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Machine Learning Approach for Extracting Uranium Nonuniform Distribution in U-Zr-RE Metallic Fuel Slugs induced by Immiscibility

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1. Introduction

SFR reactors have been studied in combination with pyro-processing technology to improve the efficiency of high-level radioactive waste disposal using spent nuclear fuel as the main feedstock. The inhomogeneous distribution of uranium and rare-earth elements due to their immiscibility has a major impact on the production of microstructurally safe nuclear fuel. A modified injection casting has been used for production of metallic fuel slugs as an alternative fabrication method. The modified injection casting prevents the evaporation of volatile elements under pressurized Ar atmosphere during the melting process [1]. In uranium-zirconium-rare earth (U-10wt.%Zr-5wt.% RE (RE: 53%Nd, 25%Ce, 16%Pr, 6%La)) alloys, the rare earth (RE) elements and uranium are immiscible and result in microstructural inhomogeneity [3-6]. RE surface layer of U-Zr-RE metallic fuel slug sause fuel-clading chemical interaction(FCCI), and several methods have recnetly been developted to remove surface layer. In the above process, the outer layer of the fuel slug must be accurately characterised to prevent the loss of uranium. This results in non-uniformity of uranium distribution, and therefore microstructural analysis is essential. K-means clustering was performed using SEM (BSE) mode image data showing atomic distribution information. The K-mean clusteirng result shows the distribution of uranium.

2. method and result

The quartz mold was preheated to 600°C, while the charged metal-fuel material was heated to 1470°C. Subsequently, the quartz mold was immersed in the molten metal fuel material at 1470°C, and Ar gas was infused to facilitate the injection of the molten metal into the quartz mold. Y_2O_3, known for its excellent performance in U-Zr-RE alloy, was applied to coat the quartz tube mold using a slurry coating method [2]. The resulting cast U-10Zr-5RE fuel slugs had a diameter of 5mm and a length of 250mm. The injection casting process was executed at a higher injection pressure of 2kgf/cm^2. Fig. 1. shows the separation of uranium and rare earth elements due to their immiscibility. Uranium and zirconium are alloyed and distributed in the same region. However, the rare earth elements are distributed separately from the uranium zone. Also, all four rare earth elements are distributed in the same region.

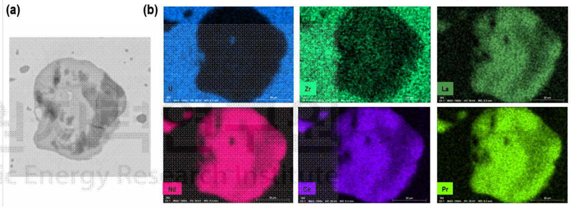

Fig. 1. SEM-EDS cross-section image of the U-10wt.%Zr metallic fuel slug (a) SEM(BSE) image (b) EDS mapping data

Figure. 2. Shows Schematic of (a) LAB color coordinate system (b) K-mean clustering. To apply machine learning techniques, the images were transferred to the LAB coordinate system, which displays contrast in RGB colors, and K-means clustering was applied.

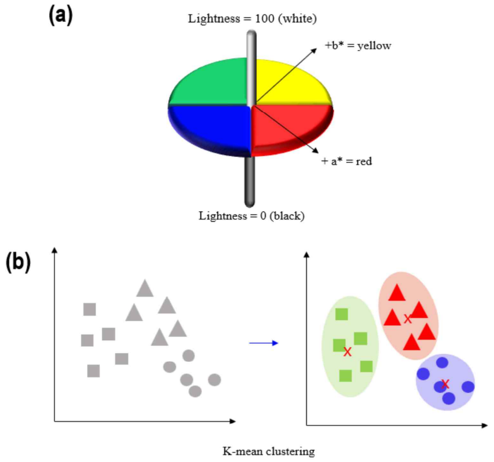

Fig. 2. Schematic of (a) LAB color coordinate system (b) K-mean clustering

K-means clustering is a popular unsupervised machine learning algorithm used for partitioning a dataset into distinct, non-overlapping groups or clusters. The objective is to assign each data point to a cluster in a way that minimizes the within-cluster sum of squares, effectively minimizing the variance within each cluster. The algorithm works by initializing K cluster centroids in the feature space, where K represents the desired number of clusters. It then iteratively assigns each data point to the cluster whose centroid is closest, followed by updating the centroids based on the mean of the data points assigned to each cluster. This process continues until convergence, where the assignment of data points to clusters and the positions of centroids stabilizes.

