Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division VIII

Condition monitoring system for cyclically loaded components using electromagnetic acoustic transducers - EMUS-4-STRESS

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ABSTRACT

Part of the power plant piping is exposed to media temperatures that fluctuate at frequencies of several Hz or even higher, which results in time-dependent temperature gradients and, therefore, varying stress in the pipe wall. Particularly in case of nuclear power plants, where component safety is of utmost importance, this load scenario creates a need for permanently installed, fatigue-related stress monitoring systems. State-of-the-art stress monitoring is performed using thermocouples attached to the outer wall of the pipes, such as in Framatome's FAMOSi. This approach works very well up to physical limits in the order of one cycle per second, beyond which the media temperature alternates too quickly for the thermocouples to notice at the outer wall. Despite not being thermally detectable from the outside, fatigue-relevant stress may be present at the inner pipe surface. The research project EMUS-4-STRESS aims at complementing FAMOSi with high-speed stress monitoring based on ultrasonic time-of-flight measurements using electromagnetic acoustic transducers (EMATs) that transmit and receive an ultrasonic wave from the outside. EMATs have proven their capability to work at temperatures of up to a few 100 °C without cooling. In a first step, four-point bending tests were performed on bars of austenitic steel 1.4550 / AISI 347 (X6CrNiNb18-10). The elastic bending stress was successfully detected using an EMAT transmitter-receiver setup. Using a horizontally polarized transverse (shear horizontal, SH) wave mode yielded the highest stress sensitivity, which was in the order of 25 MPa. Subsequently, the applicability to a pressurized pipe and a disc-shaped, quickly heated and cooled plate was shown. Finally, pressureless pipe test rig was created for investigating the fusion of FAMOSi and EMAT data in upcoming work.

INTRODUCTION

The restructuring of energy production worldwide towards increasing use of solar and wind energy is directly coupled to increasing load dynamics of fossil and nuclear power plants. This leads to an elevated risk of stress-induced fatigue in plant components exposed to varying thermal loads and pressure. Therefore, the knowledge required for decisions regarding continued operation, maintenance and condition monitoring has to be improved. Regarding piping systems, the development of a method for the monitoring of inner-wall stress is particularly relevant. The temperature-based monitoring systems applied in nuclear facilities today (such as Framatome's FAMOSi (Rudolph et al. (2012))) use a load-dependent, quasi-continuously measurable physical parameter (e.g. outer wall temperature) in order to estimate fatigue-relevant time series of multiaxial loads. In certain load scenarios, e.g. in case of high-frequency temperature transients occurring at the inner wall, these methods reach physical limits of their applicability.

The overall goal of the project EMUS-4-STRESS is the development of a method for determining the load-induced stress gradient originating from the inner wall of pipe components in case of fast load transients, by means of measurements at the outer wall, and finally fusing the developed approach with the existing FAMOSi system. The overall goal is approached in several steps: While in the first two phases, the basic applicability of electromagnetic ultrasonic transducer (EMAT) based stress measurement has been demonstrated and an application-specific transducer implementation has been developed for this purpose (Veile et al. (2019)), the main goal of the currently ongoing third phase is the synergetic combination of EMAT and FAMOSi monitoring.

MEASURING PRINCIPLE

Non-destructive ultrasonic (US) time-of-flight measurements based on electromagnetic ultrasonic transducers (EMAT) offer great potential to provide high-frequency acquisition of information on stress gradients and microstructural changes caused by sudden temperature changes inside pipes. Electromagnetic ultrasound excitation makes use of various electromagnetic interactions in conductive or ferromagnetic materials. EMATs use electromagnetic fields to generate ultrasonic sources in the test object, from which ultrasonic waves propagate in the test object. The ultrasonic wave is not generated in the probe, but directly in the test object. This requires two components: on the one hand, a static magnetic field is generated by means of an electric direct current or permanent magnet, and on the other hand, a high-frequency (HF) magnetic field is generated by means of a coil, which is superimposed on the static field. These transducers therefore do not require a coupling agent for ultrasonic injection, but are bound to electrically conductive material due to the excitation mechanisms and must be located close to the surface. Depending on the geometrical structure and arrangement of the coil and the magnets contained in an EMAT, forces are generated in the test object that excite different types of ultrasonic waves (Salzburger (1986)).

