

Real-time femtosecond laser cleaning of microcontaminants using deep learning

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Laser cleaning is used extensively across industrial manufacturing for the removal of contaminants, including rust, paint, and surface impurities [1-3]. However, conventional laser cleaning typically applies higher-than-necessary laser energy to ensure the complete contaminant removal, leading to excessive energy consumption, unintentional material removal, and potential substrate damage. A more precise and adaptive cleaning strategy can enhance energy efficiency while preserving substrate integrity.

Recent advancements in deep learning have significantly improved process control in laser materials processing [4], particularly in real-time monitoring [5], predictive visualization [6], and parameter optimization [7, 8]. These developments offer a promising insight to addressing key challenges in laser cleaning by dynamically adjusting laser parameters to optimize contaminant removal while minimizing energy consumption and collateral damage.

This work introduces a new femtosecond laser cleaning method enhanced by deep learning, where a neural network, integrated into a real-time imaging system, automatically detects and identifies particle contaminants. Each identified particle is then selectively removed using a single laser pulse with precisely calibrated pulse energy, ensuring effective and efficient cleaning without damaging the substrate. Cleaning trials were conducted on samples containing a mixture of 15 μm polystyrene microbeads and 20 μm polymethacrylate microbeads. The neural network, trained on high-resolution imaging data, can predict the optimal laser energy required for removing each type of microbead by analyzing the appearance of the microbeads in real time. This adaptive approach ensures effective removal while minimizing energy consumption and substrate damage. The proposed method is particularly suited for high-precision applications in aerospace, electronics, vehicle maintenance, and medical device manufacturing, where selective material removal is essential.

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