Signal-Process Relationships Using LDD Monitoring in Laser Beam Welding of 304L Stainless Steel

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Background & Motivation

- Laser Beam Welding (LBW) of stainless steel is an advanced technique characterized by high energy density, fast processing speeds, and localized heat input.
- Many defects and variations stem from laser parameters, composition of materials, and beam-material interactions.
- Standard process qualification can be expensive and time-consuming, depending on specific material and application requirements.
- Prior beam-material interaction studies often lack real-time monitoring, leaving process parameters to be selected empirically.
- Laser Depth Dynamics (LDD) is a non-destructive, in-situ monitoring technique that uses inline coherent imaging to measure keyhole depth in real time during welding.
- Establishing a reliable signal-to-process relationship is essential for optimizing quality control and accelerating qualification.

Figure 1. IPG Photonics YLS-6000 fiber laser System used to produce welds; 1070 µm wavelength, 600 µm spot size.

Objective & Approach

Objective: Establish a baseline Laser Depth Dynamics (LDD) dataset and process window for 304L stainless steel welds by correlating real-time LDD signals, collected across varied travel speeds and power outputs, with post-weld penetration and quality.

Approach:
Varied laser power and travel speed with a constant 5° push angle.

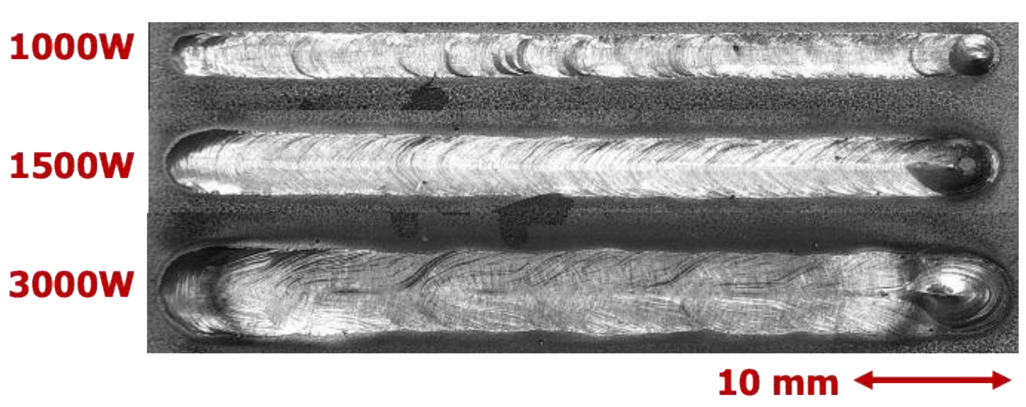

Figure 2. Black-and-white Optical image of weld beads produced at 10 mm/s for laser powers of 1000W, 1500W, and 3000W. Increasing laser power results in progressively wider weld beads and changes in surface appearance.

