Investigation of Residual Stresses in Dissimilar Copper-Steel Joint Welded by Electron Beam

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Abstract

The results of experimental determination of residual stress distribution in dissimilar materials welded by EBW method via neutron diffraction are presented. The joints between copper and stainless steel were investigated. Two samples with different beam current were welded. The residual stresses were measured using TOF diffraction method at a pulsed neutron source. The strain is determined by the relative change in the neutron time of flight. Analysis of the widths of the peaks made it possible to obtain information on microstrains in the samples. The residual stresses in copper do not exceed 100 MPa in both samples. The maximum stresses can be seen in the steel zone of thermal impact in the X component – 450 MPa.

Rezime

Prikazani su rezultati eksperimentalnog određivanja raspodele zaostalih napona u različitim materijalima zavarenim elektronskim snopom (EBW) pomoću difrakcije neutrona. Ispitivani su spojevi između bakra i nerđajućeg čelika. Zaostali naponi su mereni TOF metodom difrakcije na izvoru pulsirajućih neutrona. Deformacija se određuje relativnom promenom vremena proticanja neutron. Analiza širina vrhova omogućila je dobijanje informacija o mikrodeformacijama u uzorcima. Zaostali naponi u bakaru ne prelaze 100 MPa u oba uzorka. Maksimalni naponi se primećuju u zoni uticaja toplote čelika u X komponenti - 450 MPa.

1. Introduction

Electron beam welding is one of the modern methods of joining various refractory metals, dissimilar, chemically active, high-quality steels and high-strength alloys. The process of beam welding is characterized by two features: the welding process is realized in a vacuum environment, which guarantees obtaining the cleanest surface and degassing of the molten metal; heating occurs to very high temperatures, thus the metal melts quickly, and the seam results in a fine-grained and minimal width as a result of the treatment. Welding products composed of dissimilar materials makes it easier to join parts and improve the performance properties of structures based on them. Laser and electron beam welding greatly simplified the technology of welding of dissimilar materials.

1. Uvod

Zavarivanje elektronskim snopom je jedna od savremenih metoda spajanja različitih vatrootpornih metala, različitih, hemijski aktivnih, visokokvalitetnih čelika i legura visoke čvrstoće. Proces zavarivanja snopom karakterišu dve pojave: postupak zavarivanja se realizuje u vakuumu, što garancijuje dobijanje najčistije površine i degazaciju rastopljenog metala; zagrevanje se dešava na veoma visokim temperaturama, pa se metal brzo topi, a šav rezultuje finim zrnom i minimalnom širinom. Zavarenim proizvodima sastavljenim od raznorodnih materijala olakšavaju spajanje delova i poboljšavaju karakteristike konstrukcija izrađenih od tih materijala. Lasersko i zavarivanje elektronskim snopom uveliko je pojednostavilo tehnologiju zavarivanja raznorodnih materijala.
After electron beam welding (EBW) residual stresses and strains are originated in welding joint and in heat affected zone (HAZ) [1, 2] as a result of differential contractions which occur as the weld metal solidifies and cools down to the ambient temperature. The residual stresses strongly affect on the structure and solidity of welding joint [3] and, consequently, on lifetime of the final product. Therefore it is necessary to control their level and spatial distribution after welding process.

Over many years, internal 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, magnetoacoustic effects). However, all these methods have certain limitations. For example, using X-ray scattering and magnetic methods, only stresses near the material surface can be studied due to their small penetration depth; application of the magnetic methods is restricted to ferromagnetic materials. Moreover, the specimen texture has a significant effect on the results obtained by magnetic and ultrasonic methods. Among all these techniques, the neutron diffraction study of residual 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. Other important advantages of the neutron diffraction technique include high spatial resolution, applicability for multiphase materials, non-destructive character of the method, possibility to characterize materials microstructure and defects (microstrain, coherently scattering crystallite size, dislocation density, etc.).

The main aim of the current research work was the experimental determination of residual stress distribution in the flat steel and copper plates welded by EBW method using high resolution neutron diffraction.

