

High-Speed Forming Limit Curve (FLC)

Full-Field Deformation Analysis and FLC Determination via 3D DIC in Nakajima Testing

The **Nakajima test** is the most common technique used for determining the **forming limit curve** (FLC) in sheet materials. The FLC describes the maximum formability of the material, making it possible to reliably **assess the failure behavior** of a sheet metal and select the ideal material for a desired forming process. Forming limit analysis significantly **reduces** development times, **increases** product quality, and serves as a vital material parameter input for finite element method (FEM) simulations.

This case study was conducted in collaboration with our Austrian partner, **4A engineering**. The puncture force was applied using their **Linovis** dynamic testing machine.

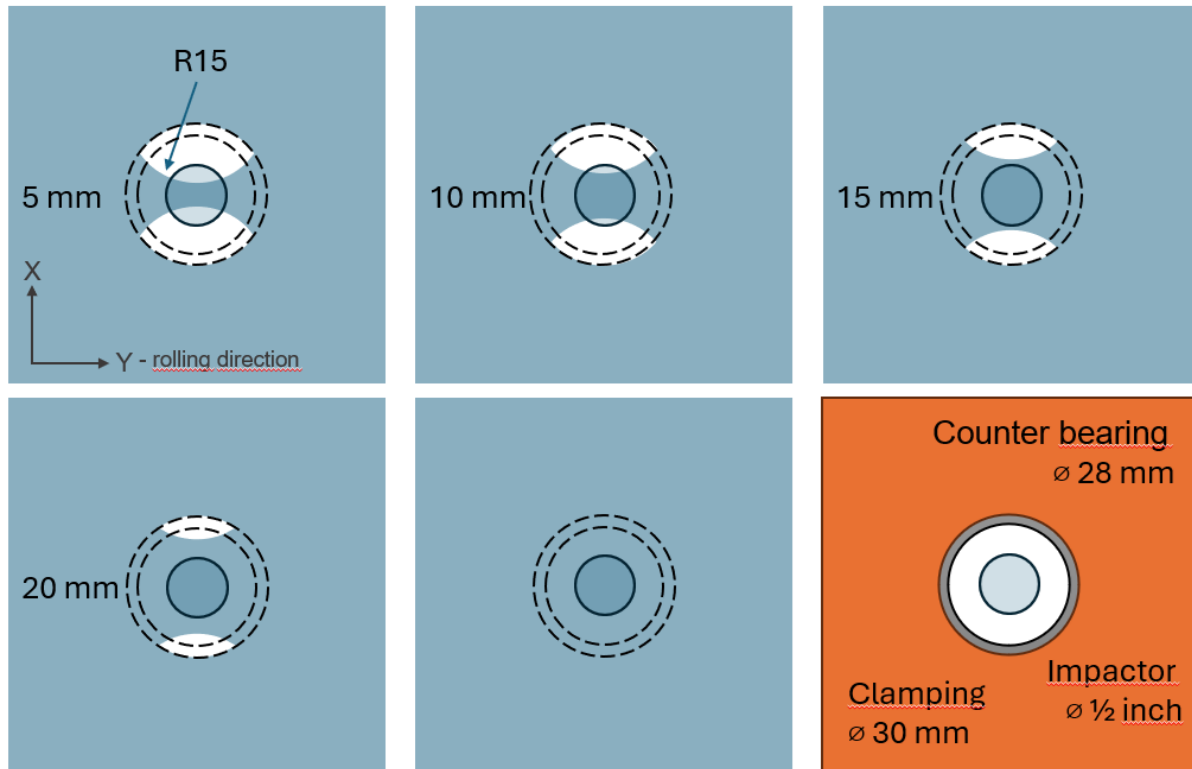
Objective

The primary objective of this study was to evaluate and map the **forming limit curves** for a sheet metal specimen at a static testing speed of **0.001 m/s** and a dynamic testing speed of **1 m/s** at a room temperature of 23 °C.



Description of the Case Study

The experiment was performed on standardized test **specimens made of HC380 steel** prepared according to the ISO 12004 standard.