Thus, in a first phase of the project, different types of waves were tested, and their sensitivity to stress detection in the austenitic steel 1.4550 (X6CrNiNb18-10) was assessed in terms of the signal-to-noise ratio S/N. This phase also revealed a strong influence of α'-martensite on the transducing efficiency and the ultrasonic time-of-flight. Furthermore, due to the changing and already production-related non-uniform occurrence of ferromagnetic α'-martensite on the surface of the paramagnetic austenitic steel sample, a mode transformation of the ultrasonic wave occurs in the vicinity of the ultrasonic transducers used. Due to this effect, only two types of ultrasonic waves were suitable for detecting the stresses. One is the horizontally polarized transverse wave (SH wave, bulk wave) and the other is the Rayleigh wave (surface wave). In case of a SH wave, the angle of incidence can be varied by using different excitation frequencies. In case of the Rayleigh wave, varying the trace wavelength of the transducer changes the penetration depth of the wave. This concept allows stress states to be determined in different depth ranges from the outside, right down to the inner wall of the pipe.

The measuring principle for detecting stress in the material is based on the acoustoelastic (AE) effect (Hughes, D.S. et al. (1956)). The latter describes the influence of elastic stresses on the speed of sound in the material. If stresses occur, the changes in the measured US time-of-flight vary in relation to the direction of stress, depending on the type of wave used and its propagation and polarization direction. These influences were first investigated in bending tests.

BENDING TESTS

For the bending tests (see Fig. 1), specimens of the piping material 1.4550 (X6CrNiNb18-10) with a length of 550 mm, a width and depth of 30 mm, each one with different phase states of α'-martensite content of 8%, 16%, 25% and pure austenitic phase states, were available. The bending specimens were loaded in increments of 2.25 kN in the range 0 kN - 9 kN, resulting in a maximum edge fiber stress between the compression dies of about 100 MPa at a support spacing of 400 mm and a compression die spacing of 200 mm. Accordingly, it was ensured for the bending tests that all US time-of-flight measurements were carried out in the elastic range.

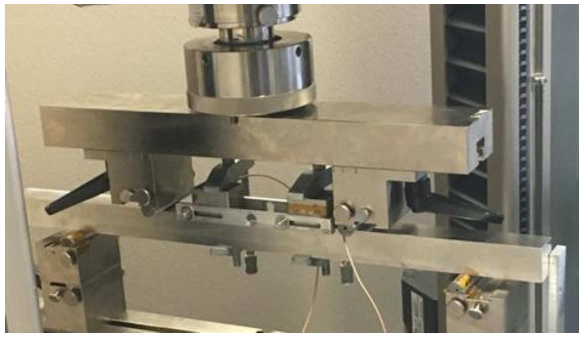

Figure 1. Measurement setup of the bending tests

For the US time-of-flight measurement with the SH and Rayleigh wave transducers, bending tests were performed in gradual increments of the load level. The tests were performed in a way that, at each load level, 20 US time-of-flight measurements were obtained from 128 averaged individual measurements for each of the different beam angles and trace wavelengths were recorded. Figure 2 and Figure 3 show the resulting time-of-flight changes obtained using the SH and Rayleigh wave transducers relative to the unloaded condition for all load levels and all specimens of different α'-martensite content.

