Real-Time In-Process Monitoring of Laser Welding Using Novelty Detection

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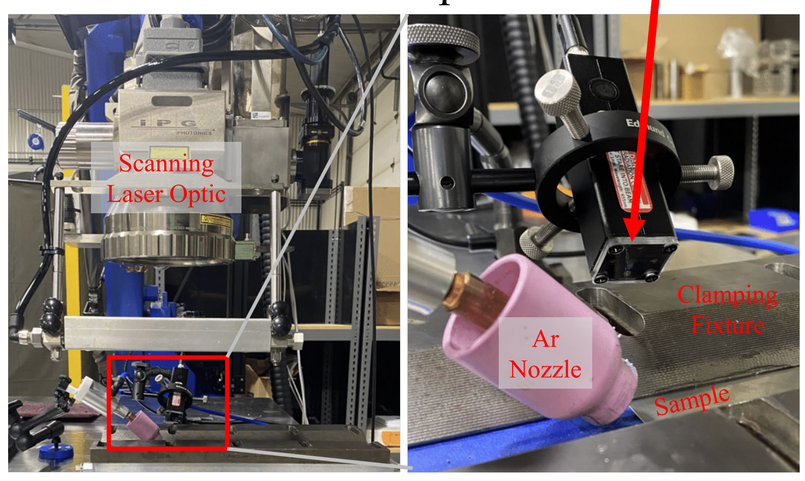
Problem Statement

- Part to part process stability is a primary focus in quality control in welding.
- While laser welding offers faster processing speeds, smaller heat-affected zones, reduced cooling times, and superior weld quality compared to traditional arc and resistance spot welding, these advantages come at the cost of increased sensitivity to process variability.
- More recently, closed-loop control and diagnostic feedback have been incorporated into commercial systems and plant-floor solutions but can be cumbersome to analyze in real-time manufacturing environments.
- This work introduces a sensing, data analysis, feature extraction, and novelty detection framework that is both robust and simple, and that can be readily integrated into industrial production environments ranging from low- to high-volume manufacturing.

Experimental Method

- Single-point photodiode sensor (420 – 675 nm wavelengths) is used to collect the optical radiation emitted from the welding plume
  - Weld experiments are outlined in the tables below for both thin sheet (0.2 mm) Ti welds and thicker sheet (1.27 mm) Al welds both in a lap weld configuration in a fixture as pictured.
  - Travel speed was 175 mm/s for the Ti and 200 mm/s for the Al
  - Welds were performed using a 6kw IPG with a scanning optic.
  - Welds were nominally 10 mm in length.

Setup



CP-Ti

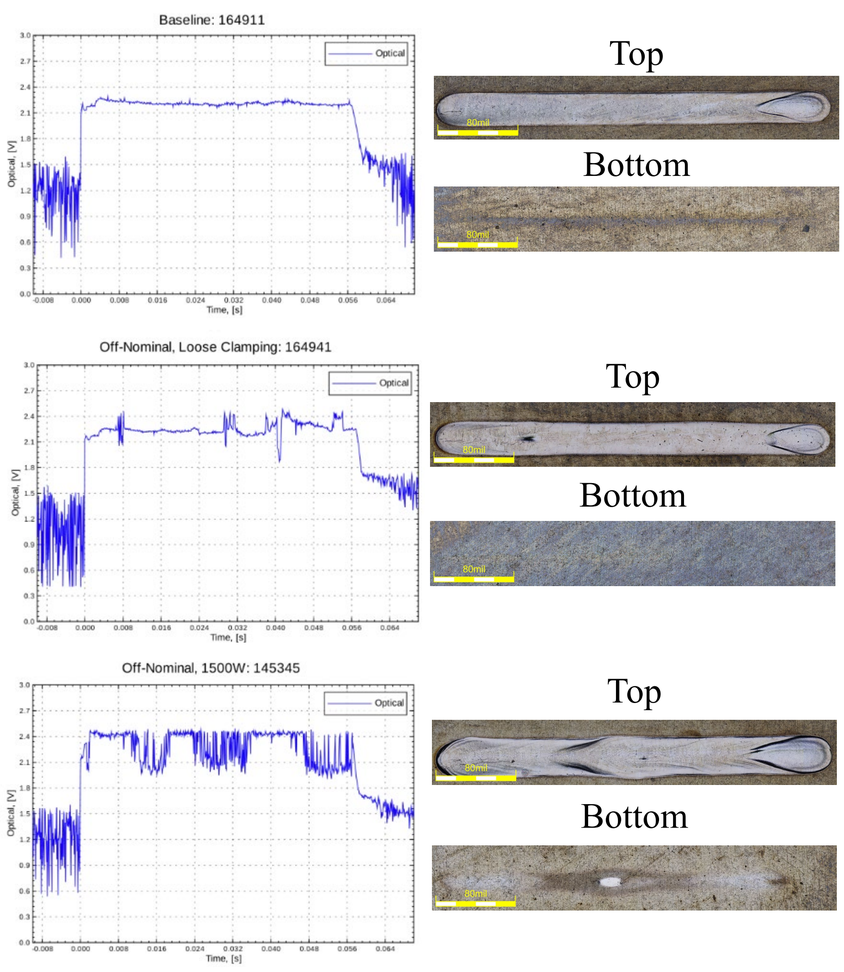
Weld ID	Type	Power, [W]	Clamping
150155	Baseline	1200	Secure
150344	Baseline	1200	Secure
164403	Baseline	1200	Secure
164839	Baseline	1200	Secure
164911	Baseline	1200	Secure
165939	Baseline	1200	Secure
165954	Baseline	1200	Secure
170350	Baseline	1200	Secure
170408	Baseline	1200	Secure
164427	Off-Nominal	1200	Loose
164636	Off-Nominal	1200	Loose
164941	Off-Nominal	1200	Loose
165342	Off-Nominal	1200	Loose
165442	Off-Nominal	1200	Loose
165642	Off-Nominal	1200	Loose
165847	Off-Nominal	1200	Loose
145950	Off-Nominal	1350	Secure
144921	Off-Nominal	1500	Secure
145345	Off-Nominal	1500	Secure
145522	Off-Nominal	1500	Secure
153334	Off-Nominal	1500	Secure
154027	Off-Nominal	1500	Secure
154750	Off-Nominal	1600	Secure
155453	Off-Nominal	1700	Secure
162416	Off-Nominal	1715	Secure
163236	Off-Nominal	1715	Secure
162227	Off-Nominal	1725	Secure
160335	Off-Nominal	1750	Secure
160056	Off-Nominal	1800	Secure

