sound velocities. We compare the measured values to theoretical sound velocities for different states of recrystallisation. These are calculated from single crystal properties of iron and orientation density functions obtained from electron back scatter diffraction at different states of recrystallisation. The measured and theoretical values show good agreement for the longitudinal sound velocity. As in [1], we observed that the correlation of fraction of recrystallized grains and the change of sound velocity strongly depends on the Ti content of the steel, making it difficult to detect the onset of recrystallisation in certain cases based on through-thickness measurements of longitudinal sound velocity. This motivated an extension of the modality towards directional measurements of surface waves and zero-group-velocity resonances. For first ex situ results we again show comparisons of experiment and theory, and discus occurring deviations.

[1] Hutchinson, B., Lindh-ulmgren, E., and Carlson, L., 2008, “Application of Laser Ultrasonics to Studies of Recrystallisation and Grain Growth in Metals,” Technology, pp. 2–7.

Identification of steel grade and predicting mechanical properties using machine learning for laser ultrasonic data

Krister Ekström[1], Filip Tuvenvall[1], Mikael Malmström[1], Anton Jansson[1]

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The hardness of steel is an important quality parameter for several industrial applications. Conventional mechanical testing is used in quality testing for material hardness and the method is time-consuming, can cause material mix-ups, and results in material waste. To address this issue, a possible on-line method for non-destructive testing (NDT) techniques such as laser ultrasonic (LUS) measurements has been explored to replace mechanical testing. In this work, machine learning models are trained to predict steel hardness using LUS measurements and data from the production process.

LUS data is collected from steel samples with a measured hardness using the Brinell protocol. Measured hardness values between 250 and 700 Brinell are used as the target values for the models. The production process data includes the chemical composition and tempering temperature. The models used in this work are Extreme Gradient Boosting (XGBoost), Multilayered Perceptron (MLP), and Convolutional Neural Network (CNN). The first two mentioned models use feature-engineered data from LUS measurements. These features include the time-of-flight for ultrasonic waves. CNN uses the raw LUS data as a univariate time series as input. Each of the models is trained solely on data from LUS measurements and both LUS and production process data to determine the effect of adding production process data. The models are optimized and tuned based on their loss on a validation set. The models are evaluated against each other based on their root mean squared error (RMSE) on a test set to determine the best performing model.

Laser Induced Phased Array Element Localisation for Accurate 2D and 3D Ultrasonic Imaging

Geo Davis[1], Mathew W Riding[1], Pete Lukacs[1], Theodosia Stratoudaki[1]

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Laser induced phased arrays (LIPAs) are phased arrays that are synthesised in post-processing but operate based on the principles of laser ultrasonics (LU). In LIPAs, the ultrasonic data are acquired following the full matrix capture (FMC) method. The FMC can be processed using delay-and-sum algorithms, such as the Total Focusing Method (TFM), and Synthetic Aperture Focusing Technique (SAFT), to generate ultrasonic images. In such algorithms, it is important to know the precise location of the array elements in order to evaluate the delay laws. The element spacing in LIPA can change during scanning as a result of the positioning errors in the linear stages and scanning mirrors used or due to inaccurate positioning of the sample. Such errors can lead to the generation of inaccurate ultrasonic images that use the 'expected' element positions rather than the 'actual' element positions during post-processing. In this study, two element localization methods are proposed, which are based on the arrival of surface acoustic waves. The methods are used to correct the positional inaccuracies of the element locations when the imaging algorithm is applied, to apply the correct delay laws and generate accurate ultrasonic images. In the first method, the ultrasonic signals of the FMC for the same element separation (diagonal signals of the Full Matrix) are considered to extract the arrival time of SAWs and calculate the true element positions on the sample. The second method implements the imaging algorithm on the surface of the sample using SAW velocity to calculate the true element locations. A 1D periodic (constant element pitch) LIPA and a 2D periodic LIPA were synthesized on a flat aluminium block with nine through side-drilled holes of 1 mm diameter placed in a radial pattern and on a flat aluminium block with four bottom-drilled flat-top holes with 2 mm diameter at varying depths, respectively. A pitch-catch array configuration was followed, allowing the simultaneous detection of bulk and surface acoustic waves. FMC was performed by scanning the generation and detection lasers across the surface of the sample. Results are presented for both 1D and 2D LIPAs that include comparison of images from before and after the positional correction of element location in TFM images.

ABSTRACTS

Laser-ultrasonic characterization of anisotropic elasticity of shape memory alloys using surface acoustic waves

Pavla Stoklasová[1], Tomáš Grabec[1], Kristýna Repček[1], Martin Ševčík[1], Petr Sedlák[1], Hanuš Seiner[1]

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Material elasticity can be characterized by non-contact measurement of surface acoustic waves (SAW) propagating on the free surface of a sample subjected to thermal or mechanical loading. The velocity of the SAW can be measured by using a line-shaped pump laser source to generate the waves and a probe laser for point-like detection of the waves. An inverse numerical method such as the Ritz-Rayleigh method [Stoklasová et al., Ultrasonics 2015] is used to determine the elasticity from the experimental data.
The conventional line source/point detector experimental setup is based on the measurement of SAW arrival times at multiple detection points realized by a probe laser beam scan. The scan requires a relatively large measurement spot on the sample surface and a long measurement time, yet still does not provide complete information. For a full characterization of the anisotropic elasticity, it is necessary to add additional experimental data (e.g., by the pulse-echo method) to fill in the missing longitudinal mode information [Grabec et al., Acta Mater 2021].
Recently, it has been shown [Stoklasová et al., Exp Mech 2021] that complete information on strongly anisotropic elasticity can be obtained using transient grating spectroscopy (TGS). The method provides additional information compared to conventional SAW measurements in a shorter time and over a smaller sample area (in the order of hundreds of micrometres). In this contribution, we discuss the potential of the TGS method for the characterization of strongly anisotropic shape memory alloy single crystals of NiFeGaCo, NiMnGa epitaxial films [Heczko et al., Acta Mater 2018] and in-situ temperature measurement of NiTi polycrystals.

