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Non-Destructive Examination of Residual Stresses in Pipes

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ABSTRACT

For the purpose of a safety, increased reliability and longer life in the operation of RBMK nuclear reactors, an installation has been developed for fast, non-destructive examination of levels of residual stresses in the full length of pressure tubes of fuel channel (FC). The installation can also monitor the development and shaping of unfavorable levels of residual stresses from separate technological operations.

The installation ensures fast non-destructive monitoring of residual stresses on all outside surfaces of as-manufactured industrial items under shop conditions with the possibility of revealing localized or heterogeneous distribution of stresses due to stress concentrators.

The results of residual stress distribution in some channel reactor tubes are brought.

INTRODUCTION

The safety, reliability and service life of RBMK reactors are largely dependent on the manufacturing quality of fuel channels and CPS channels. Important tools for achievement of this aims are assured by nondestructive testing, including optical, acoustic, magnetoelectric and X-ray techniques. The so-called «geometrical» defects of structural materials (cracks, holes, caverns, cavities) revealed by ultrasonic, eddy-current and X-ray testing, manifest themselves, as a rule, in impaired performance of the facility early in the operation, whereas the inhomogeneity of alloys, grain size differences, texture and residual stresses show up in the course of long-duration service and it is these factors that basically restrict the time of safe use of the product.

Residual stresses are counted among the adverse factors with direct bearing on the service life of tubes made of zirconium alloys. Operational experience shows that residual tensile stresses on the outer surface of pressure tubes contribute to development of defects, especially under conditions of metal hydrogenation which gives rise to delayed hydride cracking (DHC). Besides, periodic cooldowns of the reactor are likely to cause reorientation of hydrides and impaired crack resistance of the tube metal. Studies have yielded the residual stress value which is the threshold of the above processes.

For full-length pressure tubes to be examined for residual stresses throughout their length of up to 8 m without damaging the surface of the finished products, it is necessary to have special high-speed measurement techniques and automated data processing, as well as procedures, software and hardware suitable for field testing.

1. FACILITY FOR NONDESTRUCTIVE RESIDUAL STRESS TESTING

ERNKON is an X-ray facility designed for nondestructive express measurement of residual stresses over the entire outer surface of full-length zirconium pressure tubes of RBMK reactors under field conditions. ERNKON operation is based on X-ray diffractometric measurement of residual stresses in stressed surface layers of a polycrystalline material.

The ERNKON facility includes the following main components: X-ray goniometer with a hoist and radiation shielding; stabilized high-voltage power source; tube handler; operator's desk with control interfaces; measurement cabinet with a set of interface control units and a PC controller interface; computer complex.

The remote unit of the goniometer is fixed on a damping suspension above the handler by means of a two-position handling unit. The handling device provides accurate positioning and attaching of the goniometer above the surface of the inspected tube. The damping suspension relieves pressure forces and suppresses possible vibrations during contacts of the goniometer with the tube in the examined area and during the tube movement with the handler.

The X-ray optics of the goniometer has a fixed focusing configuration with two strip collimation detectors. The apparent focus produced by collimators at the primary beam (Fig.1), the examined irradiated region on the tube surface, and the surfaces of the strip collimators are found in the same focusing sphere. A narrow X-ray beam formed by the collimating system falls at an optimal angle to the tangential surface of the tube in the examined area. Strip collimators (with a resolution of 32 recording channels) are placed at intersections of the diffraction cone with the focusing sphere, tangentially to the latter. The measurement plane of the goniometer lies transverse to the inspected tube, which allows measuring circumferential residual stresses.

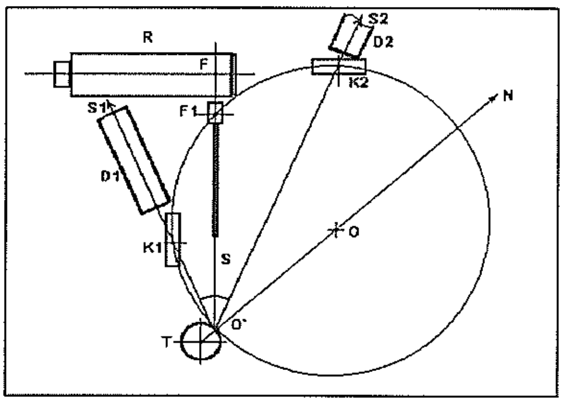

Fig.1
R - X-ray tube
D1, D2 - X-ray detectors
K1, K2 - Strip collimators
T - Inspected tube
F - X-ray tube focus
F1 - Collimator focus
S - Primary X-ray beam
S1, S2 - Diffraction beams
N - Radial direction in the center of the inspected area

2. SOFTWARE

The X-ray strain measurement procedure is based on accurate measurement of angular displacements of diffraction profiles found when plane spacing in elastically strained crystallites changes under internal residual or externally applied stresses.

