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Optimised FEM Simulation of Automated Acoustic Non-Destructive Testing of Spot Welds

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Summary:

Resistance spot welding is the prevailing technology used to join metal sheets. To guarantee weld strength and prevent structural failure, reliable quality control tests are indispensable. In an effort to automise the predominantly manually performed inspection, novel methods for automated weld spot inspection need fast simulation models with reasonable accuracy for optimisation. This work describes the process by means of a multiphysical FEM simulation of a spot weld measurement procedure. Various simulation approaches were used to obtain the best matching results with experimental data.

Keywords: Non-destructive Testing, Acoustic, Spot Weld, Simulation, Optical Microphone

Introduction

While spot welding processes are usually fully automated, the pre-dominantly used ultrasonic quality inspection is generally performed manually with handheld devices. This is associated with high labour costs and inspection results, which are prone to human errors. Consequently, car manufacturers have sought to automate this inspection process since years. The reason robot-automated testing solutions are not standard yet is related to the fact, that conventional ultrasonic testing technologies are contact-based and require a liquid coupling agent or physical contact with the weld surface itself. [1] Besides being sensitive to surface conditions like tool-imprints or roughness, such probes also require sub-mm lateral positioning, exact angular alignment and accurate contact-pressure in order to provide reliable results. [2]

A promising novel approach for automated weld-spot inspections is the combination of laser-excited ultrasound and an optical microphone, termed Laser Excited Acoustics (LEA). Typically, with LEA a contact-free scanning procedure is applied to do inspection. [3] Along the scan path, the excitation laser is pulsed on the surface, generating an impulse-like ultrasonic shockwave through thermoelastic expansion, see Fig. 1. For thin metal sheets typically used in car manufacturing, the laser excitation generates lamb waves. These waves propagate through the metal sheets and are influenced by the weld-spot geometry. Subsequently, for each laser pulse, the leaky lamb waves can be captured in air with the optical microphone at a certain distance from the excitation position. The results of LEA can be used to extract weld-spot parameters such as the nugget diameter. This work describes the setup and optimisation of a multiphysical FEM simulation model of the LEA measurement procedure. With the derived simulation model, valuable insight in the dependency of the measured signal to the experimental setup and material parameters can be gained without the need of time-consuming sample preparation and measurements.

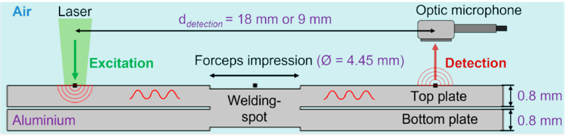

Fig. 1. 2D view of the spot weld setup with laser as optical excitation and optical microphone as detector

Simulation

For the FEM simulation the software "COMSOL Multiphysics" is used to simulate the propagating mechanical waves in the plates joint by spot welds. In this process, the interfaces "Solid Mechanics" and "Pressure Acoustics" are used to simulate the interaction between the mechanical waves in the plates and the pressure acoustics in air, for parameters see Fig. 1. With a parameter sweep and a time dependent solver the resulting signals are determined. To be more memory and speed efficient, an iterative solver is used, instead of a direct solver. With these settings the optimised simulation should achieve a similar result as the experiment. To achieve a time optimised simulation, simplifications are used to reduce the simulation time. All applied simplifications have to retain a certain level of accuracy. Therefore, the following methods were tested: Different excitation/detection method, Pressure/displacement similarity, Geometry changes.

Results

Similar to the experiment, the 2D simulation captures the pressure in air at the detection spot. Due to the large processing and memory usage, the 3D simulation instead is reduced to capture only the displacement of the top-plate. To prove, that there is only a small difference in the results between the captured signals in air and on the surface of the top-plate, an additional simulation was used for confirmation.

In Fig. 2 profile curves, which represent the detected and processed signals, with a variety of the mentioned simplifications are shown. For all 3D simulations a smaller bottom-plate has been used to reduce the geometry. In addition to that, the sensor's field of view for signal detection for all simulations has been simplified as a point detection. The 2D mechanical (mech.) coupled, 3D mech. $d_{detection}$ = 18 mm and 3D mech. $d_{detection}$ = 9 mm simulations use a mechanical point excitation on the top plate surface, as a simplified representation of the laser beam. To see the influence of the distance between the excitation and detection a simulation with a smaller spacing ($d_{detection}$ = 9 mm) was performed. With the comparison of these two profile curves, it can be seen, that the difference is marginal and consequently a small change of distance is negligible. The fastest simulation was achieved for plane wave excitation and multiple detection points, which has the advantage to capture all detected signals in one simulation without changing the detection/excitation position.

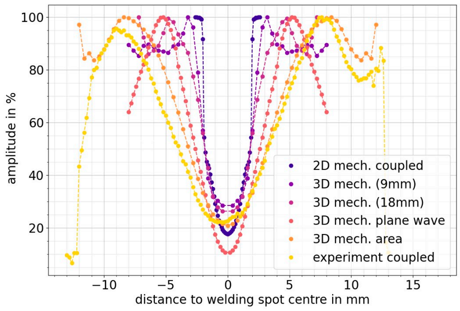

Fig. 2. Comparison of the simulated profile curves and the experiment profile curve at a welding spot diameter of 4.45 mm

For the 3D mech. area excitation simulation, which has the most similarities to the laser excitation, an area was used for the excitation. Due to the extended excitation area, the model symmetry could not be fully exploited and the model size had to be slightly increased.

In comparison to the experimental data the simulated profile curves are narrower. In course of this the 2D simulation reaches and stays at its maxima at the welding spot diameter. The 3D simulations all show a similar profile curve shape, which has a minimum in the middle, two maxima and an attenuation after the maxima. Notable is, that the distance between the two maxima of the profile curves change drastically with the change of the excitation method. Furthermore, it can be observed, that the profile curve of the experiment data is not symmetrical. The slight deviations of each side could be caused by the not perfectly symmetric welding spot and the surface conditions of the experiment.

Tab. 1: Comparison simulation runtime

Simulation type	Approx. runtime
2D mechanical and coupled	12 h to 14 h
3D mechanical, plane wave excitation	1 h to 2 h
3D mechanical $d_{detection}$ = 18mm	12 h to 16 h
3D mechanical $d_{detection}$ = 9mm	7 h to 10 h
3D mechanical, area excitation	16 h to 20 h

Conclusion

The best fitting profile curve to the experiment can be obtained by the simulation with the area excitation method, which has a longer runtime, as seen in Tab. 1 and uses more memory. Nevertheless, due to the simultaneous usage of the optimisations: excitation/detection method (area excitation / point detection), displacement similarity and geometry changes (minimised bottom plate), the experiment profile curve can be simulated in a reasonable time with limited processing resources. This allows for further studies on the dependencies on geometry and material parameters.

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