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Neutron diffraction investigation of the residual stress gradient near stainless steel - zirconium alloy interface

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Abstract. In this paper we present the results of neutron diffraction investigations of the residual stress gradient around a stainless steel – zirconium alloy interface in a bimetallic adapter. This part is used in some structures of RBMK-type reactor channels. The stresses in this component arise due to various manufacturing processes and the thermal expansion factor mismatch between the two alloys. The residual stress distribution within stainless steel part and the residual stress gradient close to the interface were investigated. The experiments were carried out on the Pulse overlap time-of-flight diffractometer (POLDI) [1] (Paul Scherrer Institute, Switzerland) and the Fourier stress diffractometer (FSD) [2] at the IBR-2 pulsed reactor (Frank Laboratory of Neutron Physics, JINR, Dubna, Russia).

Introduction

In order to predict the durability of engineering components and improve materials performance, it is necessary to understand the residual stress state of this component. The last decade has witnessed a very significant increase in residual strain measurement using diffraction of penetrating radiation, particularly using neutrons and high energy X-rays. These highly penetrating, short wavelength beams provide the basis of powerful non-destructive methods for the determination of the levels of residual stresses in engineering components. Strain measurement is achieved by precise characterisation of interplanar distances within a crystal lattice.

In this paper we present the results of neutron diffraction investigations of the residual stress gradient around a stainless steel – zirconium alloy interface in a bimetallic adapter. (Figure 1) This component is used in some structures of RBMK-type reactors channels as adapter between stainless steel and zirconium tubes. This adapter is a complex cross section cylinder with an outer steel layer and an inner zirconium alloy layer. (Figure 1 and 2) It is manufactured by vacuum sintering and welding at a temperature of 900°C.

All welding processes commonly involve the deposition of molten filler metal and the localised input of intense heat. Consequently, the surrounding parent material undergoes complex thermomechanical cycles involving elastic, plastic, creep and viscous deformation. These can result in the development of large residual stress gradients around the weld interface, which can be particularly detrimental to the service life of components operating at elevated temperatures and pressures. For this reason it is important that these residual stresses can be measured accurately. In the case of diffraction measurements this involves inferring residual stress from measured elastic lattice strain.

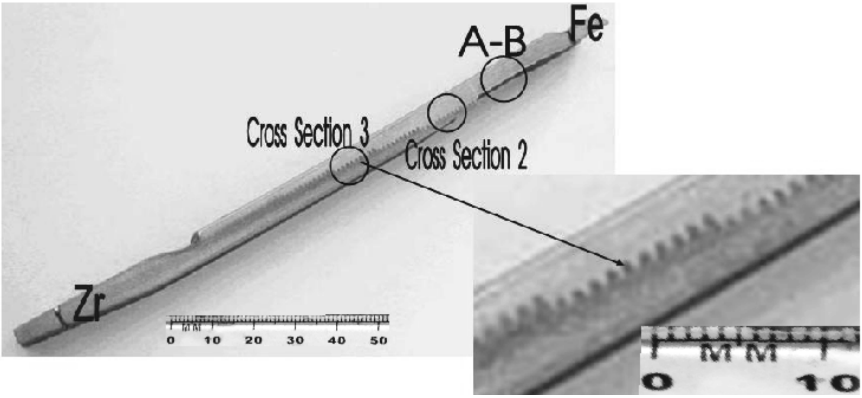


Figure 1. Cross section of the adapter's wall. The stainless steel - zirconium alloy interface and the investigated cross sections A-B, 2, 3 are shown.

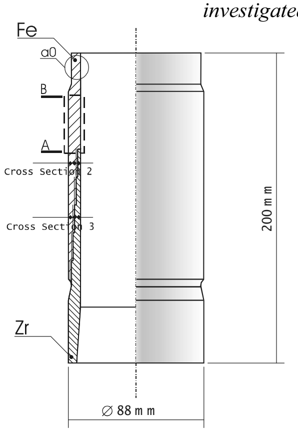


Figure 2. Bimetallic adapter stainless steel-zirconium [3].

