Influences of wobble frequency, wobble length and power compensation in Handheld Laser Beam Welding (HLBW)

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Background and objectives

- Handheld Laser Beam Welding (HLBW) adoption has accelerated rapidly since 2023 due to reduced heat input, high weld quality, lower costs, and skilled welder shortages.
- Knowledge gap: Existing codes (e.g., ASME BPVC Sec. IX) do not account for unique HLBW variables like beam oscillation (wobble), and power compensation.
- Objective: Evaluate how wobble frequency (f_W), wobble length (L_W) and power compensation (P_C) parameters correlate with bead geometry and power stability to contribute to the establishment of qualification limits.

Materials and methods

- Equipment: Miller OptX™ 2 kW HLBW system with cobot interface on a rotary positioner.
- Autogenous welds were performed using N_2 shielding gas per the parameters in Table 1.
- Workpiece: 4″ Schedule 40 SA-106 Gr. B low-carbon steel pipe in 1G position.
- High-Speed Videography (HSV): Recorded using a Phantom VEO 1310 camera at 10,000 fps to capture weld pool motion.
- Beam profiling: PRIMES MSM+ monitor was used to capture power distribution within a plane of a beam with power compensation.
- Power Measurement: CPM-F10 power monitor used to measure actual average power delivered during power compensation.

Table 1 – Welding parameters.

Parameter	Notation	Value	Unit
Beam Power*	P	1050	W
Working extension	W_L	78.5	mm
Beam spot diameter	SD	91.7	µm
Travel speed	U	52.1	cm min^{-1}
Drag angle	D_A	50	Degree
Shielding gas pressure	–	40	psi
Wobble frequency	f_W	0, 1, 5, 40 & 100	Hz
Wobble length	L_W	0, 1, 2 & 3	mm
Power compensation	P_C	0, 10 & 30	%

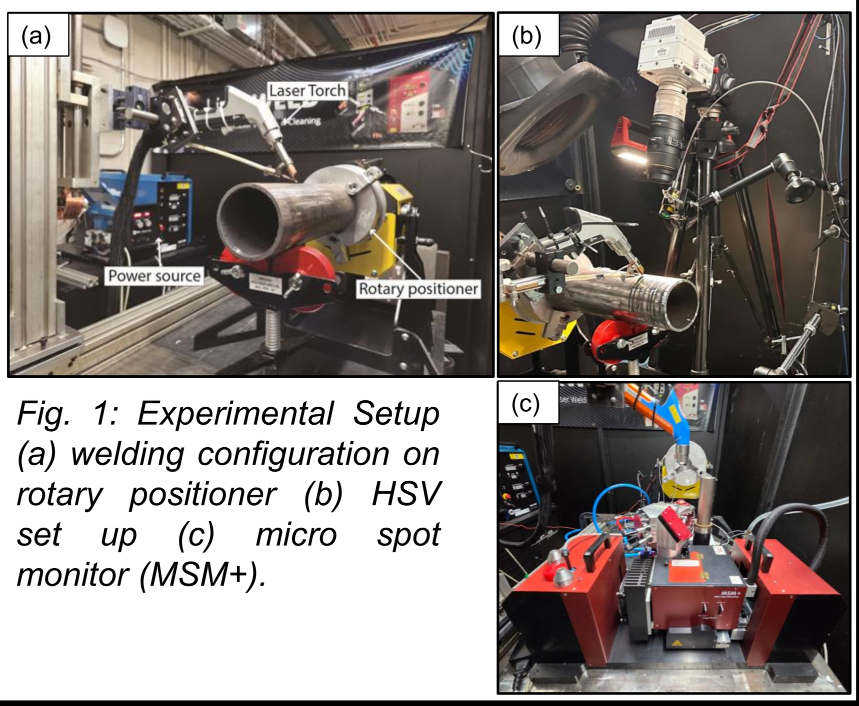

Fig. 1: Experimental Setup (a) welding configuration on rotary positioner (b) HSV set up (c) micro spot monitor (MSM+).

Wobble length L_W and penetration

- Bead width increases and penetration decreases with increasing wobble length.
- Increasing the wobble length to 2 mm or greater resulted in the formation of "fangs", i.e. penetration peaks at the bottom edges of the melt pool with reduced penetration in the middle. Fangs are attributed to zero transverse velocity at oscillation limits.

