Making the invisible visible

Real-time analysis and technological developments in laser joining

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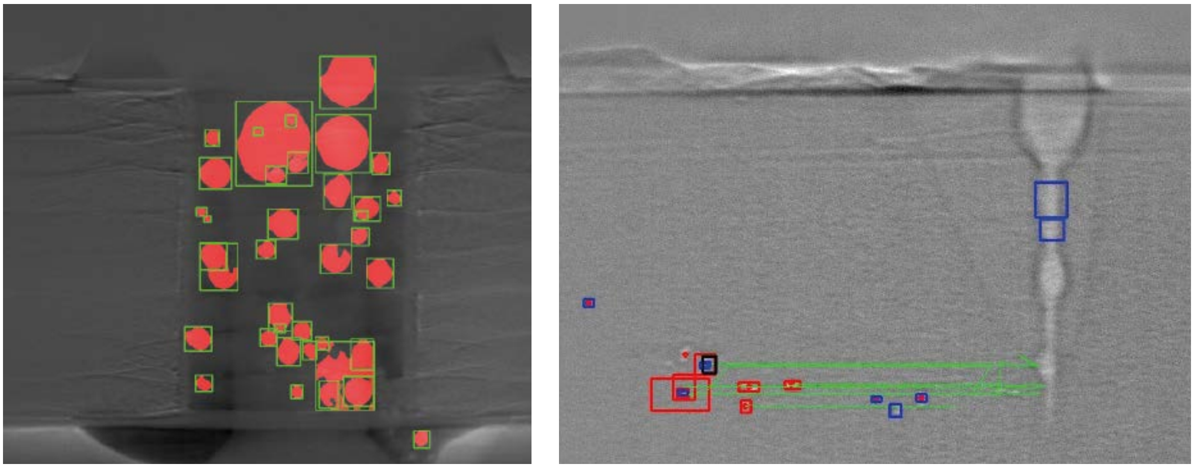

Real-time synchrotron X-ray imaging with high-speed cameras and deep-learning segmentation quantifies keyhole dynamics, porosity, and void evolution in laser welding and soldering. These measurements are correlated with multispectral optical emission data to derive robust sensor-based defect indicators and process windows. The resulting time-series models classify weld porosity and keyhole instabilities with high accuracy and identify flux activation and flux boiling as the main sources of macrovoids in through-hole solder joints, providing a foundation for digital twins that reduce development effort and increase process reliability.

Reliable laser joining in mechatronic devices is essential for modern electronics and e-mobility. However, melt dynamics and defect formation occur inside the material and remain hidden from most conventional monitoring techniques, which only capture the surface or the final joint. Using synchrotron X-ray imaging, combined with industrial laser sources and high-speed cameras, we directly observe internal dynamics during laser welding and soldering in situ. Phase contrast X-ray videography combined with deep learning-based image analysis reveals how keyholes and pores evolve in welds. In solder joints, the same approach shows how flux activation and flux boiling generate and transport voids in Sn-Ag-Cu joints on FR4 circuit boards. By correlating these X-ray insights with optical emission sensor data, we derive sensor-based indicators for internal defects and robust process windows. This lays the groundwork for data-driven process models and, ultimately, digital twins of laser joining operations that shorten process development and improve reliability.

How synchrotron X-rays make laser processes visible

Process diagnostics is a cornerstone of repeatable, high-quality laser-based material processing. Early detection of anomalies and defects reduces scrap, rework, and unplanned downtime. At the Deutsches Elektronen-Synchrotron (DESY) in Hamburg, laser processes were investigated by combining industrial laser setups with the high-energy X-ray beam of the PETRA III synchrotron. The core idea is to place the workpiece at the intersection of the laser beam and the monochromatic X-ray beam (beamline P07), enabling in situ transmission imaging during welding or soldering. The transmitted X-rays are converted into visible light by a thin GaGG:Ce scintillator and recorded with a high-speed camera (iSpeed727) at several kilohertz frame rate and a spatial resolution below 5 µm. This phase-contrast imaging, where small density differences create contrast, makes the solid, liquid and vapor phases – including the keyhole, melt pool and pores or voids – directly visible inside otherwise opaque materials.

