Heat transfer and fluid flow during laser micro spot melting

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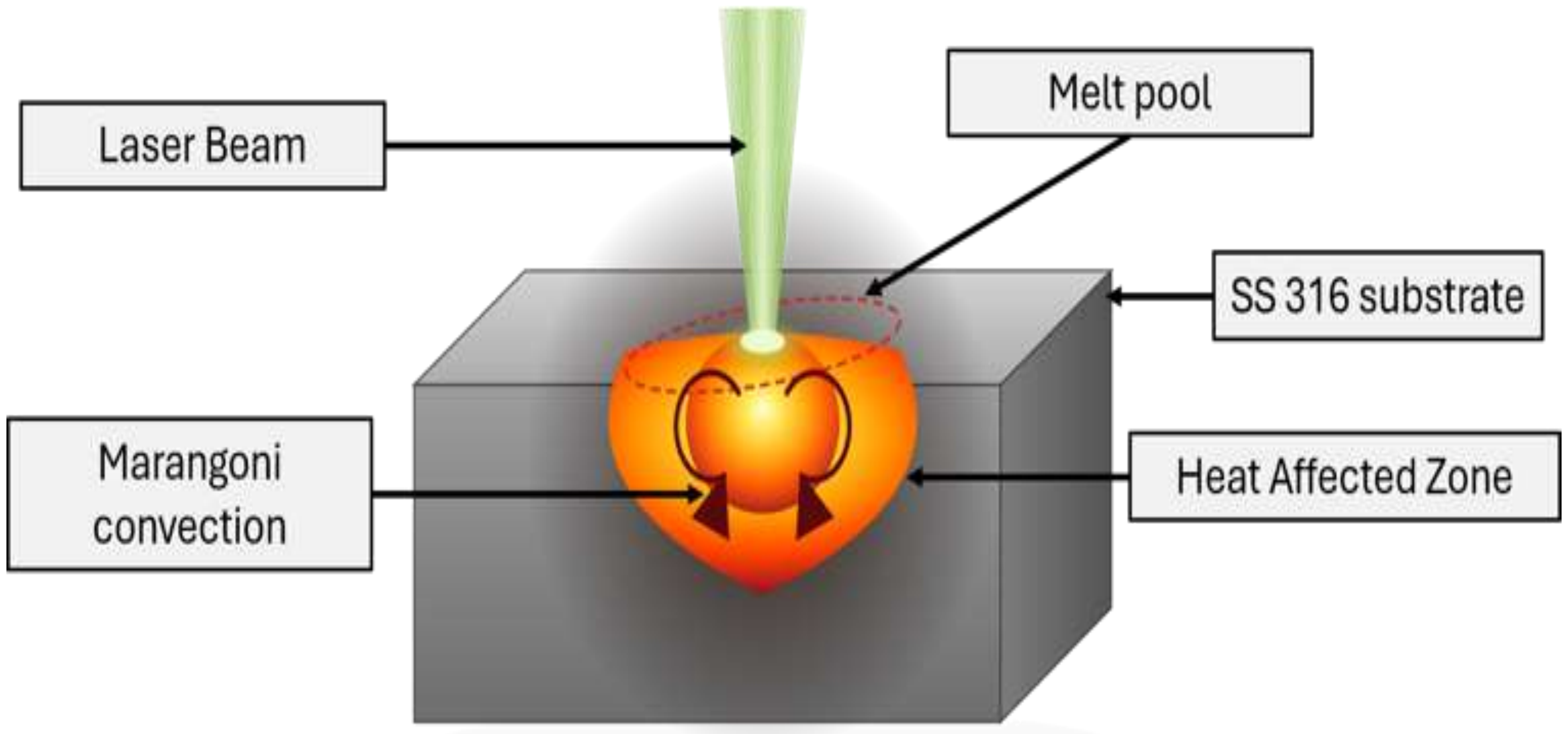

