Reinforcement Learning on Reconfigurable Hardware: Overcoming Material Variability in Laser Material Processing

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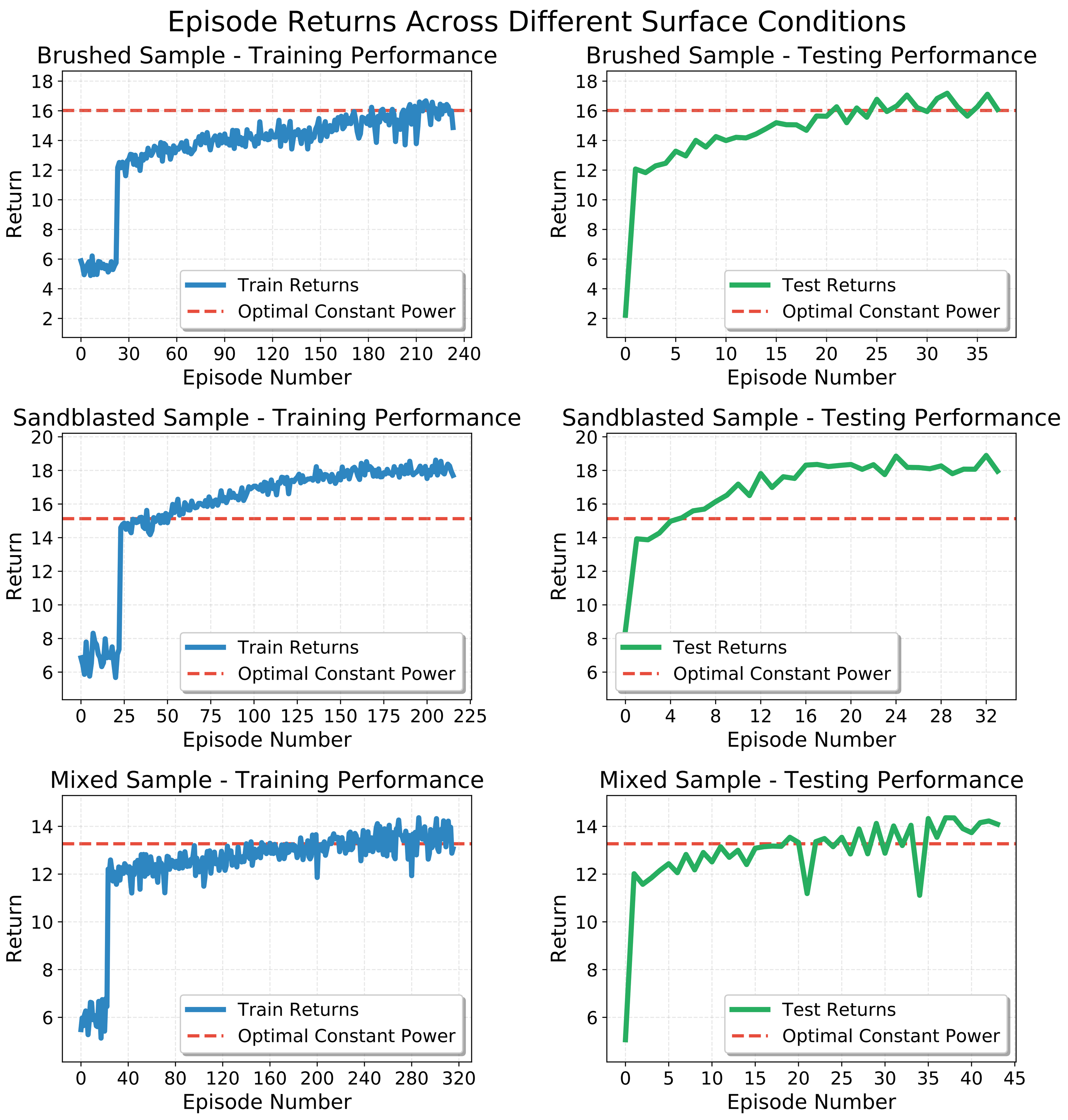
Abstract

Surface roughness and alloy variability make laser welding hard to tune by hand or with fixed-setpoint controllers. To address this issue, we embed a reinforcement-learning policy in a Xilinx Zynq FPGA, closing the loop in $\approx 3\,\mu s$ and retraining off-board between welds. On 316L steel the policy self-adapts, raising conduction-mode reward up to 23% on sand-blasted and 7% on mixed surfaces versus optimised constant power.