In this paper, we investigated the residual stresses in dissimilar joints between copper and stainless steel 304 welded by electron beam at different welding speeds beam current. Two identical samples (Fig.1) with size of 50x40x10 mm were welded in Institute of Electronics of Bulgarian Academy of Sciences (Sofia, Bulgaria) using Leybold Heraeus welding unit. Samples were prepared with a welding speed of 1 cm/s and U=55 kV. The first sample was prepared with a current I = 50 mA, second – I = 60 mA.

The neutron diffraction method was used to determine the residual stress distributions in both samples. The neutron experiments were performed...
on the FSD diffractometer at the IBR-2 pulsed reactor in the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna, Russian Federation.

2. Method

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 spacing in a gauge volume, which can be easily transformed into data on internal stresses, using known elastic constants of a material [4],

\[ \frac{d_{\text{exp}} - d_0}{d_0} \approx \Delta \frac{\sigma}{E} \]  

where \( d_{\text{exp}} \) is the measured interplanar spacing, \( d_0 \) is the same interplanar spacing in a specimen without internal stresses, \( \Delta \frac{\sigma}{a} \) is the strain as the relative change in the unit cell parameter of a material, \( E \) is the Young’s modulus of a material, and \( \sigma \) is the stress.

Figure 1. Samples welded by electron beam welding. The left side is copper, right - steel.

Slika 1. Uzorci zavareni elektronskim snopom. Leva strana je bakar, desna - čelik.

A scheme of the experimental design for determining internal stresses in a bulk object is presented in Fig. 1. Incident and scattered (at angles \( 2\theta = \pm 90^\circ \)) neutron beams are limited by diaphragms forming gauge volume in investigated specimen. Measurement of neutron diffraction spectra by \( \pm 90^\circ \) detectors (Fig. 2) allows simultaneous determination of strains in two mutually perpendicular directions. The strain is measured in the direction parallel to the neutron scattering vector \( Q \) (Q1 and Q2). The specimen region under study is scanned using the gauge volume by moving the specimen in the required directions.

The incident beam is usually formed using cadmium or boron nitride diaphragms with characteristic sizes from 0.5–1 mm to several cm depending on the purpose of the experiment. To define a gauge volume of optimum shape in the studied specimen, at the scattered beam radial Soller collimators with many (about several tens) vertical slits formed by Mylar films with gadolinium

Šema eksperimentalnog koncepta za određivanje unutrašnjih napona u objektu prikazana je na Sl. 1. Upadajući i raspršeni (pod uglom \( 2\theta = \pm 90^\circ \)) snopovi neutron, ograničeni su dijafragmama koje formiraju merač zapremine u ispitivanom uzorku. Merenje spektra difrakcije neutrova pomoću detektora \( \pm 90^\circ \) (Sl. 2) omogućava istovremeno određivanje deformacija u dva međusobno normalna pravca. Napon se meri u pravcu paralelnom vektoru raspršivanja neutrona \( Q \) (Q1 i Q2). Područje uzorka koje se proučava, skenira se pomoću merača zapremine pomeranjem uzoka u traženim pravcima.

Upadni snop obično se formira pomoću dijafragmi od kadmiijuma ili bora ili bor-nitrida, karakterističnih veličina od 0,5-1 mm do nekoliko cm, zavisno od svrhe eksperimenta. Da bi se definisala zapremina merača optimalnog oblika u ispitivanom uzorku, često se koristi rasut snop uz radijalne kolimatore sa mnogo (oko nekoliko desetina) vertikalnih proreza oblikovanih Milar filmovima sa premazom gadolinijum oksida. Radijalni Soller kolimator
oxide coating are often used. A radial Soller collimator is placed at a sufficiently large (at least 150–250 mm) fixed distance from the specimen and provides high spatial resolution along the incident neutron beam direction (0.5–2 mm).

Figure 2. Schematic of the experimental design for determining internal stresses in a bulk object. Incident and scattered (at angles 2θ = ±90°) neutron beams are restricted by diaphragms shaping a gauge volume within the specimen. Measurement of neutron diffraction patterns by ±90° detectors allows simultaneous determination of strains in two mutually perpendicular directions.