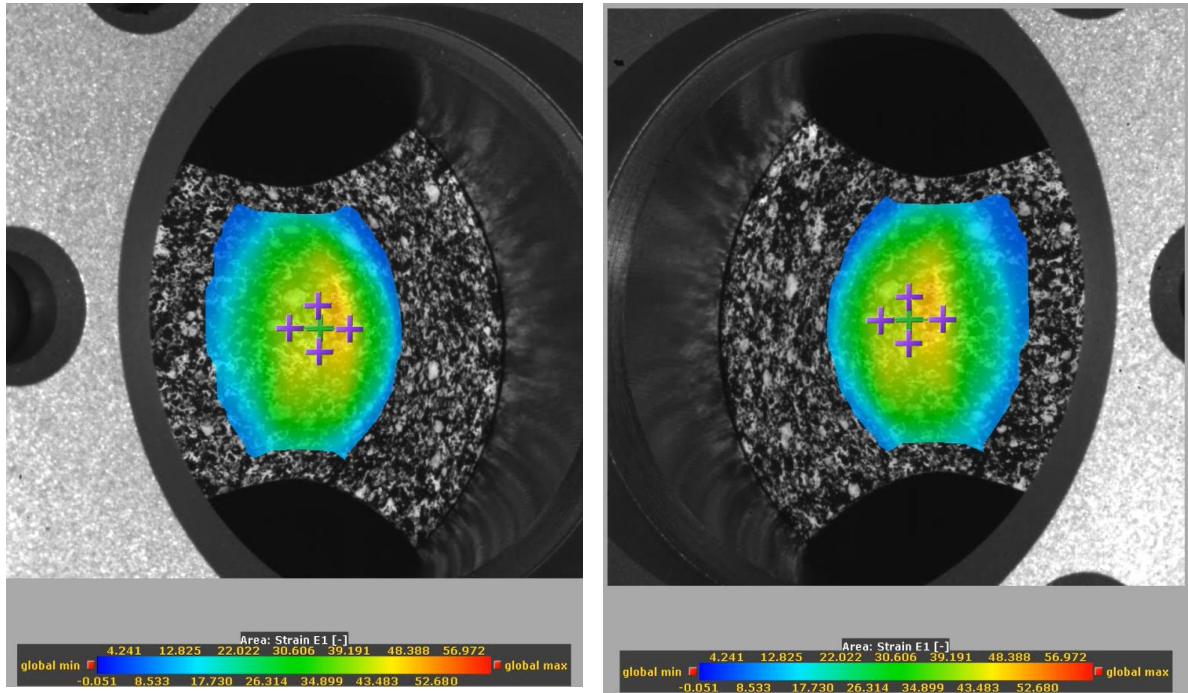
A high-contrast speckle pattern was applied to the samples using matte black and white spray paints before they were tested until fracture. Due to significant out-of-plane motion and the complex nature of the deformation, a **3D DIC configuration was required**. The highly dynamic technical setup included:

- ❖ **Testing Machine:** 4A engineering's **Linovis** dynamic testing machine, capable of reaching testing speeds up to **3.2 m/s**, a maximum force of **25 kN**, and a maximum stroke of **200 mm**.
- ❖ **Optical Setup:** A 3D Digital Image Correlation (DIC) system consisting of two synchronized **Photron Nova S9** high-speed cameras positioned at different angles to accurately reconstruct the 3D space.
- ❖ **Image Acquisition:** The cameras captured the puncture event at a resolution of **768 x 768 px** and an ultra-high frame rate of **15,000 fps**.
- ❖ **Measurement Capability:** This configuration allowed for high-precision tracking of surface displacements across all three axes (x, y, and z) to accurately capture out-of-plane deformation under both static and dynamic conditions.

