UTILISATION OF THE THERMAL NEUTRON BEAM AT RESEARCH REACTORS FOR TESTING STEEL MATERIALS USED FOR THE CONSTRUCTION OF THEIR KEY COMPONENTS

Ľ. MRÁZ
Welding Research Institute – Industrial Institute SR, Bratislava, Slovak Republic

CH. HERVOCHES, M. VRÁNA, P. MIKULA, J. ŠAROUN
Nuclear Physics Institute ASCR, v.v.i., 25068 Řež, Czech Republic

J. KOTORA
SES Tlmače, Slovak Republic

ABSTRACT

Unique properies of the neutron diffraction method for testing of steel reactor components used for construction of some of its key parts is demonstrated on the results of the following two measurements: Determination of the effect of low-temperature long-term heat treatment on distribution of residual stresses on the modified chromium-molybden steel of the type 7 CrMoVTi10-10 and known as T24 steel and determination of residual stresses in the vicinity of the electron beam welds on samples prepared by the reconstitution method.

1. Introduction

Due to the nature of nuclear energy generation, the materials used for components situated close to the reactor core are constantly bombarded by high-energy particles, namely by neutrons or fragments of an atom created by a fission event. When one of these particles collides with an atom in the material, it will transfer some of its kinetic energy and knock the atom out of its position in the lattice. This can create a chain reaction that can cause many atoms to be displaced from their original position. This atomic movement leads to the creation of many types of defects. The accumulation of various defects can cause microstructural changes that can lead to a degradation in macroscopic properties. Steel materials play a critical role in the safety of the reactors and the componets made of them e.g. the reactor vessel and pipes must be able to withstand operation at elevated temperatures and pressures for a rather long time. Construction material is subjected to a variety of chemical, mechanical and physical conditions during operation, which lead to changes, over time. Namely, they are various loads, residual stresses, flow conditions, corrosion, temperature and neutron irradiation. They have a direct influence on material hardness, ductility, brittleness, fracture toughness, cracking and thus, on the working life time of the use. Time dependent changes in mechanical and physical properties of materials are referred to as ageing. However, the reactor vessels and pipe assemblies are manufactured to their final required form, besides other things, by welding. Therefore, similar mechanical material properties with a maximum possible resistence to degradation are required also for welds. In this way, the modified chromium-molybden steel is a material that has been attracting attention for a long time. This steel belongs to the group of modified CrMo low-alloyed creep resistant steels. In our investigations we have focused on determination of residual stresses in the welds (and their vicinity) of two tubes made of 7 CrMoVTi10-10 creep resistant steel and of the 38 mm diameter and of the 6.3 mm wall thickness. The objective of this contribution is to present the effect of low-temperature long-term heat treatment on distribution of residual stresses using neutron diffraction method. The distribution of residual stresses in the vicinity of circumferential welded joints were measured in as welded conditions and subsequently after low temperature heat treatments at 450 °C for 48 hours. TIG process, filler material W Z CrMo2VTi (Union I P24) and shielding gas I1 were used for welding. The heat input in the range of 8.0 to 13.0 kJ/cm, preheat temperature 150 °C to 200 °C and interpass temperature max. 250 °C was applied. One can suppose that the used conditions can play an important role in the behavior of weld during the initial period of power station start up. As a second example, the residual stress investigations in the vicinity of electron beam welds of Charpy-V notched specimen prepared by reconstitution method with welds on one side as well as with welds on two opposite sides. Welding was performed with electron beam in a vacuum and proceeded in accordance with the ASTM E 1253 standard.

2. Experimental part

2.1 Principles of the neutron diffraction method

The principle of the neutron diffraction method is quite simple. It consists in the precise determination of the d_{hkl}-spacing of particularly oriented crystal planes [1,2]. In neutron and X-ray diffraction the angular positions of the diffraction maxima are directly related to the values of the lattice spacing through the Bragg equation $2d_{hkl} \cdot \sin \theta_{hkl} = \lambda$ (d_{hkl} -lattice spacing, θ_{hkl} - Bragg angle, λ - the neutron wavelength) and thus offer a unique non-destructive technique for investigation of stress fields. When a specimen is strained elastically, the lattice spacing changes. Then, when defining the strain ε as $\varepsilon = \Delta d/d_{0,hkl}$, it is related to a change in the lattice spacing, i.e. to a component parallel to the scattering vector Q perpendicular to the reflecting set of planes.