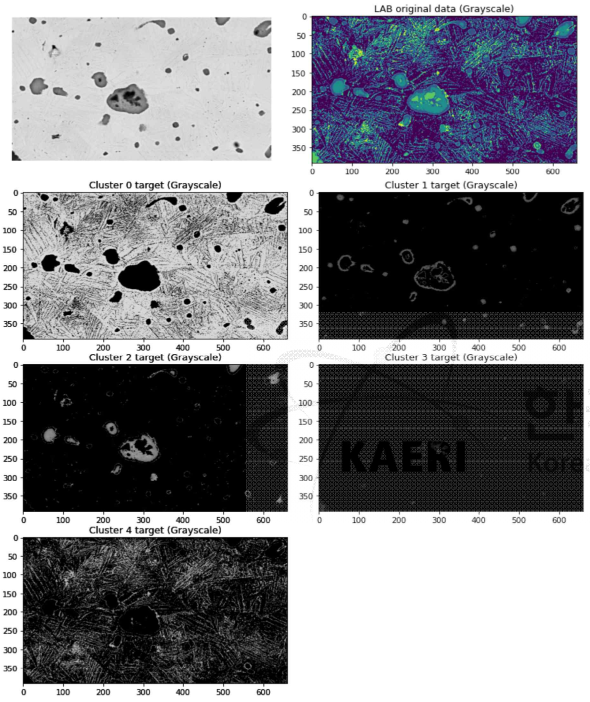

Fig. 3. SEM (BSE mode) images and their respective images clustered in the LAB color space coordinate system

Figure 3 shows each image separated by K-means clustering in the LAB color space coordinate system. Clustering 0 represented the uranium distribution zone, clustering 1 represented the border zone between uranium and rare earth elements, and clustering 2 and 3 represented the rare earth element distribution zone. The image in cluster 4 shows the lamellar structure of the U-Zr alloy. To extract the uranium distribution area, the images of clustering 2, 3, and 4 were filter masked and excluded from the original image.

Figure 4 shows the original image with the rare earth distribution region removed using a mask filter. Work-frame results using images classified within the LAB color space coordinate system show that the microstructures identified in the BSE image data were separated by K-means clustering.

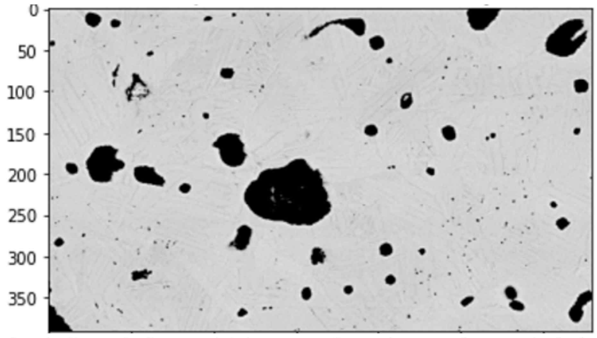

Fig. 4. SEM (BSE mode) images of uranium region excluded RE regions.

3. Conclusion

The immiscibility of uranium and rare earth elements caused the uneven distribution of uranium in nuclear fuel. Therefore, we introduced a machine learning-based work frame for nuclear fuel performance prediction and manufacturing stability.

Image classification by K-means clustering separated the uranium distribution zones in the U-Zr-RE metal core, and the uranium distribution could be predicted quantitatively.

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