This work was financially supported by the Ministry of Education, Youth and Sports of the Czech Republic in the frame of the project 'Ferroic multifunctionalities' (project No. CZ.02.01.01/00/22_008/0004591), co-funded by the European Union.

Zero-Group-Velocity Lamb modes in Anisotropic Plates

Daniel A. Kiefer, Sylvain Mezil, Claire Prada

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It is now well known that laser ultrasonic techniques are highly suitable to observe zero-group-velocity (ZGV) guided modes in metallic plates and cylinders and that these ZGV modes can be applied to the non-contact evaluation of Poisson's ratio in isotropic materials. This has been recently shown for steel plates at high temperatures [1] and for aluminum plates under stress [2]. This presentation will explain the characteristics of ZGV modes in anisotropic plates, showing that, multiple ZGV points may exist along symmetry axes of the material, which are located at minima and at saddle points of the same modal dispersion surface. The transverse-velocity modes connecting ZGV points and the associated extreme power flux skewing will be described using GEWtool [3]. Hence, this yields a comprehensive understanding of the significant differences between dispersion curves measured using a line source and those measured with a point source. These effects will be illustrated through laser ultrasonic measurements conducted on a monocrystalline silicon plate [4] and on rolled steel plates (Fig.1).

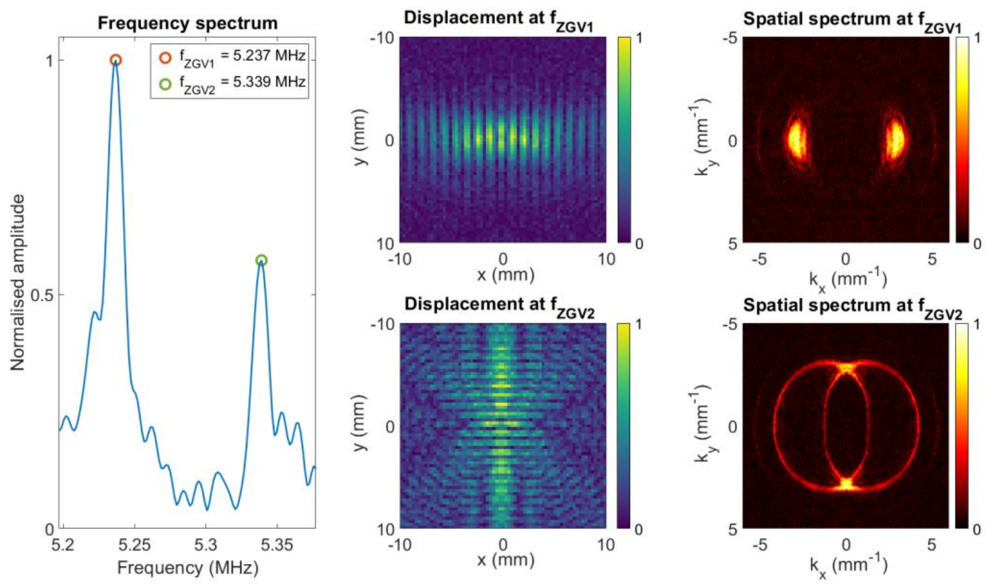

Figure 1 : ZGV modes excited by a point laser source in a rolled steel plate : local resonance spectrum (left), normal displacement magnitude at the two ZGV frequencies (center) and the corresponding spatial spectra (right).

[1] G. Watzl, et al. "In situ laser-ultrasonic monitoring of Poisson's ratio and bulk sound velocities of steel plates during thermal processes. ", Acta Materiala 235 (2022).
[2] R.E. Morales et al. "Acoustoelastic characterization of plates using zero group velocity Lamb modes", Appl. Phys. Lett. 124, 084101 (2024)
[3] D. A. Kiefer GEWtool (2023) doi: 10.5281/zenodo.10114244 (https://github.com/dakiefer/GEWtool)
[4] D. A. Kiefer, S. Mezil, C. Prada, "Beating resonance patterns and extreme power flux skewing in anisotropic elastic plates" Science Advances 9, eadk6846 (2023)

ABSTRACTS

Ultrasonic scattering of elastic waves in polycrystalline materials with elongated grains: theoretical models and numerical simulation

Juan Camilo Victoria Giraldo[1], Bing Tie[1], Jérôme Laurent[2], Alain Lhémery[2], Denis Solas[3]

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The scattering of ultrasonic elastic waves is an interesting phenomenon that can be exploited by the Laser-Ultrasonics (LU) technique to characterize the polycrystalline microstructure of components produced by Wire and Laser Additive Manufacturing (WLAM). A polycrystalline microstructure is a heterogeneous medium due to the various crystal orientations from one grain to another (each being anisotropic), and the possible presence of multiple phases. Scattering resulting from the interaction of the propagating wave with the microstructure can be observed through wave amplitude decay and the variation in the wave phase/group velocity. Indeed, if one can correlate these scattering parameters with specific parameters of the microstructure (grain size/shape, degree of anisotropy, oriented texture, etc.), one can gain useful information that can be used in real-time non-destructive testing techniques. It is therefore important to have versatile and robust theoretical and numerical models capable of estimating the scattering of elastic waves in polycrystalline microstructures.

In this work, a theoretical scattering model of bulk waves is developed based on previous models proposed by Bai and Tie [1], which is valid for grains varying from equiaxed to elongated shapes in the 3D and 2D cases. Ultrasonic scattering of bulk and surface waves in 3D and 2D polycrystalline microstructures is simulated using a space-discontinuous Galerkin framework. Ultrasonic attenuation and wave phase velocity in an Inconel 718 polycrystalline material are estimated thanks to theoretical and numerical results. First, our theoretical model is validated by comparing its prediction with numerical results obtained under the assumptions of untextured and single-phase medium. Moreover, 3D and 2D scattering phenomena are analyzed for pointing out the differences and the usefulness of 2D model to predict effects of 3D grain shape and rotation [2]. Then, the numerical model is extended to deal with the specific case of aligned crystallographic orientations in cases being found in WLAM components. It allows us to study the variations of attenuation and phase velocity with the angle of alignment of the principal crystallographic orientation.