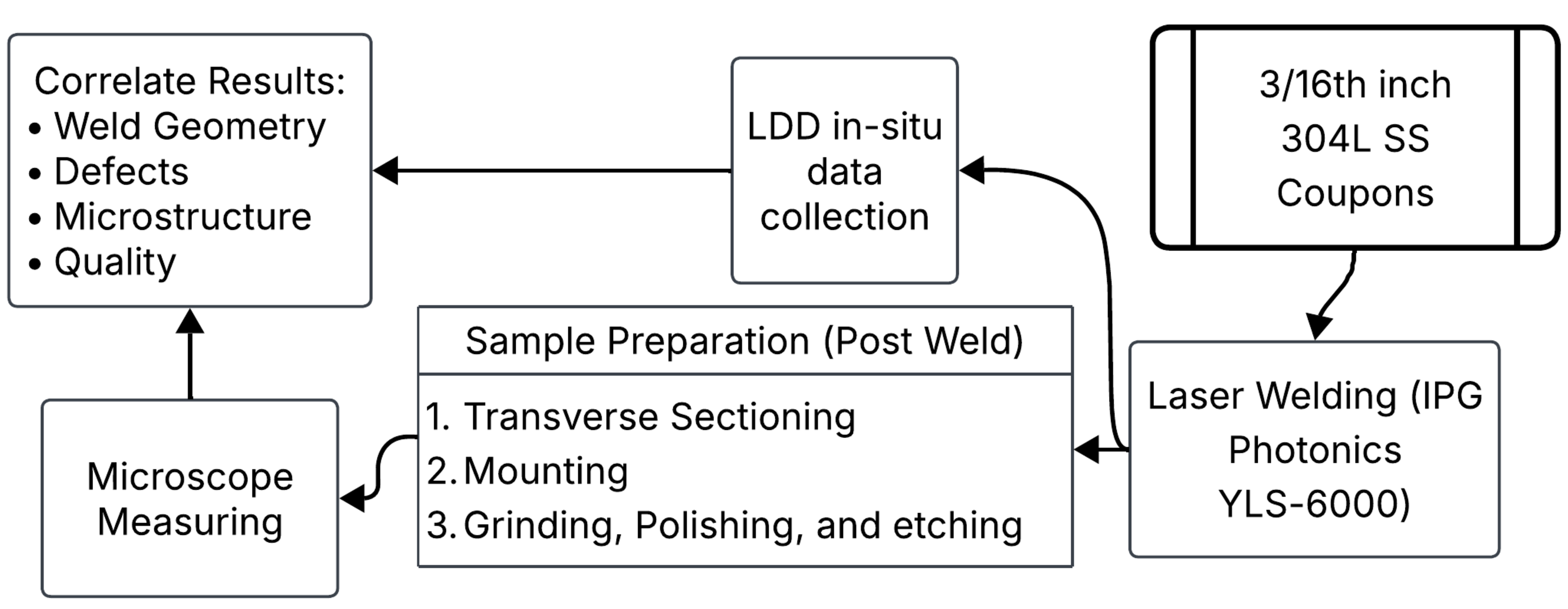

Figure 3. Research Workflow

Results & Discussion

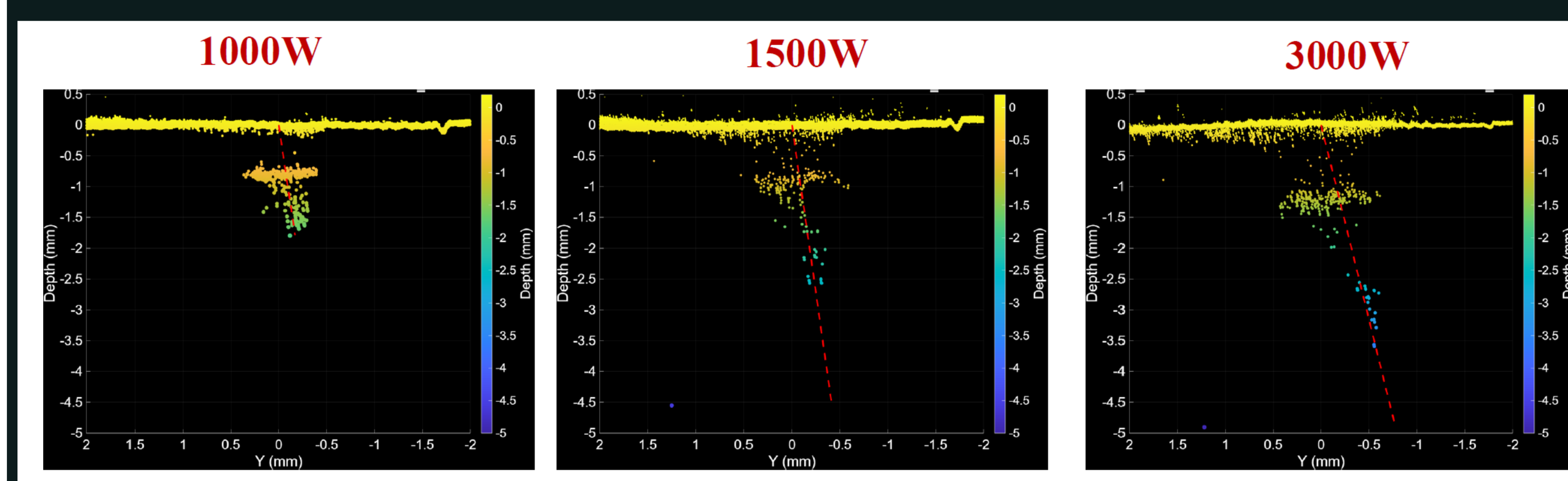

Figure 5. LDD point cloud of 1000, 1500 and 3000 W welds at 20 mm/s. Image courtesy of Richard Li

- LDD signal depth increases consistently with laser power, capturing the expected trend of deeper keyhole penetration at higher power levels. Weld direction is from left to right.