Therefore, the knowledge of the $d_{0,hkl}$ value ($d_{0,hkl}$ is the lattice spacing of the strain-free material) is a crucial task [1]. Then by differentiation of the Bragg condition we arrive at $\varepsilon = -\cot \theta_{hkl} \cdot \Delta\theta_{hkl}$. The relation for the strain ε indicates that it gives rise to a change in the scattering angle $2\theta_{hkl}$ resulting in an angular shift $\Delta(2\theta_{hkl})$ of the peak position for a particular reflecting plane illuminated by a fixed wavelength. In such a way, the shift in the Bragg angle (relative to that of the stress-free material) permits the determination of the average lattice macrostrain over the irradiated gauge volume (see Fig. 1). The conversion of strains to stresses is carried out by means of the relation

Fig. 1. Schematic illustration of a reactor source based diffractometer for strain measurement

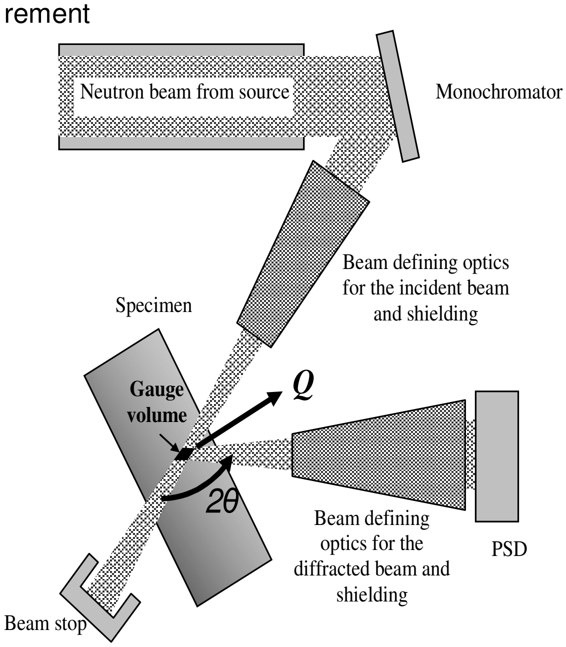
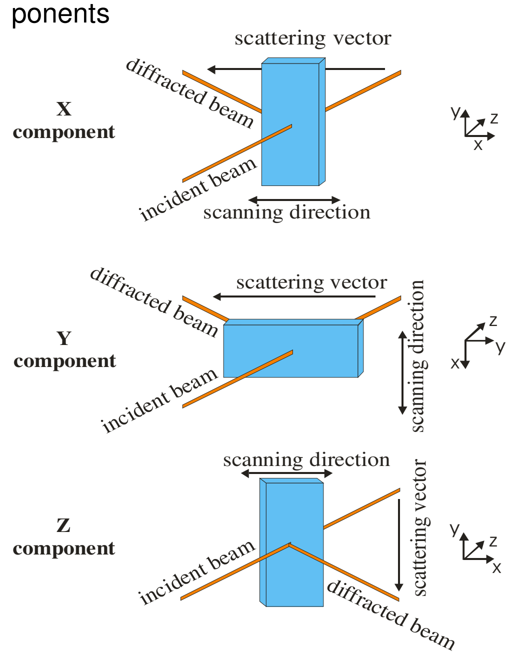


Fig. 2. Sketch of the sample setting for determination of three strain/stress components



$$\sigma_x = \frac{E_{hkl}}{(1-2\nu_{hkl})(1+\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_x^{hkl} + \nu_{hkl}(\varepsilon_y^{hkl} + \varepsilon_z^{hkl})\right] \tag{1}$$

where $\varepsilon_{x,y,z}^{hkl}$ is the *x,y,z*-component of the lattice strain measured at the *hkl* crystal lattice planes, E_{hkl} and ν_{hkl} are the diffraction elastic Young modulus and diffraction Poisson ratio, respectively. For the determination of the stress tensor in this case of steel samples, three strain components should be determined as schematically shown in Fig. 2. The residual strain/stress experiment was carried out on the dedicated neutron strain/stress scanning diffractometer (http://neutron.ujf.cas.cz/en/hk4) installed at the 10 MW medium power research reactor LVR-15 (http://cvrez.cz/vyzkumna-infrastruktura/vyzkumny-reaktor-lvr-15/) and operating at the constant neutron wavelength of 0.235 nm.