Acknowledgments
This work was part of the COLUMBO project (ANR-21-CE08-0026) funded by the French National Agency for Research (ANR).

References
[1] X Bai, B Tie, J-H Schmitt, and D Aubry. Comparison of ultrasonic attenuation within two- and three-dimensional polycrystalline media. Ultrasonics, 100:105980, 2020.
[2] J.C Victoria Giraldo, B Tie, J Laurent, A Lhémery, D Solas. Theoretical analysis of the dimensionality of ultrasonic attenuation in polycrystalline materials with elongated grains. Journal of Physics: Conference Series, 2024. (hal-04485455)

Guided waves in chromium coated zirconium cladding tubes

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Non-destructive testing (NDT) is an essential tool for guaranteeing the integrity and safety of structures. Surface waves have been studied extensively for this purpose, yielding successful applications such as crack detection or thickness measurement. These waves are efficiently generated by laser impact and well detected by laser interferometry, providing broadband and non-contact measurements.

In the present study, we used surface waves to evaluate the mechanical properties of a chromium coating deposited on a zirconium alloy (M5*) cladding tube. As chromium has a much higher shear wave velocity than M5 ($V_{T_{Chromium}}/V_{T_{M5}} \approx 1.75$) the surface wave velocity strongly depends on frequency. In the middle-frequency range, characterized by shear wavelengths smaller than the tube thickness but greater than the chromium coating thickness, the surface wave is dispersive. Eventually, more than one surface mode can be observed, depending on the properties of the chromium layer.

Elastic waves were generated by an 8 ns pulsed Nd-YAG laser source (λ=1064 nm), focused into a line perpendicular to the tube axis. The normal displacement was then measured on the sample surface with a heterodyne interferometer [1]. The wave field was acquired by scanning the laser source along the tube axis and its 2D Fourier transform yields dispersion curves of axial guided modes up to 20 MHz. In order to model these waves, the elastic constants of M5 were determined from X-ray diffraction measurements and those of chromium were taken from the literature. Using these parameters, the theoretical dispersion curves were calculated with the GEWtool code [2] and compared to the measurements (Fig.1). The excitability of each mode, estimated from its modal displacements (Fig.2), appears in good agreement with the experiment. Measurements were achieved on different chromium layers that were then characterized by adjusting the dispersion curves.

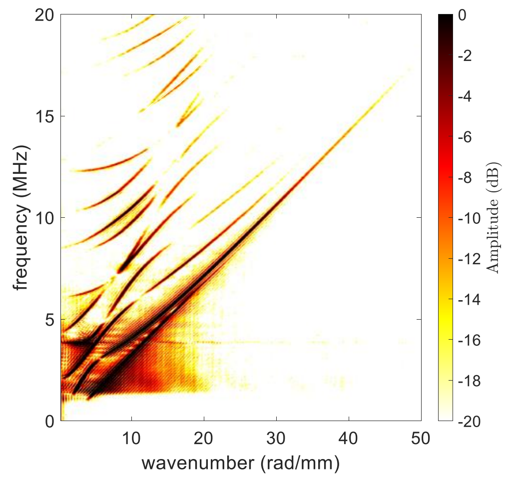

Figure 2 Experimental dispersion curves obtained on a 550µm-thick M5 cladding tube with a 15µm-thick chromium layer.

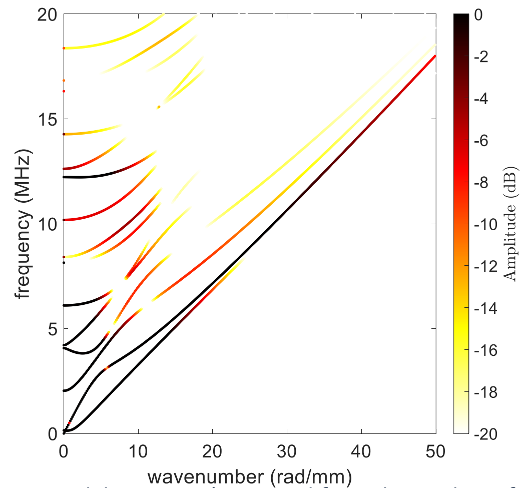

Figure 1 Excitability curves (estimated from the product of the out-of-plane and in-plane displacements) computed for a 550µm-thick M5 cladding tube with a 15µm-thick chromium layer

[1] D. Royer, E. Dieulesaint, in: Proceedings of the 1986 IEEE Ultrasonics Symposium, IEEE, New York, 1986, p. 527.
[2] D. A. Kiefer (2023). GEWtool [Computer software]. doi: 10.5281/zenodo.10114243 (https://github.com/dakiefer/GEWtool)

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ABSTRACTS

Deep-learning-based surrogate model of laser-induced elastic wave propagation in metallic microstructures with elongated grains

Frédéric Allaire[1], Filippo Gatti[2], Roberto Miorelli[1], Vincent Dorval[1], Jérôme Laurent[1]

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The displacement field of laser-induced elastic waves propagating at the surface contains information about the physical properties of the medium at shallow depths (Rayleigh wavelength). This information can be used to characterize the polycrystalline microstructure of metal components produced by Wire-Laser Additive Manufacturing (WLAM). Such components typically exhibit elongated grains due to high temperature gradients. Theoretical models relating the scattering and attenuation of bulk waves to grain geometry have been proposed; including a 2D model to predict effects of 3D grain shape and rotation [1]. The models highlight the influence of grain elongation and the possibility of extracting microstructure properties from attenuation. Effective properties can also be estimated by using FE simulations of elastic wave propagation in randomly generated microstructures [2]. The use of laser-ultrasound (LU) techniques to probe the material health of beads deposited during a WLAM process is a promising approach. These techniques can also be used to characterize the microstructure in situ. Although numerical simulations can link a microstructure to a synthetic B-scan, they take too long to enable online inspection.