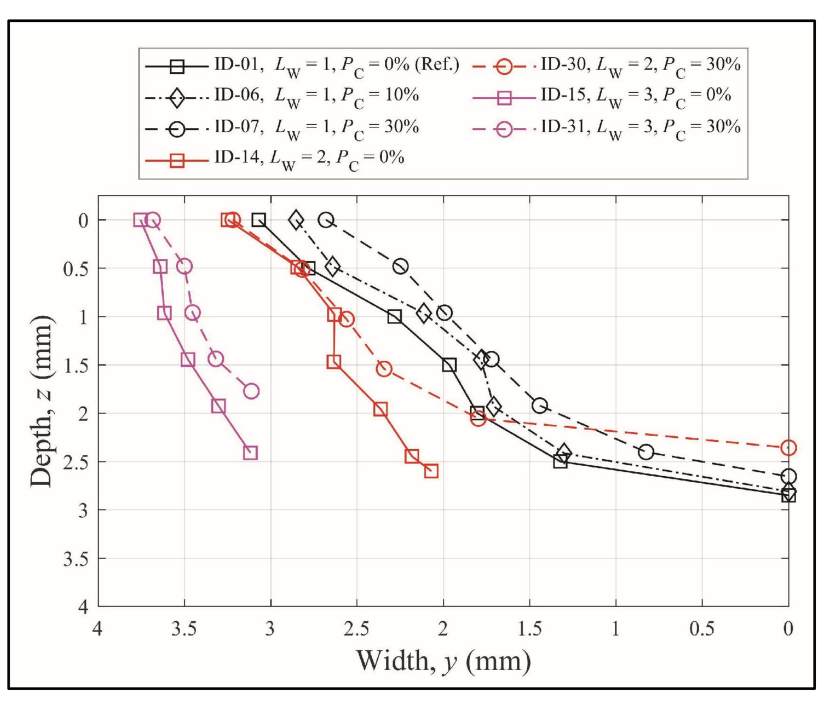

Fig. 2: Penetration profile at f_W = 40 Hz for different wobble lengths and power compensations.

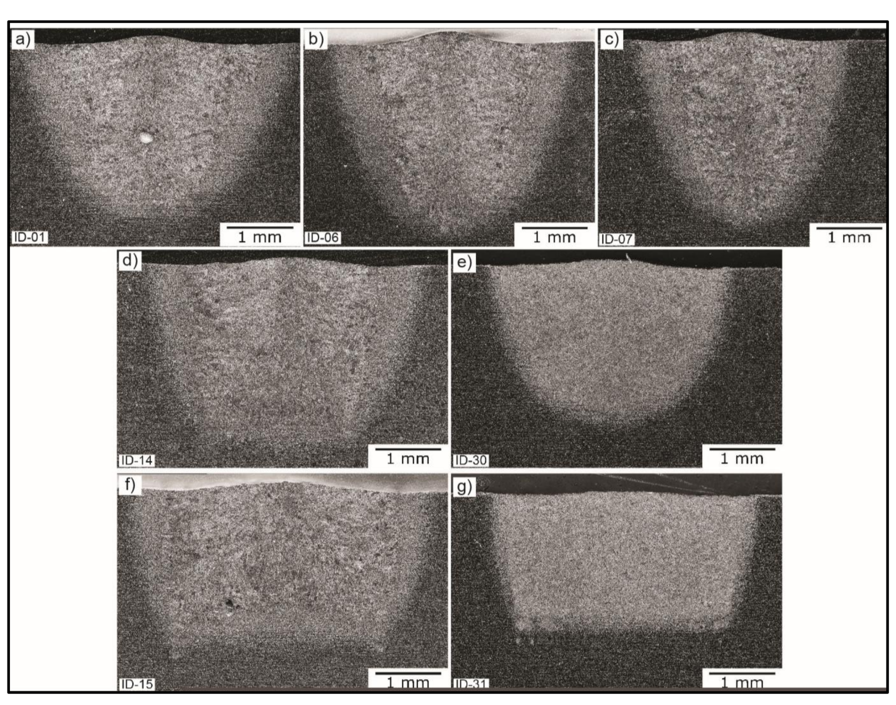

Fig. 3: Cross sections corresponding to the weld IDs from Fig 2.

