Heat and Fluid Flow during Laser Beam Welding in Space

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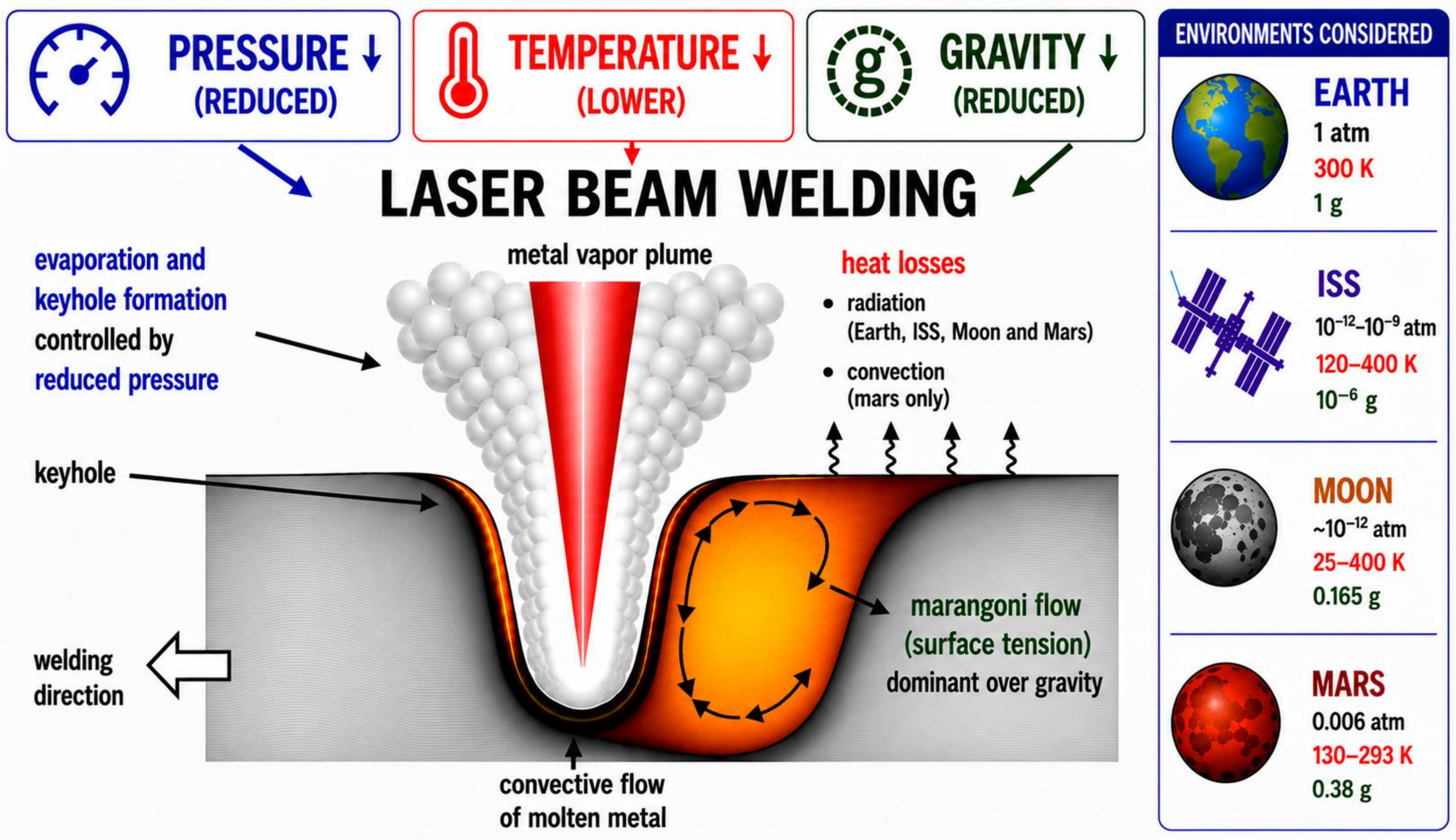

Figure 1: Key aspects for laser beam welding on SS 304 alloy under various environmental conditions.