This study explores the use of deep neural networks (DNN) as a surrogate model for mapping microstructure (input) and synthetic B-scans (output). DNNs have demonstrated satisfactory performance in surrogate modelling of 3D seismic wave propagation in heterogeneous isotropic media [3], as well as in generating realistic ultrasonic inspection data using a multi-fidelity framework that includes simulations and measurements [4]. As a preliminary step, we created a simulation database to train state-of-the-art DNN models. The architectures were inspired by convolutional neural networks and (Factorized-)Fourier Neural Operators (FNO, FFNO). The simulations were simplified 2D adaptations of configurations and FE simulations presented in [2] and adapted to a laser source. The heterogeneous media had random grain shapes and crystal orientations, with variable overall anisotropy, orientation, and elongation between each simulation. Initial findings indicate that all trained DNNs are able to provide fair mappings of microstructure to synthetic B-scan at a faster rate than the FE model. The areas that correspond to the arrival of coherent transient surface acoustic waves have the lowest relative approximation error, while structural noise is approximated fairly well but appears to be more challenging to learn. FFNO-based models produced the most accurate results, albeit with longer computational time. The simplified configurations have shown promising results and will be extended to cases that are more representative.

Acknowledgments: This work was part of COLUMBO project (ANR-21-CE08-0026) funded by the French National Agency for Research (ANR). Authors would like to thank A. Imperiale for optimising the FE code into CIVA and F. Lehmann for sharing her FFNO scripts.

References

[1] J.C Victoria Giraldo et al., J. Phys. Conf. Series, (2024).
[2] Dorval et al., Proc. Eu. Conf. NDT, (2023).
[3] Lehmann et al.,Comp. Meth. Appli. Mech. Eng., **420, (**2024).
[4] Granados et al., NDT&E Int., **139**, (2023). Nerlikar et al., ''A physics-embedded deep-learning framework for efficient multi-fidelity modelling applied to guided wave based structural monitoring'', under revision in Ultrasonics, (2024).

In situ measurement of microstructure evolution using laser ultrasonics

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Microstructure engineering is a critical aspect for thermo-mechanically controlled processing of advanced metals and alloys. In-situ laser ultrasonics for metallurgy (LUMet) is a powerful tool to monitor grain growth, recrystallization and phase transformations during thermo-mechanical laboratory simulations to expedite the development of microstructure process models. The strengths and limitations of LUMet measurements of microstructure evolution will be illustrated with selected examples for low-carbon steels, superalloys as well as titanium alloys. In addition, the development of LUMet based phenomenological microstructure evolution models will be critically analyzed.

In detail, laser ultrasonics has become an important measurement technique of austenite grain growth in steels based on analyzing the attenuation spectrum. In particular for low-carbon steels, the grain size evolution is challenging to measure with other techniques. Further, LUMet enables high-throughput measurements of the evolution of a representative mean grain size and facilitates thereby new insight into austenite grain growth for a wide range of steel chemistries and heat treatment conditions. A challenge for these grain growth studies remains to identify abnormal grain growth regimes with a mixed microstructure of fine and significantly larger grains where LUMet studies provide important indirect indications of these growth regimes but not yet conclusive evidence of the grain size distribution. Grain growth studies have also been conducted in Ni-based superalloys with elastic properties that are comparable to that of austenite in steels. Further, these grain size measurements can be extended to record recrystallization provided grain refinement occurs during recrystallization. On the other hand, recrystallization in ferrite can typically be monitored with LUMet based on changes in the ultrasound velocity due to texture evolution, i.e. only the recrystallization portion with texture changes are accessible to LUMet. Ultrasound velocity measurements with LUMet facilitate also to monitor phase transformations in steels and titanium alloys. In particular, LUMet is a powerful technique for titanium and its alloys where for example classical dilatometer studies have limitations. In steels, austenite decomposition studies with LUMet are essentially limited to transformations below the Curie temperature which are, however, of significance for many high-performance steels including line pipe and dual phase steels. Above the Curie temperature, the ultrasound velocities in ferrite and austenite are in general the same within the measurement accuracy except for highly-textured ferrite. As a result, monitoring of austenite formation with LUMet is restricted and advancements of the laser ultrasonic technique are being considered to overcome this limitation.

Application of Laser Ultrasonics in Detecting Unusual Austenite Grain Growth Behavior

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As one of the key metallurgical parameters for hot rolling, austenite grain size influences both the kinetics and products of subsequent phase transformation during cooling which determines the final properties of the as-hot rolled steel. Therefore, it is important to properly control the evolution of austenite grain size throughout the thermo-mechanical processing of steel. With the advantages of rapid, non-destructive, and in-situ measurement, laser ultrasonics has been shown to be a powerful tool for monitoring austenite grain growth in a wide range of steels and heat treatment schedules [1,2]. But most of these studies have emphasized nominal isothermal heat treatments and normal grain growth that can be described with a clearly defined average grain size. Less attention has been paid to variation of the non-isothermal heat treatment portions and situations that deviate from normal grain growth. In the present study, a Gleeble 3500 thermo-mechanical simulator equipped with a Laser Ultrasonics for Metallurgy (LUMet) system was used for the measurement of austenite grain growth. First, using a microalloyed line pipe steel it was demonstrated that the measured austenite grain size replicated previous measurements using a different laser ultrasonic system as well as was consistent with ex-situ microscopy observations, both optical microscopy and austenite reconstruction using electron backscatter diffraction (EBSD) mapping. Further, grain growth behavior for a 0.2 wt% C steel was investigated at temperatures between 900 °C and 1100 °C where heating rates of 5 and 50 °C/s, respectively, were employed before isothermal holding. These studies revealed a significant effect of heating rate on the austenite grain size obtained during isothermal holding. Whilst in general the expected increase of austenite grain size with temperatures was observed there was even in this regard a deviation as after fast heating (50 °C/s) the apparent grain size at 900 °C was larger than that at 950 and 1000 °C. With additional microscopy examination on the as-quenched samples, this unexpected behavior was found to be associated with the heterogeneous grain structure which likely resulted from the dissolution of AlN precipitates in the as-received material. It appears that changing heating rates has a tremendous effect on the dissolution kinetics of these precipitates and the resulting changes in pinning pressure on grain growth. The present investigation indicates the versatility of using laser ultrasonics to record the role of different complex heat treatment scenarios on the resulting austenite grain size evolution including the detection of unusual grain growth behavior that for example result from the interaction of grain growth with precipitation.