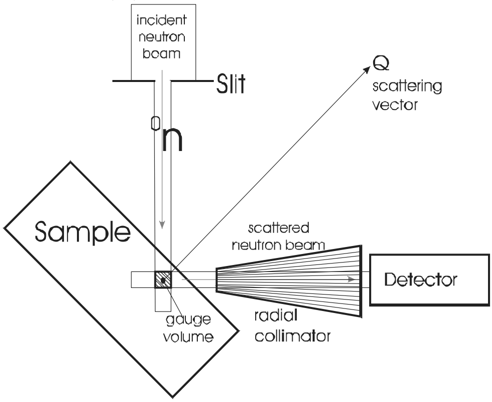


Figure 3. Layout of neutron diffraction experiment

The main aims of this work were to investigate the residual stress gradient and the residual stress state of the stainless steel around the interface. Experience shows that the large stress gradient can exist close to the interface at a cross section, where the so-called first zirconium screw tooth exists. This gradient can be the most critical factor in view of fatigue failure.

The preliminary investigations of the residual stress state of this adapter were carried out by the reverse time-of-flight neutron diffraction method (RTOF method) at Fourier stress diffractometer. The results of this study are reported at [3].

Methods

The study was performed by the neutron diffraction method on the FSD and the POLDI diffractometers which use special correlation techniques.

The principle of FSD operation is based on an application of the reverse time-of-flight (RTOF) method – a kind of correlation technique – at long pulsed neutron sources, which allows high resolution in interplanar spacing ($\Delta d/d \approx 2x10^{-3}$) to be achieved, while maintaining high flux at the instrument. The RTOF - method assumes application of fast Fourier chopper for the neutron beam intensity modulation and measuring of high-resolution correlation spectra. The main advantage of the RTOF-method, as well as of the usual TOF-method, is the possibility of simultaneously measuring many reflections, which allows the determination of residual strains along various (hkl) directions in a crystal. Additionally, the FSD resolution function has rather simple dependence on interplanar spacing d, which allows one to easily estimate microstrain averaged on all (hkl) directions from analysis of width of several diffraction peaks [2].

POLDI (Pulse-OverLap DIffractometer) is a multiple pulse-overlap diffractometer at PSI, which is designed mainly for strain-scanning experiments. The main advantage of this instrument is that it can be optimized to high flux and high resolution simultaneously, and that this optimization can be adapted to the requirements of the experiment. The high intensity is achieved by using many pulses of the chopper simultaneously which can be separated by evaluation of the time–2θ pattern of the scattered neutrons. A resolution (FWHM) of better than $2x10^{-3}$ in the whole Q-range can be achieved at a scattering angle of 90°. The used correlation method has the advantage that no a priori information about the sample is required. This method is mainly used to get qualitative information although a precise determination of the position of the Bragg lines is well possible. The correlation background, which is inherently connected with the frame-overlap method, can be reduced when a fit is applied instead of the correlation method. The fit also gives more precise information about the intensities of the Bragg reflections. Nevertheless, for strain-field measurements, the gain of intensity, which is up to two orders of magnitude compared to conventional TOF-diffractometers, always drastically overcompensates the disadvantage of the correlation background. The method provides best benefits when high resolution is necessary although only a limited number of Bragg reflections are present. Therefore, this method seems to be ideally suited for strain-scanning experiments [1].

Experiments

The experiments were carried out on the POLDI [1] and the FSD [2] neutron diffractometers. Layout of the neutron diffraction experiments is shown in figure 3. It was a typical measurement of residual stresses at TOF neutron diffractometer. For this measurement a neutron detector at the scattering angle 2θ = 90° was used. Three strain tensor components were measured with a gauge volume of 0,6 x 0,8 x 3 mm^3 for several points across the following cross sections 2, 3 and A-B (Figure 1 and 2) of the adapter wall. A typical diffraction spectrum is shown in figure 4.