AA1100

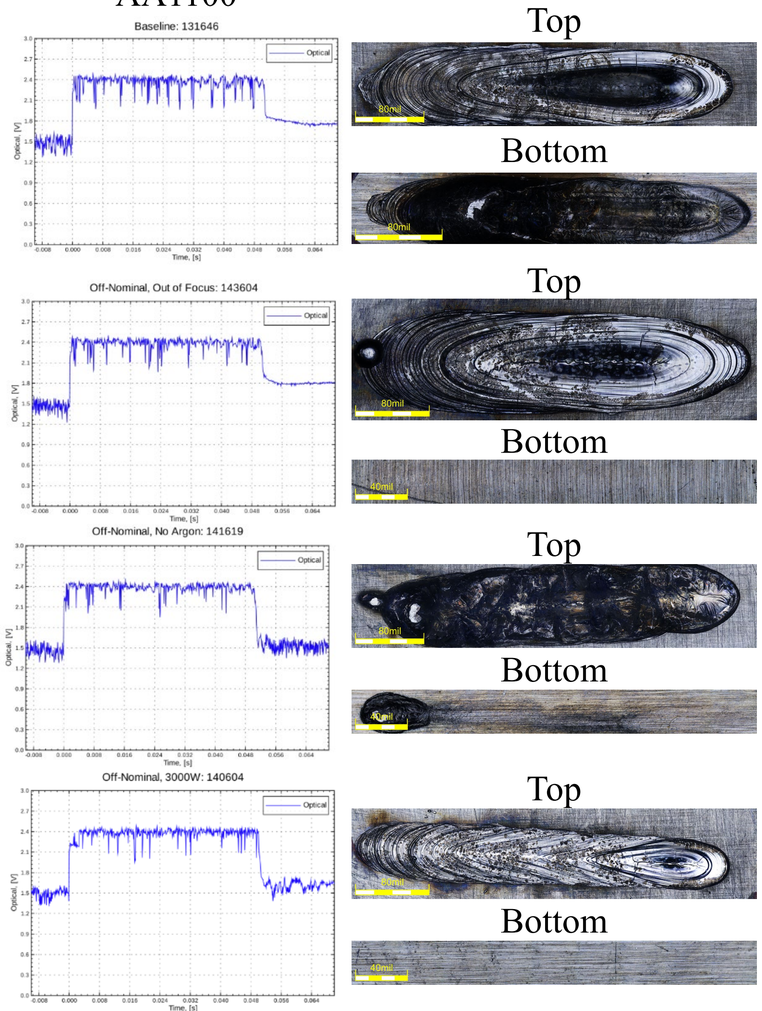
Weld ID	Type	Power, [W]	Focus, [mm]	Shielding Gas
131625	Baseline	6000	0	Yes
131646	Baseline	6000	0	Yes
131735	Baseline	6000	0	Yes
131759	Baseline	6000	0	Yes
141326	Baseline	6000	0	Yes
141330	Baseline	6000	0	Yes
141335	Baseline	6000	0	Yes
141353	Baseline	6000	0	Yes
141359	Baseline	6000	0	Yes
141408	Baseline	6000	0	Yes
135545	Off-Nominal	3000	0	Yes
140604	Off-Nominal	3000	0	Yes
141800	Off-Nominal	3000	0	Yes
141806	Off-Nominal	3000	0	Yes
135136	Off-Nominal	4000	0	Yes
141722	Off-Nominal	5000	0	Yes
141715	Off-Nominal	5000	0	Yes
134752	Off-Nominal	6000	0	No
141608	Off-Nominal	6000	0	No
141619	Off-Nominal	6000	0	No
141637	Off-Nominal	6000	0	No
143557	Off-Nominal	6000	+0.5	Yes
143604	Off-Nominal	6000	+0.5	Yes
143614	Off-Nominal	6000	+0.5	Yes