2.2 Chromium-molybden steel of the type 7 CrMoVTi10-10

2.2.1 Test weld preparation

Circumferential weld of two tubes made of 7 CrMoVTi10-10 creep resistant steel diameter of ∅ 38 mm and wall thickness of 6.3 mm has been prepared for this investigation (see Fig. 3). TIG process, medium alloyed filler material W Z CrMo2VTi (Union I P24) (typical content Cr = 2,2 %, W = 1,7 %) and argon as shielding gas have been used for welding. The heats input

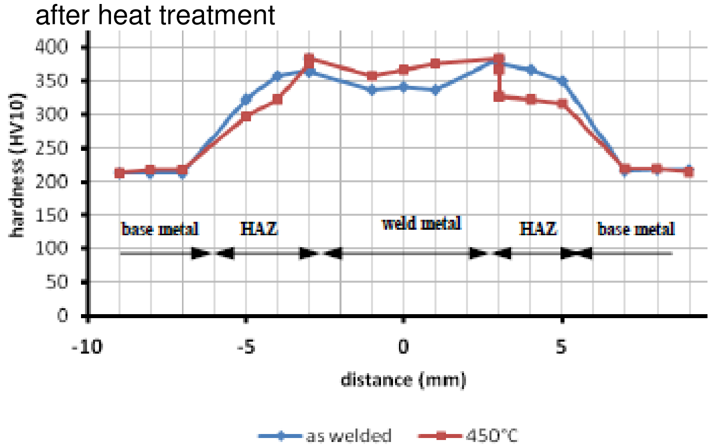
Fig. 3. Circumferential test weld of 7 CrMoVTi10-10 creep resistant steel

in the range of 8.0 to 13.0 kJ cm, preheat temperature 150 °C to 200 °C and interpass temperature max. 250 °C have been applied. Hardness distribution across butt weld was measured by Vickers method at the load of 98.1 N (HV10). Neutron diffraction has been performed in order to identify residual stress distribution in the vicinity of the circumferential weld. Hoop, radial and axial stresses have been estimated for as-welded conditions and after long term heat treatment at the temperature 450 °C for 48 hours.

2.2.2 Hardness distribution

Hardness distribution accross the circumferential test weld prior and after low temperature heat treatment is summarized in Fig. 4. No remarkable change has been noticed due to applied heat treatment.

Fig. 4. Hardness distribution accross test weld prior and after heat treatment



2.2.3 Neutron diffraction measurements

Axial, radial and hoop stresses have been estimated in the vicinity of the test weld (see Figs. from 5 to 7). The results show that all stress components of weld residual stresses dropped after low temperature long term heat treatment. The irradiated gauge volume (see Fig. 1) had the dimensions of about 3x3x3 mm^3.