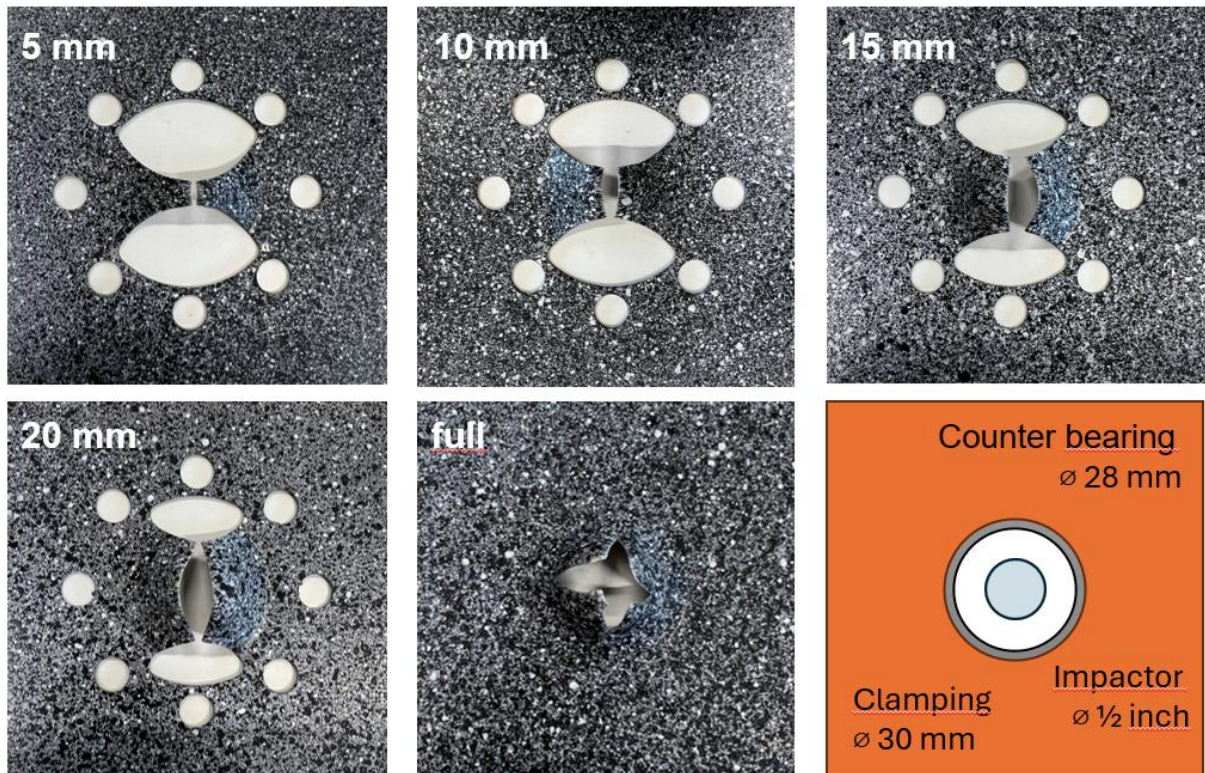


This setup allowed for high-precision tracking of surface displacements in **all three axes (x, y, z)**, with cameras positioned at different angles to accurately reconstruct the 3D space and provide high accuracy in **out-of-plane deformation**.