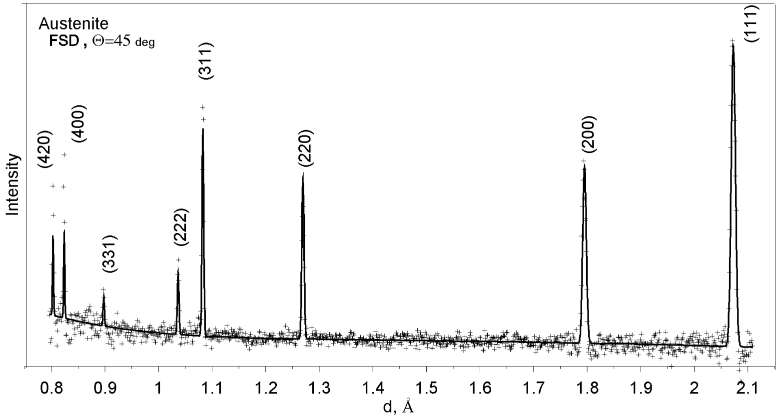


Figure 4. Typical diffraction spectrum.

Experience shows that the large stress gradient can exist close to the stainless steel – zirconium alloy interface. For a measurement of this gradient it was necessary to precisely place a small gauge volume within one of the Fe tooth (Figure 5a). The exact position of the Fe tooth inside the tube wall was found with the help of neutron scanning technique (Figure 5a, b, c).

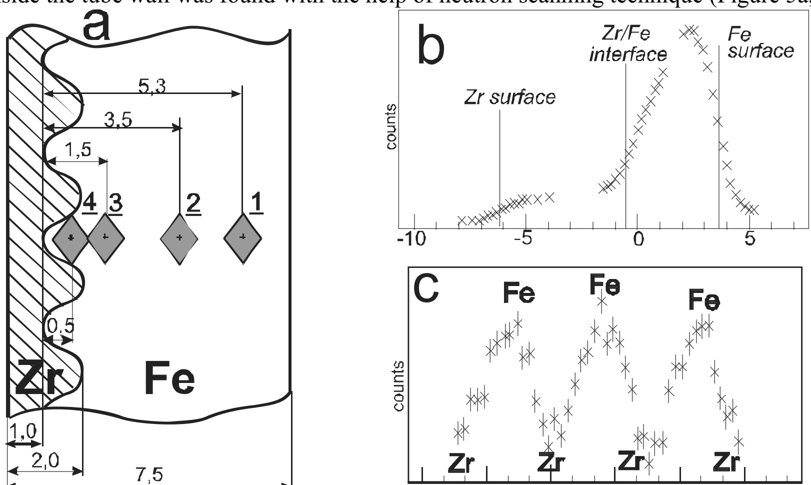
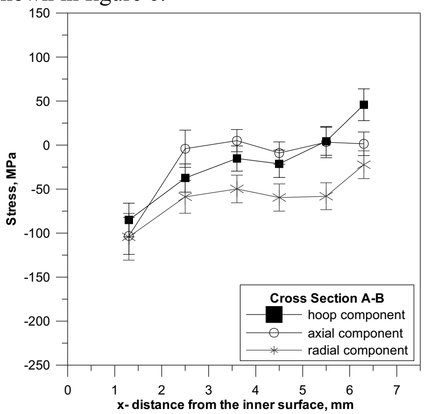


Figure 5. Neutron scanning for searching Fe teeth inside the adapter: a) position of gauge volume inside the tube wall; b)scanning across the tube wall; Zr, Fe surfaces and Zr/Fe interface are shown; c) scanning along the tube (along the welding splice) for searching Zr and Fe teeth.