Fig. 5. Axial stresses (parallel to z-axis) in the vicinity of the test weld

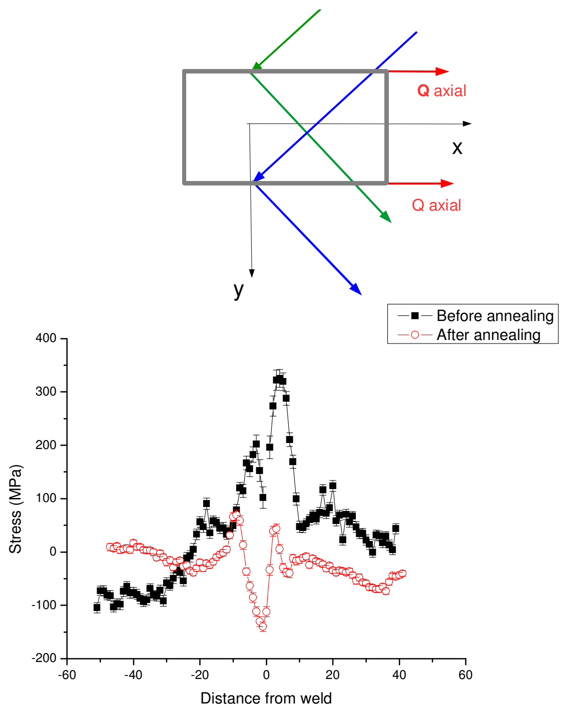


Fig. 6. Hoop (tangential) stresses in the vicinity of the test

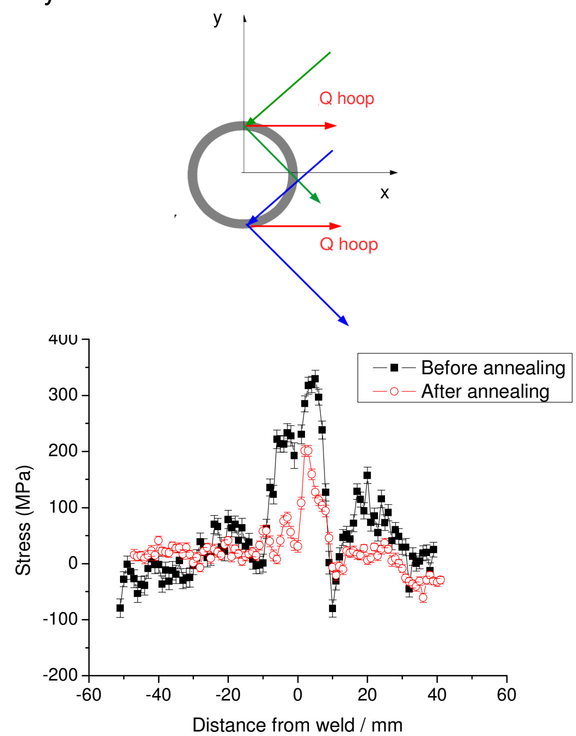
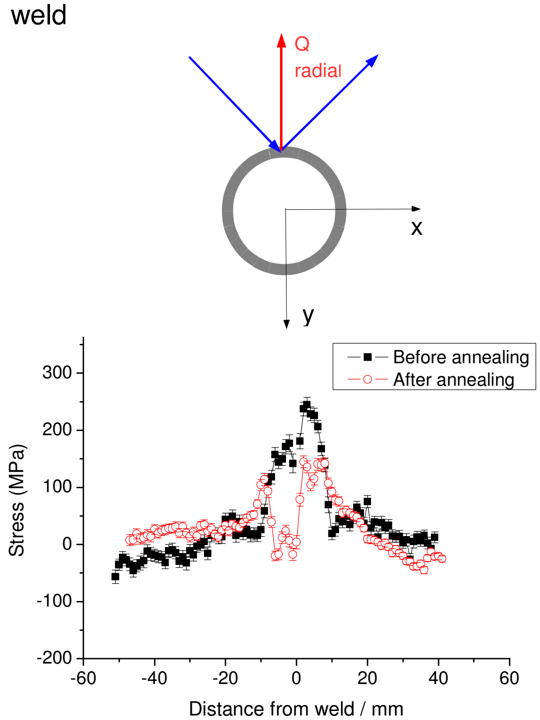


Fig. 7. Radial stresses in the vicinity of the test weld



Inspection of the obtained results reveals that the applied heat treatment did not have remarkable change of the local properties (hardness) of the weld. Despite this, the drop of residual stresses after heat treatment compared to as welded condition is clear and remarkable. According to these results we assume that low temperature heat treatment can influence final behaviour of circumferential welds in service. We expect that the results will contribute to the extension of knowledge about the behaviour of welded joints of the creep resistant T24 steel during the start up period of power stations.

