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Real-time Multi-Object Tracking of Ion-irradiation Induced Defects in *in situ* TEM Videos

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For the development and design of reactor structural materials, it is critical to understand the microstructural response of materials under extreme environments. The establishment of advanced microscopes combining *in situ* TEM with high-energy ion sources offers unique opportunities to study the dynamic behavior of radiation defects in real-time. However, *in situ* TEM experiments generate a large amount of data that remains under-analyzed mainly due to the lack of dedicated automated TEM video processing tools with the ability to perform meaningful quantitative analysis and derive defect metrics such as defect size, location, and lifetime. In this work, we developed a deep learning-based multi-object tracking (MOT) model, named *DefectTrack*, capable of robust and fast (28 frames per second) online tracking of ion-irradiation induced defect clusters. To facilitate the development of *DefectTrack*, we established an *in situ* TEM video MOT dataset following the standard *MOTChallenge* protocol [1]. The dataset comprises 1200 2048 × 2048 TEM images acquired during 1MeV Kr ions irradiation of pure Nickel at 700°C at a high temporal resolution of 9.7ms [2] and consists of a total of 243,052 defect clusters. The performance of *DefectTrack* was assessed by standard MOT evaluation metrics, and the resulting defect cluster lifetime distribution was compared to human experts using the Chi-Square and Kolmogorov-Smirnov tests. We also inspected the relationship between the MOT metrics and defect lifetime distribution measurements.

Figure 1a illustrates *DefectTrack's* MOT performance on a representative test set. The bounding box color is unchanged if a defect cluster is correctly tracked with the same tracking ID throughout its lifetime. *DefectTrack shows* excellent performance in tracking defect clusters. Two such examples are marked by orange and magenta arrows. Figure 1b presents the *DefectTrack* predicted defect lifetime bar plot during irradiation of Nickel. Each bar represents a tracked defect cluster. Such a detailed level of tracking can elucidate the fundamental mechanisms of irradiation defect formation and evolution in real-time. Figure 2a summarizes *DefectTrack's* MOT performance calculated using eight-fold cross-validation. We obtained an outstanding prediction on the test sets, with a Multi-Object Tracking Accuracy (MOTA) of 66.43±2.32%, Mostly Tracked (MT) of 67.81±2.07%, ID-F1 of 57.38±1.81%, and ID switch of 89±12, comparable to the state-of-the-art deep learning MOT models [1]. In Figure 2b, the lifetime histogram comparison shows that *DefectTrack*'s prediction closely follows the ground truth defect lifetime distribution. The chi-square test fails to reject the null hypothesis at a 0.50 significance level that the lifetimes of defects found by *DefectTrack* are drawn from the same distribution as the ground truth. We further analyze the sources of success and errors by considering the defect representations, defect size, and model training strategy. Compared to human experts, the deep learning-based MOT automated model is robust, reproducible, and 100 times faster while analyzing 25 times more defect clusters. In summary, the implementation of real-time high-throughput defect tracking to *in* *situ* irradiation TEM video data can provide new insights into the material's response to extreme environments and significantly accelerate the development of next-generation nuclear reactor materials.