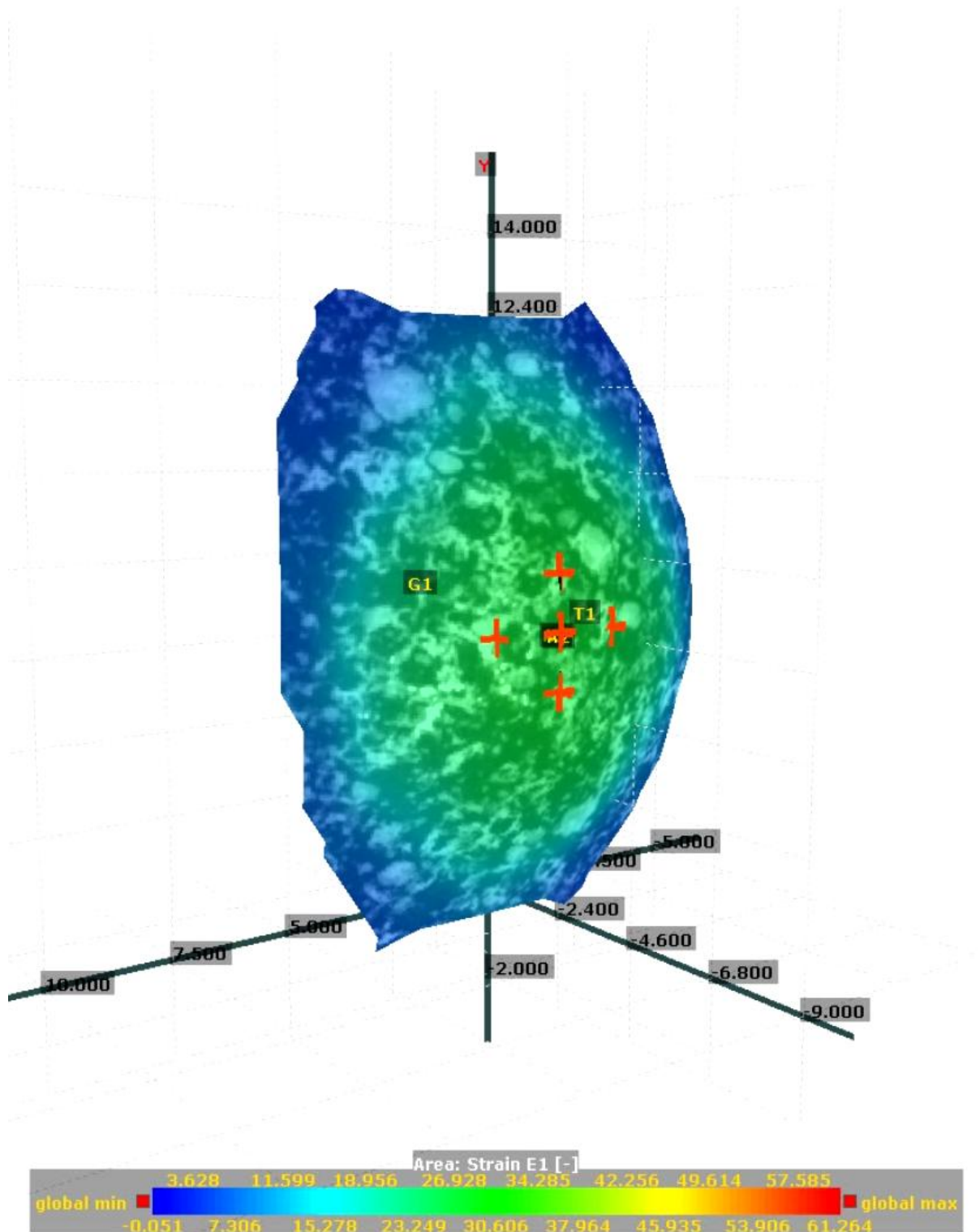




All samples were prepared according to the **ISO 12004** standard and had a **speckle pattern** applied to them using matte black and white spray paints. Then, they were tested until **fracture**.



