Deep-hole drilling to measure residual stress

BY DICK KOVAN

A British company uses a technique known as deep-hole drilling to measure residual stresses in thick-section nuclear components.

SINCE THE 1990S, stress corrosion cracking associated with dissimilar metal welds used to join primary circuit components—such as ferritic reactor pressure vessel nozzles to stainless steel piping—has been found at nuclear power plants around the world. While the development of corrosion is particularly dependent on water chemistry and on the particular constituents of the weld material, notably the level of chromium, the propagation of cracks through a component is driven mainly by stresses, including residual stresses.

Ed Kingston, managing director of VEQTER Ltd., explained to *Nuclear News* that the term "residual" refers to the stresses left in the component from the processes that it has gone through, particularly fabrication and welding. All manufactured components have such stresses, regardless of what they are made of—for example, glass, plastic, or metal. The residual stresses can be incredibly high, even on the order of the material's yield strength (the stress at which a predetermined amount of permanent deformation occurs). And so, even without the pressure of flowing coolant, a pipe can already be stressed to near its maximum yield strength.

Residual stresses are becoming more important to safety regulators, who are placing increasing demands on designers, manufacturers, and operators to ensure higher levels of safety. Measuring the full through-thickness residual stress levels of components is vital in the analysis of structural integrity with respect to concerns such as stress corrosion cracking, crack propagation, manufacturing processes, and material yield. Measuring residual stress is also critical for validating finite element (FE) models, the basic tools used for assessing stresses in a component, predicting crack propagation—which is vital for determining inspection interval—and providing the understanding necessary for operators to manage stresses in their components and, when necessary, to mitigate them.

Kingston (Photos: VEQTER)

Kingston explained that the deep-hole drilling (DHD) technique developed at the University of Bristol, in the United Kingdom, and offered by the spinoff company, VEQTER, is one of the few methods that can measure full through-thickness residual stress levels of large components in the primary circuit of a nuclear power plant.

Alternative techniques

Kingston noted that there are a number of alternative measuring techniques, none of which is the best for all stress conditions or all parts of a component. If possible, it is best to use several measurement techniques to measure the residual stresses in a component. This also provides a level of validation and cross-checking among the various techniques used.

There are two general categories of measuring methods: noninvasive and invasive. Noninvasive techniques include ordinary X-ray diffraction, high-energy synchrotron X-ray diffraction, and neutron diffraction. Each is limited by the thickness of material through which it can measure. X-rays are useful only to tens of microns below the surface; this does not even penetrate the oxide layer at the surface of large components. Synchrotron X-ray and neutron diffraction use higher energy and can peer into nickel alloys and steels a few tens of millimeters deep, which covers many of the nuclear structures of interest. The diffraction techniques, however, suffer from serious scatter problems due to the large granular structure of nickel alloys, affecting the resolution, Kingston explained. The components also have to be sent to large central research facilities for the measurements to be taken.

In an invasive—or destructive—technique, cutting or drilling into the material releases the stresses, which can be directly measured or determined analytically. Kingston described three types of invasive techniques. The least invasive, center-hole

The company

VEQTER Ltd. is a spin-off company of the University of Bristol, where the deep-hole drilling (DHD) technique was developed for use in structural engineering under David Smith, professor of Engineering Materials and cofounder of the company along with Ed Kingston, VEQTER's managing director.

The DHD technique evolved from a mining concept developed decades ago to measure stress in underground rocks. Researchers at the Central Electricity Generating Board, the organization in charge of Britain's nationalized electricity supply industry before it was partially privatized in the late 1980s, began developing the concept for use in the power engineering sector. While that research stopped before bearing fruit, the researchers' work was rediscovered in the early 1990s by Smith, who began to develop it at the university into what is now a very powerful technique. Smith continues as a full-time academic, carrying out research on the technique, with VEQTER acting as the commercial arm.—*D.K.*

Measuring residual stresses through a mock-up of a cold-leg nozzle with weld overlay

drilling, is like keyhole surgery. A tiny hole is drilled into the component, and the stresses released are measured by strain gauges on the surface. This technique, however, can measure only to a depth of 1 to 2 mm below the surface.

To determine the residual stresses through a large component or a large section of a component, a more invasive technique is needed. A totally invasive technique involves cutting up the component into tiny cubes—"slicing and dicing it like a carrot," Kingston said—and recording the stress in each cube with strain gauges. This can provide full through-thickness measurements of stress in a component.

The DHD technique is an alternative to this destructive approach (see accompanying sidebar). With this method, which Kingston calls semi-invasive, a hole of only a few millimeters in diameter (depending on the component) is drilled through the component. A cylindrical section around the hole is then cut out of the component, releasing the residual stresses within the section. The initial residual stresses can be calculated from knowledge of the diameter of the hole before and after the stresses are released.

The residual stresses of components with a thickness of up to 750 mm, which covers practically all components in nuclear engineering, can be measured with this method. Because the technique is not accurate within the first millimeter of the surface, however, a center-hole drilling measurement can be carried out first, followed by drilling through the same location using the DHD technique.