Figure 1: Process schematic of laser spot melting

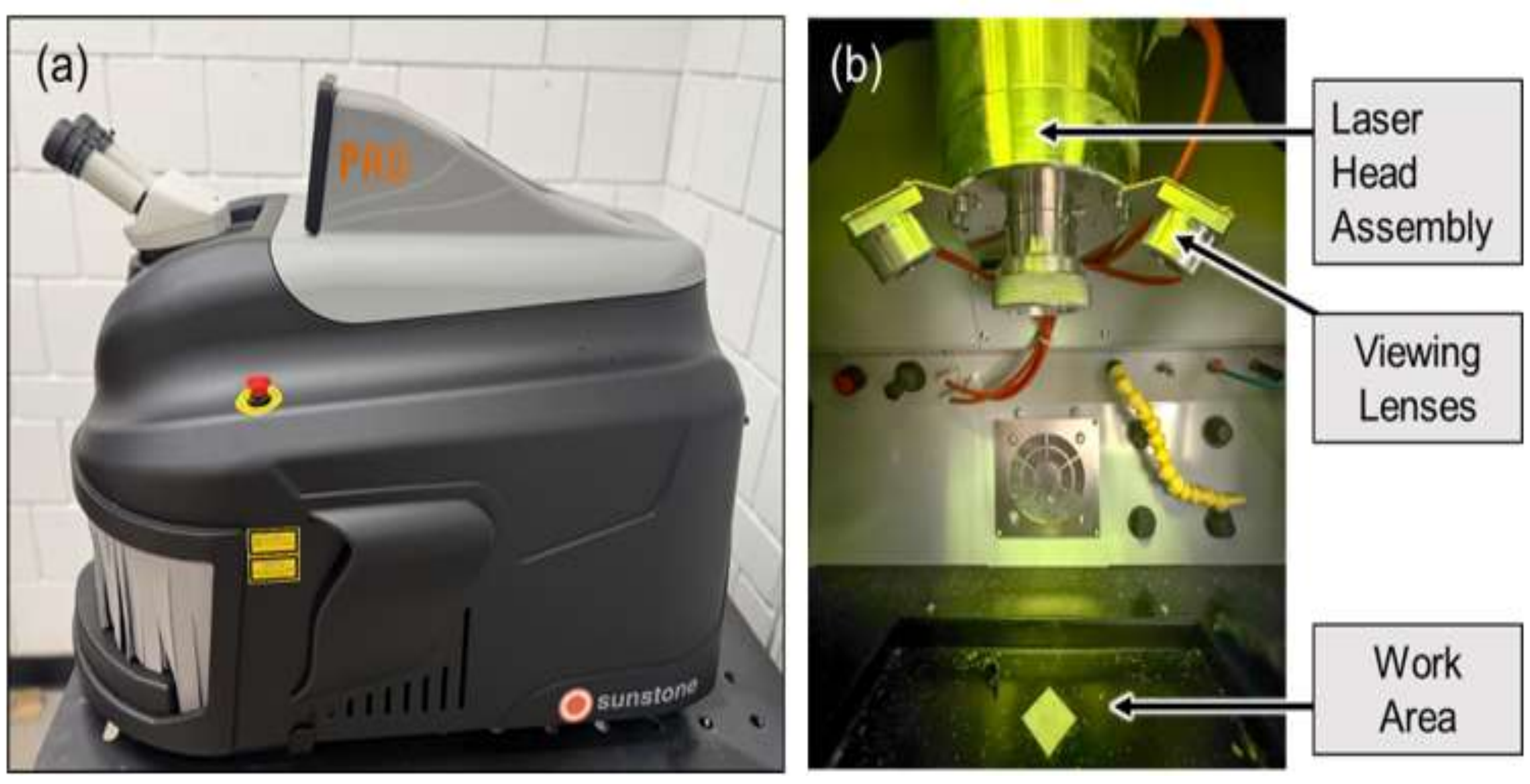

Figure 2: (a) Sunstone PRO laser spot-welding system & (b) interior view

Problem Statement and Objective

- Laser micro spot melting involves complex heat transfer and Marangoni-driven fluid flow, yet the combined effects of process parameters and material properties on melt-pool behavior are not fully understood.
- The objective of this study is to develop and validate a 3D transient numerical model to evaluate how laser power, spot radius, and pulse duration affect melt-pool geometry, temperature, and fluid flow, while introducing a dimensionless index to quantify the dominant forces.

Methods

- A 3D transient finite-volume model was developed to simulate heat transfer and Marangoni-driven fluid flow during laser micro spot melting of SS 316.
- Experiments were conducted on 3-mm SS 316 using a 1064 nm pulsed Nd;YAG laser by varying power, pulse duration, and spot radius at constant 6 Hz frequency.
- Melt-pool dimensions were measured using 20x confocal microscopy and compared with numerical predictions for model validation.

