Extending reactor life, accurately measuring material stress

LWRS Program research develops tools to assess fracture toughness

Xiang (Frank) Chen
Oak Ridge National Laboratory

John Echols
United Kingdom Atomic Energy Authority

Materials Research Pathway

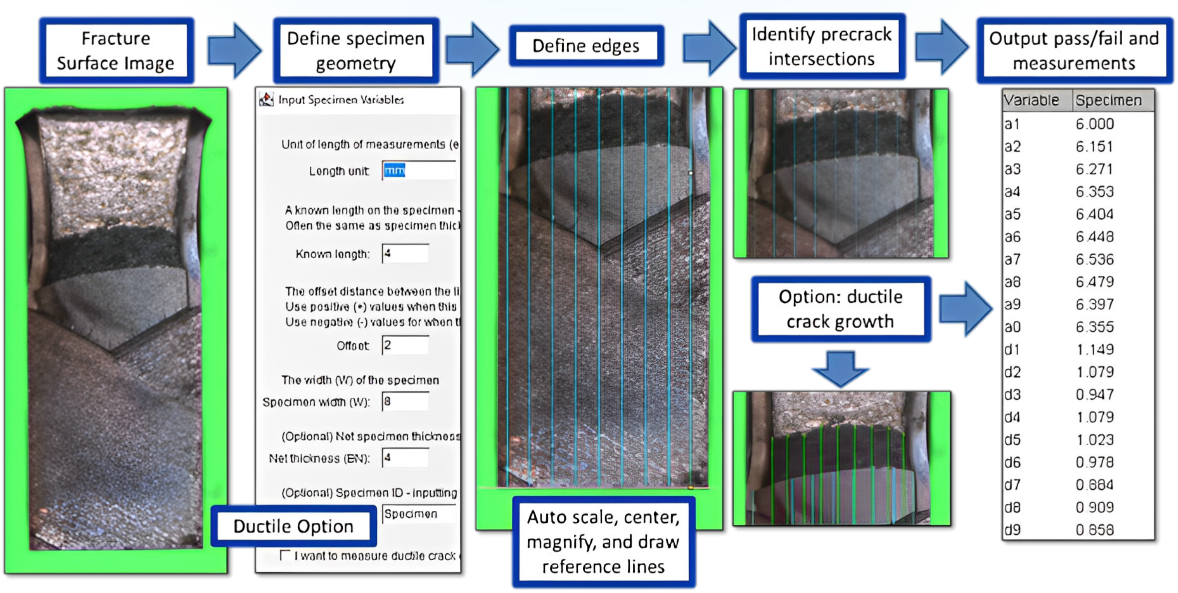
Components inside of a nuclear reactor pressure vessel must tolerate superheated water, stress, vibration, and an intense neutron field. Over the lifetime of these components, monitoring for degradation of materials is vital to ensuring the performance of the structures, systems, and components in a nuclear reactor vessel.

Extending service lifetimes of nuclear reactors to 60 years and beyond increases the stress on its materials. Light Water Reactor Sustainability (LWRS) Program is researching the behavior of materials inside of a nuclear reactor so that we can understand and predict how they will behave over time. The LWRS Program is developing mitigation and repair guidelines as well as new material alternatives for existing components.

Fracture toughness measures how well a material can withstand cracking when subjected to stress. Degradation can vary between the different systems, structures and components and it is very important to identify issues early, before catastrophic failure of the component occurs. The ASTM International test standards require precise crack length measurements to calculate fracture toughness. Historically, the crack length is measured from the fracture surface using a toolmaker microscope, which is a tedious and time-consuming process, and there is no open-source software available that meets the ASTM standards.

Fracture toughness values are a basis for structural flaw tolerance assessment. All commercial light water reactors have pressure vessels made of ferritic low

Figure 1. Interface of an automated crack length measurement software utilizing the ImageJ environment.