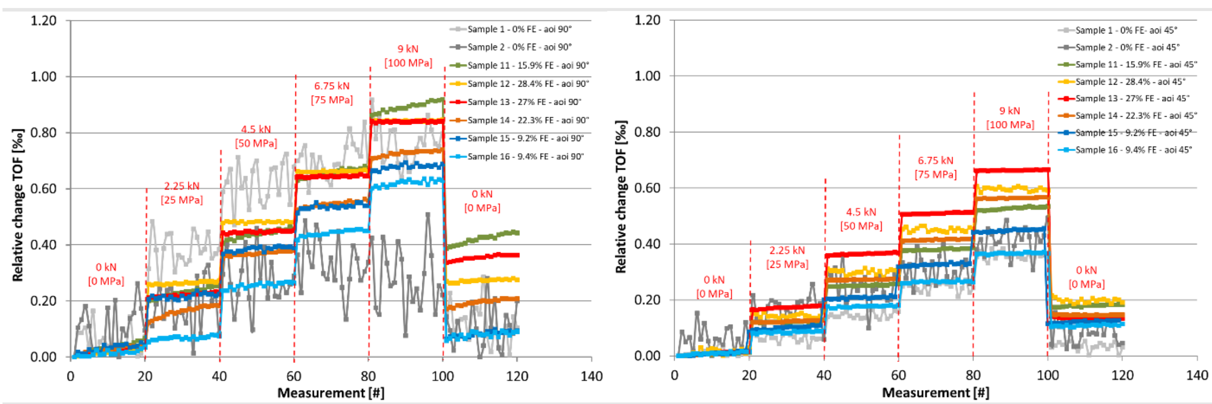

Figure 2. Results of the US time-of-flight (TOF) measurements of the SH wave in the bending test, Left: angle of incidence (aoi) 90° to surface normal, Right: angle of incidence (aoi) 45° to surface normal

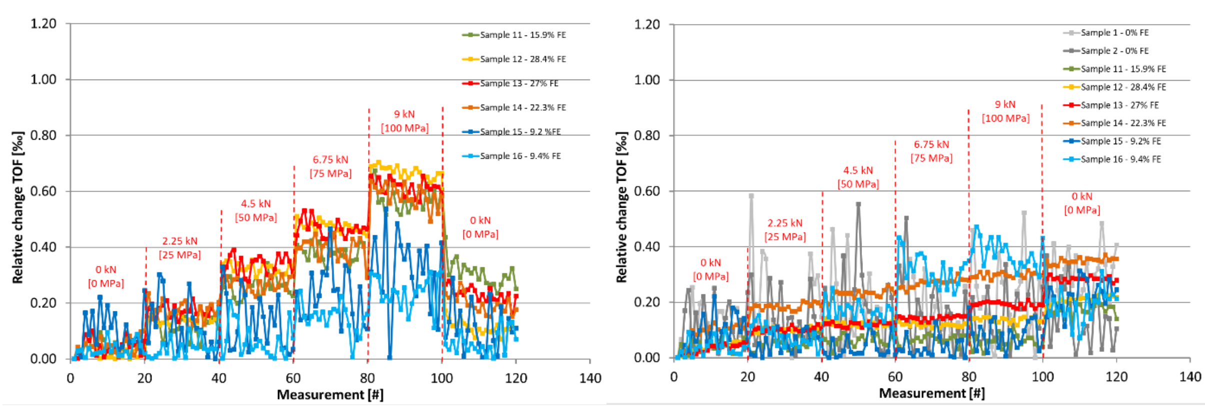

Figure 3. Results of the US time-of-flight (TOF) measurements of the Rayleigh wave in the bending test, Left: trace wavelength of 3 mm, Right: trace wavelength of 6 mm

A clear dependence of the registered US time-of-flight on the individual load levels was observed. Effect size and/or S/N were smaller for purely austenitic specimens and specimen 16 using the grazing SH wave (90° to surface normal). Increased fluctuations in the individual measurements can be explained by the purely austenitic phase condition and the associated scattering of the US waves. Figure 3 shows the time-of-flight changes relative to the unloaded condition obtained using the Rayleigh wave transducers with trace wavelengths of $\lambda_s = 3\,mm$ and $\lambda_s = 6\,mm$ for all load levels and all specimens of different α'-martensite content. It can be noted that the measurements in the discussed bending tests using the SH-wave transducers provide both higher reproducibility of the individual measurements and higher resolution in terms of stress determination than the Rayleigh wave transducers do. At the same time, a clear influence of α'-martensite content (independent of the incident angle of the SH wave) on the measured US time-of-flight was detected. It was shown that a higher content of α'-martensite leads to an increased time-of-flight change. Based on the results shown, it was decided to use the SH-wave transducers for the subsequent investigations on a pressurized pipe.

DEMONSTRATION ON PRESSURIZED PIPE

After the SH wave transducers had shown a good performance in terms of measurement effect and S/N ratio in the bending tests, a new transmitter-receiver pair of this transducer type was built for demonstration on a pipe-shaped sample (still without temperature influence, but now creating stress by pressurizing the water-filled pipe). The transducers were geometrically adapted to the outer diameter of the pipe. This adaptation was carried out in such a way that the propagation direction of the SH wave was in the axial direction and its polarization direction was in the circumferential direction of the pipe, i.e. in the direction of the greatest stress in terms of magnitude, since the best possible resolution of the stress can be achieved in this configuration.