Slika 2. Šema eksperimentalnog koncepta za određivanje unutrašnjih napona u rasutom objektu. Upadni i raspršeni (pod uglom 2θ = ± 90 °) neutronski zraci ograničeni su dijafragmama koje oblikuju merač zapremine unutar uzorka. Merenje uzoraka difrakcije neutrona detektorom od ± 90 ° omogućava istovremeno određivanje deformacija u dva međusobno normalna pravca.

Figure 3. Part of the diffraction spectrum of the α-Fe reference specimen, measured on the FSD neutron diffractometer in the high-resolution mode using 90°-detector. The experimental points, the profile curve calculated by the Rietveld method and difference curve are shown. Bars indicate diffraction peak positions.

Slika 3. Deo difrakcionog spektra referentnog uzorka α-Fe, mereno na FSD neutronskom difrakterometru u režimu visoke rezolucije, korišćenjem detektora 90 °. Prikazane su eksperimentalne tačke, kriva profila izračunata Rietveld-ovom metodom i kriva razlika. Trake označavaju pozicije vrha difrakcije

The principle of the determination of the lattice strain is rather simple and it is based on the Bragg's law

\[ 2d_{hkl} \sin \theta = \lambda \] (2)

where \( \lambda \) is the neutron wavelength, \( d_{hkl} \) is the interplanar spacing, and \( \theta \) is the Bragg angle. The neutron diffraction method is very similar to the X-ray technique. However, in contrast to the characteristic X-ray radiation the energy spectrum of thermal neutrons has a continuous character (Maxwellian distribution). The velocity of thermal neutrons is rather small and this gives the

Princip određivanja deformacije rešetke je prilično jednostavan i zasnovan je na Braggovom zakonu

\[ 2d_{hkl} \sin \theta = \lambda \] (2)

gde \( \lambda \) je talasna dužina neutrona, \( d_{hkl} \) je interplanarni razmak, a \( \theta \) je Bragg-ov ugao. Metoda difrakcije neutrona veoma je slična tehničkim rendgenskim zrakom. Međutim, za razliku od karakterističnog rendgenskog zračenja, energetski spektar toplotnih neutrona ima kontinuirani karakter (Makvellian distribucija). Brzina toplotnih neutrona je prilično mala i ovo daje priliku da se analizira
opportunity to analyse the neutron energy using it's time of flight during the experiment at a pulsed neutron source. When using TOF diffraction method at a pulsed neutron source, the strain is determined by the relative change in the neutron time of flight $\Delta t/t$. Depending on the neutron wavelength, the peak position on the time scale is defined by the condition [see 3]:

$$t = \frac{L}{v} = \frac{2mL\sin \theta}{h}$$

(3)

where $L$ is the total flight distance from a neutron source to the detector, $v$ is the neutron velocity, $m$ is the neutron mass, $h$ is Planck's constant, $dhkl$ is the interplanar spacing, and $\theta$ is the Bragg angle.

Therefore, in case of TOF neutron diffraction the lattice strain is determined as

$$\varepsilon_{\text{lattice}} = \frac{d_{\text{hkl}} - d_{\text{hkl}}^0}{d_{\text{hkl}}^0} = \frac{\Delta d}{d}$$

(4)

where $d_{\text{hkl}}$ and $d_{\text{hkl}}^0$ are the interplanar spacing for strained and unstrained lattices, and $t$ is the neutron time of flight.

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 [5]. This is especially convenient to do that using a TOF diffractometer with the functional dependence of the peak width on the interplanar spacing [7].

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

(1)

where $W$ is the peak width, $C_1$ and $C_2$ are the constants defining the diffractometer resolution function and known from measurements with a reference specimen, $C_3=(\Delta a/a)2$ is the unit cell parameter dispersion (microstrain), and $C_4$ is the constant related to the crystallite size.