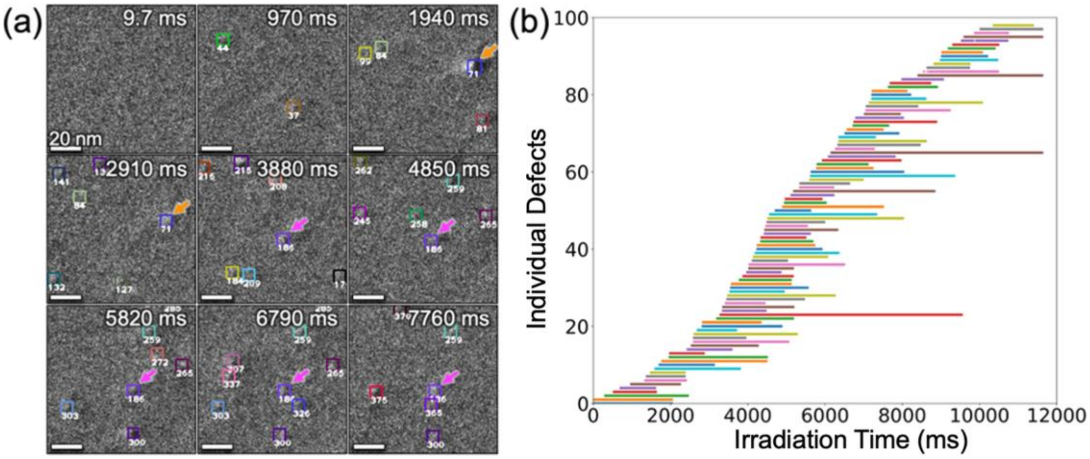
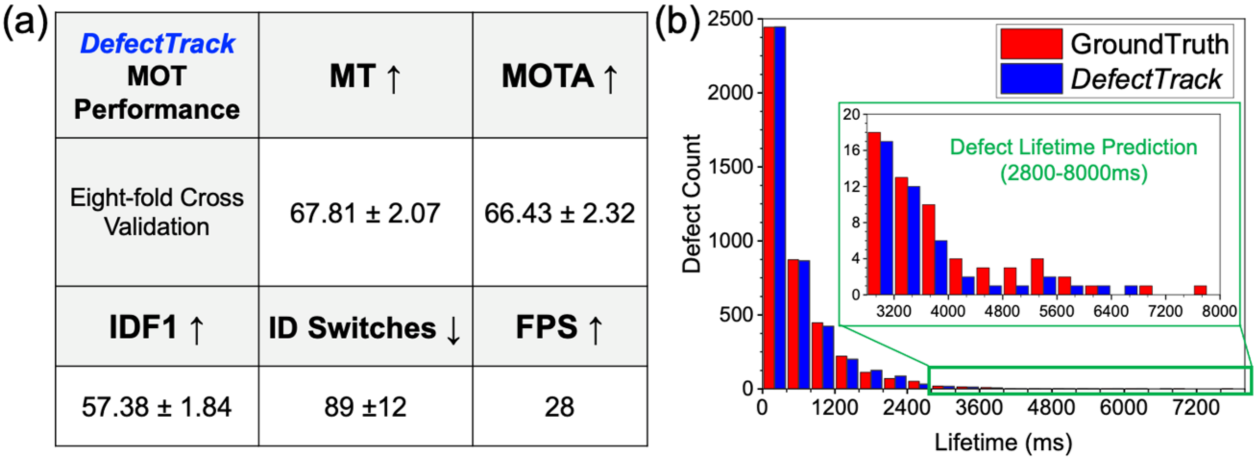


Figure 1. The visualization of *DefectTrack's* multi-object tracking performance on a representative test set. (a) Cropped 256 × 256 video frames of *DefectTrack* prediction with a time interval of 970ms showing tracked defect clusters marked by bounding box and unique tracking IDs. (b) Lifetime bar plot showing as defect clusters tracked by *DefectTrack* with lifetime > 900ms during irradiation of Nickel. The start and end time corresponds to the formation and annihilation of the defect clusters, and length is the tracked duration.


(a)

DefectTrack **MOT Performance**	**MT ↑**	**MOTA ↑**
Eight-fold Cross Validation	67.81 ± 2.07	66.43 ± 2.32
IDF1 ↑	**ID Switches ↓**	**FPS ↑**
57.38 ± 1.84	89 ±12	28

Figure 2. Multi object tracking performance of *DefectTrack* for the defect clusters in *in situ* irradiation TEM video. (a) The standard MOT evaluation metric showing the average model performance with standard deviations over the test sets. Note that the up arrows indicate the higher the score the better the tracking performance, and vice versa (b) Histogram of defect lifetime distribution predicted by *DefectTrack* and ground truth. Bin-width is determined by the Doane method.

References:

[1] P Dendorfer et al., International Journal of Computer Vision **129** (2021), p. 845.
[2] M Li, WY Chen and PM Baldo, Materials Characterization **173** (2021), p. 110905.