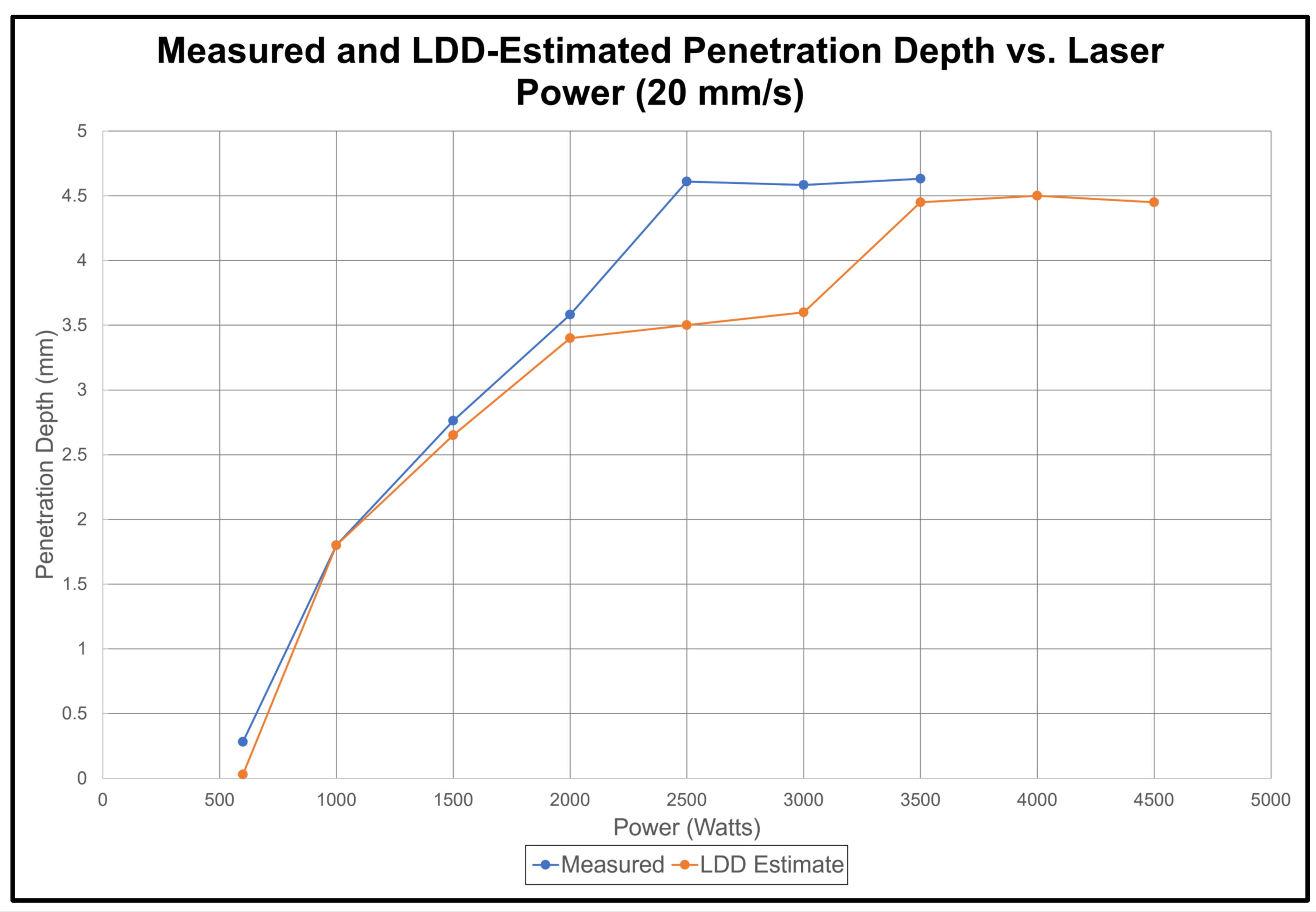

Figure 6. Penetration depth vs. power at 20 mm/s, comparing measured cross-sectional penetration depth with LDD-estimated penetration depth. **Trend is consistent across all tested speeds (10-40 mm/s).**