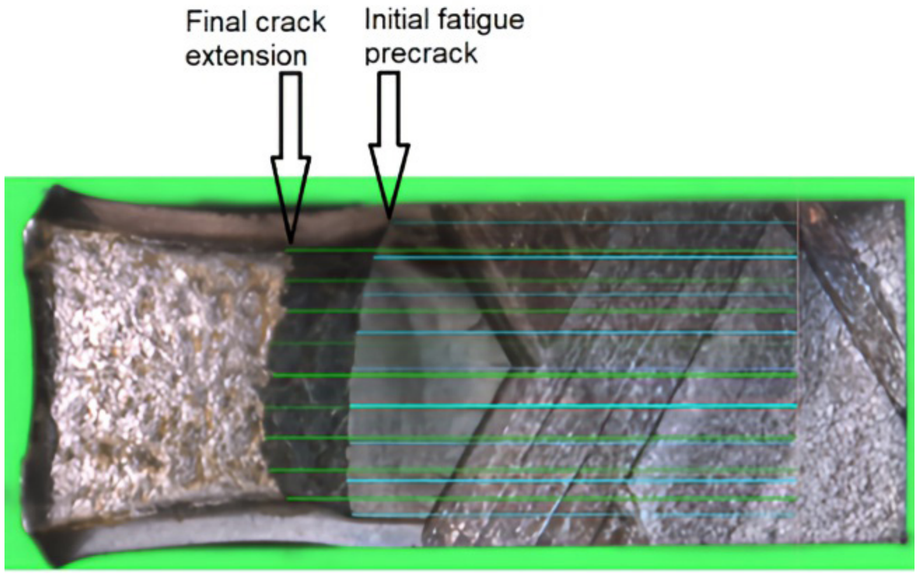


Figure 2. Optical image of a sample after fracture toughness testing with both initial and final crack length measurement.

alloy steels and its structural integrity relies upon our accurate understanding of the changes in the pressure vessel materials' fracture toughness over the time of operation. The analytical approach developed for ferritic steels, called the Master Curve method, can be used to directly measure fracture toughness properties of the irradiated pressure vessel. The data can then be more precisely used for assuring structural integrity during continued operation.

The Master Curve approach has been gaining acceptance throughout the world, and it is expected that nuclear power plant operating life can be extended by using this method. Researchers have developed an automated crack length measurement software macro using ImageJ software, an open-source Java-based image processing program originally developed at the National Institutes of Health, Bethesda, Maryland and the Laboratory for Optical and Computational Instrumentation at University of Wisconsin, Madison. User-written plugins, developed using a built-in editor and Java compiler, enable a wide range of image acquisition, processing, and analyses (Figure 1 and Figure 2).

A macro written in ImageJ automates tasks and performs complex operations on images. LWRS Program researchers developed a macro to automate crack length measurements, focusing on the following objectives:

- Compatibility with various image file formats (e.g., jpeg, gif, png, bmp, tiff, etc.).
- Automated image rotation and conversion of pixel distance to physical measurements.
- Flexibility to perform measurements from user-defined reference positions.
- Accordance with ASTM E1820 and E1921 standards.
  - ASTM E1820 testing determines the ductile fracture toughness of metals by testing a fatigue pre-cracked specimen.
  - ASTM E1921 testing covers the determination of a reference temperature to characterize the fracture toughness of ferritic steels that experience cleavage cracking.

To test the software, the LWRS Program researchers partnered with ASTM E08 committee members who were from Westinghouse Electric Co., the National Institute of Standards and Technology, the global industrial gases and engineering company, Linde PLC, University of Pittsburgh, VTT Technical Research Centre of Finland, Brazil's University of São Paulo, and COMTES FHT a.s., a privately owned Czech Republic research organization. Positive feedbacks with minor editorial changes were received from the ASTM E08 committee members.

The next steps will be to finalize the ImageJ macro, publish a software and user manual, and align it with ASTM E1820 and E1921 standards. The research and development of products developed from the LWRS Program will be used by utilities, industry groups, and regulators to help understand how materials in a reactor pressure vessel behave when subjected to long-term operation conditions.

It is expected that by using this method to test the integrity of materials used in reactors will help reduce the operating costs by offsetting maintenance costs due to better predictive models for component lifetimes, reduce costs for repairs, or extend the performance of plants through the selection of improved replacement materials.