Motivation

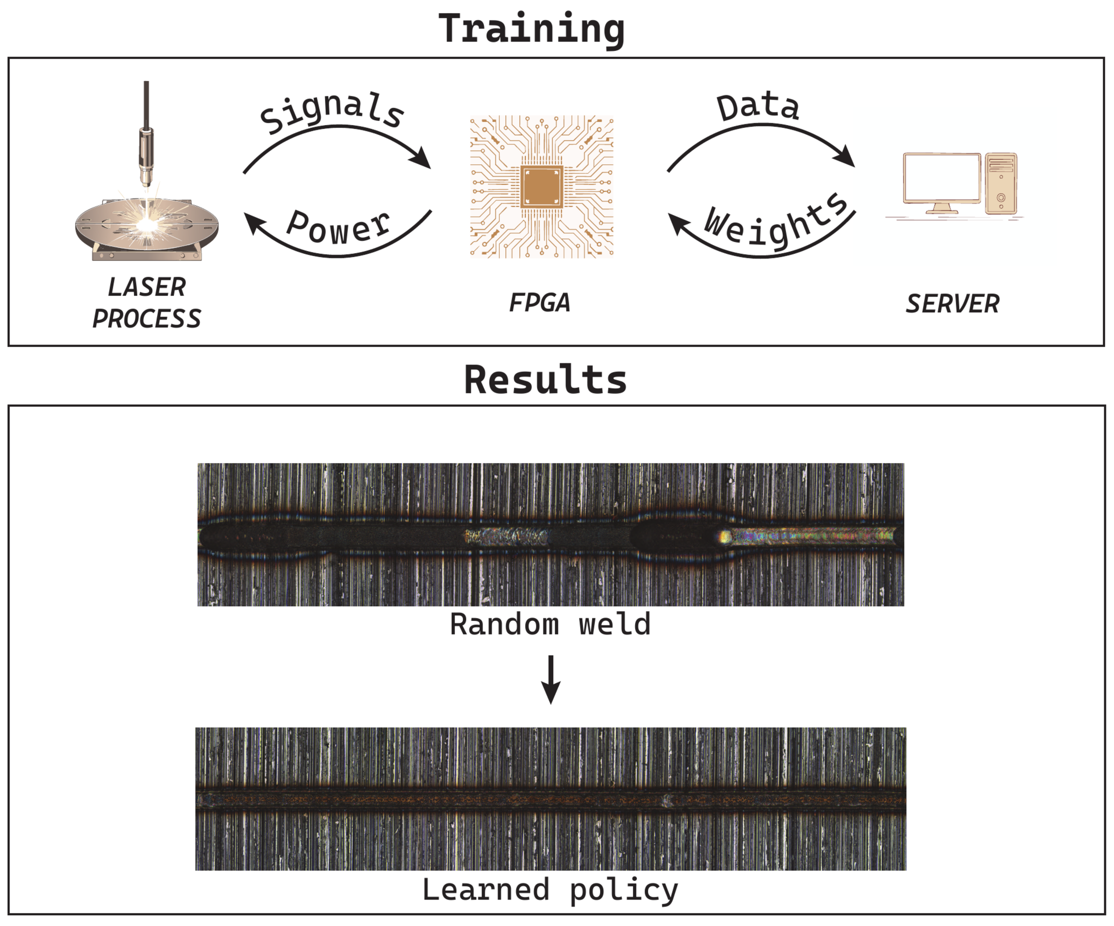
- Laser welding underpins automotive, aerospace, medical devices.
- Small changes in surface finish shift optimal power by tens of watts.
- An on-chip RL controller delivers deterministic, μs-scale reactions and removes time-consuming trial-and-error tuning.