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An experimental study of elasticity in polycrystalline iron using laser-ultrasonics

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Information from many types of ultrasonic measurements is closely related to elastic properties of the material which derive from its constituent crystals. For isolated crystals there are tensorial descriptions that can be adapted for all types of loading conditions. These parameters describe the basic anisotropy of the crystals which vary from very slight to extreme depending on the material. The situation is less clear when treating the more usual polycrystalline structures. In these, the elasticity depends not only on these purely crystalline parameters but also on their mutual interaction in the composite body. Many models have been proposed in the literature to describe the elastic behaviour of polycrystals but, as far as we are aware, there has never been a rigorous experimental investigation to test these models.

A correct experimental verification necessitates that the test material corresponds to the assumptions on which the models are based and these do not generally apply in readily available materials. The necessary conditions include primarily:

1. Completely random texture giving isotropic behaviour
2. Equi-axed grains
3. A reasonably monotonic distribution of grain sizes
4. Grain size that are small in comparison with the material body to minimize the influence of surface relaxations.

It is also desirable to test the observations over a range of different crystalline anisotropy as, for example, defined by the Zener ratio 2c44/(c11-c12) for cubic crystals.

We have achieved these intentions by hot isostatic pressing (HIP) pure iron power into a fully dense block and then measuring the velocity of longitudinal (P) elastic waves using laser-ultrasonic equipment together with a Gleeble thermal simulator The measurements were made at different temperatures between room temperature and 900°C to vary the crystalline anisotropy. For iron, Zener's ratio varies for 2.42 to 7. 44 over this temperature range.

Resulting values are presented and compared with various theoretical models.

Austenite grain growth in as-cast and as-hot rolled steels

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The manufacturing of high-performance steel products, e.g. line pipe steels, involves carefully tailored thermo-mechanical controlled processing (TMCP). In a hot mill, the as-cast steel slabs are austenized in a re-heat furnace followed by a series of rough and finish rolling passes. These high temperature steps result in austenite conditioning by grain growth and recrystallization followed by cooling of the steel on the run-out table where austenite decomposition takes place to obtain the desired microstructure and properties of the hot-rolled product. Laser Ultrasonics for Metallurgy (LUMet) provides an in-situ, high-throughput, non-destructive method to measure the austenite grain size evolution. Typically, austenite grain growth is measured starting from hot-worked samples but in the present study the emphasis is on simulating austenite grain growth in samples from as-cast slabs of two line pipe chemistries. These grain growth results are compared with those observed when conducting conventional grain growth tests in as-hot rolled samples. LUMet results were supplemented with selected austenite reconstruction mapping using Electron Backscattered Diffraction (EBSD). The LUMet measurements in the as-cast material showed significant scatter in the apparent austenite grain size evolution with little test repeatability. On the other hand, austenite grain growth in the as-rolled material was measured with little scatter and good repeatability. The latter results are within the accuracy of measurements in agreement with the EBSD austenite reconstruction maps that indicate grain sizes of typically less than 100 μm and a homogeneous grain structure following a log-normal size distribution. In contrast, the austenite reconstruction in the as-cast material revealed a mixed microstructure with a few very large grains measuring close to a millimeter and many fine grains with sizes well below 100 μm. These fine grains are typically embedded as rows within the large grains. It appears that they primarily determine the attenuation spectrum in the LUMet measurements which suggested average grain sizes similar to those of these fine grains. These observations are in contrast to previously recorded LUMet grain sizes in abnormal grain growth scenarios where the large grains primarily determine the attenuation spectrum. In these classical abnormal grain structures there are separate areas of fine and large grains with very few fine island grains in the large grains which is unlike the heterogeneous grain structures observed in the as-cast material. Further analysis is needed to appreciate the evolution of these complex grain structures that in the present case are expected to be primarily affected by the distribution of TiN precipitates. In addition, it will be worthwhile to conduct an in-depth evaluation of laser ultrasonic data including potential extension of laser ultrasonic techniques with the aim to obtain in-situ information on grain structure distribution.

In-Situ Grain Size Measurement During Dynamic Recrystallization And Hot Rolling Simulations By Laser Ultrasonics

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The real-time grain size measurement has recently been realized by laser ultrasonics in the hot-rolling process [1]. This enables quality control, the possibility of direct feedback to the process control system, as well as feedback to the set-up calculation which is performed before each transfer bar is sent through the finishing mill to be rolled. The gauge provides novel insights into how the material behaves during production. This is especially useful for low-alloyed steels that phase transform at cooling to room temperature making it difficult to use traditional metallographic methods to estimate prior austenite grain structure.

However, the grain size gauge is currently only installed at one position in the mill, thus, providing measurements at a single point in the process. To better understand how material behaves during the whole process the GLUS® testbed at Swerim, which is the combination of the thermo-mechanical simulator GLEEBLE and laser ultrasonics can be used. The method provides a unique possibility to explore and validate alloying concepts on a smaller scale to increase the understanding of how material properties evolve during for example annealing or hot-rolling processes. In this work, this is demonstrated for an austenitic stainless steel making it possible to confirm LUS measurements with room temperature observations.

