INTRODUCTION

Over many years, internal stresses in materials have been studied using various nondestructive techniques: X-ray diffraction, ultrasonic scanning, and various magnetic techniques (measurements of magnetic induction, permeability, anisotropy, Barkhausen effect, magnetoacoustic effects). However, all these methods have certain limitations. For example, using X-ray scattering and magnetic methods, not only stresses near the material surface can be studied due to their small penetration depth; moreover, application of the magnetic methods is restricted to ferromagnetic materials. Moreover, the sample texture has a significant effect on magnetic and ultrasonic methods. Among all these techniques, the neutron diffraction study of stresses has a special place, since, in contrast to conventional methods, neutrons can penetrate materials to a depth of 2–3 cm for steels and to 10 cm for aluminum. Advantages of neutron diffraction are so significant that specialized diffractometers were developed for studying internal stresses, i.e., the FSD (Fourier stress diffractometer) [9, 10, 11]. In this paper, we briefly describe the method for studying internal stresses using neutron diffraction, consider requirements for the parameters of the diffractometer at the pulsed neutron source, describe the FSD setup developed at the IBR-2 reactor, and present the results of test experiments.

METHOD FOR MEASURING INTERNAL STRESSES USING A LONG-PULSE NEUTRON SOURCE

Internal stresses existing in a material cause corresponding lattice strains, which, in turn, results in shifts of Bragg peaks in the diffraction spectrum. This yields direct information on changes in interplanar spacings in a gauge volume, which can be easily transformed into data on internal stresses, using known elastic constants of a material,

$$\frac{d_{\text{exp}} - d_0}{d_0} = \frac{\Delta a}{a_0} \approx \sigma/E,$$

where \(d_{\text{exp}}\) is the measured interplanar spacing, \(d_0\) is the same interplanar spacing in a sample without internal stresses, \(\Delta a/a_0\) is the strain as the relative change in the
where $\lambda$ is the neutron wavelength, $d_{hkl}$ is the interplanar spacing, and $0$ is the Bragg angle. In this case, the lattice strain is determined as

$$\varepsilon_{hkl} = (d_{hkl} - d_{hkl}^0)/d_{hkl}^0 = -\Delta 0 \cot \theta$$

or

$$\varepsilon_{hkl} = (d_{hkl} - d_{hkl}^0)/d_{hkl}^0 = \Delta t/t,$$

where $d_{hkl}$ and $d_{hkl}^0$ are the interplanar spacings for strained and unstrained lattices, respectively, and $t$ is the neutron time of flight. When using a two-axis diffractometer at a source with continuous flux, the strain is determined by the change in the scattering angle, $-\Delta \theta \cdot \cot \theta$. When using the time-of-flight (TOF) method at a pulsed source, the strain is determined by the relative change in the neutron time of flight $\Delta t/t$. Depending on the wavelength, the peak position on the time scale is defined by the condition

$$t = L/v = \lambda mL/h = 2mLd_{hkl} \delta \sin \theta/h,$$

where $L$ is the total flight distance from a neutron source to the detector, $v$ is the neutron velocity, $\lambda$ is the neutron wavelength, $m$ is the neutron mass, $h$ is Planck’s constant, $d_{hkl}$ is the interplanar spacing, and $0$ is the Bragg angle.

Based on known values of the Young’s modulus, the required interplanar spacing measurement accuracy can be estimated, so that the $\sigma$ determination error would not exceed, e.g., 20 MPa, which is, as a rule, quite sufficient for engineering calculations. For aluminum, $E \approx 70$ GPa, hence, it is sufficient to measure $\Delta a/a_0$ with an accuracy of $3 \times 10^{-4}$; for steel, $E \approx 200$ GPa, and the accuracy should be better than $1 \times 10^{-4}$. These requirements appreciably exceed the capability of conventional neutron diffractometers whose resolution, as a rule, is $\leq 1\%$, i.e., the diffractometer for measuring internal stresses should have high resolution.

Existing practice showed that a required accuracy can also be achieved for diffractometers with monochromatic neutron beams, operating at stationary reactors, and for TOF diffractometers operating at pulsed neutron sources. Without going into details of experimental design in these two cases, we only note that a main advantage of the former version is a larger luminosity and, hence, the possibility of sample scanning with good spatial resolution. In the latter case, a fixed and most optimal 90° experimental geometry is easily implemented and, in contrast to the former case, several diffraction peaks are simultaneously measured, which allows analysis of stress anisotropy.

An analysis of the shape (width in the simplest case) of diffraction peaks can yield information on lattice distortions in individual grains (microstrain) and their sizes. This is especially convenient to do that using a TOF diffractometer with the functional dependence of the peak width on the interplanar spacing,

$$W^2 = C_1 + C_2 d^2 + C_3 d^2 + C_4 d^4,$$