- LDD-estimated penetration depth closely tracks manually measured values across the tested power range, demonstrating the effectiveness of LDD-based monitoring. Deviations at intermediate power levels may reflect inherent limitations of the LDD in closed-keyhole mode for full-penetration welds.

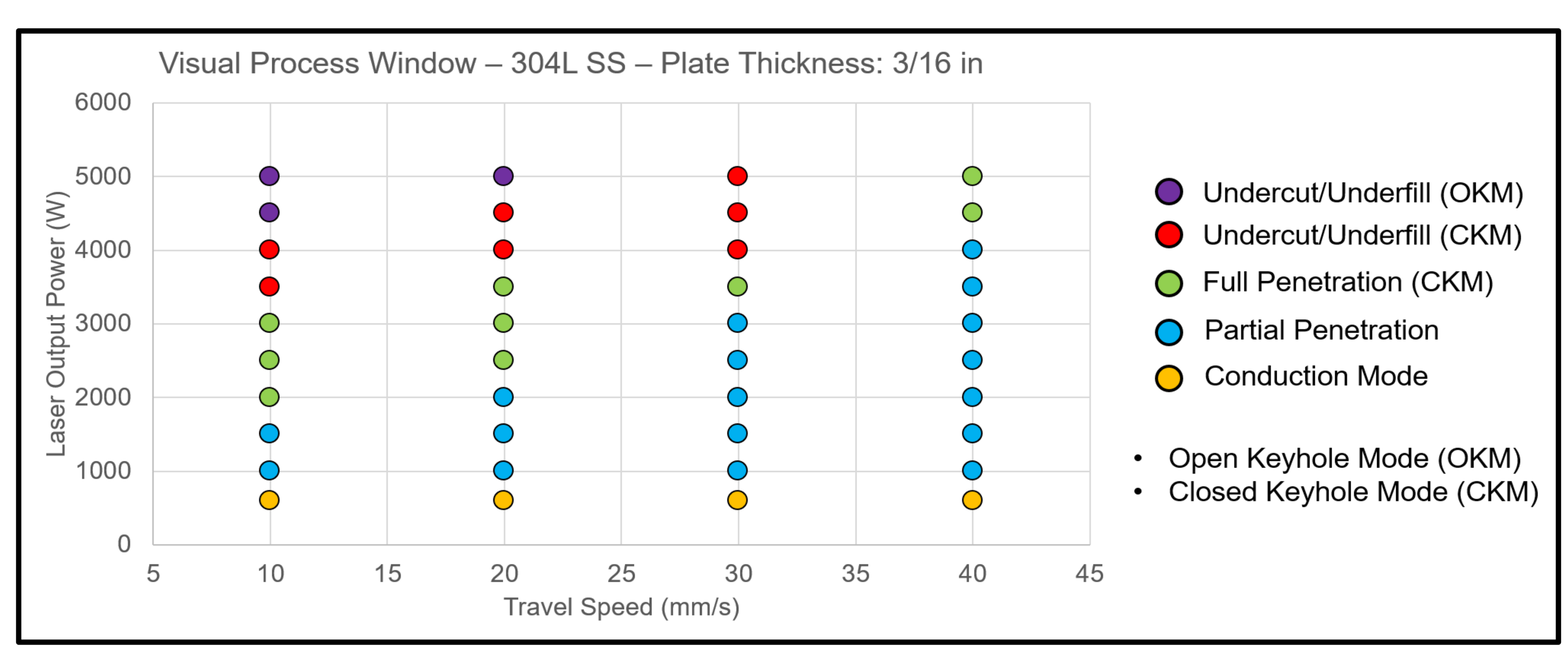

Figure 7. Visual process window for laser welding of 304L stainless steel (3/16 in plate thickness), showing the tested combinations of laser output power (600–5000 W) and travel speed (10–40 mm/s). Colors indicate the observed weld condition for each parameter combination.