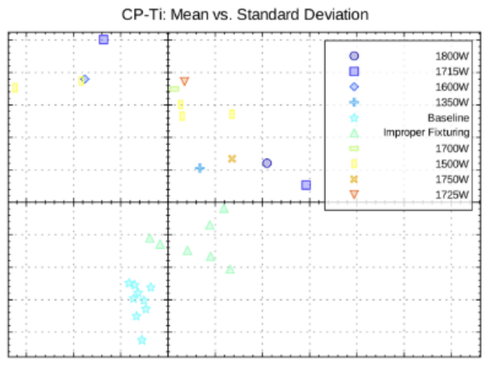
Results

CP-Ti

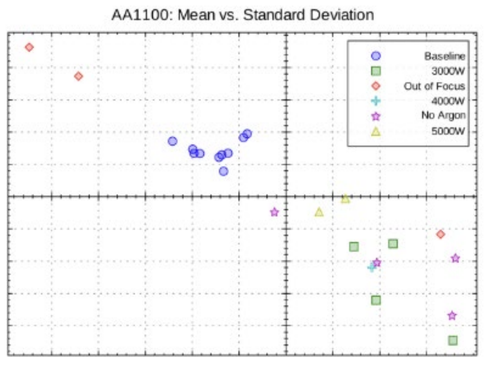


AA1100





Descriptive statistics are calculated to reduce the time-domain signal to a set of discrete features. Principal component analysis (PCA) is then applied to transform the multi-dimensional feature space derived from a set of baseline welds. The eigenvectors obtained from the PCA are used to project new observations onto the newly formed two-dimensional principal component space. The location of the projected data within this space is used to classify new welds as either nominal or off-nominal relative to the baseline population.

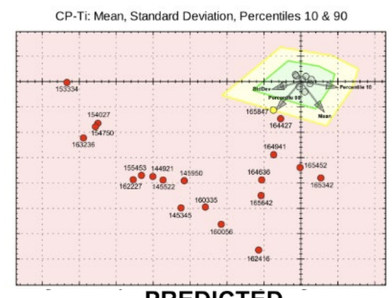


Conclusions

1. The laser welding plume can serve as an effective in process metric for fault detection.
2. The PCA model captures the baseline operating signature of the laser welding process and can distinguish off nominal welds from baseline welds.
3. The novelty detection approach presented in this effort further provides:
   i. The ability to detect faults without relying on historical fault data, contrived fault conditions, or large numbers of training instances.
   ii. Easy retraining with minimal human intervention or extensive tuning of rules.
4. Finally, while all classification techniques have trade-offs, the advantages of the proposed framework include:
   i. Unsupervised learning that does not require labeled fault data.
   ii. Straightforward implementation suitable for industrial deployment.
   iii. Graphical and intuitive interpretation of results, easily communicated to non-technical stakeholders.

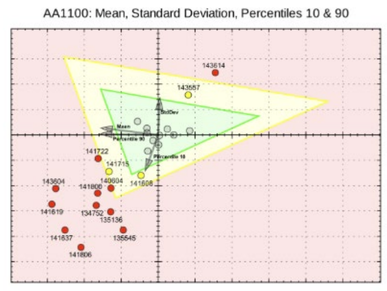
Discussion

- Analysis of the CP-Ti off-nominal data shows a pronounced positive shift that is strongly correlated with the 90th percentile, closely reflecting the visual dynamics observed in the optical signal.
- The single-holdout validation confirms enhanced model robustness for the baseline welds and successfully classifies all off nominal welds.



ACTUAL \ PREDICTED	POSITIVE (Off-Nominal Behavior)	NEGATIVE (Nominal Behavior)
POSITIVE (Off-Nominal Behavior)	TRUE POSITIVE: 180	FALSE NEGATIVE: 0
NEGATIVE (Nominal Behavior)	FALSE POSITIVE: 0	TRUE NEGATIVE: 9

Accuracy	100%	Precision	100%
True Positive Rate	100%	False Positive Rate	0%



ACTUAL \ PREDICTED	POSITIVE (Off-Nominal Behavior)	NEGATIVE (Nominal Behavior)
POSITIVE (Off-Nominal Behavior)	TRUE POSITIVE: 137	FALSE NEGATIVE: 3
NEGATIVE (Nominal Behavior)	FALSE POSITIVE: 0	TRUE NEGATIVE: 10

Accuracy	98%	Precision	100%
True Positive Rate	97.86%	False Positive Rate	0%

- Analysis of the AA1100 off-nominal data shows that three welds fall within the “suspected” boundary, compared to only one in the previous results.
- The single-holdout validation confirms improved model robustness for the baseline welds; however, two off-nominal welds are misclassified: weld 141715 is incorrectly classified twice, during the second and tenth holdouts, and weld 141608 is misclassified once, during the seventh holdout.