In the following ultrasonic stress determination, the water pressure was varied from 0 to 180 bars in steps of 45 bars, resulting in a load stress of a maximum of 90 MPa in the circumferential direction of the pipe. The SH wave transducers were placed at three positions along the pipe circumference and the time-of-flight was measured for two different angles of incidence (aoi = 90° and aoi = 45° to surface normal) as a function of the internal pressure in the pipe. Same as in the bending tests, 20 ultrasonic time-of-flight measurements were taken for each pressure level, each measurement consisting of 128 averaged individual sweeps for the two angles of incidence. The entire measurement setup is shown in Figure 4 (right). Figure 4 (left) shows the obtained time-of-flight changes using the SH wave transducers relative to the unloaded condition for all set internal pressures of the pressure vessel at three circumferential positions. At all three measuring positions along the circumferential direction (left, center, right) using both angles of incidence, a detection limit in the range of approx. 25 MPa was achieved for both pressurization and pressure relief.

In this first step, the potential of electromagnetically excited horizontally polarized transverse waves using different beam angles for stress measurement was thereby demonstrated for pipe components of the austenitic material X6CrNiNb18-10 operating from the outside of the pipe. Within the ongoing implementation phase of the project, the approach was extended with regard to higher measuring speed (> 10 Hz), improved sensitivity, temperature resistance for 350 °C operating conditions and determination of multiaxial loads. The intention was to implement a performance that allows for complementing the FAMOSi system in speed.

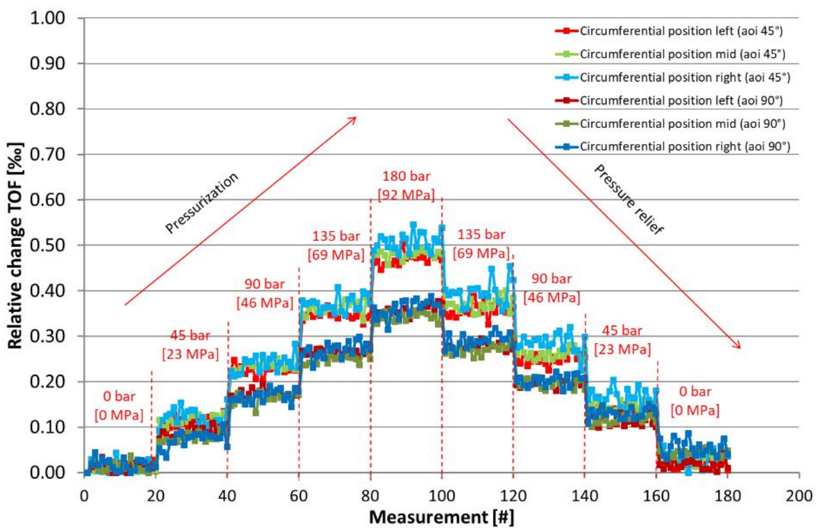

Figure 4. Left: Change in the time-of-flight (TOF) of the SH wave on the pressure vessel for two angles of incidence and three positions depending on the circumferential stress, Right: Demonstration of stress measurement using EMATs on a pipe (position: center) of 1.4550 material

PLATE TESTING BENCH

In order to generate and measure higher temperature and stress gradients, a plate test rig was developed. Figure 5 shows its schematic design as well as the related technical implementation. The plate (1) made of austenitic stainless steel 1.4550 with a diameter of 300 mm and a thickness of 10 mm was fixed in position by means of three clamps. An induction coil (2) connected to a high-frequency generator with 10 kW maximum power from comp. TRUMPF Hüttinger was positioned below the plate with an air gap of 3 mm. A horizontal movement allows the induction coil to be shifted and aligned by means of a stop centered under the plate. Below the induction coil a water pipe with a full-cone nozzle (3) was localized, which enables cooling of the entire underside of the plate at a defined water pressure and distance from the plate. According thermal simulation this experimental setup enables the underside of the plate to be heated up to approx. 350 °C within 40 seconds at maximum generator power and then cooled down quickly by the water cooling system, thus generating fast temperature and stress changes. The simulation was verified by temperature measurements using 11 thermocouples type K positioned at different diameter of the plate and different depth (see. Fig. 5a).

