

## AI-based Fatigue Crack Behavior Analysis of Al Alloy Using ML-DIC Images

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### 1. Introduction

As nuclear power plants shift toward flexible operation to balance renewable energy loads, components face increased fatigue from cyclic thermal and pressure stresses. Accurate assessment of the stress intensity factor ( $\Delta K$ ) and crack growth rate ( $da/dN$ ) is now critical for structural integrity and safe maintenance. This study evaluates an ML-DIC film, which combines mechanoluminescence (ML)  $SrAl_2O_4:Eu^{2+}, Dy^{3+}$  (SAO) with carbon nanotube (CNT), as a high-precision sensor. We utilized the luminescence of SAO to pinpoint crack tip locations and applied Digital Image Correlation (DIC) to the CNT patterns to quantify the surrounding strain fields and  $\Delta K$  values [1]. Furthermore, we developed a CNN-based AI model that leverages ML stress images and DIC strain data to automate the prediction of crack propagation. This integrated approach enhances nuclear safety through early detection and optimizes operational efficiency by identifying the ideal timing for maintenance [2].

### 2. Methods and Results

In this study, an AI-based predictive model was developed by integrating ML and DIC techniques to analyze the fatigue crack behavior of Al7050-T7451 alloy. For the experiments, an ML-DIC film, fabricated by mixing SAO and CNT was applied to the specimens, and fatigue crack propagation tests were conducted at a load ratio of 0.1 in accordance with ASTM E647 standards. Images were captured at 60 FPS under varying UV light conditions, and the precise location and length of the crack tip were calculated using Python-based image processing. Additionally, the strain fields were visualized using Ncorr (MATLAB-based software) to quantitatively calculate the  $\Delta K$ .

Analysis revealed that the average height difference between the crack paths of the film and the specimen was only 13.331  $\mu m$  in the fatigue regime, demonstrating the film's superior crack-tracking performance. While ML intensity and strain fields expanded linearly with increasing applied load and  $\Delta K$ , the ML analysis did not fully capture the crack closure phenomenon compared to DIC due to afterglow effects.

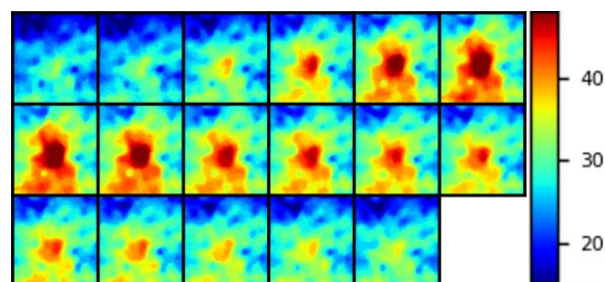


Fig. 1. ML intensity field according to load increase

Finally, when the collected data were trained on various CNN models (ResNet-50, VGG-16, EfficientNet, and DenseNet), predictive performance was maximized by integrating both ML and DIC data. For  $\Delta K$  prediction, the ResNet-50 model showed the highest accuracy with a coefficient of determination ( $R^2$ ) of 0.95, while for  $da/dN$  prediction, the DenseNet model recorded the best performance with an  $R^2$  of 0.96. This research suggests that the combination of ML-DIC technology and AI serves as an effective tool for structural integrity assessment and fatigue life prediction.

CNN model	$R^2$
ResNet-50	0.95
VGG-16	0.92
EfficientNet	0.91
DensNet	0.93

Table 1.  $\Delta K$  prediction result

CNN model	$R^2$
ResNet-50	0.95
VGG-16	0.94
EfficientNet	0.71
DensNet	0.96

Table 2.  $da/dN$  prediction result

### 3. Conclusion

In this study, an ML-DIC film composed of SAO and CNT was utilized to precisely analyze fatigue cracks in Al7050-T7451 alloy and to develop a predictive AI model. Experimental results demonstrated that the film detected crack paths with a minimal deviation of less

than 13.331  $\mu\text{m}$  from the specimen, while confirming a linear correlation between ML intensity, strain fields, and the  $\Delta K$ . Notably, the ResNet-50 based AI model automatically predicted  $\Delta K$  and the  $da/dN$  with a high accuracy of  $R^2$ . This system, capable of stable operation even in extreme environments such as dark-field conditions, is expected to significantly contribute to structural integrity assessments and the establishment of optimized maintenance strategies.

## **REFERENCES**

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