Due to its semi-invasive nature, DHD is usually carried out on specially fabricated mock-ups, which are exact replicas of the actual components before they are installed in a plant. Measurements have been carried out on irradiated components that were extracted from an operational plant and fully decontaminated before being taken to a laboratory for testing. As the residual stress in the component would have been released during disassembly, however, this exercise

Using the deep-hole drilling technique

The deep-hole drilling technique can measure residual stresses at great depths within metallic and nonmetallic components. The company's laboratory facilities, which can handle test components weighing up to 3 metric tons, house specialized machines that are able to measure stresses at depths from 1 mm to 750 mm below the material's surface. Should it be impractical to transport components to the lab, on-site measurements can be carried out.

The technique is a semi-invasive, mechanical strain relief technique (that is, the strain of the component is measured during stress relief from the removal of a small amount of material). The procedure used can be divided into the following four basic stages:

- Stage 1: Reference bushings are attached and a small-diameter reference hole is gun-drilled through the component and bushings.
- Stage 2: The diameter of the reference hole, $Ø_0$, is measured through the entire thickness of the component and reference bushings.
- Stage 3: A cylinder of material containing the reference hole along its axis is cut from the component, using an electro-discharge machining process.
- Stage 4: The diameter of the reference hole, Ø, is remeasured through the entire thickness of the cylinder and reference bushings.

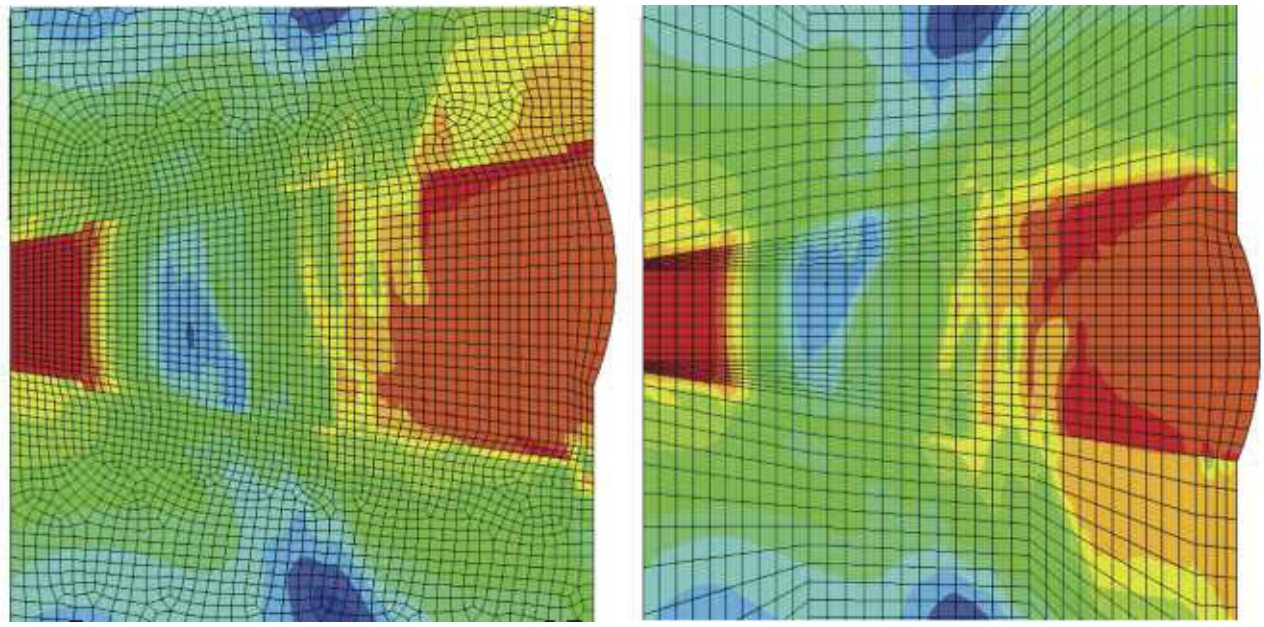
The diameter of the reference hole measured in Stage 2, $Ø_0$, is the diameter when residual stresses are present. During Stage 3, the residual stresses are relieved, and so the diameter of the reference hole measured in Stage 4, Ø, is the diameter when residual stresses are not present. The differences between the measured diameters in Stages 2 and 4 enable the original residual stresses to be calculated. The mathematical analyses used for the calculations originate from the theory of elasticity on the behavior of a plate with a hole subjected to a uniform stress field.—*D.K.*

was of limited value. The next step in developing this technique would be to use DHD to measure residual stress in a radioactive component before it is to be removed from a plant, either to be replaced or because the plant is being decommissioned.

A relatively new invasive method described by Kingston is the "contour" technique, which was developed at Los Alamos National Laboratory. It uses wire electrical discharge machining to slice the component in half while measuring the deflection of the surface as the stresses are released. From this deflection, the residual stress can be calculated. This technique, he said, is useful to cross-compare with DHD. In a recent Nuclear Regulatory Commission/Electric Power Research Institute (EPRI) research program (discussed later), he added, these two techniques were shown to be the most useful and reliable methods for measuring residual stresses in the large nuclear components examined. The portability of DHD is a particular advantage over the contour technique, which, he noted, is lab-based.