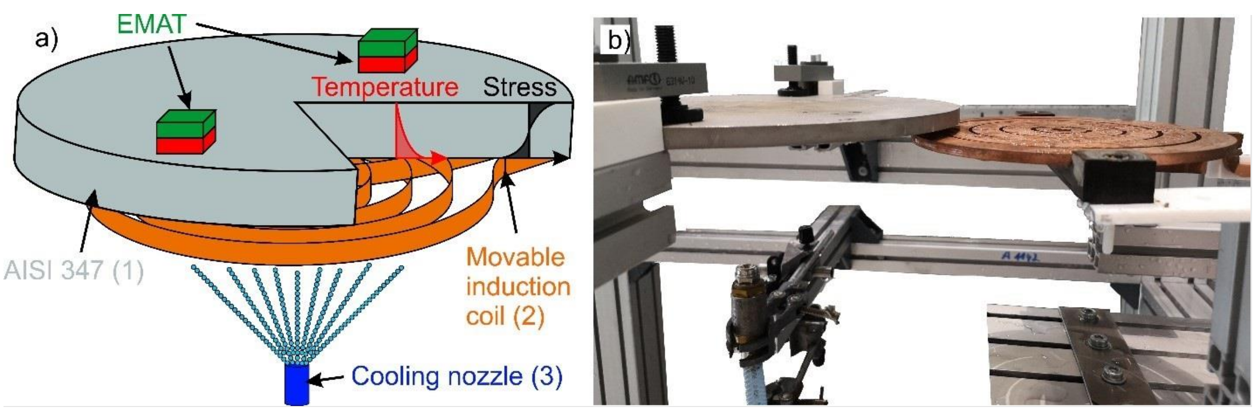

Figure 5. a) Schematic and b) technical design of the experimental setup

For this, several holes with a diameter of 0.5 mm were drilled by means of eroding at defined positions on the top of the plate and to different depths. Figure 6b plots the temperature versus time for a 45-second heat-up with maximum generator power of 10 kW, short switchover time, and subsequent water cooling. Here, the color of the temperature curve corresponds to the indicated position of the thermocouple from Figure 6a. The temperature measurement indicates, a rotationally symmetrical temperature distribution with decrease of temperature with increasing plate radius. Furthermore, the measurement confirms higher temperatures towards the bottom of the plate, as expected. In Figure 6c, the values of the temperature measurement after exactly 40 seconds are compared with the thermal simulation, which shows the temperature curve on the top and bottom of the plate. Taking into account possible sources of error, such as the exact depth position of the thermocouple or the influence of the drilled hole on the temperature flow, acceptable agreement was found.

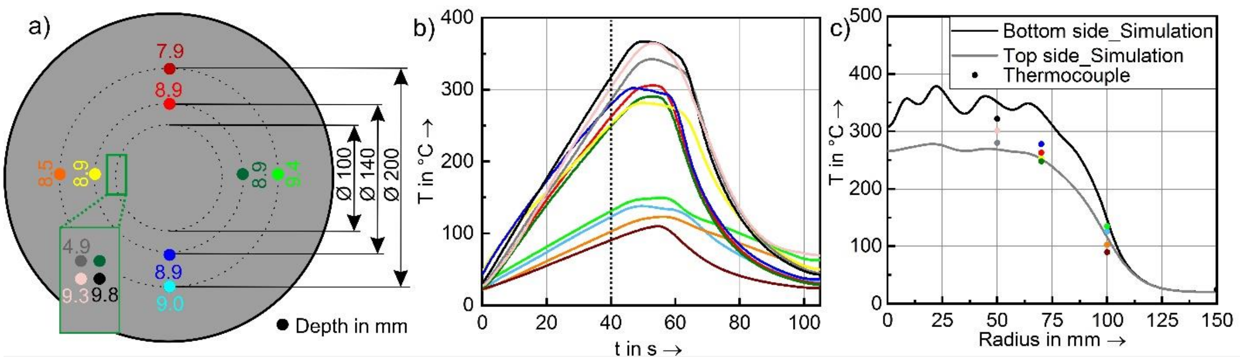

Figure 6. a) Position of the thermocouples b) temperature-time curves and c) temperature after 40 seconds heating time with maximum generator power; comparison of simulation (lines) with thermocouples measurements (points)

