Sensor-based Monitoring of Laser and Hybrid Laser–Arc Welding: From Process Dynamics to Component Distortions

Abstract

Welding is a fundamental joining technology, with estimates suggesting involvement in up to 60% of industrial manufacturing. As component complexity increases and production volumes rise, joining processes must deliver higher productivity while meeting increasingly stringent quality requirements. Laser welding and hybrid laser–arc welding are increasingly adopted in this context, offering high precision, low heat input, and excellent suitability for automation in high-throughput manufacturing. In parallel, industrial quality assurance is trending toward higher inspection coverage (up to 100% in some applications). Achieving such coverage solely through offline non-destructive testing is costly and slow, motivating in-process sensing and real-time monitoring to reduce scrap, rework, and inspection effort. At the same time, multiple coupled physical mechanisms govern these processes, making weld-quality variations difficult to interpret and attribute to a single cause.

Monitoring systems are typically based on measurable process signals, including optical, acoustic, and thermal responses. Weld quality is governed by phenomena spanning multiple length and time scales: different mechanisms dominate from the process zone to the component level, and no single observable is sufficient to characterise quality. Accordingly, this thesis develops and validates in-process monitoring strategies for laser and hybrid laser–arc welding through three complementary case studies spanning local process behaviour, weld-section integrity, and component-level dimensional response, and evaluates whether acoustic, optical, and thermal sensing can provide quantitative, application-relevant indicators suitable for production-oriented monitoring.

At the process scale, a membrane-free optical microphone was used to monitor remote laser welding of AA1050 aluminium overlap joints, demonstrating sensitivity to keyhole-regime transitions, including blind-to-passing-through keyhole; feature-level fusion with photodiode spectral emissions provided complementary information but did not consistently outperform acoustic features alone. At the weld-section scale, OCT enabled in-situ penetration-depth monitoring in hybrid laser–arc welding of S355 steel, capturing depth trends up to an effective depth of ∼6 mm. At the component scale, infrared thermography provided in-process thermal histories that constrained a thermo-mechanical FEM model, enabling prediction of angular distortion in thin aluminium welding with errors below 0.3% for representative conditions.

Overall, the results show that quantitative monitoring outputs can be obtained across complementary decision levels and can support a more comprehensive assessment of weld quality than single-sensor monitoring alone. The thesis provides validated workflows and operating envelopes and complements the technical results with a deployment-oriented discussion of industrial applicability, scalability, and limitations, laying the groundwork for future integrated monitoring and, where feasible, closed-loop quality control.