Study of residual stresses in CT test specimens welded by electron beam

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Abstract. The paper reports result of residual stress distribution studies in CT specimens reconstituted by electron beam welding (EBW). The main aim of the study is evaluation of the applicability of the welding technique for CT specimens’ reconstitution. Thus, the temperature distribution during electron beam welding of a CT specimen was calculated using Green’s functions and the residual stress distribution was determined experimentally using neutron diffraction. Time-of-flight neutron diffraction experiments were performed on a Fourier stress diffractometer at the IBR-2 fast pulsed reactor in FLNP JINR (Dubna, Russia). The neutron diffraction data estimates yielded a maximal stress level of ±180 MPa in the welded joint.

1. Introduction
One of the most important components of nuclear installation is the reactor pressure vessel (RPV). The safety of the RPV is ensured by mechanical testing of the surveillance Charpy or CT specimens. During reactor operation, the surveillance samples are exposed to the same thermal and radiation conditions as the RPV material.

In order to increase the number of irradiated samples of reactor steel, sample reconstruction by an electron beam welding (EBW) procedure is usually applied. The residual stresses and microstrains resulting from the EBW process are important parameters responsible for the service life of reconstituted Charpy or CT specimens [1, 2]. Over many years, residual stresses in materials have been studied using various non-destructive techniques: X-ray diffraction, ultrasonic scanning and various magnetic techniques (measurements of magnetic induction, permeability, anisotropy, Barkhausen effect, magnetoacoustics effects). The non-destructive techniques for stress determination seem to be the most informative, because they allow one to work with the original product and the real stress distribution. However, all these methods have strong limitations in the depth of penetration and materials used. Neutron diffraction enlarges and complements the capabilities of other methods for determining residual stresses. Neutron diffraction experiments are less common than X-ray diffraction due to the

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difficulty in obtaining particle fluxes, but allow one to study a wider range of products without destroying them, due to the high penetrating ability of neutrons.

We present theoretical calculation of the temperature fields during electron beam welding, together with results of neutron diffraction measurement of the residual stresses.

2. Experiment and modeling

2.1. Experimental measurement of residual stress distribution

The material used in this study was 18MND5 low-alloyed steel with chemical composition (wt % C 0,18; Si 0,25, Mn 1,6; Cr 0,17; Ni 0,64; Mo 0,61; V 0,12; Cu 0,13). Figure 1 shows the welded CT specimen and a cross-section of the seam welded at a beam power of 3 kW and welding speed \( V = 10 \text{ mm/s} \). The insert from the test material (1) is welded to the holder (3) for the CT test. The insert had dimension 10\( \times \)10\( \times \)24 mm. The final dimensions of CT specimen were 26\( \times \)24\( \times \)10 mm.

The Fourier stress diffractometer (FSD) is a specialized high-resolution neutron diffractometer for residual stress studies [3, 4] located at channel 11A of the IBR-2 fast pulsed reactor in FLNP JINR. The correlation RTOF method used by the FSD allows a resolution of \( \Delta d/d \approx 0.001\text{-}0.004 \) on a short flight base of \( \sim 5.5 \text{ m} \) [5]. The instrument has two wide-aperture radial collimators with spatial resolution of 1.8 mm in front of each 90˚ detector. This allows the selection of a small scattering volume (gauge volume) inside the sample studied. Scanning the sample as installed on a precise Huber goniometer with a small gauge volume yields information on the residual strain distribution in the material. The typical accuracy of residual stress determination on the FSD diffractometer is 10-20 MPa for steel.

In the current study, the residual stresses were measured in the middle of the sample along the scan line (Y-axis) at 12-14 points. At each point investigated, three mutually orthogonal strain tensor components were measured with a gauge volume of 40 mm\(^3\) (2\( \times \)2\( \times \)10 mm). The resulting stresses were averaged over the gauge volume. The scan step between two successive points was selected to be 2 mm.

2.2. Temperature fields modeling using Green’s functions

If the specific heat \( c_p \), density \( \rho \) and heat conductivity \( \lambda \) of the material are temperature independent, the time and spatial temperature distribution \( T(\mathbf{r}, t) \) in a medium satisfies the transient conduction equation:

\[
\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T).
\]
where $\alpha = \lambda/\rho c_p$ is the heat diffusivity of the material and $f(r,t)$ is the distribution of the source.

Equation (1) describes a three-dimensional non-homogeneous heat conduction problem, which has the following solution, expressed in terms of a three-dimensional Green’s function [6]:

$$T(r, t) = \frac{\alpha}{\lambda} \int_{\tau=0}^{t} d\tau \int_{R} G(r, t | r', \tau) f(r', \tau) dV' + \int_{R} G(r, t | r', \tau) |_{\tau=0} F(r') dV', \quad (2)$$

where $F(r')$ is the initial temperature distribution.