- This process window defines the weld modes and defect boundaries across varying laser powers and travel speeds, giving the reference weld quality data used to correlate in-situ LDD signals with actual weld attributes.

Conclusions & Current Progress

- Established a baseline process window and keyhole LDD dataset for 304L stainless steel welds across varied travel speeds and power outputs.
- LDD-estimated penetration depth closely tracks manually measured values, supporting LDD as a promising in-situ tool for post-weld measurements, though further validation is needed for full-penetration weld conditions.

Future Work

- Correlate process signals with weld quality via a multi-modal sensor setup including LDD, photodiodes, and spectrometers.
- Validate LDD accuracy across the full process window, including full-penetration and defect-boundary conditions.
- Relate LDD signal stability to weld defects, including porosity.

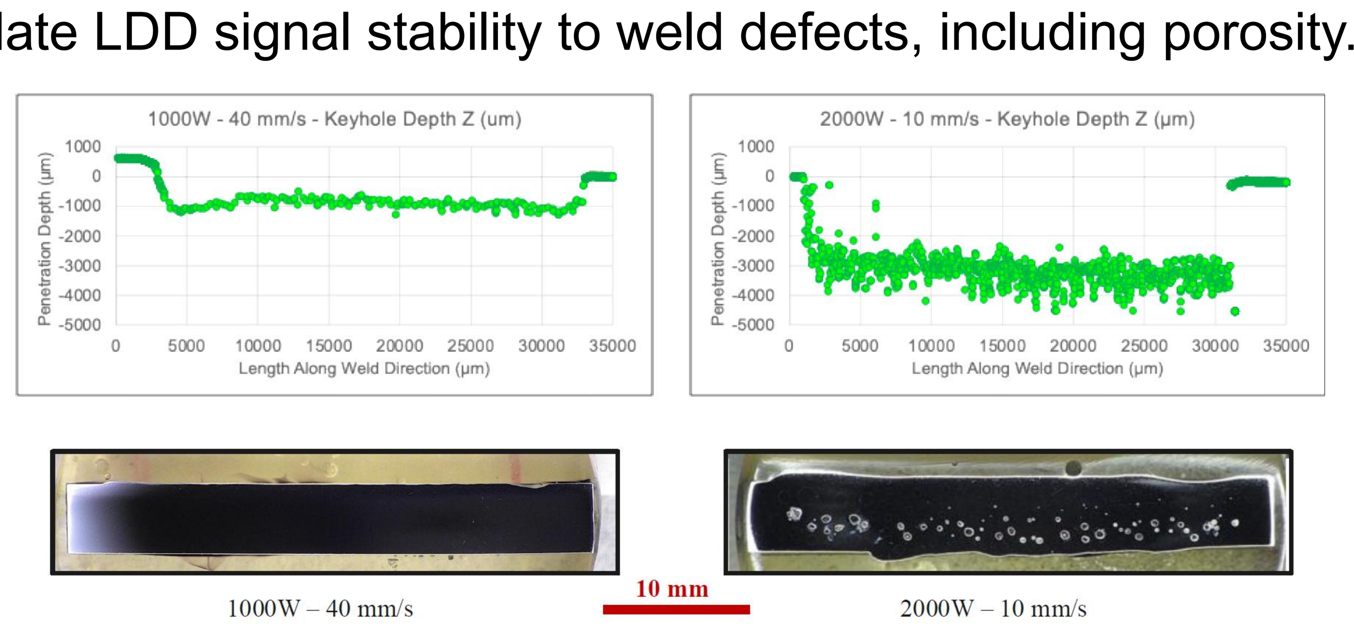

Figure 4. Representative LDD keyhole depth signals and corresponding weld cross-sections for stable (1000 W, 40 mm/s) and unstable (2000 W, 10 mm/s) welding conditions. Stable signals corresponded to 0.06% porosity, while unstable, noisy signals corresponded to 4.25% porosity. **Signal stability appears to correlate with weld porosity, motivating further validation across the full process window**. Cross-sectional images courtesy of Richard Li.

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