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Original Article

Evaluation of axial and tangential ultimate tensile strength of zirconium cladding tubes

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ABSTRACT

Different methods of axial and tangential testing and various sample geometries were investigated, and new test geometries were designed to determine the ultimate tensile strength of zirconium cladding tubes. The finite element method was used to model the tensile tests, and the results of the simulations were evaluated. Axial and tangential tensile tests were performed on as-received and machined fuel cladding tube samples of both E110 and E110G Russian zirconium alloys at room temperature to compare their ultimate tensile strengths and the different sample preparation methods.

1. Introduction

Anisotropic materials may have significant differences between their tangential and axial ultimate tensile strengths (UTSs), and they should be measured separately. Because zirconium alloy nuclear fuel cladding materials are typically anisotropic due to the production technology, such properties can be determined by longitudinal (axial) and ring (tangential) tensile tests. The most important factors affecting the results of the tensile strength measurement are the temperature of the test, the machining method of the specimens, and—for ring specimens—the friction between the sample and the dies. Another feature is the tensile deformation rate, which can be controlled by the crosshead speed of the universal tensile testing machine. Because the tube geometry is given, the test specimens have to be produced from the tubes. Before tensile tests are carried out, finite element analysis may be required to evaluate the applicability of the tensile test specimen geometry chosen for the tests and improve it if needed.

2. Methodology review

2.1. Axial tensile tests

Several techniques have been developed for axial tensile strength measurement of nuclear fuel cladding tubes. To obtain a well-defined gage section, the tubes are milled to form a reduced section. The samples are pin loaded with pinholes drilled at the sample ends apart from the gage sections. Mostly, tubes with two narrow wings are used, or they can be cut in half into two semi-tubes to be measured separately. During the tensile test, the plastic deformation develops only in the gage sections. The stresses are almost uniform along these sections up to necking. The tensile test data measured this way are often considered to be more accurate. The difficulty of this test lies within the thin cladding from which the test specimens are to be machined. The small size and complex shape of the sample limit the tools and methods usable for the preparation and the achievable accuracy. With the use of fine mechanical Computer Numerical Control (CNC), milling the size of the samples may be considered close to the given nominal value.

It should be noted that axial tensile sample requires usually 10 to 12 times longer tubes than hoop tensile tests. With irradiated material, this can be a problem because the amount of irradiated material available for such tests is limited. It is also known that in general, the irradiation eliminates the anisotropic behavior of the

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cladding tubes, and irradiated materials show isotropic behavior after one or two campaigns in the reactor [1]. In this case, the axial tensile test does not seem to be the most economical method of material testing.

It is relatively simple to carry out axial tensile tests because it does not require complex experimental devices, and there is no need to perform complex calculations to interpret the tests. They may also be carried out in normal operation and accident-relevant conditions covering a very wide range of temperatures and strain speeds. However, the determination of the axial stress has significant disadvantages. The material is tested in the longitudinal direction under uniaxial conditions, while in typical simulated accident conditions the cladding failure is mainly due to longitudinal cracks, which suggests that in these cases, the tangential load is dominant.

2.2. Tangential tensile tests

Several techniques have been developed around the world to measure the tangential tensile strength of zirconium cladding tubes. The same characteristics can be defined through the tension test of annular specimens as with the axial samples (yield strength, tensile strength, and total and uniform elongation), but the load is mainly tangential. An important feature of ring tensile testing is that the specimen may deform significantly as the load increases, and it does not keep its original ring geometry.

The tests can be done using full rings or machined test specimens. The benefits of examining narrow rings are that only a small amount of material is needed for each specimen. This is a clear advantage if only limited quantities are available, such as irradiated materials. However, for postirradiation examination of a material's characteristics, especially the measurement of embrittlement, it is clear that the probability that the sample has a weak point (e.g., a hydride blisters) is less in case of a short sample; therefore, more short samples have to be examined to determine the material's behavior instead of a few long samples.

The simplest way to prepare tensile test samples is to cut rings from the tubes; however, machined rings are usually used; therefore, the tensile cross section can be defined more precisely. These are prepared by milling the two sides of the ring, creating two opposite narrow wings. The small size and complex geometry require precision mechanical devices. A number of different procedures have been developed to measure the tensile strengths of such rings.