Learning curves



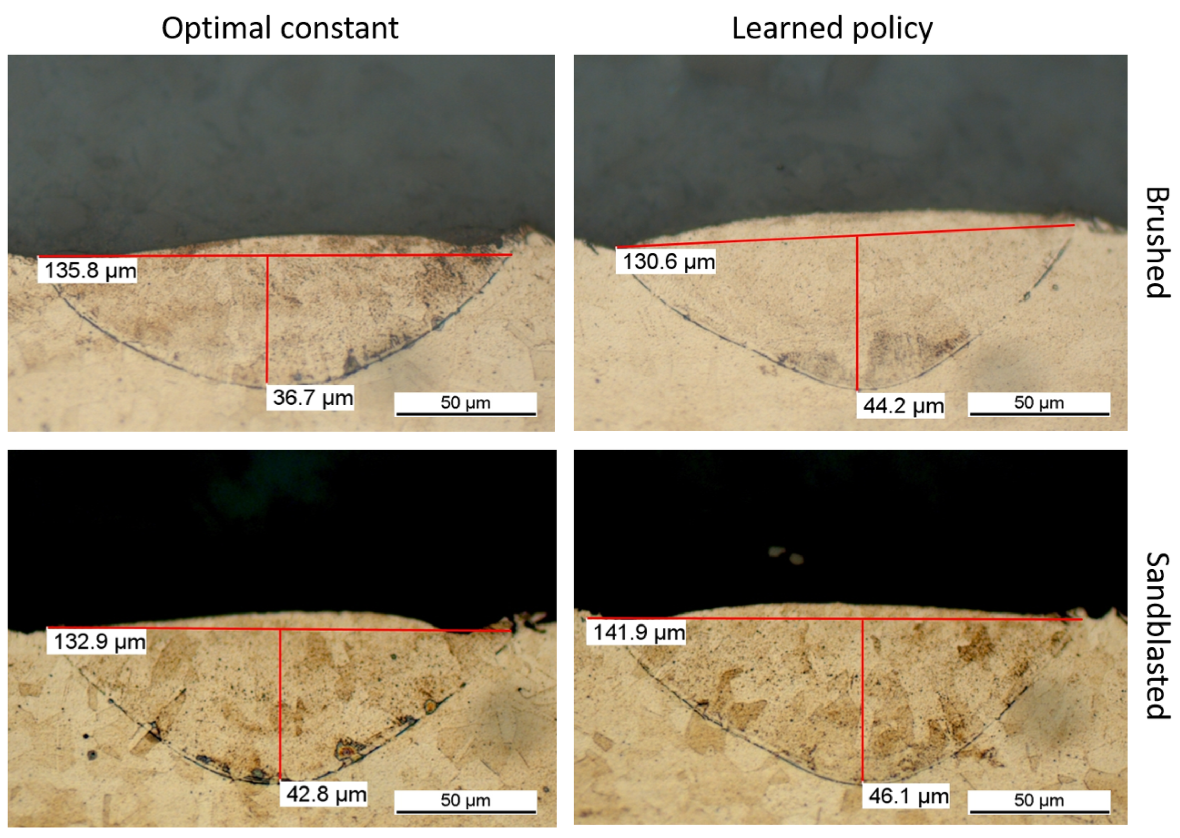
The agent converges in < 200 episodes. It matches the baseline on smooth plates and exceeds it on rough and mixed surfaces, achieving +22–23 % cumulative reward. Exploration noise is visible only in training runs; test-only runs confirm stable gains.

Overview of method



- *Sensors* $\rightarrow$ *FPGA*: 100 kS s^{-1} photodiodes feed an 8-bit MLP that outputs laser-power commands every 10 ms window ($< 4\,\mu s$ compute).
- *FPGA* $\rightarrow$ *Server*: episodic data drive SAC+QAT training; fresh weights return over Ethernet before the next weld, enabling continuous on-line improvement.

Qualitative results: melt-pool cross-sections



Learned policy yields wider, deeper conduction-mode pools without keyhole defects on both brushed and sand-blasted zones, indicating better fusion and lower porosity risk than constant-power welding.

Conclusions

- First μs-latency RL control of laser welding on reconfigurable hardware.
- No preset depth targets or heavy reward engineering required.
- Adapts across surface finishes; concept scales to other laser processes and alloys.

Reference

G. Masinelli, C. Rajani, P. Hoffmann, K. Wasmer, D. Atienza, “Reinforcement Learning on Reconfigurable Hardware: Overcoming Material Variability in Laser Material Processing,” *IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2025.