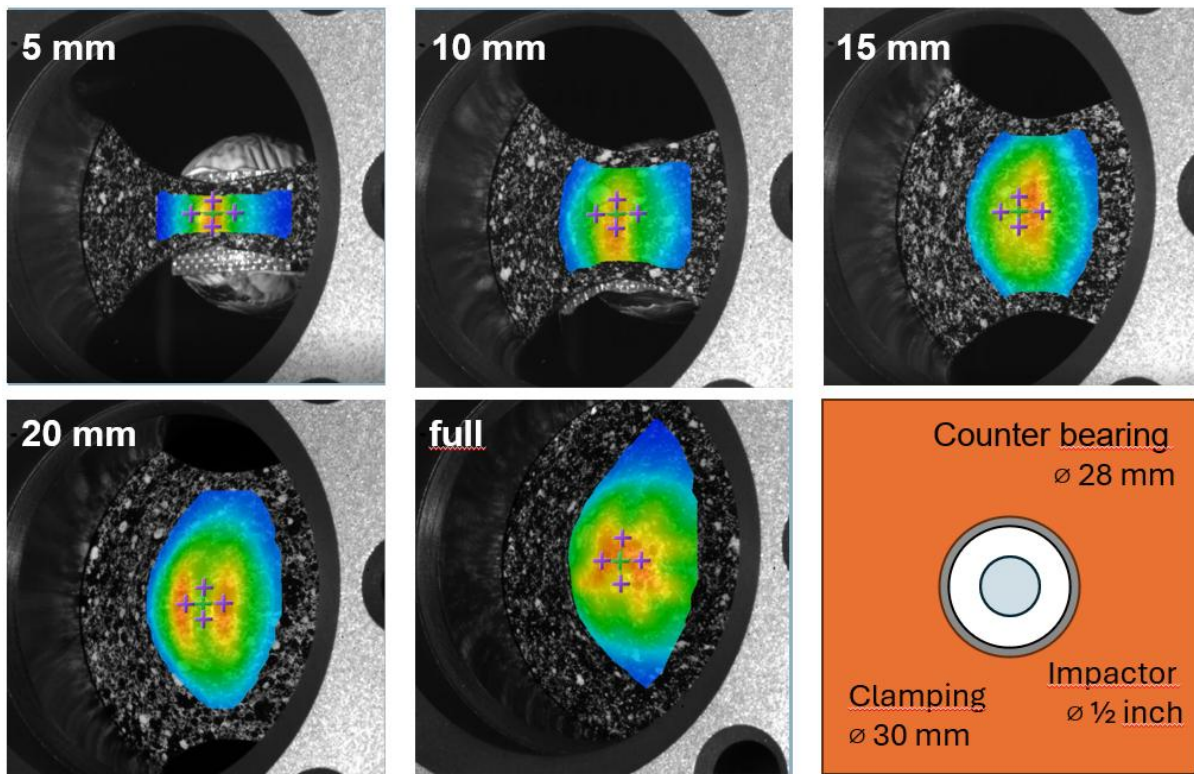
A **3D graph** may be displayed, showcasing the out-of-plane displacement during the puncture.