The plate test rig with applied EMAT is shown in Figure 7 (left). Compared to the previous experiments shown, these sensors are designed to be waterproof and temperature stable up to 350°C using special magnets and wires. In addition, special sensor housings were made of aluminum, which are equipped with cooling fins so that the heat can be dissipated into the environment as quickly as possible. Transmitter and receiver are mounted on a ceramic rail that keeps the distance between them constant so it can be guaranteed that any difference in time-of-flight is related to the effects in the plate. EMAT measurements were started after heating, otherwise the sensors would be influenced by the magnetic field of the inductive heating. As the cooling process begins, the ultrasonic time-of-flight decrease due to its temperature dependence (see Fig. 7 (right)). The temperature dependence of the ultrasound in the material used, leads to a change in time-of-flight of about 2.1‰ per 10 degrees temperature change and overlaps with the changes in time-of-flight caused by stresses. This explains why the effect that occurs differs significantly in magnitude from the preliminary investigations. As before, the measurement was performed using SH waves with an angle of incidence of 45° and 90° to surface normal, which are alternately excited by switching the excitation frequency during measurement.

The differences in the decrease of time-of-flight between the ultrasonic waves with the two different angles of incidence (see Fig. 7 (right)) can be explained by the different cooling conditions at the top and bottom of the plate, as well as by the different stress components present in the plate. In addition, small plastic deformation of the plate due to the thermal gradients was observed. It can be assumed that this circumstance influenced the travel paths of the ultrasonic waves differently, depending on the aoi. An investigation regarding which stress components are present and how strongly they affect the different ultrasonic time-of-flights is part of the still ongoing project.

The developed US electronics works at a repetition rate of approx. 1000 Hz. In the measurement shown in Figure 7 (right), every 10 subsequent ultrasonic A-scans were averaged, and one time-of-flight value was evaluated from each averaged A-scan. The effective repetition rate of this process therefore is around 100 Hz. As the system automatically alternates the US frequency in order to obtain aoi = 90° and aoi = 45°, respectively, the total repetition rate of the TOF measurement, including averaging and both angles of incidence, is approximately 50 Hz. This rather high-frequency sampling rate of TOF as a stress-sensitive parameter will be used in the future to complement the lower-frequency FAMOSi system. The setup described in the next section will be used for this purpose.

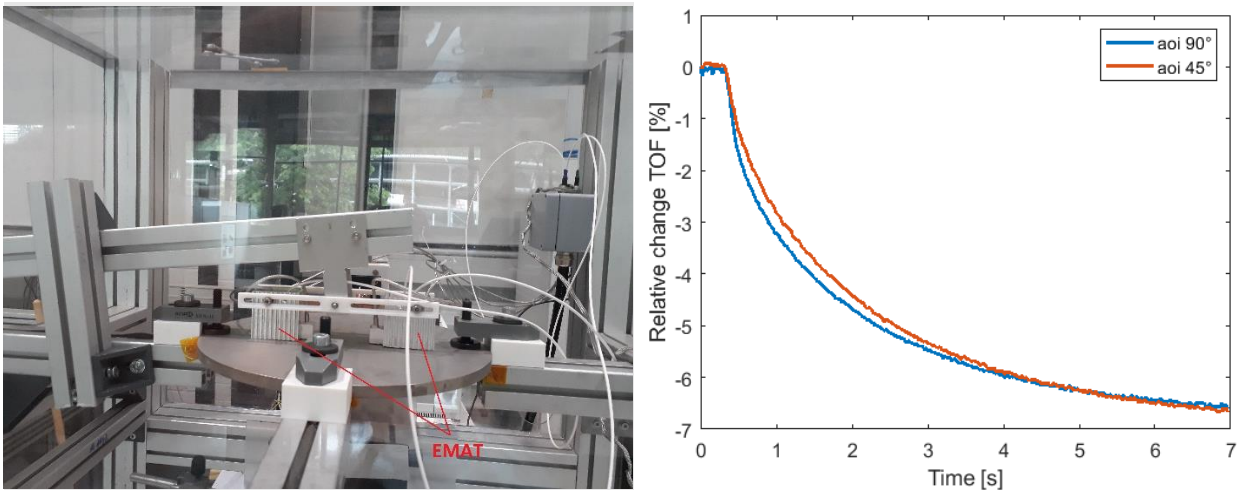

Figure 7. Left: EMAT measurement setup on plate, Right: Change in the time-of-flight (TOF) of the SH wave on plate testing bench for two angles of incidence (aoi) during cooling