2.3 Electron beam welds on samples prepared by reconstitution method

2.3.1 Sample preparation

The technique of constructing specimens from small pieces of material is usually called reconstitution. Such miniaturized specimen technology permits the characterization of mechanical behaviour while using a minimum volume of material. The compound specimen is achieved by attaching an additional material (studs) around a material of interest (the insert material) which results in a test specimen of standard dimensions. The incorporation of a small piece from a previously tested specimen into a compound one, allows e.g. to multiply the number of tests. This can be especially important if the amount of the available material is restricted and mechanical parameters have to be determined. Very often one can meet with such necessity in the nuclear power plant industry e.g. nuclear pressure vessel surveillance, failure analysis, and namely, in post irradiation testing when a manipulation with a large strongly radioactive sample would be very tough. The interface between the stud and the insert is created by using welding techniques. However, before testing the mechanical properties, the microstructure after welding has to be examined to ensure that the material in the vicinity of the notch, is from the point of the presence of residual stresses, essentially unchanged after the welding process. For example, it is well known that the residual stresses resulting from the welding process can be nonnegligible. In our case electron-beam welding (EBW) was used. Welded pieces were of low-alloy ferritic steel material. The total dimensions of the samples were 10 x 10 x 55 mm^3. Fig. 8 displays the photos of a specimen prepared by joining three pieces (stud + insert + stud) by welding only on one side and the same sample as installed at the neutron beam defined by input and output slits. Furthermore, we had at our disposal, and also measured, samples welded from both sides. The central part of the sample was made of reactor pressure vessel steel (surveillance material). Welding was performed with electron beam in a vacuum and proceeded in accordance with the ASTM E 1253 standard.

Fig. 8. Photos of one of the specimens with the weld on one side (left) and as installed on the neutron beam defined by slits (right)

2.3.2 Neutron diffraction measurements

The obtained experimental results of residual stress measurements in the vicinity of the weld joins at different depths are shown in Fig. 9 and Fig. 10. Figs. 9 and 10 document that quite significant residual stresses are present in the vicinity of electron beam welds. Their maximum achieves the value 400-500 MPa. They are, of course, not present at the depth of 7.5 mm of the sample with the weld only on one side where the heat affected zone is missing (see Fig. 9 below). Taking into account stress distribution along the scan-axis in the material (along the longest edge of the sample) it can be seen that rather large stresses are extended in the area of the length of about 5 mm from the weld.

Fig. 9. Residual stress scans performed at different depths in the material for the sample with the weld on one side