Power compensation

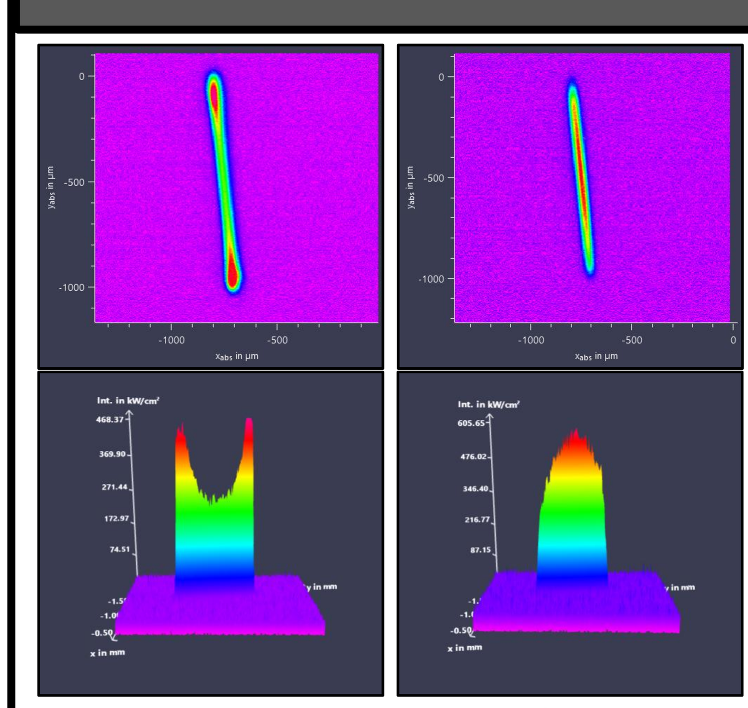

Fig. 4: Laser power distribution for 1000 W at and 1 mm wobble without compensation (left) and with 80% compensation (right).

What is it?

- Power compensation is an attenuation power at the edges of the beam wobble path to compensate influences of dwell time.
- Power compensation affects average power (currently not captured by ASME Sec. IX).

Plane profiling with MSM+

- Plane profiling shows the power distribution across a given wobble setting.
- Power density is decreased at the edges of the wobble.

Power compensation model:

- Sinusoidal wobble movement (speed).
- Linear decay of power from wobble center to edges (sinusoidal with time).

$$P_{Avg} = P_{set} - \frac{2}{\pi}\left[P_{set} - (1 - P_C)P_{set}\right]$$

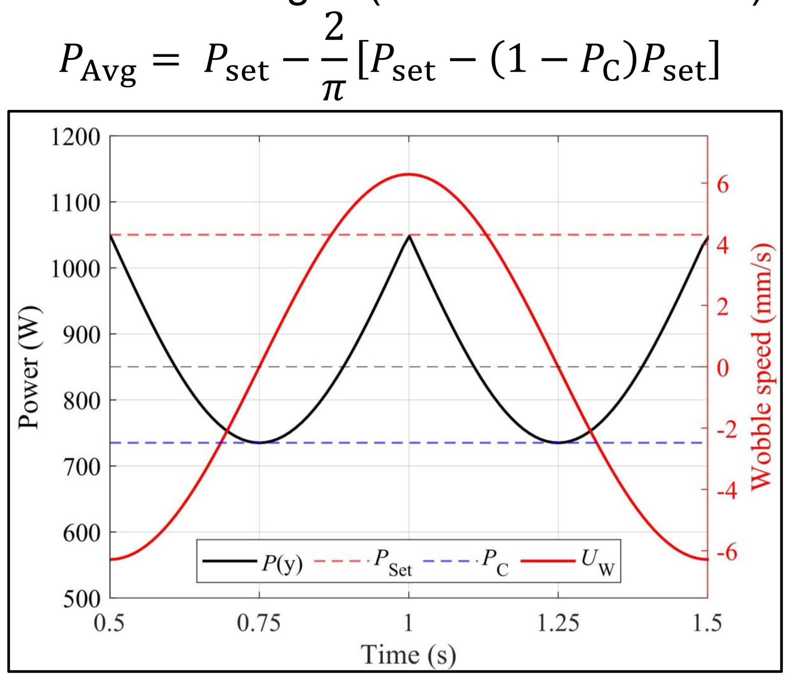

Fig. 5: Power compensation and wobble speed for $f_W = 1$ Hz, $L_W = 2$ mm, $P_{set} = 1050$ W, and $P_c = 30$ %.

Table 2: Measured averaged power (P_{Meas}) and calculated average power (P_{Avg}) for different power compensations (P_C) and relative errors.

