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Benefits of utilizing CellProfiler as a characterization tool for U–10Mo nuclear fuel

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ABSTRACT

Automated image processing techniques have the potential to aid in the performance evaluation of nuclear fuels by eliminating judgment calls that may vary from person-to-person or sample-to-sample. Analysis of in-core fuel performance is required for design and safety evaluations related to almost every aspect of the nuclear fuel cycle. This study presents a methodology for assessing the quality of uranium–molybdenum fuel images and describes image analysis routines designed for the characterization of several important microstructural properties. The analyses are performed in CellProfiler, an open-source program designed to enable biologists without training in computer vision or programming to automatically extract cellular measurements from large image sets. The quality metric scores an image based on three parameters: the illumination gradient across the image, the overall focus of the image, and the fraction of the image that contains scratches. The metric presents the user with the ability to 'pass' or 'fail' an image based on a reproducible quality score. Passable images may then be characterized through a separate CellProfiler pipeline, which enlists a variety of common image analysis techniques. The results demonstrate the ability to reliably pass or fail images based on the illumination, focus, and scratch fraction of the image, followed by automatic extraction of morphological data with respect to fission gas voids, interaction layers, and grain boundaries.

1. Introduction

Understanding the performance of nuclear fuel materials under irradiation is critical to the development of new nuclear fuels. The Reduced Enrichment for Research and Test Reactors (RERTR) program aims to convert research and test reactor fuels from high enrichment (>20 wt.% uranium-235) to low enrichment (<20 wt.% uranium-235) in order to meet nuclear non-proliferation goals [15]. Many of the research reactors still fueled with highly enriched uranium (HEU) have fissile atom density requirements too high to be met by existing low enriched uranium (LEU) fuels, thus requiring the development of new fuels with higher uranium atom densities [15]. The Idaho National Laboratory (INL) conducts extensive research on uranium–molybdenum (U–Mo) fuels, which have high uranium atom densities. The two major forms of U–Mo fuels are dispersion and monolithic fuels, both in plate form [13]. Dispersion fuels contain U–Mo fuel particles (45 to 150 μm in diameter) imbedded in a modified aluminum matrix, while monolithic fuels consist of U–Mo foils rolled to a thickness of roughly 250 μm and clad in aluminum [13]. Advancements in imaging technologies present the potential to examine the fuel microstructures in new ways. CellProfiler, a biologically-aimed software developed by the Broad Institute can quantitatively measure sample characteristics from thousands of images automatically [3]. This study will discuss the practicality of CellProfiler as a tool for the assessment of nuclear fuel micrograph image quality as well as for the automated characterization of fuel microstructures.

2. Background

Many research and test reactors around the world were originally designed to operate on highly enriched fuels. To convert these reactors to LEU fuel, the fuel density has to significantly increase to maintain the net uranium-235 density in order to match the neutronic profile of the HEU core [15]. The best way to accomplish that goal is to use uranium in a metal form; however, metallic uranium is extremely brittle and must be alloyed for use as a reactor fuel [8]. Molybdenum is one of the most promising alloying elements. Molybdenum stabilizes the uranium gamma phase, making the metal less susceptible to thermally induced phase changes; and, it also reacts very slowly with uranium in solid solution [10]. Molybdenum is also highly corrosion resistant, has a high melting point (2623 °C), a high thermal conductivity (168 W/mK), and a low thermal neutron absorption cross section (2.48 b) [2]. All of these factors make U–Mo one of the most studied alloy systems in the RERTR program. As a relatively new fuel type, there are many opportunities for characterization research in which image processing can play a significant role.

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Human-scored or hand-calculated image analysis is time consuming and qualitative, usually categorizing sample features in an image as 'hits' or 'non-hits'. By contrast, automated analysis can quickly produce consistent, quantitative measures for a collection of images. In addition to uncovering subtle features of interest that would otherwise be missed, conclusions can be drawn directly from the repeatable quantitative measurement of many images [3]. This capability provides an opportunity to observe nuclear fuels from a new perspective; however, the success of digital image processing is highly dependent on maintaining the consistency of the imaging and evaluation conditions. Automated porosity detection in ceramic nuclear fuels is currently used only as a rough comparative tool on account of the large influence that imaging conditions have on the automated results. Image analysis software can correct for minor shifts in processing parameters with respect to contrast and illumination, but sample preparation can dramatically impact the automated results. Alterations of pore shape near the cross-section face as a result of grinding and polishing prevent pores in ceramic materials from being measured absolutely; however, measuring the porosity of metallic materials through digital image analysis of micrographs is well-established and convenient [1]. Automated porosity identification routines generally involve a histogram analysis illustrating the distribution of shades of gray [1]. The frequency of pixel distributions along a scale of brightness intensities ranging from 0 (black) to 255 (white) are used for segmentation (binarization of an image into regions of interest) based on objective criteria [9]. This approach can form the basis for fission bubble and interaction layer identification in U–Mo fuels. Significant difficulty is introduced when the desired objects don't fit into to a single intensity bin. One goal of this research is to establish a process to automatically deal with these intensity deviations while reliably quantifying the microstructures in an image.

