Ultrasound Process Monitoring in High-Speed Laser Welding with Wavelet Scattering Transform for Low-Latency Defect Classification

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In the advanced field of high-speed laser welding within Non-Destructive Evaluation (NDE), the need for automated in-process monitoring has intensified, especially as the industry aims for superior welding quality at increasing welding speeds. A key focus of this pursuit is achieving improved temporal resolution of defect classification, essential for effective real-time monitoring. To this end, acoustic process monitoring has emerged as a preferred method. This research particularly emphasizes ultrasound process monitoring, tapping into its capability to access information from deep regions of materials, its broad frequency response, and its cost advantages in data acquisition and analysis. Alternative methods, including X-ray techniques, present specific challenges. They require high-speed imaging, often entailing expensive solutions with limited accessibility, introduce safety concerns in work environments, and struggle with penetration during butt welding. Similarly, camera-based methods are mainly constrained to surface observations and are notably vulnerable to environmental variables such as changes in illumination and dust, and face computational complexities. In stark contrast, ultrasonic signals engage with the entire scope of the welding process, offering a detailed view of its internal behaviour. Building on this capability, our research delves deeper into acoustic monitoring for high-speed laser welding under realistic environmental impairments. We commence our investigation by comparing structure-born and airborne ultrasound sensors, a comparison that has not been extensively explored in the current state of the art. Furthermore, we present a novel feature extraction approach by seamlessly integrating traditional algorithms with the Wavelet Scattering Transform. After extracting these robust features, we apply a neural network as a classifier, specifically to detect and classify welding defects, such as artificially introduced notches that mimic real-world defects in laser welds. The primary aim is to discern these notches and categorize them based on their width. The research achieved an accuracy exceeding 90% with signals 2ms in length, a commendable feat considering the intricacy of the classification challenge. Moreover, alongside the typical experimental conditions, which predominantly feature laser welding robot noise, this study also embraced real-world industrial challenges, such as background noises and cross-jets, to ensure a more comprehensive and thorough analysis. The results highlight a path forward, propelling the laser welding industry towards elevated standards of reliability and efficiency.