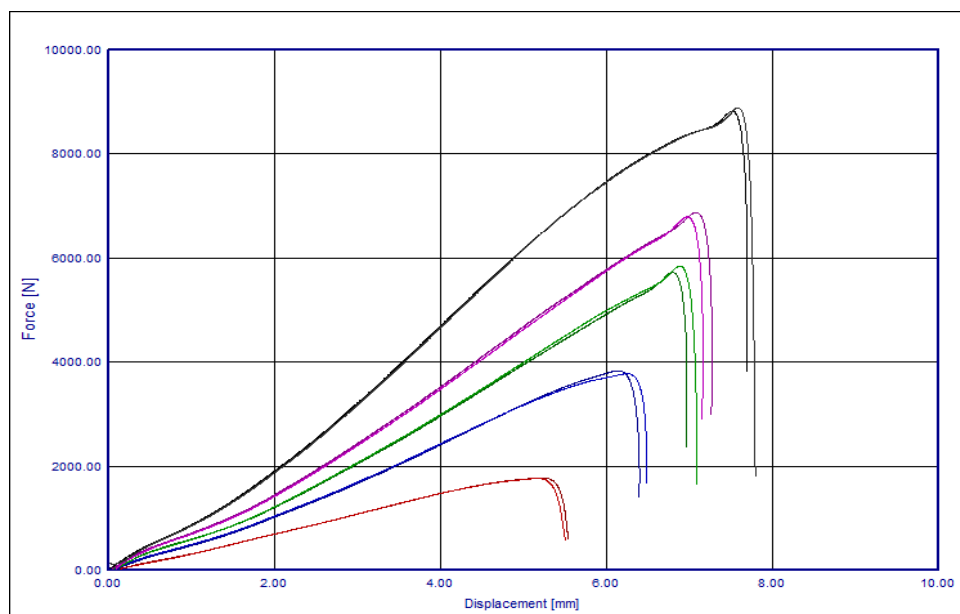
Results

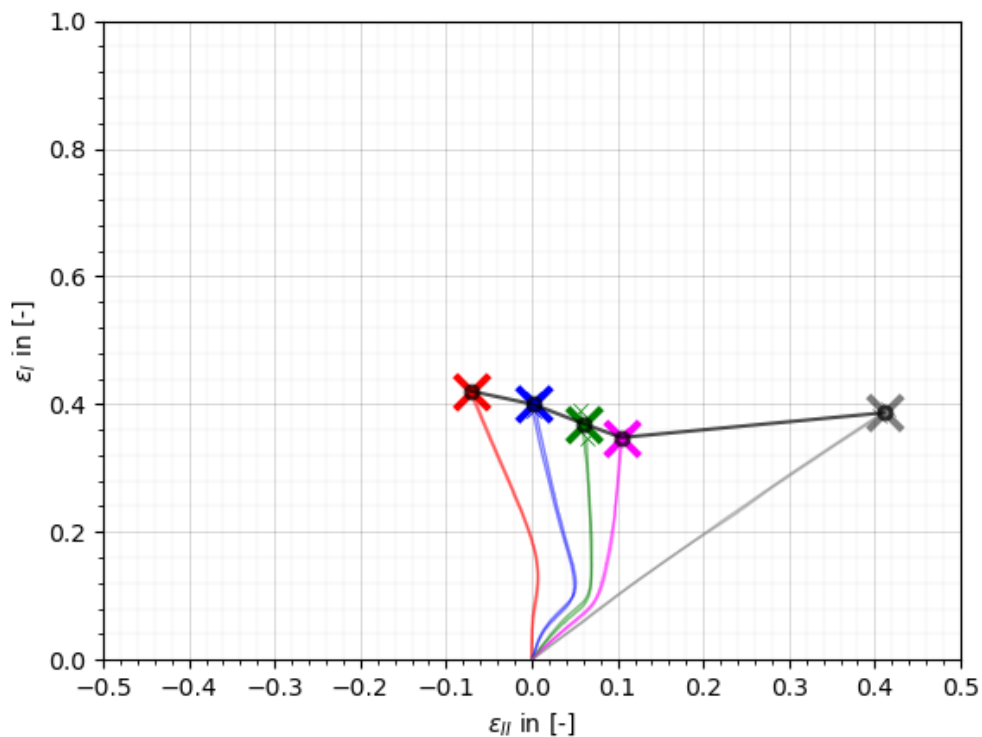
Full-field strain was evaluated for all samples as well as the elongation between two points in both horizontal and vertical direction. The gauge length was 2 mm.

The strain, load and displacement data was further processed to obtain the Forming Limit Diagram.