PIPE TESTING BENCH

A pressureless piping test facility was designed and erected at Framatome GmbH site in Erlangen / Germany (Fig. 8). It is based on water as a medium and allows for the generation of test transients of different temperature change rates in the temperature range between 10 °C (in winter, respectively 15 °C in summer) and 90 °C. A cooler is used in order to hit the minimum temperature. The piping section is flown through by hot water and the cooling down is realized by jet spraying of cold water in the region of interest. The planned measurement regions on the pipe need space for the sensors (EMAT and FAMOSi hardware).

A simulation of the thermal transient loading scenarios was carried out using Finite Element Analyses. The commissioning of the test stand took place on June 24, 2021 at the Framatome GmbH site in Erlangen. Different temperature change rates were realized and the corresponding temperatures were recorded in terms of fluid and outer pipe measurements as a function of time. The temperature measurement on the outer wall of the pipe was done with and without insulation. The future positioning of the EMAT measurements was considered.

Figure 8. Pressureless test facility at Framatome GmbH site in Erlangen / Germany

A dedicated test series (still without applied EMAT) was realized. Four load cases (transients) with cycle periods of 400 s (load case 1), 40 s (load case 3), 10 s (load case 4) und 4 s (load case 5) were carried out. An additionally planned cycle period of 2 s (load case 2) could not be carried out due to the switching inertia of the test rig. The data recording was carried out at a frequency of 4 Hz, and the results were documented. All tests were successfully simulated by way of FAMOS FFE (see Rudolph, J. et al (2012)) in the following steps: importing the measurement results in FAMOSi, calculation of the inner wall temperatures by way of FAMOSi FFE, calculation of the inner wall stresses by way of FAMOSi FFE, calculation of the courses of temperature by way of ANSYS, calculation of the courses of stresses by way of ANSYS, importing the ANSYS calculation results in FAMOSi, comparison of results FAMOSi FFE versus ANSYS, discussion of results. The finite element model used for the transient simulation is shown in Figure 9.

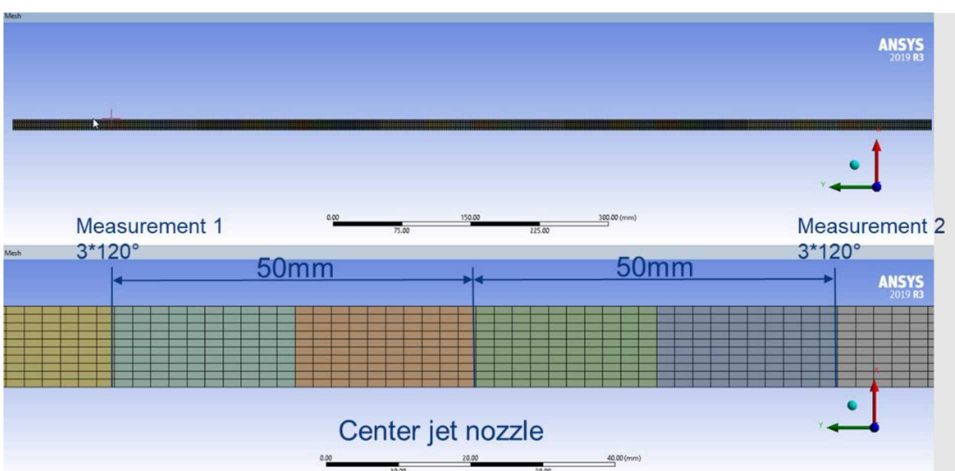

Figure 9. Finite Element model for transient simulation

The ANSYS results are used for benchmarking the FAMOSi FFE results in terms of the capability to resolve rapid repetitions of transients based on the outer wall temperatures and the calculation of inner wall temperatures. The temperature gradient amounts to 100 K/s.

The following conclusions were drawn: 1. Temperatures in the region of interest are almost equally distributed; 2. For the load cases 1, 3 and 4 there is a good agreement of stresses calculated by way of FAMOSi FFE and ANSYS; 3. For the load case 5 there is no good agreement of stresses calculated by way of FAMOSi FFE and ANSYS. The axial stresses calculated by way of FAMOSi FFE only amounted to about 50 % compared to ANSYS. This is shown as an example in Figure 10.