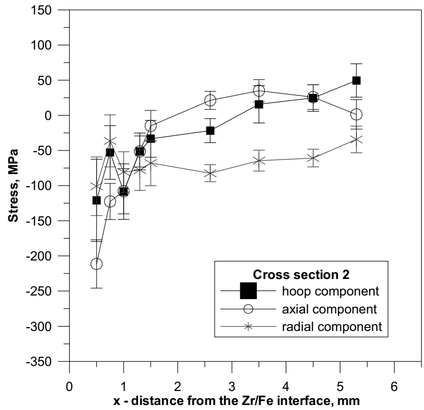
At the first stage a scan across the tube wall was carried out, where the positions of Zr surface, Fe surface and Zr/Fe interface were found (Figure 5b). At the second stage a scan along the tube axis (along the welding splice) was carried out and Zr and Fe teeth were found (Figure 5c). So the exact positions of each Fe teeth were determined. The measurements of residual stresses close to the interface were carried out as typical measurement of residual stresses by TOF neutron diffraction method. Layout of the neutron diffraction experiments is shown in figure 3. “Stress-free” reference measurements were made at a corner of the specimen.

Results

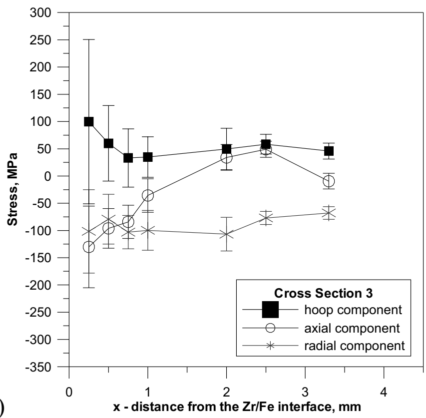
Results of neutron diffraction residual stress measurements across all three cross sections are shown in figure 6.



a)



b)



c)

Figure 6. Residual stress distribution across: a) cross section A-B; x=0 - inner surface, x= 7,5 – outer surface of tube; b) cross section 2; x=0 - Zr/Fe interface; c) cross section 3; x=0 - Zr/Fe interface

An analysis of these distributions allows to seen that the residual stress level in all three cross sections does not exceed 100 MPa.

The axial and hoop components of residual stress tensor on all three cross sections are practically the same. The noticeable difference in the cross section 3 can be consequence of the uncertainties of residual stress measurement at some points and the presence of surface effect.

The radial components on all three cross sections are negative and its values depend on the thickness of stainless steel part of wall. The compressive residual stresses should have a beneficial influence on the fatigue performance of the adapter, which works under tensile load conditions. They should act in the opposite direction to those caused by the tensile load and accordingly improve the resulting stress state of the adapter. However the stresses of compression near the surface are very small and can not entirely compensate enclosed tensile load.

There is the residual stress gradient close to Zr/Fe interface in cross sections 2 and 3. The value of this gradient is quite small (up to 100 MPa/mm).

The cross section A-B is the most dangerous from the point of view of fatigue failure of the adapter and the most probable origin of fatigue cracks. Such a situation has arisen as a result of a combination of two adverse factors, which are coexisting in the given cross section. The first and the most important factor is the lowest value of the compressive stresses. The last but not least factor is the presence of the stress concentrator in cross section A–B.

It is possible to create a large compressive residual stress in the cross section A–B with the help of a corresponding heat treatment. Such stresses compensate against the negative effect of the stress concentrator that exists in the given cross section. Moreover, it compensates for the operational tensile load and accordingly improves the residual stress state of the adapter, its operational characteristics and its durability.

Summary

The study was performed by the neutron diffraction method on the POLDI (PSI) and the FSD (FLNP) diffractometers. With the help of the neutron scanning technique the Zr and Fe teeth were found and the residual stress gradient close to stainless steel – zirconium alloy interface was determined. The cross section A-B is the most dangerous from the point of view of fatigue failure of the adapter but its stress state can be improved with the help of a corresponding heat treatment.

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