For the laser welding experiments, continuous-wave (cw) infrared disk and fiber lasers were used to weld copper samples. The samples were mounted on a linear axis and

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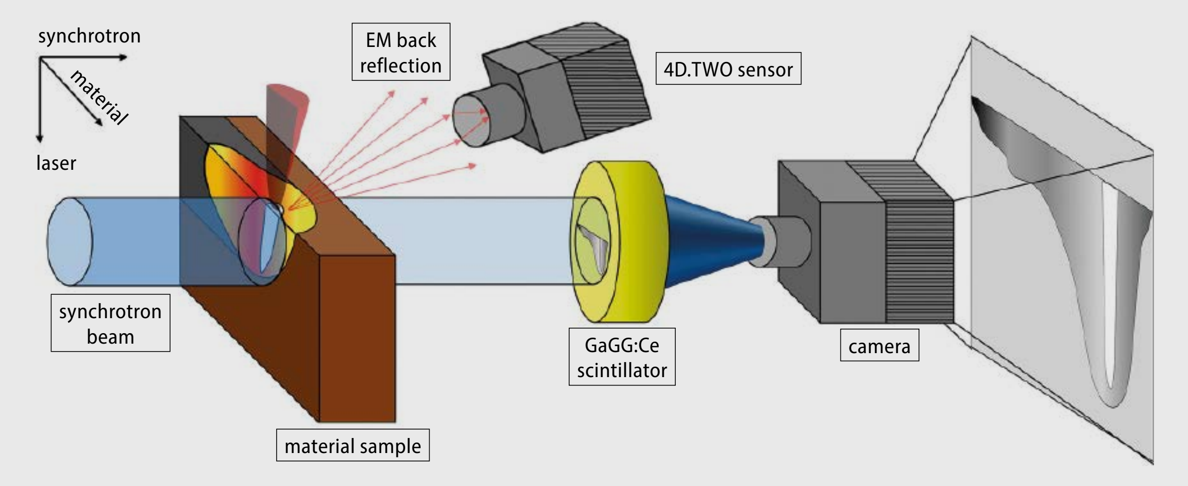

Fig. 1 Schematic experiment setup at DESY P07 for laser welding with simultaneous X-ray and process emission recording

moved at constant speed through the crossing point of the laser and synchrotron beam, generating long, well-defined weld seams that could be imaged over time. For laser soldering experiments, through-hole pin headers on FR4 PCBs were soldered using a 450 nm blue diode laser and Sn-3.0Ag-0.5Cu solder wire. A multisample carrier was positioned statically in the beam intersection, allowing multiple solder joints to be examined under identical conditions.

In all cases, the synchrotron recordings were synchronized with external process sensors. A multispectral 4D.TWO sensor observed the process from an off-axis position and recorded optical emissions from 353 – 1850 nm in 32 bands at 5 kHz. The raw X-ray image sequences were flat-field corrected, contrast-enhanced, rescaled, and analyzed using deep-learning-based instance segmentation (Mask-R-CNN/YOLO) to extract keyhole geometry, melt pool shape and pore/void statistics frame by frame. This combination of in situ synchrotron imaging and synchronized emission data provides a time-resolved, quantitative view of internal process dynamics and defect formation in both laser welding and soldering, which cannot be obtained using conventional surface-based monitoring.

Example 1: Laser welding – correlating emission signals and internal defects

Validating laser weld quality in metallic materials is difficult. Keyhole dynamics and pore formation occur inside the workpiece on millisecond time scales and are only indirectly reflected in conventional surface-based sensors. In this practical example, multispectral process emission data are systematically correlated with in-situ synchrotron X-ray imaging [1]. The emission sensor measures optical radiation in 32 spectral bands, while the X-ray images serve as ground truth for internal defects.

Copper alloys Cu ETP and CuSn6 with thicknesses of 2 – 3 mm are welded using several continuous wave infrared disk and fiber lasers (1030 and 1070 nm, up to 7.7 kW). To extract quantitative defect information, a Mask R CNN network segments the keyhole and pores in the X-ray videos