P_{Set} [W]	P_C [%]	P_{Meas} [W]	P_{Decay} [%]	$P_{Avg.}$ [W]	Rel. Error [%]
500	0	565.68	---	---	---
	10	533.50	5.69	529.66	0.72
	30	450.85	20.30	457.64	1.51
	50	366.86	35.21	385.62	5.22
	30*	439.86	22.24	457.64	4.04
	30**	437.86	22.65	457.64	4.59
1000	0	1112.70	---	---	---
	10	1046.40	5.96	1041.782	0.44
	30	912.10	18.03	900.15	1.31
	50	778.20	30.06	758.49	2.53
	30*	902.61	178.88	900.15	0.27
	30**	900.05	19.11	900.15	0.01
1500	0	1620.90	---	---	---
	10	1535.10	5.29	1517.67	1.14
	30	1349.80	16.72	1311.30	2.85
	50	1178.10	27.32	1104.92	6.21
	30*	1350.40	16.68	1311.30	2.90
	30**	1343.10	17.13	1311.30	2.37

* $L_W = 3$ mm, $f_W = 40$ Hz
** $L_W = 1$ mm, $f_W = 100$ Hz
All other values correspond to $L_W = 1$ mm, $f_W = 40$ Hz

Wobble frequency f_W effects

- Low Frequencies (1–5 Hz): Produced asymmetric cross-sections and "worm-shaped" surface ripples because high travel speed relative to f_W caused the keyhole to lag transversally.
- High Frequencies (40–100 Hz): Yielded consistent, symmetric bead widths and stable weld pool behavior.
- Penetration decreased slightly with higher frequencies (≈ 0.40 mm or 12% difference between 1 Hz and 40 Hz).

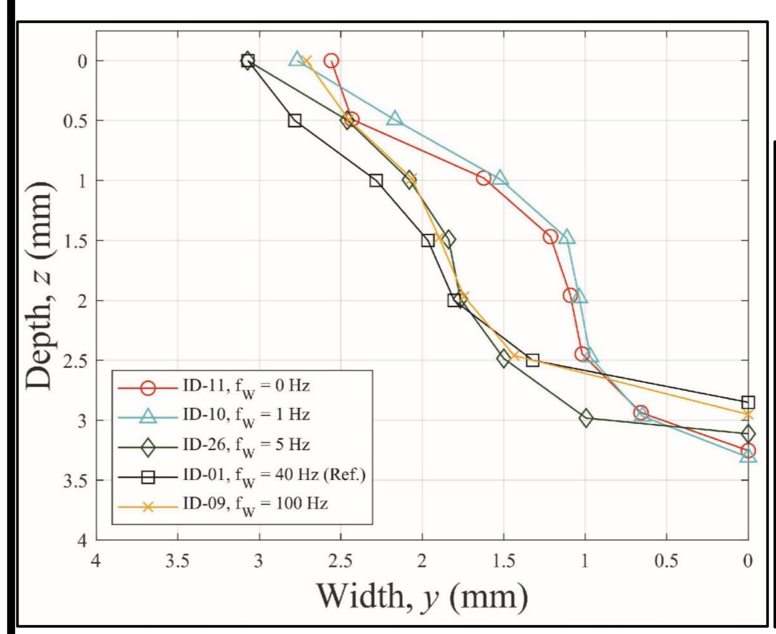

Fig. 6: Penetration profiles at $L_W = 1$ mm for different wobble frequencies.

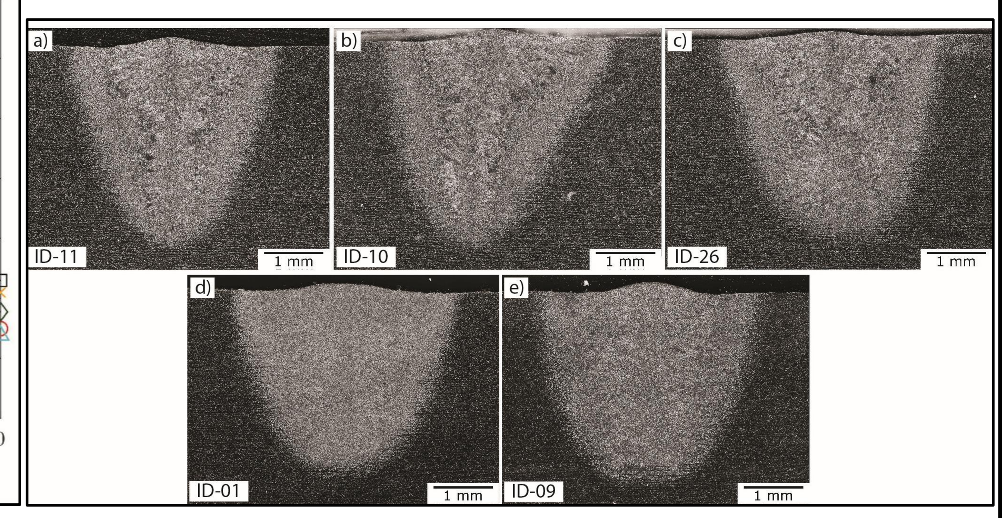

Fig. 7: Cross sections corresponding to the weld IDs from Fig 6.