The volume source beam distribution $f(r, t) = f_V(\xi, \eta, \zeta, \tau)$, where $\xi = x' = x - r \cos \theta$, $\eta = y' = y - r \sin \theta$ ($r$ and $\theta$ are the polar coordinates) and $\zeta$ is the depth of the point of integration, can assume different forms depending on the type of the beam motion and the source shape chosen.

In case of welding along a straight line, the heat source function shape could be chosen to be a cone with a base radius $r_0$, height $h$ with Gaussian distribution at any plane $\zeta$ and moving along a straight line. Then the integration over $\zeta$ is limited from $\zeta = 0$ to $\zeta = h$ and equation (2) is transformed to:

$$T_V(x, y, z, t) = T_0 + \int_{0}^{h} \int_{0}^{\pi} \int_{-\pi/2}^{\pi/2} \frac{\alpha}{\lambda} f_V(\xi, \eta, \zeta, \tau) \left[ \exp \left( -\frac{r^2 + (z-\zeta)^2}{4\alpha(t-\tau)} \right) \right] r dr d\theta d\zeta d\tau . \quad (3)$$

Bearing in mind that the cone radius in plane $\zeta$ is

$$r_{\zeta} = r_0 \frac{h-\zeta}{h} \quad (4)$$

and the volume of the cone is smaller by a factor of three than the volume of a cylinder with the same base, which determines a normalizing coefficient over the cone volume, the cone heat source is defined as:

$$f_V(\xi, \eta, \zeta, \tau) = 3 \frac{Q}{h} \left( \frac{3Q}{\pi r_0^2} \right) \exp \left( -3 \frac{(\xi - \nu \tau)^2 + \eta^2}{r_{\zeta}^2} \right) \frac{3Q}{\pi r_0^2} \exp \left( -3 \frac{h^2}{(h-\zeta)^2} \frac{(\zeta - \nu \tau)^2 + \eta^2}{r_0^2} \right) \quad (5)$$

Equation (3) with the cone source (5) can be used for calculation of the temperature in case of welding.

We used the Wolfram Mathematica [9] numerical integration tool, which works adaptively, reaching a preliminary specified accuracy. Separating the numerical integration into many independent numerical integrations allows one to make use of the parallel computing implemented by Mathematica for multicore computers, thus achieving a significant acceleration of the calculations. The total temperature increase at a given point is calculated as the sum of the contribution of each integrand.
3. Results and discussion

The calculated temperature distribution for EBW of CT specimens presented in figure 2a exhibits high temperature gradient along the Y coordinate. At a lower source speed, heating to a higher temperature and a slower cooling rate are observed (see figure 1b and figure 2a). The closer a certain point to the weld seam, the higher the temperature. This directly affects the residual stress distribution after the welding process. In our case, the welding speed was 10 mm/sec, corresponding to the middle line in figure 2a.

The information on the hardness of the material in the weld region (figure 2b) was used as the initial experimental data. Neutron diffraction made it possible to measure directly the residual strains caused by the thermal action and then recalculate them into residual stresses. During the neutron diffraction experiments, the residual strain distributions were obtained in three perpendicular directions. Then, the residual stresses were calculated according to Hooke's law using a commonly applied approach [7]. The residual stress distributions obtained are shown in figure 3. Position Y = 0 mm corresponds to the weld center. The negative values of the Y coordinates belong to the insert of the witness sample material, the positive, to the CT test holder. It can be seen that all three components of the residual stress tensor have a quite low level (about 180 MPa) in the weld region and the stresses drop rapidly in the insert.

![Figure 2. a) Calculated temperature distribution for different welding speed and electron beam power 3 kW; b) Experimental microhardness of the weld and the heat-affected zone at beam power 3 kW and welding speed V = 10 mm/s.]

![Figure 3. Measured residual stresses in the specimen.]

The maximum values of the residual stresses of the X and Y components reach a level of 100 MPa in the near-weld region and the overheating section. At a depth of 3 mm from the welded seam, there are practically no effects from the heat-affected zone during welding, which is typical for electron-beam welding [8]. The tempering area ends in this zone and the residual stresses drop rapidly to almost zero. The divergence of the stresses in the holder, shown on the right-hand side of the graph, should be attributed to the peculiarities of the technology of its manufacture; it does not affect the results of the mechanical CT tests.
The experimental results show a narrow region of thermal action for all three components of the strain tensor. This is in good agreement with the calculated temperature field data (figure 2a). The calculations show practically no effect of the zone of thermal action at a distance of ±2 mm from the weld at different welding speeds.

4. Conclusions
The temperature distribution during electron beam welding of alloyed steel show high gradients, which directly affects the residual stresses.

Using neutron diffraction study of the CT test sample, the residual stress distributions were determined in three directions in the material. All components of the strain tensor have a low level of residual stresses (~ 180 MPa) in the weld region.

The calculations width of the temperature-effect zone were confirmed by the neutron diffraction experiment. The width of the thermal exposure zone is several millimeters.

The low level of residual stresses and the narrow zone of thermal influence indicate a slight change in the structure of the material after welding. Therefore, the results obtained allow us to recommend the use of electron beam welding for manufacturing CT test samples.

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