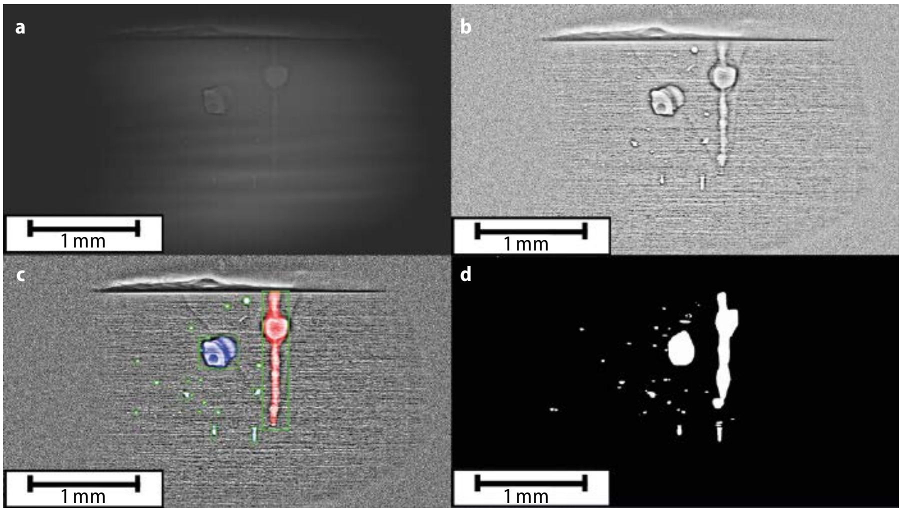

Fig. 2 Raw DESY recording (a, brightness increased); post-processed (b), flat-field corrected, contrast-enhanced and rank filtered; AI-annotated and segmented (c); extracted geometric information (d)

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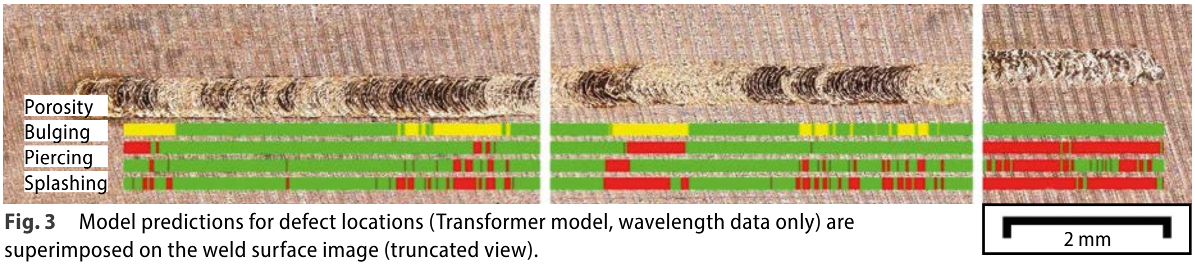

Fig. 3 Model predictions for defect locations (Transformer model, wavelength data only) are superimposed on the weld surface image (truncated view).

(**Fig. 2**). This deep-learning model segments the vapor capillary (keyhole) and individual pores frame by frame, yielding time-resolved geometric statistics such as keyhole depth and width, pore size and position, and melt pool boundaries.

From these X-ray sequences, we construct weld quality labels. Porosity is expressed in four ranges of projected pore area (0 – 1 %, 1 – 5 %, 5 – 15 %, 15 – 100 % of the melt region). In addition, three keyhole defect types are defined:

- Bulging (strongly bottom-heavy keyhole volumes that tend to trap gas)
- Piercing (fast depth changes)
- Splashing (rapid changes in keyhole opening associated with blowout).

The central idea is to use synchrotron-based labels to calibrate and interpret the much cheaper emission data. Because the 32 spectral channels are strongly correlated, preliminary analyses with Principal Component Analysis and autoencoders show that only a few latent variables already capture more than 95 % of the variance. This indicates that many channels are redundant and can later be pruned without losing defect-relevant information.