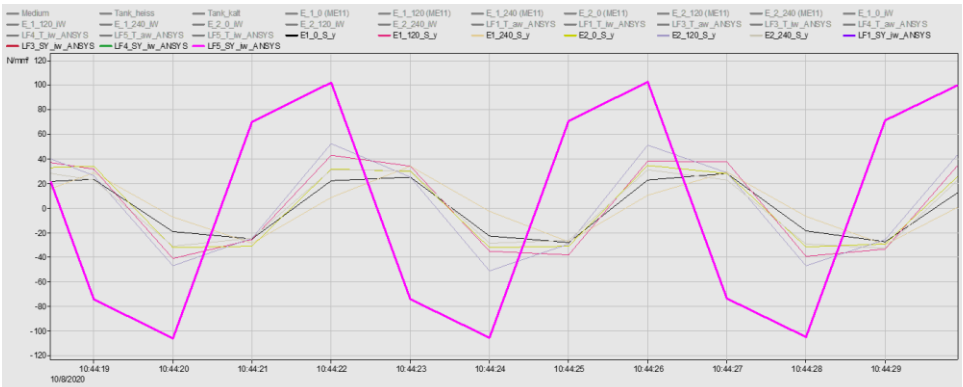

Figure 10. Comparison of axial stress results at the inner wall obtained by way of ANSYS (pink curve) and by means of FAMOSi FFE (other curves) for load case 5.

For comparison, axial stresses obtained by means of ANSYS and by means of FAMOSi FFE are almost equal in the case of the slow repetition of transient load case 1, as shown in Figure 11.

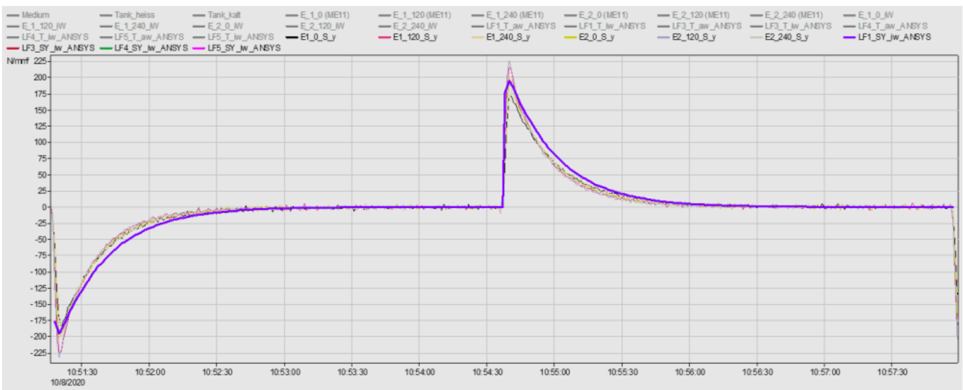

Figure 11. Comparison of axial stress results at the inner wall obtained by means of ANSYS and by means of FAMOSi FFE for load case 1.

Under the conditions of load case 5 the limits of FAMOSi FFE for the calculation of rapid repetitions of transients are reached. For this load case, which is to be repeated, the intended synergies between FAMOSi and EMAT are to be demonstrated in the ongoing project.

CONCLUSION

EMATs were used to detect inner-wall stress in in austenitic AISI 347 steel, based on ultrasonic time-of-flight changes that were measured by exciting and receiving the US wave from outside the pipe. The overall goal and intention of this approach is to complement existing thermal stress monitoring with high-speed EMAT measurements. Bending tests on rectangular bars and experiments using a pressurized pipe have shown that, stresses down to 25 MPa can be detected with EMATs. Moreover, stress gradient transients were created by inductively heating and water-cooling a plate of AISI 347 steel, and successfully detected with a temperature-stable EMAT setup. Further validation will be performed, amongst other tests, in a pressureless piping test rig at Framatome GmbH, Erlangen. The test rig was implemented, and the detection limits of FAMOSi were validated using FEM and experiment.

ACKNOWLEDGEMENTS

The authors would like to thank the German Federal Ministry of Economics and Technology for the financial support of the project family EMUS-4-Stress (EMUS-4-Stress 1: FKZ: 1501475; EMUS-4-Stress 2, FKZ: 1501554; EMUS-4-Stress 3, FKZ: 1501603).

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