An algorithm and a program were drawn up for computation of residual stresses, using the $Sin^2\Psi$ Technique with statistical smoothing of diffraction line intensity variations, with calculation of the exact position of diffraction lines by parabolic approximation and by the center of gravity, and with least-squares calculation of linearized dependence of diffraction angle displacement on the rotation angle Ψ. The data are corrected for loss of focus in the survey geometry by comparing the calibrated unstrained specimens with the same surface curvature and under the same conditions.

ERNKON operation is controlled exclusively by a personal computer, following the specially developed algorithms and programs with the help of a controller, interface and amplifier units KAMAK. The drivers are integrated into one software package for ERNKON operation control.

The calculated residual stresses with the associated computation errors, the estimated diffraction line half-width and the position of the examined tube areas are entered in the data file for each tube, as well as in the local database, and are displayed on a screen at the check instrumentation interface. If residual stresses exceed the maximum permissible level, an «above normal» signal is sent to the display with sound accompaniment and to the tube section marker for the handler control unit. When a tube fully passes through the examining zone of the ERNKON facility, all the data filed are processed, the extreme values, average values for all measurements and variations (with stresses found in excess of the specified level) are determined, extreme stress areas and nidi are located in the coordinate map of the tube surface. The results are stored in the local database for each inspected tube. Integrated data from testing performed in keeping with the schedule of residual stress examinations, are printed out for documentation.

3. REFINEMENT OF THE RESIDUAL STRESS MEASUREMENT PROCEDURE

The main procedures and conditions for express measurement of residual stresses were tried out at the ERNKON facility and, for comparison, at the X-ray diffractometer DRON-UM. Long piece tubes cut off from industrial tubes were used as specimens. Linear dependence on $Sin^2\Psi$ was demonstrated by laboratory diffractometric measurements of circumferential residual stresses, carried out on zirconium tubes for 13 rotation angles Ψ in the range of 0 to 60 degrees (Fig. 2). Only two coordinate points or, in this case, two rotation angles Ψ suffice are necessary for determining the linear dependence parameters. This condition is realized in the X-ray optics of the ERNKON facility with two stationary strip detectors.

Experimental studies on circumferential residual stresses in zirconium tubes showed nonuniform distribution of tangential stresses. The characteristics of tangential stress distribution were analyzed to determine the smallest permissible step of scanning over the coordinate grid of the tube surface to find out stress concentrators. This minimum step was estimated at 30 degrees, with the average half-width of the nonuniformity peak being in the order of 90-100 degrees.

The specified level of residual stresses (up to +200 MPa) was set up by a specially designed collet-type loading device, with dispensation inside the tube. Loading and calibration of residual stresses (+50 MPa to +200 MPa) on the surface of a loaded stub tube, followed the $Sin^2\Psi$ measurement and calculation procedure with the use of the X-ray diffractometer DRON-UM in a goniometric holder of a special design. The calibrated tubes were then put together to form a coaxial assembly for connection to the pressure tube tested.

Calibration testing involved stepwise spiral scanning covering the entire outer surface of the calibrated tube assembly and yielded the average value, variance, extreme values and a map of residual stress distribution.

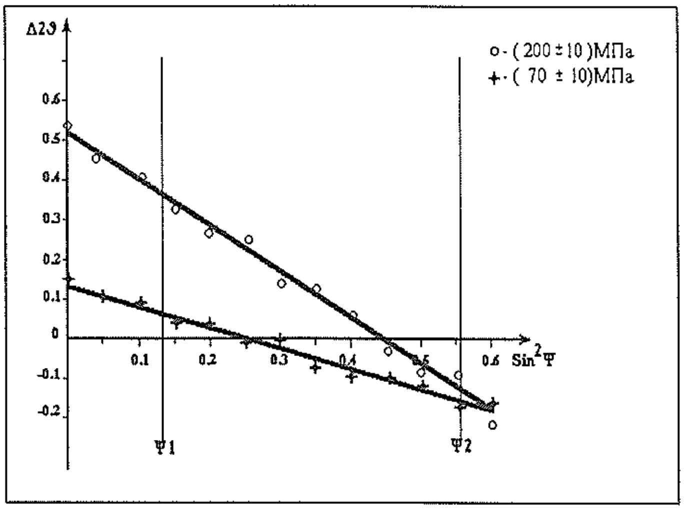

Fig.2

The dependence of diffraction angle displacement (Δ2θ) from $Sin^2\Psi$ for the residual stresses.

During selected checks, the calibrated tube assembly was brought close to the examined surface area. The repeated test involved a check on the measurement reproducibility with more precise location of the sites and values of extreme stresses.

The average rate of residual stress measurement at the ERNKON facility was 10 minutes per linear meter of a tube in the range of -300 MPa to +300 MPa, with a sensitivity of at least 20 MPa.