Thermomechanical simulations are made corresponding to a 6-stand finishing mill, with different deformation strategies reaching the same total deformation. Grain structure is monitored with laser ultrasonics on 316L. In addition, we will present the results from grain size measurement during the deformation showing the capability of GLUS to capture the microstructure evolution such as dynamic recrystallization.

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ABSTRACTS

Laser Ultrasonics for Monitoring of Metal Additive Manufacturing

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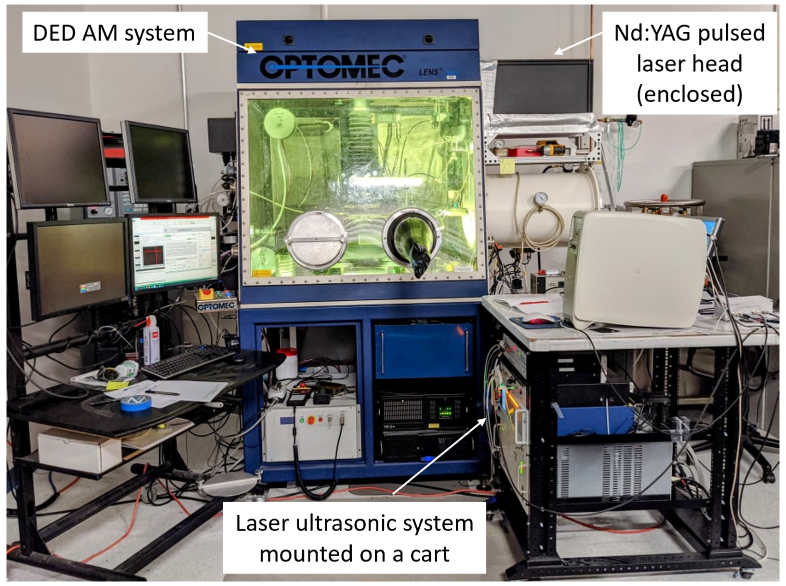

Laser ultrasound system integrated into Directed Energy Deposition Additive Manufacturing chamber

The additive manufacturing (AM) of metal components is a technology that is moving forward at a rapid pace. Although there are many AM variants, using a laser to melt metal powder to form complex shapes is one of the most popular techniques. Two specific forms of laser AM – powder bed fusion and directed energy deposition – are alternatives to machining wrought metals. While flaws in conventional machined parts are most likely to break the surface, flaws in AM parts could be anywhere. Therefore, the requirements for quality assurance testing are entirely different for AM components than machined parts. Researchers are exhausting a broad variety of testing methodologies to identify the best solutions and their limitations.

Some of the challenges of quality assurance testing of AM parts having complex geometries can be mitigated by process monitoring of the layer-by-layer deposition. We propose purely noncontact laser ultrasound generated Rayleigh waves for monitoring the current AM surface layer. An adaptive interferometer is used to detect the broadband Rayleigh wave pulses. Linear ultrasound features can be used for material characterization and flaw detection. However, if we employ nonlinear ultrasound features it should be possible to assess features of the material's microstructure that dictate strength and fracture properties. Early results on Inconel 718 suggest a viable methodology based on the evolution of the progressive waveform. Future tests aim to demonstrate in-situ measurements on rough AM surfaces.

Harnessing Spatially Resolved Acoustic Spectroscopy (SRAS) ++ for Elasticity Imaging of Materials

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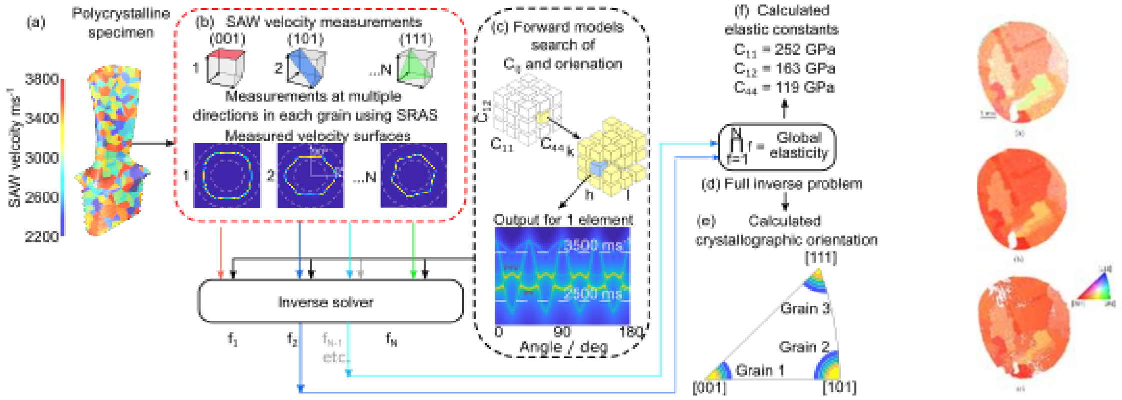

Figure 1. Algorithm schematic of SRAS++ and Cij results of a heat-treated Ni.

Measuring the single-crystal elastic stiffness matrix of polycrystalline materials is critical for predicting the macroscopic mechanical behavior of materials. A new method for measuring the single-crystal elastic stiffness matrix of polycrystalline materials is presented in this paper. It builds on the capabilities of Spatially Resolved Acoustic Spectroscopy, a laser ultrasound technique for measuring the surface acoustic wave velocity. Combining measurements from multiple acoustic propagation directions it is possible to determine the crystal orientation of the grains [1]. This paper details recent work to also determine the elastic constants of polycrystalline materials from the same measurements.

The proposed method for measuring the single-crystal elastic stiffness matrix of polycrystalline materials combines the SAW measurements with an inverse solver to extract both the orientation and elasticity. The ability of the solver to extract Cij without a-priori knowledge of the crystallographic orientation comes from solving Cij globally for a multitude of (initially) unknown crystal orientations [2]. Figure 1 demonstrates this process. A polycrystalline specimen (a) is measured to produce velocity surfaces for each grain (b), these are fed into the inverse solver, where they are compared to the database of velocity surfaces calculated from the forward model (c) for all crystal orientations and for all elastic constants chosen. By determining the best fit (d) across all grains both the individual grain orientations (e) and the shared optimal single crystal elastic constants can be determined (f).