Discussion

Wobble length:

- At small wobble lengths ($L_W = 1$), the beam spot remains inside a single, stable molten pool, yielding a smooth material flow.
- At larger wobble lengths ($L_W = 2$ mm to 3mm), the beam sweeps across a much wider path (for a given f_W), forcing the keyhole to travel near the solid-liquid boundary
- Rapid sweep speed through the oscillation center reduces dwell time, leading to shallower centerline penetration relative to the edges.

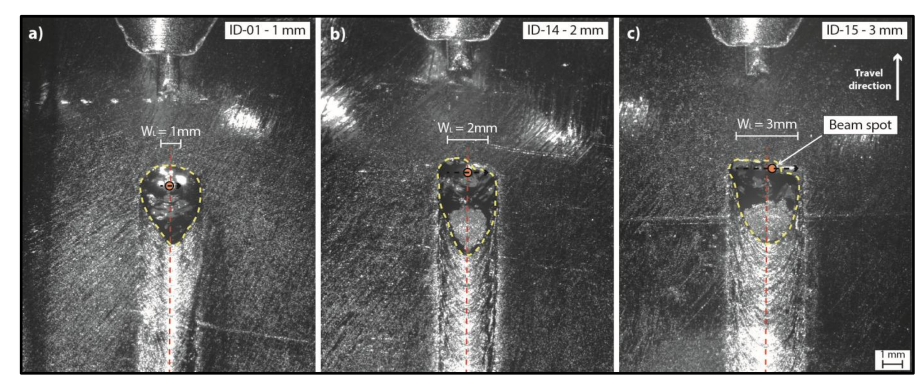

Fig. 8: High-speed video frames for experiments carried out with different wobble lengths a) LW = 1 mm b) LW = 2 mm c) LW = 3 mm.

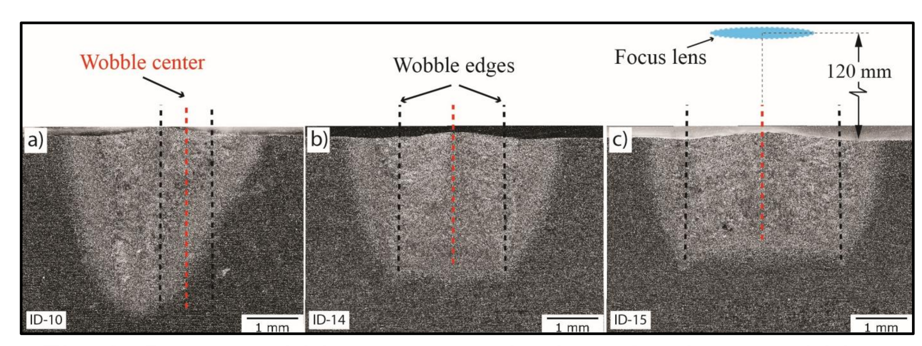

Fig. 9: Beam wobble center and edges for three wobble conditions: a) ID-10: $f_W = 1$ Hz, $L_W = 1$ mm. b) ID-14: $f_W = 40$ Hz, $L_W = 2$ mm. c) ID-15: $f_W = 40$ Hz, $L_W = 3$ mm

Wobble frequency:

- At low f_W (1 to 5 Hz), high linear travel speed relative to beam oscillation frequency causes a large wobble pitch. The bottom of the keyhole lags the beam spot on the pool surface causing asymmetric penetration profile and "worm-shaped" surface ripples.
- At high f_W (40 to 100 Hz), rapid beam sweep acts as a quasi-line heat source, keeping the keyhole in a single stable pool to produce symmetric, uniform beads.