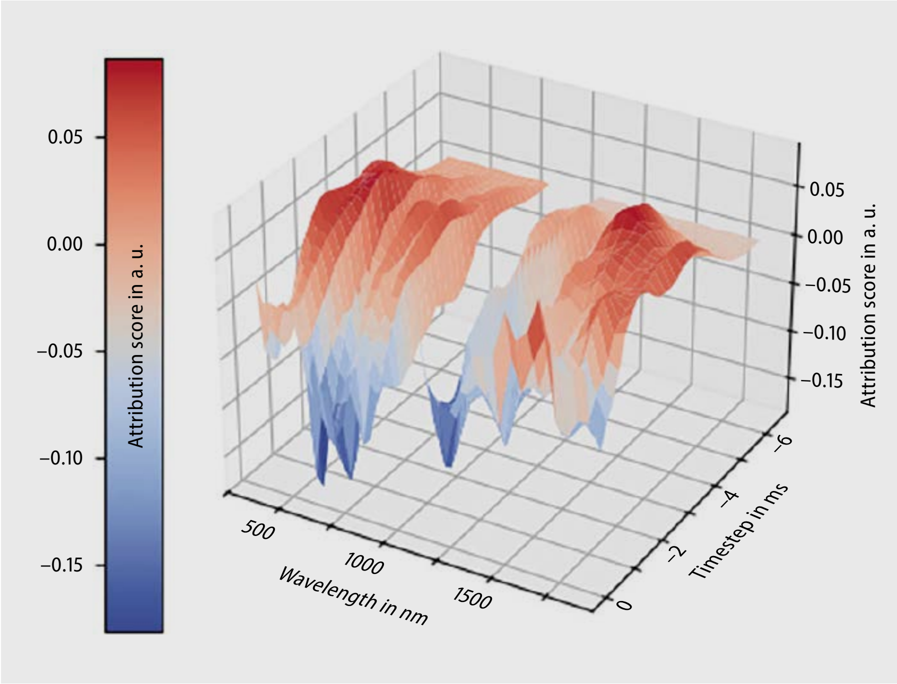

Fig. 4 Normalized LSTM IG attribution analysis for bulging keyhole defect over the whole dataset (negative attributions blue, positive attributions red)

In the next stage, deep time-series models (LSTM and Transformer architectures) are trained to predict defect labels derived from the X-ray data using only the emission data. Despite the imbalance between “good” and “defective” segments, the best models achieve around 90 % overall accuracy, with especially high accuracy for strongly porous segments. This shows that local temporal context in the emission signal is crucial for reliably distinguishing porosity levels and keyhole instabilities.

Applying the trained models to real welds demonstrates that predicted defect locations correlate well with visible surface irregularities such as blowouts and weld pool disturbances, even though the labels were derived from internal X-ray imagery (**Fig. 3**). The sensor-only model can thus reconstruct a time-resolved defect map along the weld seam.

The third pipeline stage uses the attribution method Integrated Gradients to analyze which wavelengths and time intervals contribute most to each defect decision. In simple terms, this method estimates how much each input feature “pushes” the model towards a certain classification. For bulging keyholes, for example, the analysis reveals characteristic patterns (**Fig. 4**): an overall increase in emission across the spectrum several milliseconds before the event, followed by specific shifts between visible and infrared bands as the keyhole volume expands and absorption conditions

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change. Aggregating these patterns over many welds provides a data driven ranking of spectral channels that are most informative for a given defect type. This data driven ranking helps to design leaner sensor configurations by focusing on the most informative spectral bands.

Example 2: Laser soldering – understanding void formation in through hole joints

The study focuses on soldering 2.54 mm through hole pin headers to FR4 printed circuit boards (a standard glass fiber-reinforced PCB material) using flux-cored Sn-Ag-Cu (SAC305) solder wire [2]. A 450 nm blue diode laser (approx. 40 W, 250–350 ms exposure) is used to exploit the higher absorption of solder and copper compared with conventional infrared lasers, improving initial coupling and reducing the energy needed for wetting and filling the via. Phase contrast effects enable separation of solid, liquid and gaseous phases, so solder flow, flux behavior and voids can be tracked in real time inside an otherwise opaque joint. This is crucial, because conventional X-ray inspection provides only static images after the process, whereas here the complete dynamic evolution is visible.

From the segmentation masks, geometric statistics such as pore size, total projected pore area, position in the via, and temporal evolution are derived. This enables quantitative analysis of how voids nucleate, grow, merge, move, and shrink during the entire soldering and cooling cycle. Two main mechanisms for macrovoids (≥ 100 µm) were identified:

Flux activation

In the early heating stage, flux is transferred from the solder wire to the hot header pin. Activators reduce oxide layers and release gases (VOCs, CO_2, water vapor). Small bubbles form at the interface between pin, flux and partially molten solder (**Fig. 5**). These micropores are initially below or near the 100 µm threshold but merge as molten solder is drawn into the via by gravity, surface tension and capillary forces. This aggregation of micropores into macropores is clearly visible in the high-speed X-ray data and shows that even moderate energy input can lead to void formation if flux gases cannot escape.

