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In-situ tube burst testing and high-temperature deformation behavior of candidate materials for accident tolerant fuel cladding

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A B S T R A C T

One of the most essential properties of accident tolerant fuel (ATF) for maintaining structural integrity during a loss-of-coolant accident (LOCA) is high resistance of the cladding to plastic deformation and burst failure, since the deformation and burst behavior governs the cooling efficiency of flow channels and the process of fission product release. To simulate and evaluate the deformation and burst process of thin-walled cladding, an in-situ testing and evaluation method has been developed on the basis of visual imaging and image analysis techniques. The method uses a specialized optics system consisting of a high-resolution video camera, a light filtering unit, and monochromatic light sources. The in-situ testing is performed using a 50 mm long pressurized thin-walled tubular specimen set in a programmable furnace. As the first application, ten (10) candidate cladding materials for ATF, i.e., five FeCrAl alloys and five nanostructured steels, were tested using the newly developed method, and the time-dependent images were analyzed to produce detailed deformation and burst data such as true hoop stress, strain (creep) rate, and failure stress. Relatively soft FeCrAl alloys deformed and burst below 800 °C, while negligible strain rates were measured for higher strength alloys.

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1. Introduction

In both normal operation and accident conditions, the fuel cladding is the most critical core structure in fission reactors because it is subjected to extreme conditions but has to function as the first safety barrier [1–3]. A fuel cladding material is selected considering a variety of aspects such as neutron absorption cross section, mechanical strength and ductility, irradiation and thermal creep resistance, resistance to embrittlement, thermal expansion and conductivity, and chemical compatibility [2–4]. In light of the Fukushima Daiichi accident, however, demonstrating an improved level of accident tolerance is emphasized in the assessment of fuel performance, and a number of candidate materials and coatings are being studied to develop cladding materials with enhanced accident tolerance capacity [5,6]. Cladding behavior governs the cooling efficiency of flow channels and the process of fission product release; hence, during a loss-of-coolant accident (LOCA), the most important property of fuel cladding might be the resistance of the cladding material to plastic deformation and burst at high temperatures. Therefore, the key benchmarking properties for demonstrating accident tolerance should include the deformation-to-burst behavior of tubular specimens in a LOCA condition.

Traditionally, tube burst testing using high-pressure gas has been performed to measure the burst temperature as a function of internal pressure and to assess the performance of new and irradiated cladding specimens [7–14]. Typically a ~30 cm (1 foot) long tubular specimen is employed in such tube burst testing [14]. It has been realized, however, that the efforts to develop and assess new accident tolerant fuel (ATF) cladding candidates in a short time period require obtaining both the basic material property data and the structural (or cladding) performance data in a limited time. Therefore, to experimentally simulate the cladding behavior during severe accidents, there has been a demand to develop a more efficient testing and evaluation methodology to obtain those property and structural performance data simultaneously. Ideally, a new method can be combined with cost-efficient irradiation experiments to comply with the demand for collection of a larger variety of data during pre- and post-irradiation deformation-burst

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tests. This research aimed to establish a new testing and evaluation method for simulating cladding behavior in accident conditions and to comparatively assess the performance of new cladding candidates.

Recently, a new deformation-burst testing method was pursued to provide in-situ high-temperature deformation data as well as the traditional burst pressure-temperature data [15]. In particular, the in-situ cladding deformation record can provide creep rate and true wall stress data, which are essential in the assessment of fuel performance under LOCA conditions. It was also considered that the advancement of LOCA analysis tools like three-dimensional (3D) finite element modeling [16] may require additional detailed data, such as creep rate, under biaxial loading over the whole temperature range of the simulated accident. In the present research, therefore, a new high-temperature testing technology using pressurized thin-walled tubular specimens has been developed: a computer-controlled high-resolution camera with a filtering system has been used to obtain the in-situ deformation and burst data under simulated accident conditions. This article intends to provide enough information to allow other researchers to use the technology and to compare the starkly different responses of materials to a simulated condition.

The application experiment carried out in this research was intended to produce detailed in-situ mechanical property data for prospective ATF cladding materials. High-temperature tube deformation testing was performed for ten candidate ATF cladding materials. Among the test specimens were pressurized thin-walled tube specimens of FeCrAl alloys, oxide dispersion strengthened (ODS) FeCrAl alloys, and nanostructured ferritic alloys (NFAs), i.e., 14YWT and 9YWTV. For the relatively soft FeCrAl materials, the process of plastic deformation and burst ended below 800 °C and the plastic (creep) strain and strain rate up to the burst temperature were calculated. The higher strength alloys, on the other hand, showed little change in diameter and did not fail before the system limit temperature of ~1100 °C was reached.

