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Improving Powder Characterization for Cold Spray with Physics-Informed Synthetic Data Generation

Powder characterization is critical for powder-based additive manufacturing, including Cold Spray. With an informed characterization of powder morphology, practitioners can improve feedstock design, optimize spray parameters, and model the relationships between critical velocity and deposition quality. While machine learning has emerged as a powerful tool for automating or accelerating characterization, it is frequently limited by the scarcity of high-quality labeled data. For example, by integrating computer vision components, labeling SEM micrographs to capture powder morphology can be performed in seconds, whereas hand-labeling can require over an hour for densely populated micrographs. However, because manual labeling is costly and time-consuming, it is difficult to acquire a sufficiently large dataset for effective model training. Further, advanced modalities, such as particle depth, occluded regions, and 3D reconstruction, are difficult to pair with existing microscopy data, making it impossible to train a model. To address these limitations, we present a physics-informed synthetic data generation pipeline and a unified multimodal dataset. To bridge the gap between synthetic and real data, we develop a physics-conditioned translation framework that converts rendered scenes into realistic AI-generated SEM micrographs, while preserving both edge fidelity and geometric accuracy. Extensive experimental evaluation confirms that translated synthetic data significantly improves particle segmentation accuracy in low-label regimes, outperforming real-only and raw-rendered baselines, particularly on stricter metrics such as AP@95. Additionally, we demonstrate that foundation models trained on large-scale natural images like urban scenes can be successfully adapted for high-precision volumetric analysis and depth prediction, providing a scalable solution for advanced scientific capabilities.