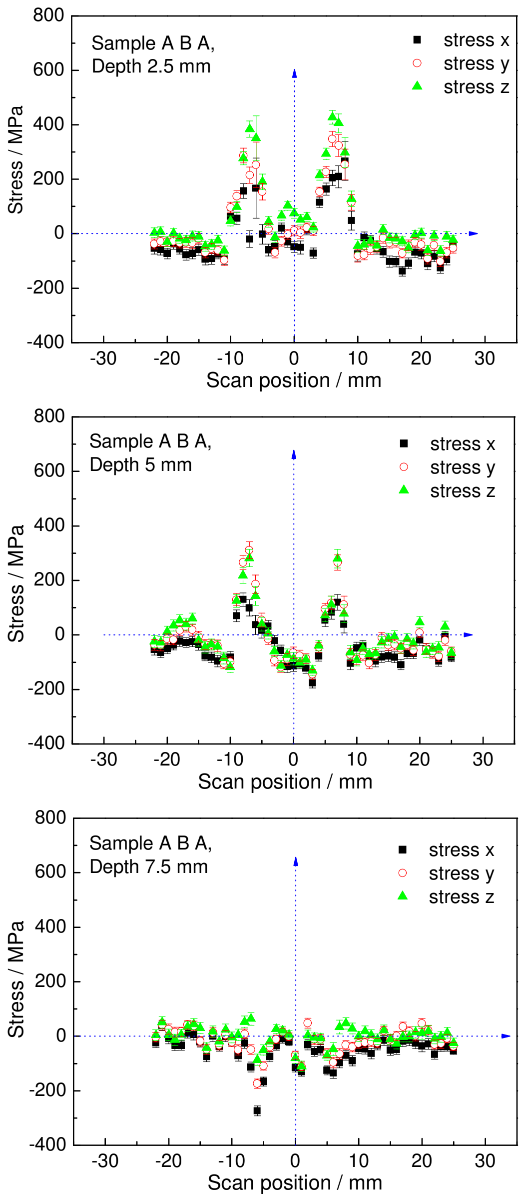
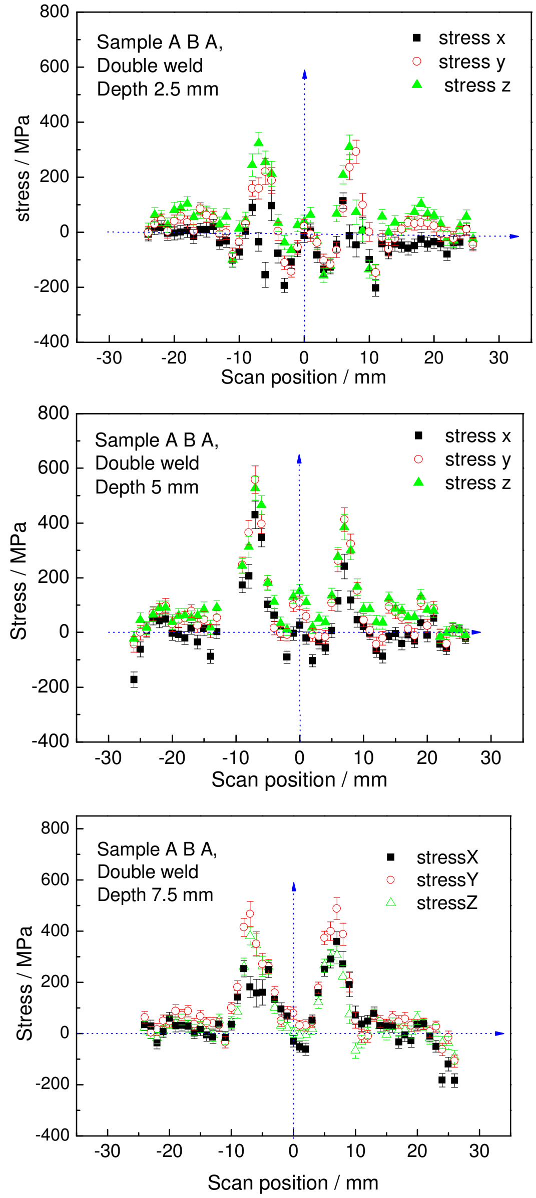


Fig. 10. Residual stress scans performed at different depths in the material for the sample with the weld on both sides



3. Summary

The paper demonstrates the results of two neutron diffraction applications for the estimation of residual stress distribution in the vicinity of the circumferential weld of creep resistant T24 steel and in the vicinity of the electron beam weld on the testing sample prepared by the the reconstitution method. In the first case, the obtained results show that even the low temperature long term heat treatment can influence the level of residual stresses. One can suppose that this effect can play an important role in the behavior of weld during initial period of power station start up. In the second case of the samples prepared by the reconstitution method quite large residual stresses are present in the vicinity of electron beam weld. Significant stresses are extended in the area of the length of several millimetres and in the case of the welding on both sides, the stresses reach even the middle area of the stud, where mechanical tests should be carried out. Finally, it can be stated that a large penetration depth and selective absorption of neutrons make the neutron diffraction technique a powerful tool in non-destructive testing of materials. In fact, this technique is one of few nondestructive methods that can facilitate 3-D mapping of residual stresses in bulk components.

Acknowledgement

The related experimental studies were carried out at the CANAM infrastructure of the NPI ASCR Rez supported by Czech Science Foundation GACR through the project No. 16-08803J.

References

[1] Hutchings, M.T., and Krawitz, A.D., (Eds.), 1992, "Measurement of residual and applied stress using neutron diffraction*", NATO ASI Series, Applied Sciences, Vol. 26*, Kluwer Academic Publisher, 1992.

[2] Stelmukh, V., Edwards, L., Santisteban, J.R., Ganguly, S., and Fitzpatrick, M.E., 2002, "Weld stress mapping using neutron and synchrotron x-ray diffraction", *Materials Science Forum Vol. 404-407,* pp. 599-604.