2. In-situ deformation and burst testing system

2.1. Background on high-temperature imaging

The main goal of the imaging-based deformation measurement system is to perform in-situ observation and recording of high-temperature deformation and burst while a tubular specimen is exposed to a simulated accident condition. The images of deforming tubes can be easily converted into dimensional data (during or after a test) and then into hoop strain values, from which one can calculate creep strain rate, failure strain, and true stress at the wall. The image recording will also enable precise detection of the deformation initiation temperature. Another benefit of using an image recording system is that simultaneous dimensional measurements at multiple positions can be pursued with an affordable programming effort.

In preparation for the present research, previous dimension measurement methods were reviewed to adopt the best practices of existing optical techniques. Video cameras have become affordable for dimensional measurements, even ones with high resolution and high data transfer rate. The most common method of optical measurement is using digital image correlation (DIC) to provide precise strain analysis and displacement measurement; for instance, high-pressure burst testing was performed on tubes made of composite fiber-reinforced silicon carbide [17]. Full-field strain analysis has been conducted using 3D DIC, and an acoustic emission technique was used to detect damage events during high-pressure burst testing. Lyons et al. [18] conducted high-temperature deformation measurement using DIC, in which the highest temperature was 650 °C and no light filters or special light sources were used. Lately, new methods for high-temperature strain measurement using band-pass filters and short-wave illumination have been developed, and such techniques have been used at 1000 °C and higher [19–21]. Full-field thermal deformation and thermal expansion coefficients for an austenitic stainless steel were determined up to 1200 °C to demonstrate the workability of the method [20]. Further development in imaging techniques has shown that a technique of clustering cameras can help obtain a full 3D geometry of an object [22], and an extended high-temperature DIC method employing ultraviolet (UV) lights and special UV optics almost completely eliminated the light emitted by high-temperature specimens [23].

Another technique for high-temperature imaging is using the difference in emission wavelengths between materials. Guo et al. [23] assembled special high-temperature DIC equipment capable of working up to 2600 °C, which was using the difference in high-temperature emission spectra between carbon and tungsten that formed a speckle pattern on specimens. That is, since the intensity of thermal radiation from tungsten at high temperature is far below that from carbon, a reliable contrast can be produced to provide DIC measurement.

2.2. Imaging device and optics arrangement

An algorithm based on image analysis technology was developed in the present research to detect and track the selected points, so that a personal computer can simultaneously perform video streaming and concurrent data processing at multiple points during temperature ramping. Further, specific techniques based on those used in the aforementioned studies were adopted and modified for the present tube burst testing. The first issue in high-temperature testing was the steep temperature gradient that may lead to severe air convection [18], particularly near the observatory windows where lenses are closely spaced. Since the index of refraction of light is sensitive to the temperature of matter, it could affect image stability and thus decrease the precision of dimensional measurements. In this research, the influence of convection was effectively suppressed by running small fans at the outer protective glass of view windows and by installing multiple protective glass sheets to form multiple air layers. However, it was not possible to fully eliminate the air convection and steep temperature gradient within the short distance between the lenses and filters and the furnace window (several centimeters). Also, all windows were made of high-quality optical glasses.

The second issue was the intense thermal radiation at elevated temperature, which usually causes faint and blurry images. As furnace temperature increases, the maximum intensity of thermal emission shifts from the infrared band to the visible light band. When the visible light signal becomes strong, the image quality decreases drastically below about 800 °C. A known technique is to replace the thermal radiation with its broad wavelength band with a light beam with near-single wavelength [19–21]. A similar but simplified technique was used in the present work: to form clear specimen images in the camera, the wavelengths emitted from heated furnace internals are almost completely removed by using a set of filters attached to the camera lens, and two monochromatic blue light sources are used to illuminate the specimens in the furnace. Those two light sources are installed on the front door of the furnace and illuminate the specimen through two windows. The intensity of blue light was adjusted to maximize sharpness at the edges of specimen images since the strain and creep rate calculations required accurate measurements of tube diameters [24].

A view of the camera–light-source system is shown in Fig. 1(a). Details of the camera and optical components are as follows. The