We demonstrate this technique to measure the elastic constants of Nickel alloy (in figure 1) and Titanium, which have hexagonal and cubic crystal structures and discuss extensions of this technique to other crystal structures such as tetragonal materials such as Tin.

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ABSTRACTS

Unveiling the Mysteries of Material Recrystallization in-situ through Spatially Resolved Acoustic Spectroscopy

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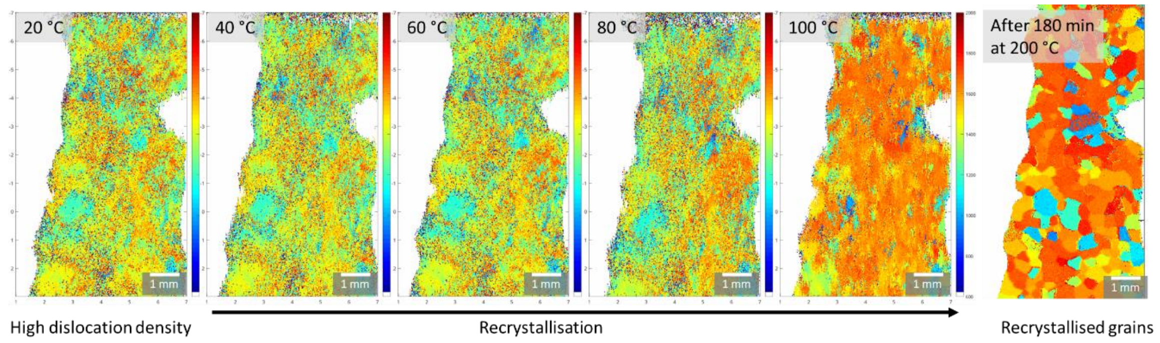

Figure 1. Velocity map obtained at different temperatures (20°C to 200°C) of recrystallisation for Tin.

Monitoring the recrystallisation of materials is crucial in various industries, such as transport, food, and energy. By monitoring these processes, it can be possible to ensure that the desired outcomes are achieved, such as obtaining a specific crystal structure or controlling the grain size of a material by combining different temperatures and times of exposure (annealing). Additionally, understanding recrystallization can offer advancements in material design and the improvement of different properties to confront new industry requirements.

In this paper we demonstrate how the recrystallisation of tin, starting in a highly deformed state, can be monitored using Spatially Resolved Acoustic Spectroscopy (SRAS) [1]. SRAS is a powerful tool for material characterization, capable of imaging the microstructure, identifying the crystallographic orientation of each grain and determining the elastic modulus of various engineering alloys. Notably, SRAS is a non-destructive and versatile technique, allowing for the rapid measurement of large samples compared to other techniques. The SRAS technique utilizes laser ultrasonics to robustly, and repeatably measure the surface acoustic wave velocity. These measurements can then be mapped to create images of material microstructure [2].

We will show the real time monitoring of recrystallization of new grains in regions exhibiting high plastic deformation (Figure 1). This phenomenon is evidenced by changes in the acoustic waves and, consequently, in the elastic properties when the new grains begin to appear in different orientations. This new achievement enables the real-time observation of phenomena occurring at different temperatures, opening up research opportunities that are highly beneficial for materials scientists and other researchers alike.

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Induction hardening depth measurements by laser ultrasound for automotive industry

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Induction hardening is a heat treatment process for improving the hardness and surface wear resistance in the top layer without losing toughness in the core of the component. Induction hardening is typically used for components such as crank shafts in the automotive industry. The resulting hardening depth that impacts the performance, can be varied by changing temperature and/or time. Today the quality control consists of destructive Vickers hardness testing by microscopy only before and after a production-campaign, which may be days or weeks of manufacturing. In a worst-case scenario, the destructive testing after the campaign detects that the quality of the hardened surfaces is below acceptable levels which might require that the whole batch must be scrapped. This work will solve this problem by demonstrating the use of an integrated system based on a non-destructive testing method.

This work will demonstrate how a laser ultrasonic-based system can be used to image the microstructural difference in depth, and thereby quantify the resulting hardening depth. The hardened surface results in a fine martensitic structure compared to a significantly coarser microstructure of the bulk, which can be imaged by looking at the back-scattered signals. The results to be presented will show the accuracy of laser ultrasonic data compared to destructive microscopy. The major advantage with laser ultrasound, compared with other non-destructive testing methods, is that it is a contact free method and is therefore more suitable for inline automation and implementation in complex industrial processes.

ABSTRACTS

Laser resonant ultrasound spectroscopy: analyzing materials with temperature.

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Laser-ultrasound methods are non-destructive techniques for fully contactless characterization of materials. These methods are advantageously usable for measurements at different temperatures, where the direct mechanical contact of the examined material with ultrasonic probes should be avoided.

Resonant ultrasound spectroscopy (RUS) exploits the fact that the resonant frequencies depend on the density, shape, orientation of crystallographic axes and elastic constants of the sample. Thanks to these facts, it is possible to determine the elastic properties of the given material from the resonant frequencies [1].

Our laser-based RUS is able to measure the full set of elastic coefficients and internal friction in millimeter-sized samples. A block diagram of the RUS measurement is shown in Fig 1. Due to the contactless setup, the measured samples are put into temperature chambers. We use three different systems, which differ in temperature range. The cryogenic system is coupled with a nitrogen cryostat, allowing a temperature range of 80K-300K. The second chamber is equipped with Peltier elements, having a temperature range of 240K-400K. The third system has resistive heating modules and a temperature range of 320K-1000K.