Pilot operation of the ERNKON facility followed a program of tests involving an assembly of calibrated stub tubes and two industrial tubes cut from pressure tubes 88x4 mm in diameter, made of zirconium alloy Zr 2,5 % Nb. The first tube, 190 cm long, was taken before the straightening operation and the second one, 240 cm in length, after straightening. In the process of testing, the tube was moved in a stepwise spiral motion (with a step of

ΔL=50 mm along the tube direction and a rotation angle of ΔF=60° through the tube circumference) by the handler with the positioning error of no more than ±1 mm.

Fig. 3 depicts the measured distribution of circumferential residual stresses for the pressure tube selected before the straightening operation. Analysis of examination results obtained at the ERNKON facility shows that the pressure tube taken for checking after final annealing but before straightening has residual stresses over its entire surface varying from -25 MPa to 40 MPa. For the pressure tube taken after straightening (Fig. 4), the residual stresses over its entire surface range from 15 MPa to 120 MPa. In the latter case, two nidi were detected, 1200 mm apart, where residual stresses approached the permissible limit (100 MPa).

CONCLUSION

The pilot facility ERNKON was designed for express nondestructive measurement of residual stresses in full-length pressure tubes to be tested under field conditions, with a capability for detecting and locating nonuniform distribution and concentrators of stresses.

The ERNKON results obtained for industrial tubes demonstrated the testing capabilities and showed distribution of residual stresses ranging from -300 MPa to +300 MPa, measured with a sensitivity of 20 MPa.

The average rate of residual stress measurement was 10 minutes per linear meter of a pressure tube.

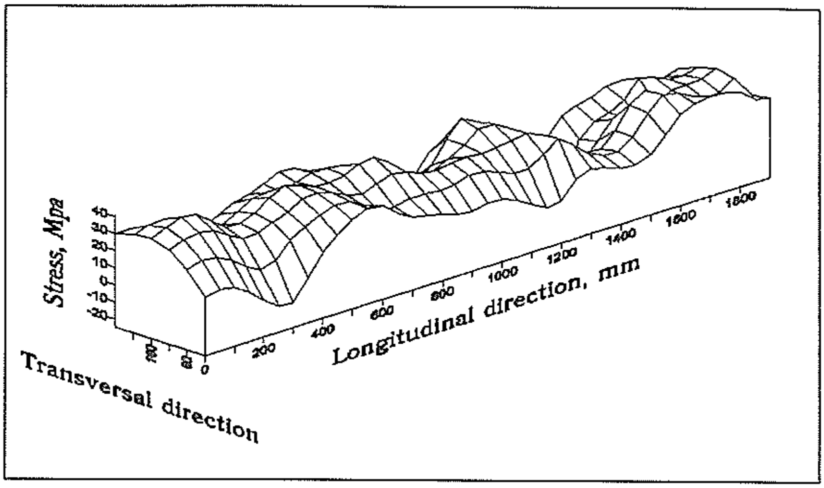

Fig.3

The measured distribution of circumferential residual stresses for the pressure tube before the straightening operation.

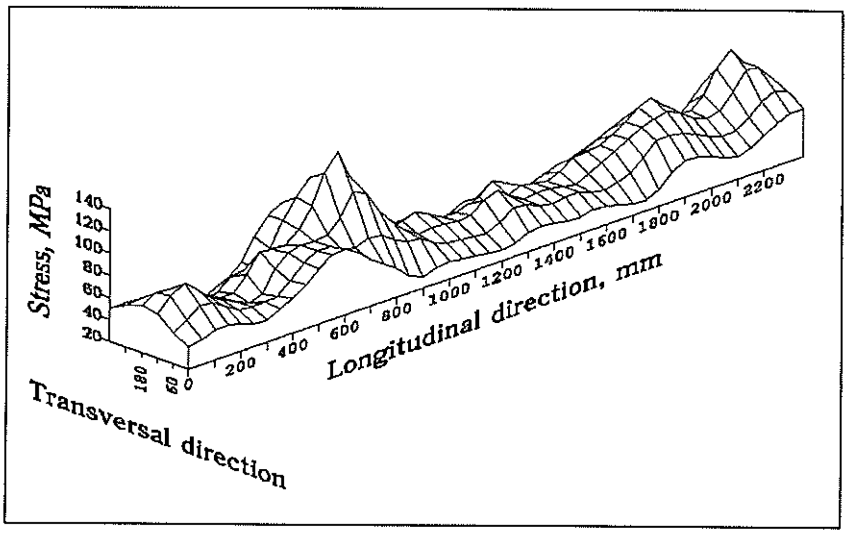

Fig.4

The measured distribution of circumferential residual stresses for the pressure tube after the straightening operation.