

Surface Defect Detection of HANARO Fuel: A Review of Machine Learning-Based Methods

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1. Introduction

The recent advancements in artificial intelligence (AI) have led to significant breakthroughs across numerous domains. In particular, deep learning (DL) has demonstrated exceptional performance and is being actively utilized in diverse fields, including cybersecurity, natural language processing, bioinformatics, robotics and control, and medical image analysis. By effectively learning complex patterns within unstructured data, such as images, text, and clinical datasets, DL provides superior accuracy compared to traditional machine learning (ML) approaches. These broad applications are underpinned by its robust representation learning capabilities and the capacity to process large-scale datasets. [1]

In the field of computer vision, convolutional neural networks (CNNs) serve as a pivotal methodology for defect detection. Specifically, CNNs have been implemented as a core technology for identifying various anomalies on product surfaces, demonstrating high efficacy in defect classification. [2, 3] Furthermore, A study has shown that applying CNNs to wafer surface inspection in semiconductor manufacturing can effectively replace manual visual inspection. [4]

Therefore, this study investigates recent research on applying advanced AI technology to the HANARO research reactor. Surface defect inspection can be specifically applied to HANARO fuel management. The implementation of DL-based techniques can mitigate human error, reduce inspector workload, and ensure the manufacturing of fuel rods with consistent quality. To facilitate the application of AI technology in the visual inspection of HANARO fuel, this study reviews existing literature, identifies areas for technical issues, and outlines future research directions.

2. Visual Inspection of HANARO Fresh Fuel

Visual inspection of HANARO fresh fuel is one of the procedures for ensuring safe reactor operations. This inspection is conducted following the fabrication of fresh fuel rods and prior to their loading into the reactor core to verify their mechanical integrity. The process primarily involves a visual assessment of the fuel surface's soundness. Inspectors manually check the surface for potential manufacturing defects, such as scratches or foreign material, while also verifying the structural robustness of assembled components and compliance with design specifications through

dimensional accuracy. Such inspections guarantee the initial integrity of the fuel and preemptively mitigate potential defects that could arise during reactor operation. Furthermore, once the fuel has been utilized, subsequent inspections are restricted to remote camera-based monitoring due to radiation, making naked-eye re-inspection impossible. Consequently, the visual inspection phase of the fresh fuel before its initial use remains an important process.

Fig. 1 shows the HANARO fuel assemblies, and Fig. 2 shows the defect inspection of fuel rods, fuel assemblies, and spent fuel. [5]

3. Machine Learning-based Methods

In image recognition using DL technology, DL has demonstrated excellent performance in fingerprint recognition using CNN and medical image classification using CNN. [1] In particular, these methods can be extended to the detection of surface defects in steel plates. Surface defects of steel plates may include scratches, cracks, pitting, delamination, etc. [6]

The surface defects of the fuel rod may differ from the main defects of the steel plate, but it is assumed that most of the surface defects on the fuel surface are similar to those of the steel plates. And, there are few studies to detect surface defects in nuclear fuel with AI technology. Accordingly, it is necessary to review the surface defect detection methods of a representative metal, steel plate.

Surface defect detection using ML can be divided into a traditional ML method and a method using DL. An important feature that distinguishes this is whether learning using CNN is performed or not.

First, traditional ML methods are broadly categorized into two types: texture-based or shape-based types. Texture-based methods are further divided into four categories: statistical-based methods, filter-based methods, structural-based methods, and model-based methods. Meanwhile, shape-based methods are typically classified using either contour or area descriptors.

Second, using DL methods include supervised methods, unsupervised methods, and weakly supervised method, and depending on whether there is enough data for learning, the method available varies. [7] DL using CNN was proven to be excellent on computer vision. For example, it has become play an import role in fingerprint identification and medical image classification. [2]

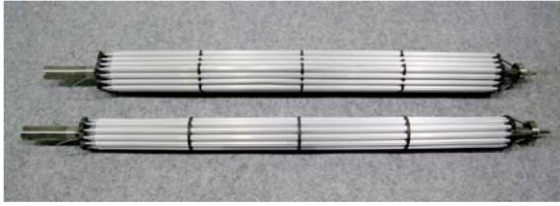


Fig. 1. HANARO fuel assemblies.

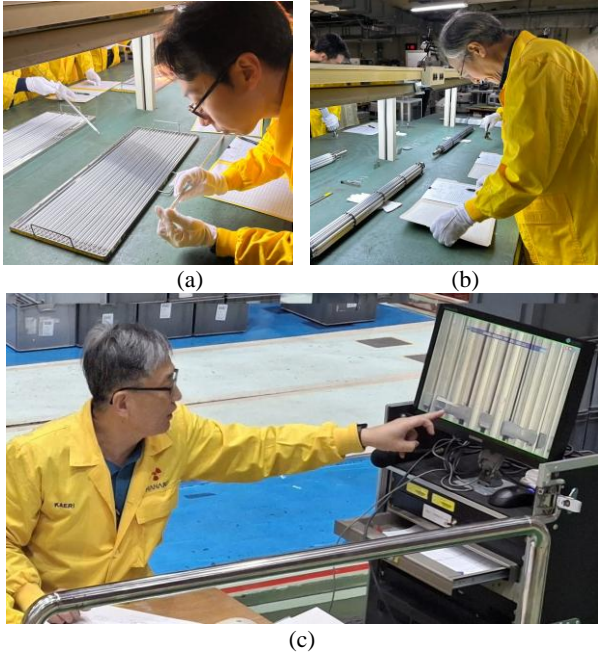


Fig. 2. Defect inspection (a) Fuel rods (b) Fuel assemblies (c) Spent fuel.

4. Challenge Issues

The surface defect detection of metal object, such as steel, commonly faces several issues. If AI technology is to be applied to the surface defect detection of HANARO fuel, which is manufactured from aluminum, these same issues must be carefully considered. [7, 8]

- **Insufficient Data Samples:** DL algorithms may fail to properly detect defect due to insufficient training data, which leads to overfitting.
- **Unbalanced Data Samples:** If the sample distribution across defect classes is imbalanced, or if the majority class predominates, the algorithm may exhibit biased or poor performance on minority classes.
- **Real-Time Detection Requirements:** In industry field, time means cost. Thus, real-time detection should be performed. Proper use of hardware and software should be considered with accuracy and speed.
- **Small Object Detection:** Since a tiny defect provides less information and weak feature representation, the algorithm tends to miss the small

defect. Specially, it is significant impact on aerospace, automotive, and electronic products.

5. Conclusions

Defect inspection of the fuel is currently conducted to ensure the structural integrity and safety of nuclear fuel at HANARO. To alleviate the labor-intensive nature of such manual processes and minimize the risks associated with human error, the integration of DL has been briefly reviewed. In reviewing the challenges of surface defect detection, particularly in common metallic materials like steel, several critical issues have been identified. Specifically, the scarcity of qualitative training datasets, the inherent difficulty of small object detection for minute anomalies, and the necessity of optimized hardware configurations for real-time inference remain issues. Consequently, these technical issues must be systematically addressed to successfully implement AI-driven defect inspection for HANARO fuel.

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