Results

- Numerical predictions closely matched the experimental confocal images, validating the computed melt-pool shape and dimensions.
- Increasing laser power and pulse duration increased heat input, producing higher temperatures, stronger outward Marangoni flow, and a broader, deeper melt pool while a smaller spot radius further intensified energy density and fluid velocity.
- Process maps showed that fluid velocity was more sensitive to spot radius than melt-pool size.

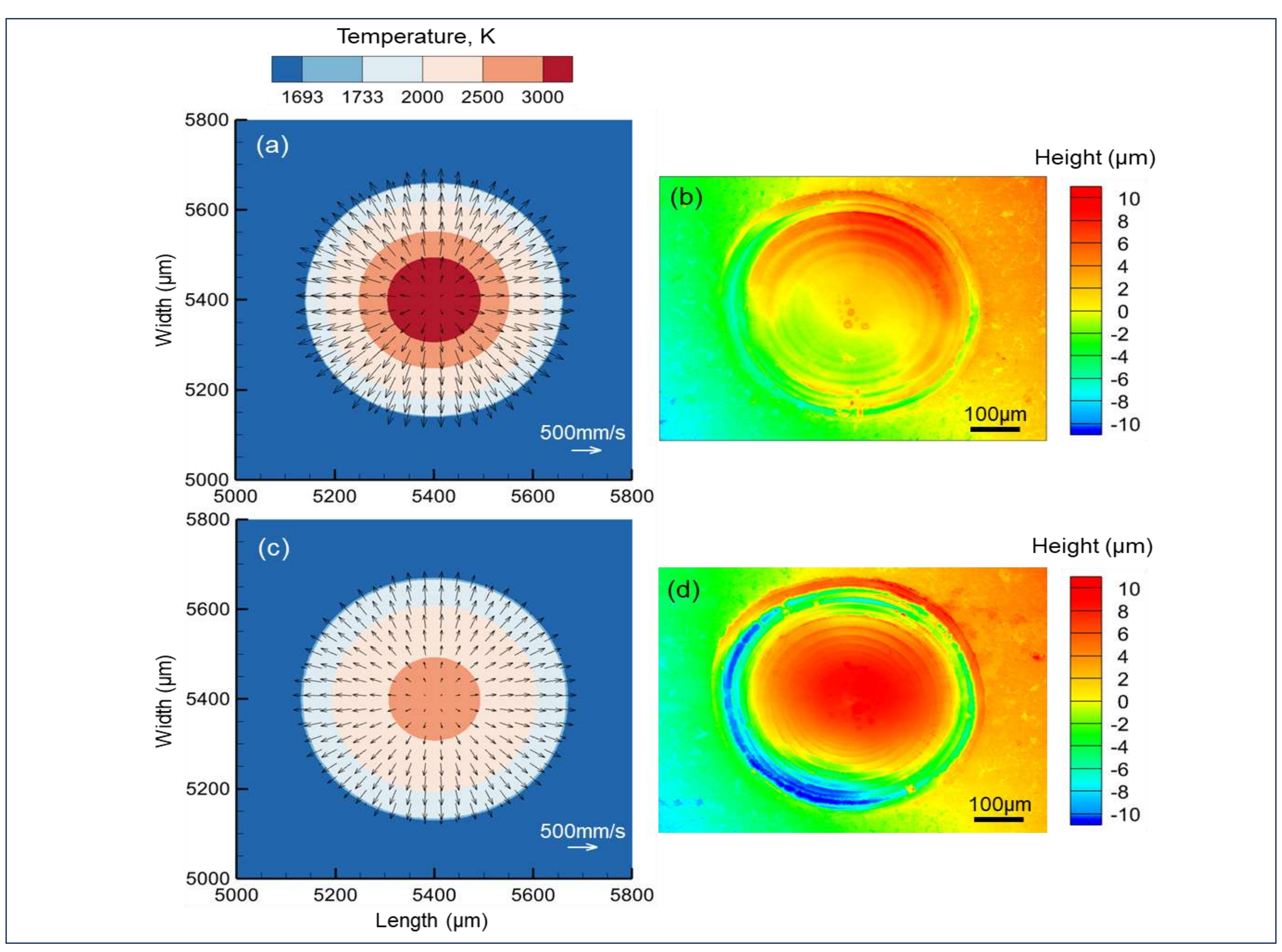

Figure 3: Temperature and velocity field and corresponding confocal for (a)-(b) P = 0.8 kW and (c)-(d) 1.0 kW