3. Experiment

TOF neutron diffraction study of residual stresses in welded specimens was performed on FSD Fourier diffractometer [6, 7] at fast pulsed IBR-2 reactor in FLNP JINR, Dubna, Russia. FSD diffractometer is dedicated for residual stress studies in bulk industrial components and new advanced materials. A special correlation technique - a fast Fourier chopper for the primary neutron beam intensity modulation and the RTOF method for data acquisition - makes it possible to obtain high resolution neutron diffraction spectra $\Delta d/d = 2×4×10^{-3}$.

During the experiment on the FSD neutron diffractometer a small scattering volume (gauge volume) of the size of 2x2x24 mm for EBW specimen were defined using radial collimators in front of the 90° detectors (Fig. 4). The specimens were scanned across weld regions along middle energy, neutron, koristeći vreme leta tokom eksperimenta na impulsnom izvoru neutrona. Kada se koristi difrakcija metoda TOF na izvoru impulsa neutrona, naprejanje se određuje relativnom promenom vremena leta neutrona $\Delta t/t$. Zavisno od talasne dužine neutrona, položaj vrha na vremenskoj skali je definiran uslovom (vidi 3):

$$t = \frac{L}{v} = \frac{2mL\sin \theta}{h}$$

(3)

gde je $L$ ukupna dužina leta od izvora neutrona do detektora, $v$ je brzina neutrona, $\lambda$ je talasna dužina neutrona, $m$ je masa neutrona, $h$ je Plankova konstanta, $dhkl$ je interplanarni razmak, a $\theta$ je Bragg-ov ugao.

Zbog toga se u slučaju TOF difracije neutrona, deformacija rešetke određuje kao

$$\varepsilon_{\text{mi}} = \frac{d_{\text{hkl}} - d_{\text{hkl}}^0}{d_{\text{hkl}}^0} = \frac{\Delta d}{d}$$

(4)

gde su $d_{\text{hkl}}$ i $d_{\text{hkl}}^0$ interplanarni razmak za deformisane i nedeformisane rešetke, a $t$ je vreme leta neutrona.

Analiza oblika (širina u najjednostavnijem slučaju) difrakcionih vrhova može dati informacije o izobiljenjima rešetki u pojedinim zrnima (mikrodeformacija) i njihovim veličinama [5]. Ovo je posebno pogodno za korišćenje TOF-ovog difraktometra sa funkcionalnom zavisnošću širine vrha od interplanarnog razmaka [7].

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

(2)

gde je $W$ širina vrha, $C_1$ i $C_2$ su konstante koje definišu funkciju razlučivanja difraktometra i poznate su iz merenja sa referentnim uzorkom, $C_3=(\Delta a/a)2$ je disperzija parametara jedinične ćelije (mikrodeformacija), a $C_4$ je konstanta povezana sa veličinom kristalita.

3. Eksperiment

Studija o zaostalim naponima TOF difrakcijom neutrona na zavarenim uzorcima izvedena je na FSD Fourier-ovom difraktometru [6, 7], na brzo pulzirajućem IBR-2 reaktoru u FLNP JINR, Dubna, Rusija. FSD difraktometar namenjen je studijama zaostalih naprezanja u različitim industrijskim komponentama i novim naprednim materijalima. Specijalna tehnika korelacije - brza Fourierova sekalica za modulaciju intenziteta primarnog snopa neutrona i RTOF metoda za prikupljanje podataka - omogućava dobijanje spektra difracije neutrona $\Delta d/d = 2×4×10^{-3}$ visoke rezolucije.

Tokom eksperimenta na FSD neutronskom difraktometru, određeni su mali volumeni raspršivanja (zapreminska vrednost) veličine 2x2x24 mm za EBW uzorak pomoću radijalnih kolimatora ispred detektora od 90° (Sl. 4). Uzorci su skenirani na području šava duž srednje linije line of
the specimen thickness. Orienting a specimen in a certain way, the main components of residual strain in three mutual perpendicular directions (with respect to the direction of the neutron scattering vector Q) were measured.