1. PROBLEM STATEMENT AND OBJECTIVE

- **Laser beam welding** enables **deep-penetration joining for in-space manufacturing.**
- **Coupled pressure, temperature, and gravity** effects remain insufficiently understood, limiting prediction of thermo-fluid behavior and fusion-zone geometry.
- **Objective: Develop a unified thermo-fluid framework for SS304 alloy using laser beam welding across Earth, ISS, Moon, and Mars conditions (Figure 1).**

2. METHODS

- **Developed** a **3-D thermo-fluid model** incorporating **evaporation, keyhole dynamics, heat transfer, and melt-pool flow.**
- **Simulated** transient **weld behavior** using an **in-house finite-volume solver (Intel Fortran).**

3. RESULTS AND DISCUSSIONS

- **Reduced pressure** enhances **keyhole penetration**, **lower temperature** reduces **fusion-zone** size, and **Marangoni flow** dominates over **buoyancy** during laser welding of SS304 alloy **(Figure 2).**
- **(Figure 3)** shows **similar Marangoni-driven recirculation** under all **space environments**, while **higher temperatures** sustain a larger molten pool.
- **Model validation** between **predicted and experimental profiles** for SS 304 alloy with 16 kW power and a welding speed of 17 mm/s **(Figure 4).**
- **NASA laser beam welding experiments and EBSD characterization** verified reliable weld formation under **Earth** and **reduced-gravity conditions,** providing **experimental evidence** for **future lunar infrastructure assembly and on-orbit spacecraft repair (Figure 5).**