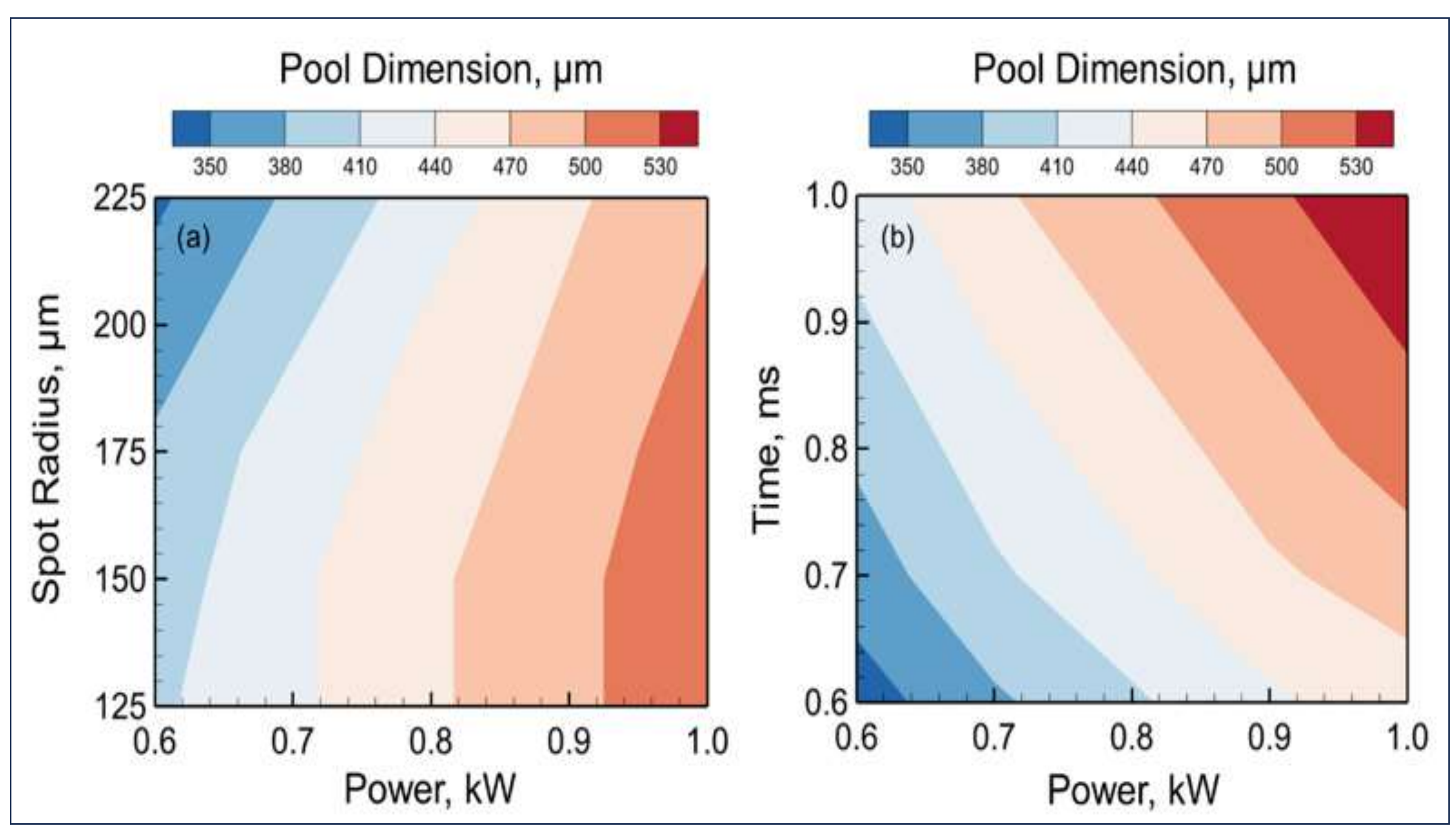

Figure 4: Pool Dimension Process Maps with (a) spot radius and power and (b) pulse duration and power

Spot Melting Index Equation

- The dimensionless spot melting index equation (ζ) is a dimensionless parameter that we have derived combining laser processing conditions and material thermophysical properties:

$$\varsigma = \frac{Pt}{\rho r^2 d\,(C_p \Delta T + \Delta H_f)}\left(\frac{f A_{tp}}{\alpha}\right)$$