In the first case (Fig. 1A), the inner diameter of the ring is roughly equal to the circular heads that they are placed on, and the rings are loaded so that the machined section is facing where the two heads meet, perpendicular to the direction of the pull. The disadvantage of this method is that the tensile region of the specimen is deformed and flattened during the test, and the stress is not purely tangential. This approach was used by the French Atomic Energy Agency (CEA) [2] and previously in the AEKI (the predecessor of current MTA EK) [3].

In the second case (Fig. 1B), the same design was used as in the previous one, but the machined parts of the rings are located at the top and bottom of the heads, in the direction of the pull. These tests typically give higher maximum load values than when the machined parts of the rings are to the sides. The friction coefficient between the tensile head and the ring is a critical parameter; therefore, appropriate lubrication must be provided. This type of test is used by the Japan Atomic Energy Agency [4] and the Korea Atomic Energy Research Institute [5].

In the third case, to keep the ring geometry round, an intermediate piece called "dog bone" is used, which prevents the flattening of the narrowed section [6], but it also induces some localized shear depending on the exact geometry (Fig. 1C). With the machined section of the ring specimen placed in the pulling direction perpendicular to the load, the inner diameter of the ring is roughly equal to the curvature of the dog bone piece. However, inserting this dog bone between the dies is difficult, especially considering high temperature measurements. This approach is used by the Argonne National Laboratory (USA) [7] and Studsvik (Sweden) [8].

The fourth kind of test was developed by the National Research Center "Kurchatov Institute" (Russia) [9]. While Western researchers examined mainly Zircaloy alloys, this institute mainly studies Russian cladding alloys (e.g., E110). The distortion of the full, roughly shaped ring in this case is very significant because the mandrel diameter is significantly smaller than the inner diameter of the ring (Fig. 1D). The specimens were not narrowed, but microincisions were used to accurately monitor the deformation of the samples. This approach differs significantly from the others: the maximum bending strength is at the beginning of the test.

3. Materials and methods

Over the past 20 years, numerous mechanical tests have been performed in the AEKI and later in MTA EK on the E110 and the E110G cladding tubes [10]. A significant part of these measurements was performed on oxidized and hydrogenated samples representative of incident and accident conditions.

The zirconium for the currently used E110 cladding alloy is produced 60% through an iodine process and 40% through an electrolytic process. In the iodide method, the gaseous zirconium tetraiodide is condensed on a thin tungsten filament and thermally decomposed, wherein the zirconium metal is deposited on the tungsten (van Arkel–de Boer procedure). During the electrolytic process, potassium hexafluorozirconate ($K_2[ZrF_6]$) or zirconium dioxide is mixed with molten salts (e.g., KCl and NaCl or ZrF4 and NaF), and the zirconium precipitates from the melt on the electrode surface. In the western countries, the Kroll process is widely used, where zirconium tetrachloride is reduced with magnesium, and the residual magnesium in the metal is evaporated in vacuum, leaving a sponge. The zirconium metal in the new E110G cladding comes from this sponge (70%) (in Russian "*Gubka*", hence the "G") and the iodide process (30%). The chemical composition of E110G alloy remains the same, 99% zirconium and 1% niobium, but permissible levels of certain trace element concentrations change.

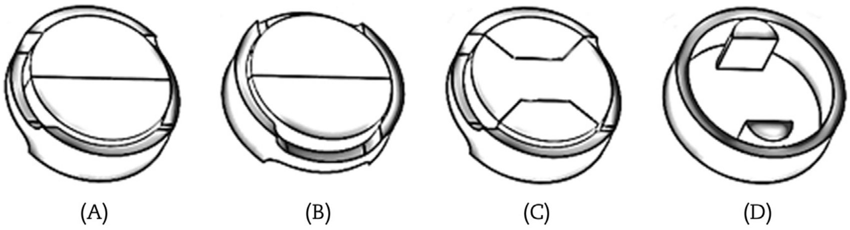

Fig. 1. Four different methods of tangential tensile testing. (A) Side machined ring (B), top-bottom machined ring, (C) side-machined ring with dogbone, (D) small mendrels.