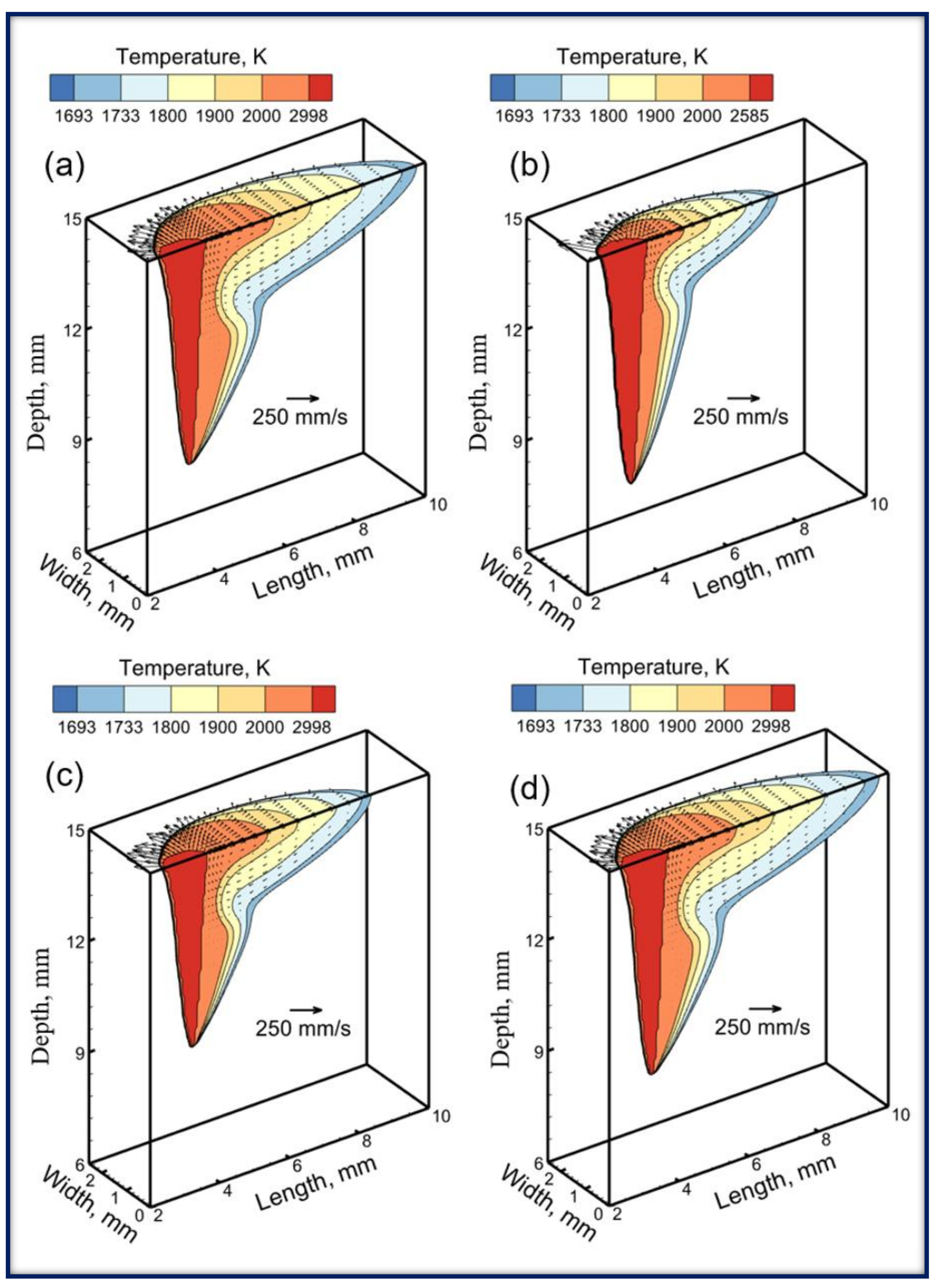

Figure 2: Calculated 3D temperature and velocity distributions under various processing conditions of (a) 1 atm, 300K, and 1g (9.81 m/s^2) (b) 0.1 atm, 300K and 1g (9.81 m/s^2) (c) 1 atm, 100K, and 1g (9.81 m/s^2) (d) 1 atm, 300K, and 10^{-6}g (9.81×10^{-6} m/s^2).