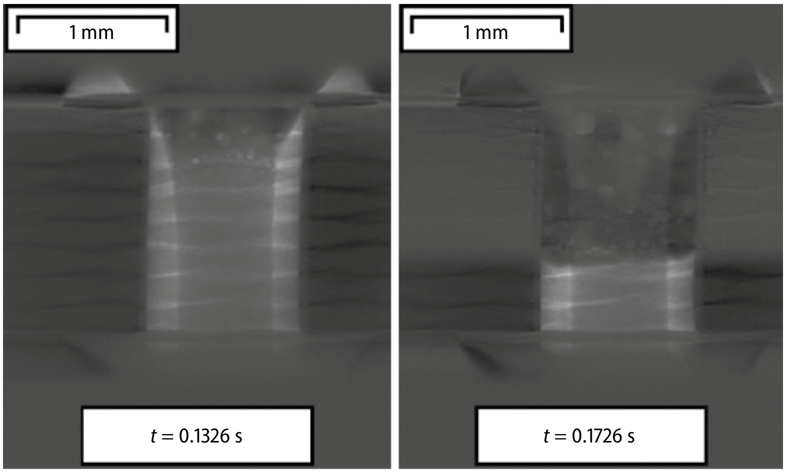

Fig. 5 Flux activation in progress, converting the oxide layer of the header pin into gaseous form illustrate how small bubbles nucleate at the pin-solder interface and later merge into macrovoids ($P(L)$ = 40 W, t = 350 ms).

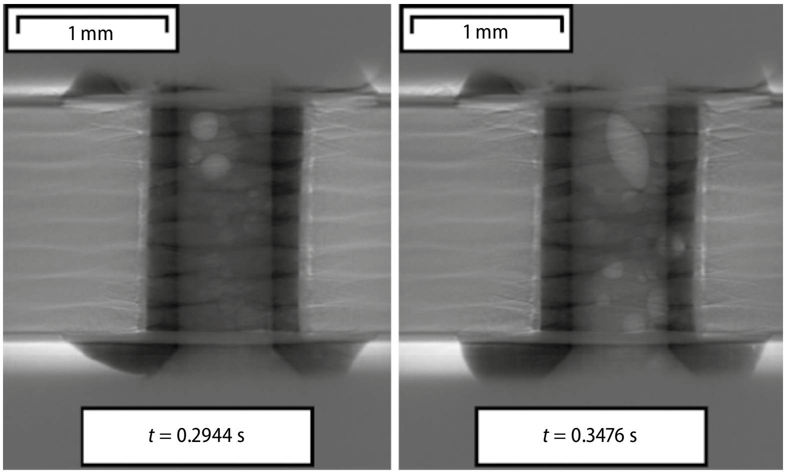

Fig. 6 Flux boiling due to overheating shows violent pore expansion and ejection when the energy input exceeds the optimal process window ($P(L)$= 40 W, t = 350 ms).

Flux boiling due to overheating

To shorten cycle times, holding time should be reduced and laser power increased. However, this can oversaturate the solder and flux with energy, causing the flux to decompose and boil, which leads to rapid expansion and collapse of gas bubbles (**Fig. 6**). The AI-derived total pore area development over time shows a distinct regime where large pores suddenly form and are violently moved or expelled from the joint. This "boiling regime" dominates macrovoid formation when the energy input is too high.

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Conclusion

The laser welding investigations show how high-cost in-situ synchrotron imaging can be used once to calibrate and interpret comparatively simple optical sensors. After calibration, the multispectral sensor alone can classify weld segments into porosity classes and keyhole defect states in (quasi) real time with high accuracy. This reduces the need for destructive testing, supports lean sensor design by highlighting redundant wavelengths, and lays the foundation for robust, data-driven process monitoring and digital twins for laser welding of copper and related materials.

The combination of blue-laser soldering, in situ synchrotron imaging, and deep-learning-based pore analysis enables detailed, time-resolved understanding of void formation inside through-hole solder joints. Macrovoids mainly arise from flux-related gas formation, especially during overheating. From these observations, process windows for laser power and interaction time can be derived to minimize flux boiling while ensuring complete filling. Board design (via geometry, FR4 quality) and preconditioning (moisture control) are identified as key levers for reducing void nucleation.

Overall, we demonstrate a scalable methodology using synchrotron-based in situ diagnostics and AI to build physically informed, data-driven models of laser material processing and then transfer this knowledge to robust, sensor-only monitoring in industrial environments. This forms a key building block for digital twins of laser welding and soldering processes, which promise shorter development cycles, reduced trial-and-error effort, and higher process reliability for future mechatronic applications.

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