4. Results
Copper and steel have very different mechanical and physical properties. These features exerted a great influence on the stress distribution in the welded samples. The stress diagrams clearly show the difference between the two materials Fig. 5-6. The residual stresses in copper do not exceed 100 MPa in both samples. The maximum stresses can be seen in the steel zone of thermal impact in the X component. The first sample has lower stresses in the Z component than second sample. The residual stresses in the Y component in both cases are small, do not exceed 100 MPa.

4. Rezultati
Bakar i čelik imaju veoma različita mehanička i fizička svojstva. Ove karakteristike imale su veliki uticaj na raspodelu napona u zavarenim uzorcima. Dijagram naprezanja jasno pokazuje razliku između dva materijala Sl. 5-6. Preostali naponi u bakru ne prelaze 100 MPa u oba uzorka. Maksimalni naponi se primećuju u zoni uticaja topote na čeliku u X komponenti. Prvi uzorak ima niža naprezanja u komponenti Z u odnosu na drugi uzorak. Preostali naponi u Y komponenti u oba slučaja su mali, ne prelaze 100 MPa.
Analysis of the widths of the peaks made it possible to obtain information on microstrains in the samples (Fig. 7-8). The level of microstrains in the first sample is slightly higher than in the second. The discrepancy in the components far from welding indicates the presence of microstrains in the starting material.

Analiza širina vrhova omogućila je dobijanje podataka o mikrodeformacijama u uzorcima (slika 7-8). Nivo mikrodeformacija u prvom uzorku je neznatno viši nego u drugom. Nesklad u komponentama daleko od mesta zavarivanja ukazuje na prisustvo mikrodeformacija u početnom materijalu.

**Figure 6.** Residual stress in the studied EBW specimen No. 2. ($I = 60 \text{ mA}$)

**Slika 6.** Zaostlai naponi na proučavanom uzorku EWB Br. 2. ($I = 60 \text{ mA}$)

**Figure 7.** Residual microstrain in the studied specimen No. 1. ($I = 50 \text{ mA}$)

**Slika 7.** Zaostali naponi na proučavanom uzorku Br. 1. ($I = 50 \text{ mA}$)

**Figure 8.** Residual microstrain in the studied specimen No. 2. ($I = 60 \text{ mA}$)

**Slika 8.** Zaostali naponi na proučavanom uzorku Br. 2. ($I = 60 \text{ mA}$)
5. Conclusions
The residual stresses in dissimilar joints between copper and stainless steel 304 welded by electron beam at different beam current were investigated. Copper and steel have very different mechanical and physical properties. These features exerted a great influence on the stress distribution in the welded samples. The residual stresses in copper do not exceed 100 MPa in both samples. The maximum stresses can be seen in the steel zone of thermal impact in the X component – 450 MPa. The higher the beam current is, the higher the residual stresses are.

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References

[1] V. Michailov, V. Karkhin, P. Petrov “Principles of welding” Peter the Great St. Petersburg State Polytechnic University, 2016, 256p.
[2] Lindgren L.E., “Numerical modelling of welding”, Comput. Methods Appl. Mech. Eng., Vol. 195, Issue 48-49, pp. 6710-6736, 2006
[3] Turna M., Sahul M., Ondruska J and Lokaj J., “Electron beam welding of copper to stainless steel” Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, Volume 22, No.1
[4] Allen A.J., Hutchings M.T., Windsor C.G., “Neutron diffraction methods for the study of residual stress fields”, Advances in Physics, Vol. 34, No. 4, pp. 445-473, 1985
[5] Mittemeijer E.J., Welzel U., “The 'state of the art' of the diffraction analysis of crystallite size and lattice strain”, Z. Kristallogr., Vol. 223, pp. 552-560, 2008
[6] Bokuchava G.D., Aksenov V.L., Balagurov A.M. et al. “Neutron Fourier diffractometer FSD for internal stress analysis: first results”, Applied Physics A: Materials Science & Processing, Vol.74 [Suppl1], pp. 86-88, 2002
[7] Bokuchava G.D., Balagurov A.M., Sumin V.V., Papushkin I.V., “Neutron Fourier diffractometer FSD for residual stress studies in materials and industrial components”, Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques, Vol. 4, No. 6, pp. 879-890, 2010