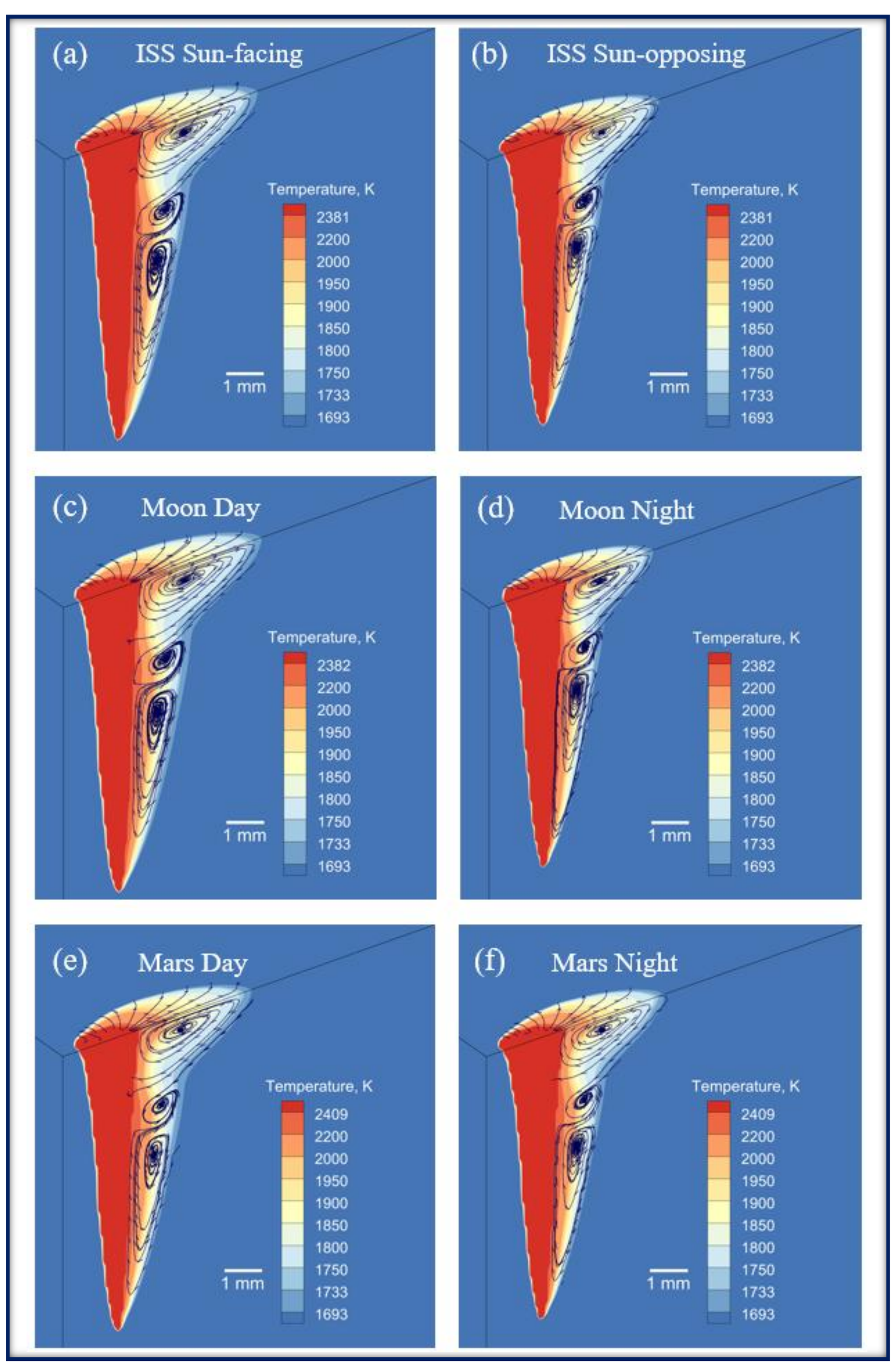

Figure 3: Calculated temperature fields and stream traces illustrating the velocity distributions inside the molten pool of (a) 350K, (b) 150K, (c) 380K, (d) 80K, (e) 260K, and (f) 160K during laser beam welding of SS304 alloy.

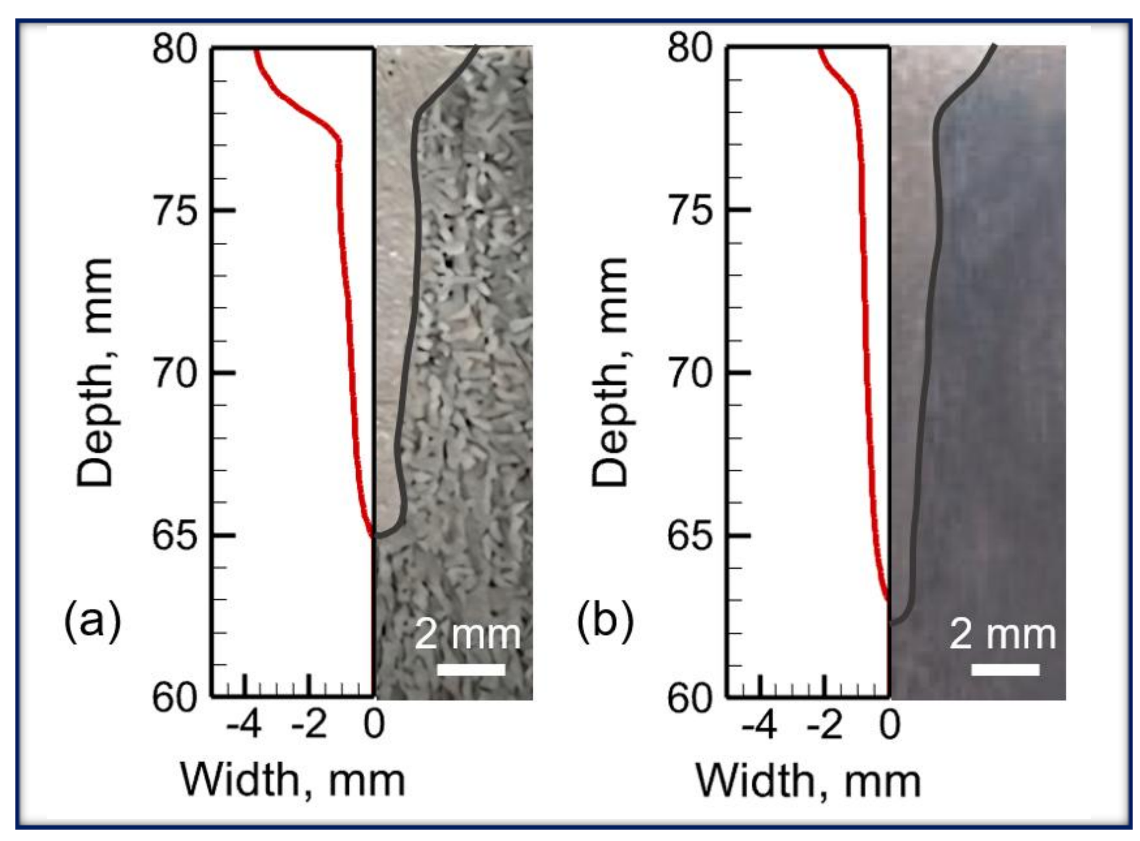

Figure 4: The model (left) was validated based on cross-sections from two experimental tests (right): (a) 1 atm and (b) 0.5 atm. **Experimental images from:** A. Youhei et al. Science and Technology of Welding and Joining, 2014.

4. CONCLUSIONS

- **Earth, ISS, Moon, and Mars** produce **distinct fusion-zone geometries** through the coupled effects of pressure, temperature, and gravity.
- **Pressure controls** keyhole penetration, **temperature governs** molten-pool evolution, and **gravity** has only a minor influence because **Marangoni flow** dominates during **horizontal welding**.
- **Expand this model** to **multi-pass and multi-layer** laser processing, enabling **predictive process design** for in-space manufacturing.