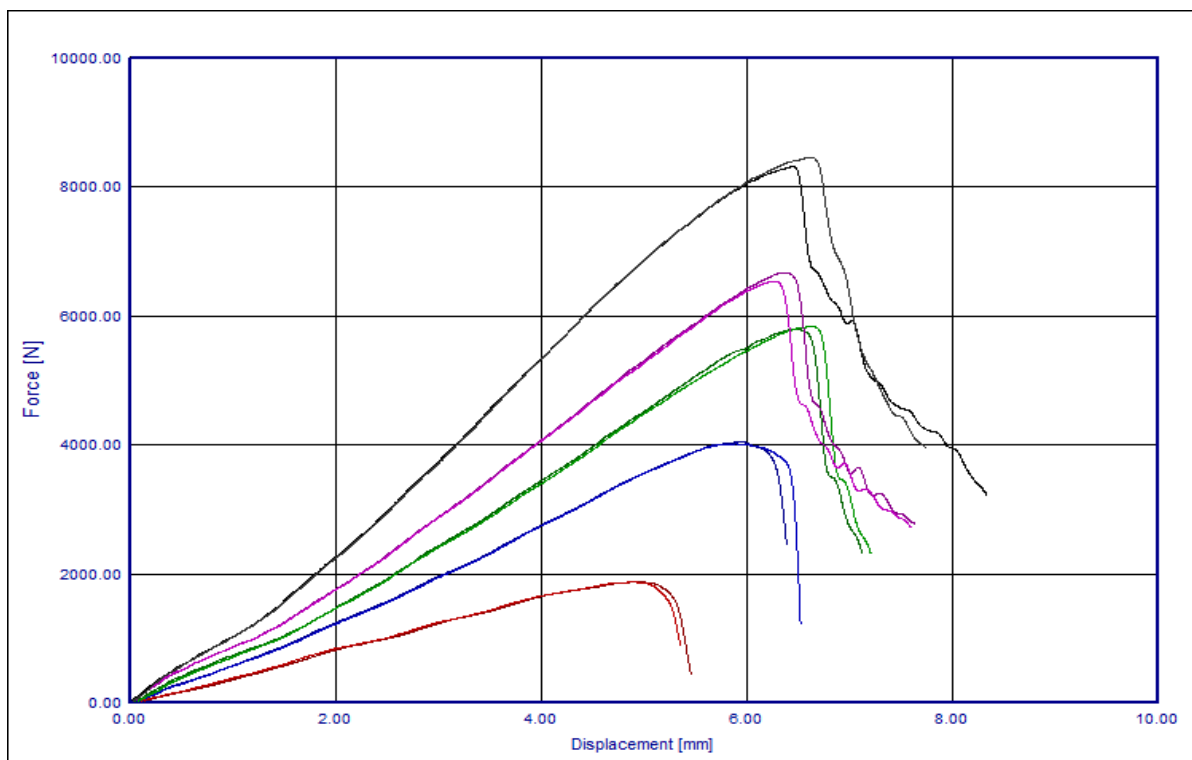


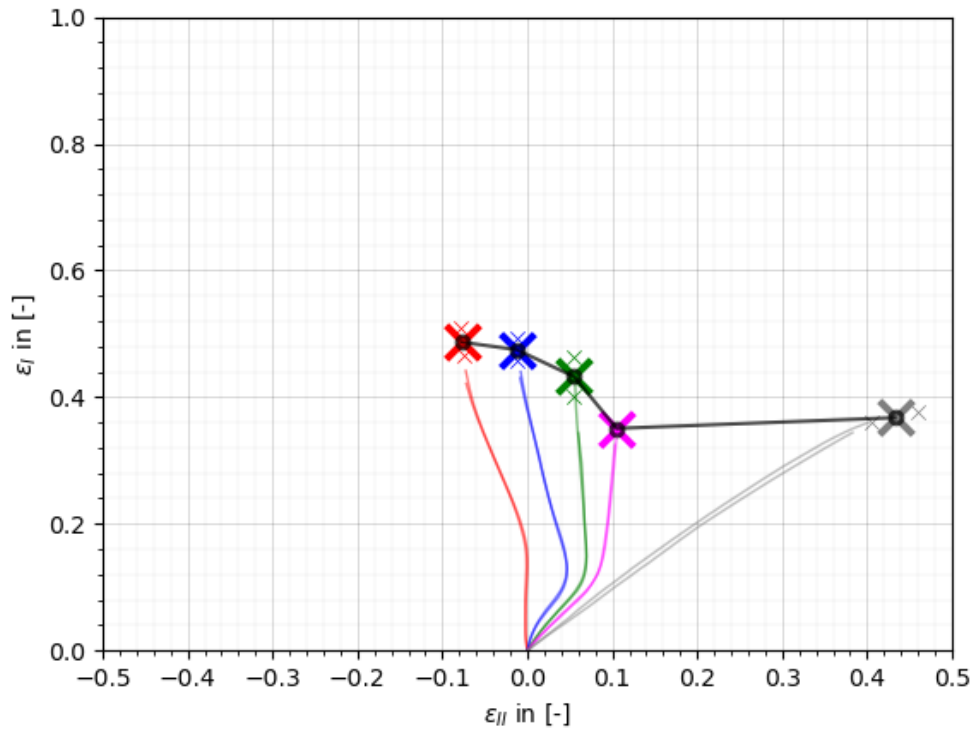
Static test – 0.001 m/s



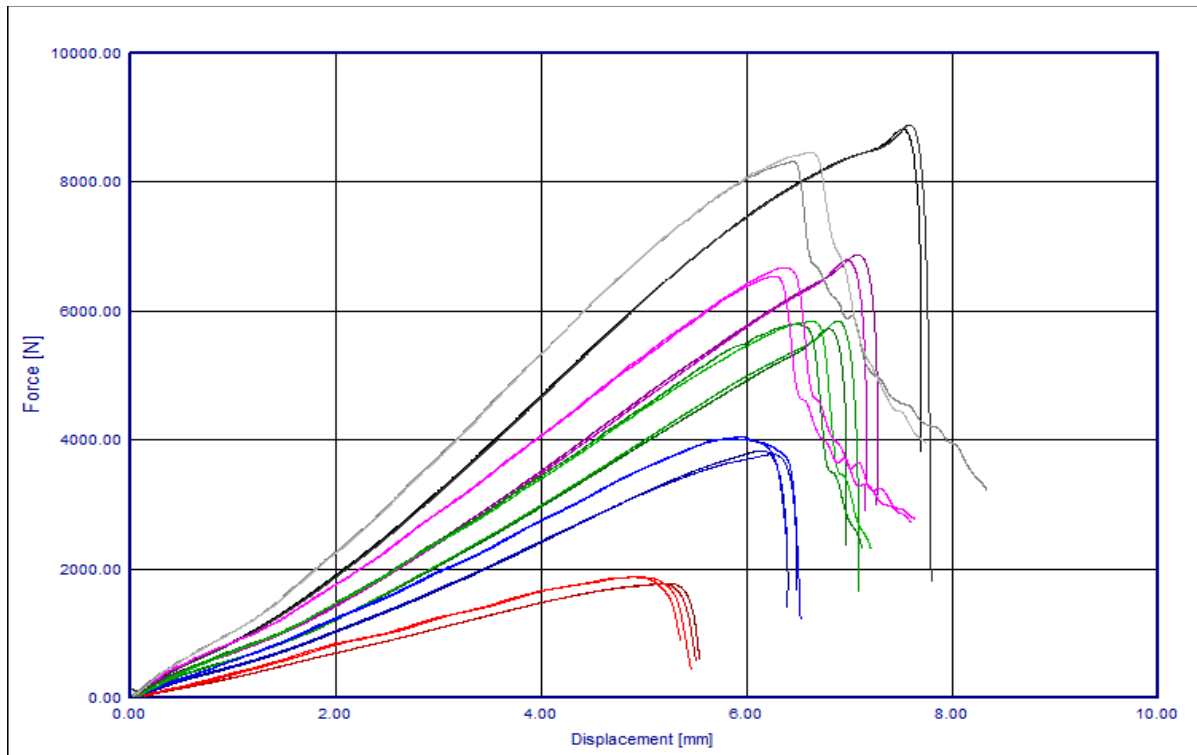


Dynamic test - 1 m/s





Comparison



Nakajima Testing requires 3D DIC

- ❖ **3D Space Reconstruction:** Accurately captures high out-of-plane deformation and complex 3D surface displacements where 2D systems fail.
- ❖ **Full-Field Strain Profiling:** Provides continuous surface measurement up to the exact point of fracture, revealing localized deformation behavior.
- ❖ **Static to Dynamic Versatility:** Delivers consistent, highly precise deformation analysis across a massive range of testing speeds (from 0.001 m/s to 1 m/s).
- ❖ **FEM Simulation Input:** Directly generates high-fidelity material parameters to refine and validate sheet-forming simulations.

Conclusion

In collaboration with [4A engineering](#), [Mercury RT](#) successfully captured **full-field 3D strain** and out-of-plane displacement data at **15,000 fps** during **Nakajima** testing. This advanced 3D DIC workflow provides precise forming limit analysis under both **static** and **dynamic** conditions, enabling the accurate generation of **forming limit curves** for high-quality sheet metal engineering.