- Here, P is laser power, t is pulse duration, r is spot radius, f is pulse frequency, d is plate thickness, ρ is density, C_p is specific heat, ΔT is temperature rise, H_f is latent heat of fusion, α is thermal diffusivity, and A_{tp} is temporal projected heat-propagation area.
- The fitted curve shows a consistent trend across the study and published data

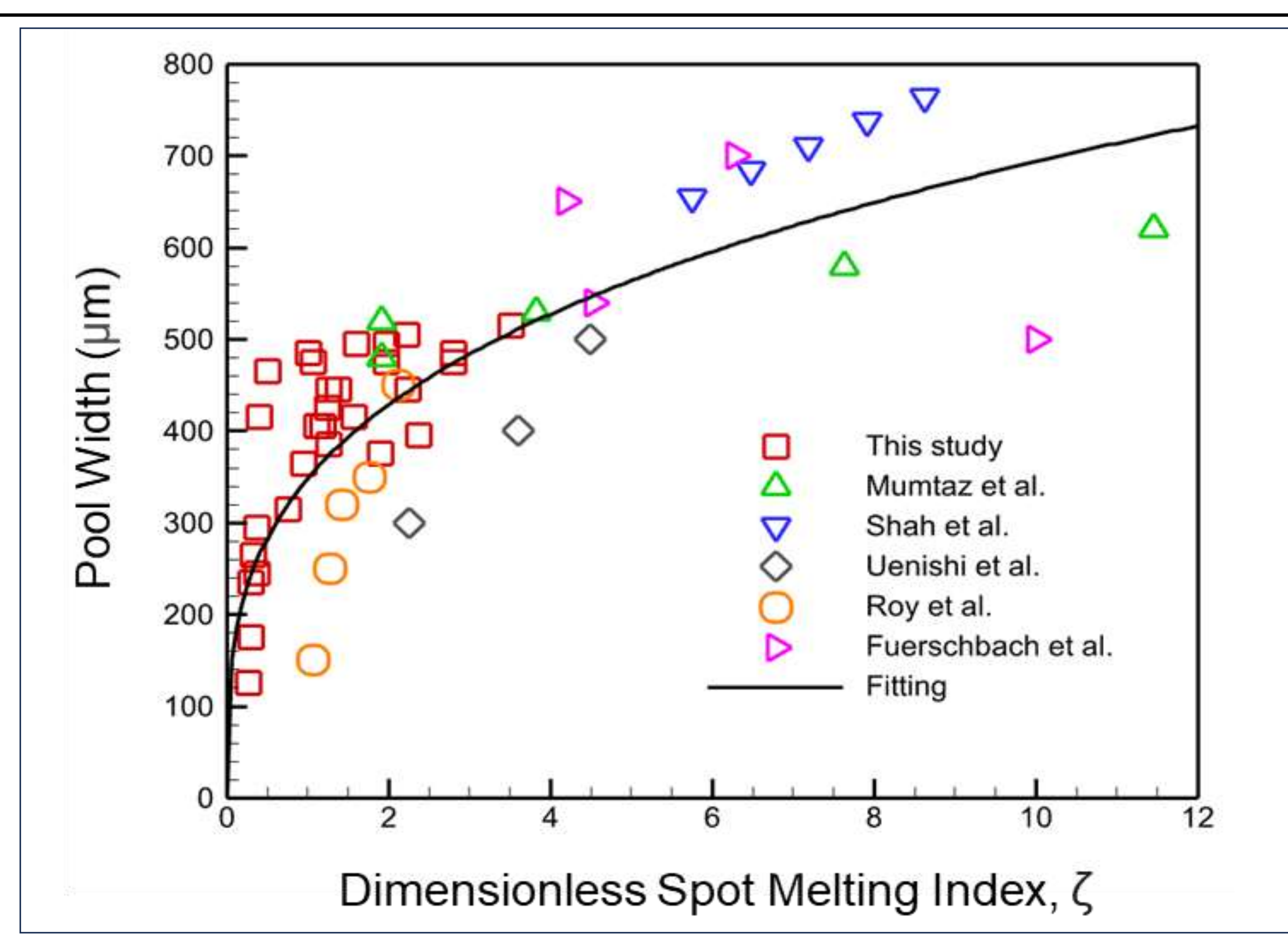

Figure 5: Dimensionless Spot Melting Index fitting curve

Conclusions

- A dimensionless spot melting index was developed to combine key process parameters and material properties.
- The index showed a consistent correlation with melt-pool width across this study and published data, supporting process optimization & comparison.

Acknowledgments

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