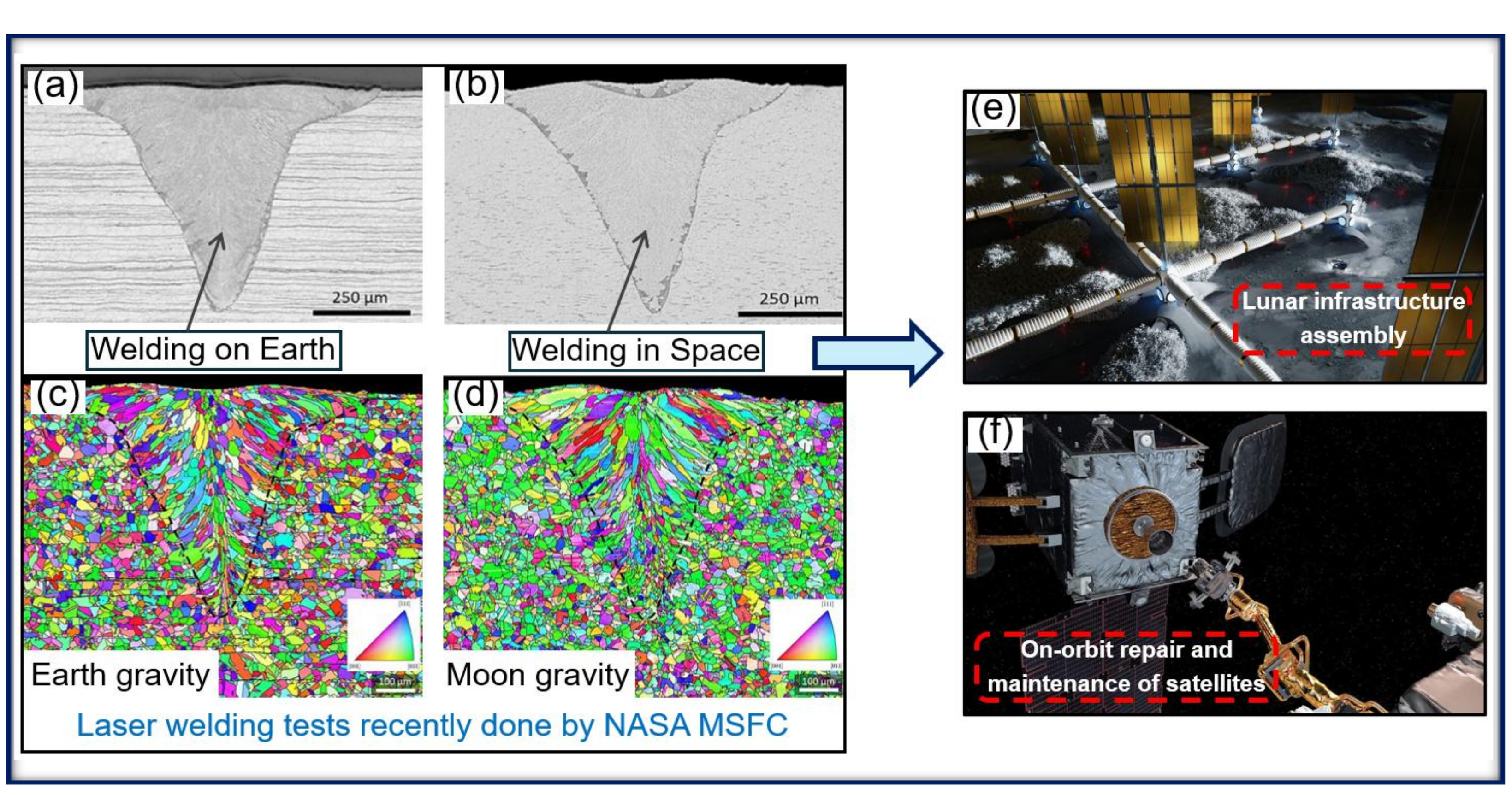

Figure 5: NASA laser-welding experiments and EBSD characterization validate the reliability of joining for future in-space manufacturing, lunar infrastructure assembly, and on-orbit spacecraft repair. **Experimental EBSD images from:** Riffel et al. Materials & Design, 2026.

5. ACKNOWLEDGEMENTS

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