Validating the technique

A considerable amount of testing has been carried out over the past 20 years at the University of Bristol and VEQTER to validate the DHD technique, Kingston said. The simplest experimental approach is to fabricate samples stressed with known loads, which provides a straightforward opportunity for this or any other measuring technique to prove its accuracy. To validate its capability on more complicated samples, the university (primarily) and VEQTER have taken part in a number of round-robin exercises in Europe, where teams from academic and research institutes, as well as



A display showing finite element modeling of a weld using deep-hole drilling measurements

nuclear operator organizations, test different techniques on a single test component. The results are then compared, and are also used to validate FE models and to compare the methods used by different computational teams. These exercises often identify weaknesses and limits to the reliability and accuracy of the various techniques and the teams' ability to use them.

Projects and programs

VEQTER participated in two major programs investigating component integrity in the wake of corrosion problems that beset the nuclear industry in the 1990s, one in Japan and the other in the United States. A national program called Integrity Assessment of Flawed Components with Structural Discontinuity was conducted from 2001 to 2007 by the Japan Nuclear Energy Safety Organization. Several full-scale plant mock-ups were built for this program with VEQTER and other organizations performing various measurement techniques. In addition to carrying out some of the work at its laboratory in the United Kingdom, VEQTER shipped its test equipment to Japan to do the measurements on site on

The mini deep-hole drilling machine was developed for measuring residual stresses from the internal diameter of a pipe in cases where the external diameter is difficult to access.

full-scale mock-ups. The results, Kingston said, were pulled together to get best-case residual stress profiles through the components and to validate FE models.

The U.S. investigation, the Joint NRC/EPRI Weld Residual Stress Validation Program (2009–2011), did many of the same things as the Japanese program. Mock-ups were constructed and round-robin exercises carried out using different techniques to measure and assess the residual stresses in these manufactured components and also to validate FE models. Among other results, this work led to the development of best-practice guidelines for carrying out FE analyses, Kingston said.

In both of these programs, DHD was the main technique used to carry out measurements through the full thickness of the components, Kingston said, and, he added, the results were regarded quite highly by the organizers.

VEQTER is also involved in assessing new fabrication methods and welding techniques, as well as FE validation and safety case work. In the United Kingdom, Rolls-Royce contracts the company to assess possible new techniques for use in fabricating the company's nuclear submarine reactors, including testing the quality of welds by measuring the residual stresses generated. In France, VEQTER has also carried out work for Areva to test new welding techniques for new component designs to determine whether they provide expected improvements.

Recently, VEQTER has also done work for Westinghouse and British Energy (now part of EDF Energy) for Sizewell B, Britain's only operating pressurized water reactor, related to a potential cracking problem. The company carried out residual stress measurements on mock-ups of components with the welds that were of concern and with mitigating weld overlays in order to again validate FE analyses. The work is being used to prepare a safety case to demonstrate to the regulator that the stresses are known and can be managed using the weld overlay mitigation process.

Another project for British Energy concerns the integrity of the graphite moderator bricks within its advanced gas-cooled reactors (AGR), which the company hopes to continue to operate beyond their current licenses. The dimensions and the physical and material properties of the graphite moderator change due to the reactor environment, which generates stresses that can cause distortions and cracking. There are concerns that by 2015, the changes in the graphite will prevent free movement of the fuel or control rods through the blocks, and so the buildup of stresses must be measured to determine whether cracking might occur. VEQTER is developing a new DHD machine that can work in high-radiation environments and can access the core using the current AGR inspection tools. British Energy hopes to be able to demonstrate that the stresses are lower than now estimated, and that the reactor will be safe for continued operation.

The incremental DHD technique

The development of a variation on the technique, referred to as "incremental" DHD, increases the accuracy of this method, particularly when components with high levels of residual stress are being measured. If the stresses in a component are not high, the component will essentially return to its unstressed condition as the stresses are released, like an elastic band, Kingston said. If the residual stresses are extremely high, however, releasing them may induce a plastic flow in the metal, preventing a return to its unstressed condition. Therefore, it would not be possible to accurately determine the original residual stress field, or to correctly model crack propagation. The incremental DHD process releases the residual stress in incremental steps, rather than all at once. Although this does not prevent the occurrence of plastic deformation, it is still possible, Kingston said, to accurately determine the initial residual stress condition with this method.

VEQTER is now carrying out incremental DHD, which was developed three or four years ago at the University of Bristol, as standard practice, because the welds or regions of concern tend to be where there are very high stress levels.

Measurements have not yet been carried out on any irradiated components—that is, anything that is radioactively hot. More recently, a new DHD machine has been developed that can work remotely on irradiated materials. Next year, Kingston expects to be working with EPRI to carry out some measurements on radioactive components still attached to a reactor immediately prior to decommissioning. This will provide the nuclear industry with more realistic residual stress measurements that incorporate the effects of radiation on components' physical and material properties, the original manufacturing residual stresses, and the "fit-up" stresses resulting from installation and plant operation. NN