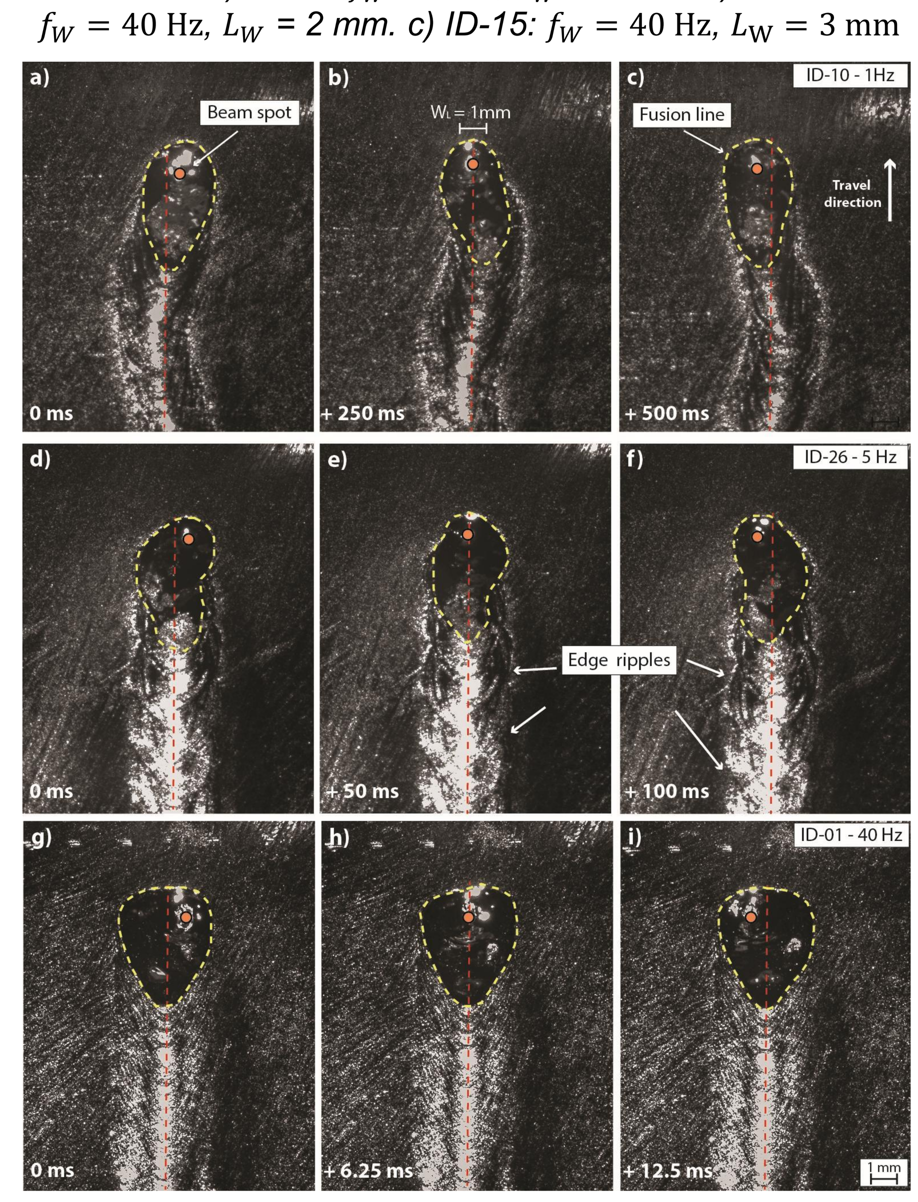

Fig. 10: High-speed video images of molten pool and bead shape for f_W of 1 Hz (a, b and c), 5 Hz (d, e and f) and 40 Hz (g, h and i).

Compensation:

- Power compensation successfully removes penetration fangs at higher L_W, yielding a uniform, flat penetration profile.

Code & qualification implications:

- Wobbling or oscillating parameters are not captured under ASME sec. IX for a handheld laser welding device (only machine or automatic).
- Under ASME Sec. IX (QW-409.21), a > 5% reduction in power constitutes an essential variable change requiring procedure requalification.
- Essential Variable Threshold: Applying even a modest 10% power compensation results in an average power drop > 5%.

Conclusions

- Wobble Effects & Qualification: Longer wobble lengths reduce centerline depth while higher frequencies stabilize the pool; mechanical testing is necessary to establish qualification boundaries.
- Energy Control via Compensation: Power compensation is an effective tool to prevent localized penetration peaks in wide wobble configurations.
- Regulatory Compliance: Because power compensation inherently decreases delivered average power, guidelines for the power compensation variable are recommended to be established for HLBW procedure qualification.

Acknowledgements

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