The measurements of resonant spectra in such a broad temperature interval (80K - 1000K) allow us to understand the intrinsic behavior of various materials. This will be presented on several types of materials, which e.g. undergo phase transitions, or their elastic properties change with temperature.

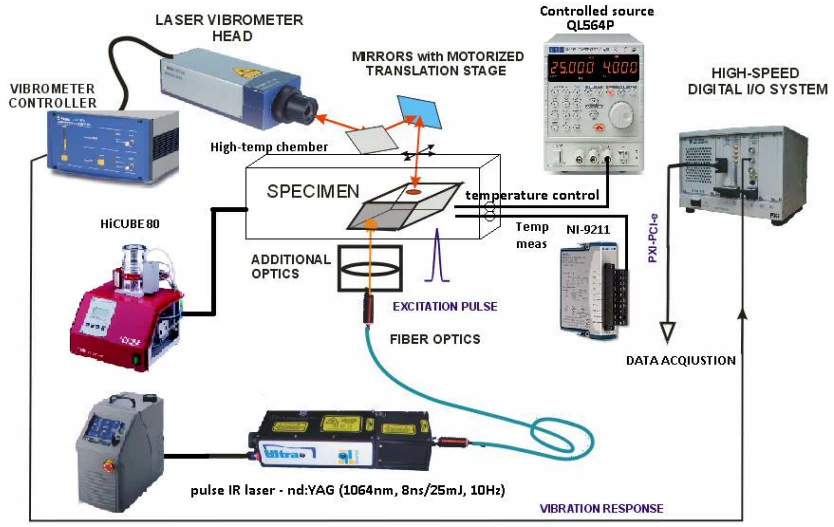

Fig 1. Block diagram of the RUS

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Surface Breaking Crack Detection on Thin-walled Austenitic Stainless Steel Cylindrical Rods with Periodic Ribbed Structures Using Laser Ultrasonics

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Figure 1. Photograph of an AGR fuel rod showing the ribbed pattern and a notch across the ribs.

Advanced gas-cooled reactor (AGR) fuel rods used in nuclear industry are made of thin-walled austenitic stainless steel consisting of periodic ribbed structures. Inspection of the rods for stress-corrosion cracking would enable a preventive regime for fuel storage in water ponds prior to geological disposal. The periodic ribbed structure of the rod offers significant challenges to conventional contact and near-contact non-destructive testing (NDT) methods for crack detection on the rods. This work presents the experimental implementation of laser ultrasonics (LU), a non-contact method, to detect cracks in the fuel rods. An inspection approach is presented where the two lasers for ultrasonic generation and detection are both scanned with a step size equal to the pitch of the thread to ensure that both laser beams are incident in the gap between two adjacent ribs. Short time Fourier transform of the acquired ultrasonic A-scans and dispersion curves are used to identify the generated Lamb wave modes. Crack-like features in the form of electrical discharge machined (EDM) notches are used in this study to demonstrate the method. The presence of the notch induces a mode cut-off feature and frequency shift of Lamb modes due to a change in thickness, signaling its presence. Finite element results are presented to support the experimental findings. Experimental results are presented from an EDM notch of depth 150 µm and width 480 µm, simulating a surface breaking crack, on austenitic stainless steel cylindrical ribbed rods of 15 mm diameter, 330 mm length, and 400 µm wall thickness.

ABSTRACTS

Thin Film Characterization by Transient Grating Spectroscopy

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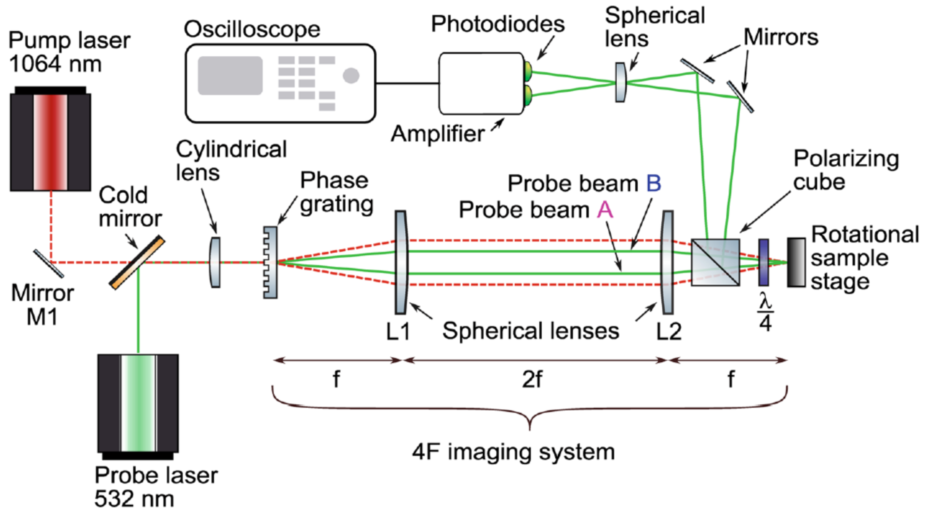

Figure 1. Transient grating spectroscopy setup [1].

Transient grating spectroscopy (TGS) is a powerful technique for characterizing acoustic wave propagation along free surfaces of materials. Using a differential heterodyne detection setup, TGS allows highly sensitive measurement of surface wave velocity dispersion at wavelengths that are larger than but comparable to the thickness of the thin layers typically in the order of micrometers. This enables contactless in-situ local measurements of continuously graded films or epitaxial layers exhibiting anisotropy. The developed minimization-based inverse procedure combined with a Ritz-Rayleigh numerical model can then be used to determine the elasticity and thickness of the film. Furthermore, the model is also capable of simulating a multilayer system, e.g. when a buffer layer is present due to the fabrication process. The approach was used to analyze nickel-titanium films prepared by combinatorial sputtering or epitaxial growth. [1,2] The precise estimation of Young's modulus and the local thickness of the film is crucial for the sputtering process, making this TGS approach a potential tool in the field.

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