

Deep Learning Based Automated Detection of Clustered Helium Bubbles in Ion-Irradiated Materials

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Tungsten (W) is a leading candidate material for plasma-facing components in nuclear fusion reactors. However, severe irradiation environments induce the formation of Helium (He) bubbles [1], which significantly degrade the mechanical properties of the material. Quantitative evaluation of the size, density, and distribution of these bubbles via Transmission Electron Microscopy (TEM) is critical for understanding degradation mechanisms. Currently, this evaluation relies heavily on manual counting, which is excessively time-consuming, subjective, and prone to human error, particularly when bubbles are densely clustered or overlapping.

In this study, we employed Cellpose [2]—a deep learning architecture originally developed for biological cell detection—to investigate its efficacy in segmenting clustered He bubbles. By utilizing its unique gradient-tracking algorithm, we aimed to overcome the limitations of conventional thresholding in resolving overlapping bubble boundaries.

In this proof-of-concept study, we trained the model using a limited set of TEM images with preliminary annotations. Despite the presence of label noise from non-expert annotations, the model demonstrated robust feature extraction capabilities, successfully identifying individual bubbles in clustered regions. The model achieved a baseline mean Intersection over Union (IoU) of 0.45 against expert ground truth. Qualitative error analysis revealed that while the model effectively identifies isolated bubbles, it faces significant challenges in regions characterized by non-uniform contrast fluctuations. The artifact introduces substantial noise, leading to both false positives (misidentifying oxide patches as bubbles) and false negatives (masking actual bubbles within the mottled background). This observation provides a clear roadmap for enhancing the model's discriminative power, ensuring the reliability of the pipeline even under challenging imaging conditions.

This study demonstrates the feasibility of repurposing advanced bio-imaging AI architectures for metallurgical defect analysis. Even with limited and imperfect training data, the proposed pipeline provides a highly promising foundation for high-throughput, quantitative evaluation of irradiation damage, paving the way for data-driven materials design in nuclear applications.

[1] Trinkaus, H. (1983) 'Energetics and formation kinetics of helium bubbles in metals', *Radiation Effects*, 78(1–4), pp. 189–211. doi: 10.1080/00337578308207371.

[2] Stringer C, Wang T, Michaelos M, Pachitariu M. (2021) 'Cellpose: a generalist algorithm for cellular segmentation', *Nature Methods*, 18(1), pp. 100–106. doi: 10.1038/s41592-020-01018-x.