Plate type nuclear fuel geometries are often used by research reactors requiring a high neutron flux, especially those specializing in isotope production or material testing. The long, thin nature of the plates enables high in-core uranium loadings and optimizes heat transfer [7]. Fig. 1 depicts the typical cross-section dimensions of a U–Mo fuel plate. Monolithic fuels consist of a 0.3 mm thick hot rolled foil that is bonded to the zirconium diffusion barrier and cladding through hot isostatic pressing [18]. Dispersion fuels replace the monolithic plate and diffusion barriers with a fuel and matrix particle compact [13]. Dispersion fuel fabrication involves preparation of a fuel and matrix (aluminum with a 0.2 wt.% silicon inclusion) powder compact, encapsulation of the fuel form into an aluminum assembly, and hot and cold rolling to obtain the final bonded fuel plate [16]. Full size plates are typically 56 mm thick and 570 mm long [16].

The Hot Fuel Examination Facility (HFEF) at INL is responsible for the majority of the radioactive material research described in this paper [22]. Irradiated U–Mo fuel is sliced, sampled, and imaged in the HFEF hot cells. An on-site electron microscopy technician is responsible for all of the images used for fuel qualification. The analysis of the generated images is performed by a separate group of experts.

Determining which images are worth extracting data from is an important step in the characterization process. This research aims to develop a metric that can score an image purely based on the imaging techniques used. Such a metric could be useful to eliminate poor quality images and reinforce optimal imaging conditions. Once an image meets the desired quality metric, the image can be reliably characterized. The automated characterization of fuel micrographs following selection presents unique challenges that are explored in the latter half (Section 5) of this paper.

3. CellProfiler

CellProfiler is an open-source program designed to enable biologists without training in computer vision or programming to automatically extract cellular measurements from large image sets [11]. The software is attractive as a tool for nuclear fuels analysis based on its user interface and its ability to extract data based on a multitude of parameters.

Analysis in CellProfiler starts with building a pipeline. A pipeline is a series of modules, each designated to process, measure, or identify a specific aspect of an image. The LoadImages module is capable of retrieving images or stacks of images and giving them identifiable names for subsequent modules to access. If a module alters an image, the user is instructed to name the resultant output image to call it later on in the pipeline. At the end of the pipeline, CellProfiler can export any measurements or math performed by the pipeline to a spreadsheet or database for further analysis. Unlike other image analysis tools such as ImageJ [19], CellProfiler is intended to process sets of images with virtually zero user input once the pipeline has been created. Despite the advantages that come with this style of image analysis, the input parameters are not set by the user on a per image basis; therefore, while the image processing and data extraction modules may apply as intended to one image, they may not necessarily apply to another. This creates a need for rigorous quality control checks and data verification. The next section details a method developed for the assessment of input image quality.

4. Automated quality control metric

Image selection and standardization is an important first step in the automated image analysis process. Poor quality images that result from problems in sample preparation or imaging techniques can cause inaccuracies during image analysis. Additionally, the technician that creates the image may not be person who is performing the image analysis. Thus, a quality control metric can help the imaging technician to distinguish between an image that is useful for automated analysis and an image that is not. The metric designed in this project scores an image based on three parameters: the illumination gradient across the image, the overall focus of the image, and the fraction of the image that contains scratches. These parameters can all be managed during sample preparation and imaging.

Use of an automated quality control metric during image acquisition will limit the degree to which important features are obscured by defects in the images provided for analysis. The quality metric presents the user with the ability to 'pass' or 'fail' an image based on a reproducible quality score. The resultant CellProfiler pipeline quantifies each of the three criteria and yields a metric scoring the image quality on a scale from 0 to 10 for each criterion. Each parameter is scored using a

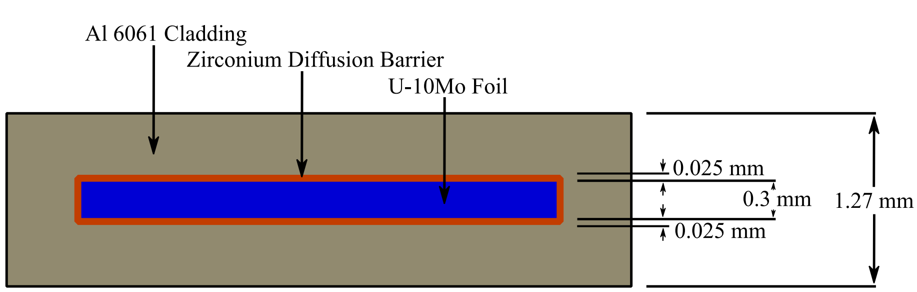

Fig. 1. Cross section of a monolithic U–Mo fuel plate.