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

Ispitivanje zaostalih napona u raznorodnom spoju bakar-čelik zavarenom elektronskim snopom

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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.

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.

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Key words: electron beam welding, dissimilar joints, neutron diffraction, residual stresses, microstrains

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. Zavarena su dva uzorka sa različitom strujom snopa. Zaostali naponi su mereni TOF metodom difrakcije na izvoru pulsirajućih neutrona. Deformacija se određuje relativnom promenom vremena proticanja neutrona. 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. 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 garantuje 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 aluminium. 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

Nakon zavarivanja elektronskim snopom (EBW) nastaju zaostali naponi i deformacije u zavarenom spoju i u zoni uticaja toplote (HAZ-ZUT) [1,2] kao rezultat različitih skupljanja koje nastaju kada metal šava očvrstne i ohladi se do temperature okoline. Zaostali naponi značajno utiču na strukturu i čvrstoću zavarenog spoja [3], a samim tim i na životni vek krajnjeg proizvoda. Zbog toga je potrebno kontrolisati njihov nivo i prostornu raspodelu nakon zavarivanja.

Već više godina se proučavaju zaostali naponi u materijalima korišćenjem različitih tehnika bez razaranja: difrakcije rendgenskih zraka, ultrazvučnog skeniranja i različitih magnetnih tehnika (merenja magnetne indukcije, permeabilnosti, anizotropije, Barkhausenovog efekta, magnetno-akustičkih efekata). Međutim, sve ove metode imaju određena ograničenja. Na primer, pomoću rasipanja rendgenskih zraka i magnetnih metoda, samo mali naponi u blizini površine materijala, se mogu proučavati zbog njihove male dubine prodiranja; primena magnetnih metoda ograničena je na feromagnetne materijale. Šta više, tekstura uzorka ima značajan uticaj na rezultate dobijene magnetnim i ultrazvučnim metodama. Među ovim tehnikama, kod ispitivanja zaostalih napona, difrakcija neutrona ima posebno mesto, jer za razliku od konvencionalnih metoda, neutroni mogu prodirati kroz materijale do dubine od 2 do 3 cm za čelik i do 10 cm za aluminijum. Ostale važne prednosti tehnike difrakcije neutrona su visoka prostorna rezolucija, primenljivost za višefazne materijale, nerazorni karakter metode, mogućnost karakterizacije mikrostrukture materijala i oštećenja (mikrodeformacije, koherentno rasipanje veličine kristalita, gustina dislokacija itd.).

Glavni cilj trenutnog istraživačkog rada bilo je eksperimentalno određivanje raspodele zaostalih napona u ravnim čeličnim i bakarnim limovima zavarenim EBW postupkom, pomoću difrakcije neutrona visoke rezolucije.

U ovom radu smo istražili zaostale napone u različitim spojevima između bakra i nerđajućeg čelika tipa 304, zavarenih elektronskim snopom, pri različitim jačinama snopa. Dva identična uzorka (slika 1) dimenzija 50x40x10 mm zavarena su u Institutu za elektroniku Bugarske akademije nauka (Sofija, Bugarska) pomoću Leybold Heraeus jedinice za zavarivanje. Uzorci su pripremljeni brzinom zavarivanja od 1 cm / s i $U = 55$ kV. Prvi uzorak je pripremljen sa strujom $I = 50$ mA, drugi - $I = 60$ mA.

Metoda difrakcije neutrona korišćena je za određivanje raspodele zaostalih napona u oba uzorka. Eksperimenti sa neutronima izvedeni su na



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],

$$\frac{(d_{\text{exp}} - d_0)}{d_0} = \frac{\Delta a}{a} \approx \frac{\sigma}{E} \quad (1)$$

where d_{exp} is the measured interplanar spacing, d_0 is the same interplanar spacing in a specimen without internal stresses, $\Delta a/a_0$ 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 σ is the stress.

FSD difraktometru na impulsnom reaktoru IBR-2 u Frank laboratoriji za fiziku neutrona, Institut za nuklearna istraživanja, Dubna, Ruska Federacija.

2. Metoda

Unutrašnja naprežanja koja postoje u materijalu izazivaju odgovarajuće naprežanje rešetki, što zauzvrat dovodi do pomeranja Bragg-ovih vrhova u difrakcionom spektru. Ovo daje direktne informacije o promenama interplanarnog rastojanja u zapremini merača, koje se lako mogu transformisati u podatke o unutrašnjim naponima, koristeći poznate elastične konstante materijala [4],

$$\frac{(d_{\text{exp}} - d_0)}{d_0} = \frac{\Delta a}{a} \approx \frac{\sigma}{E} \quad (1)$$

gde je d_{exp} izmereni interplanarni razmak, d_0 je isti međuplanarni razmak u uzorku bez unutrašnjih naprežanja, $\Delta a/a_0$ je naprežanje kao relativna promena parametra jedinične ćelije materijala, E je Jungov modul materijala, i σ je napon.

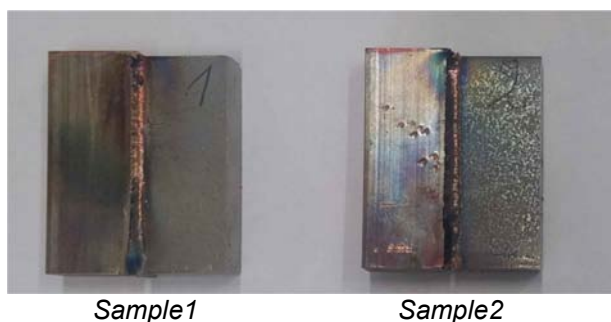


Figure 1. Samples welded by electron beam welding. The left side is copper, right - steel.
Slika 1. Uzorci zavareni elektronskim snopom. Leva strana je bakar, desna - čelik.

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 (Q_1 and Q_2). 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 merače zapremine u ispitivanom uzorku. Merenje spektra difrakcije neutrona 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 (Q_1 i Q_2). Područje uzorka koje se proučava, skenira se pomoću merača zapremine pomeranjem uzorka u traženim pravcima.

Upadni snop obično se formira pomoću dijafragmi od kadmijuma 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 rasuti 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).

postavljen je na dovoljno velikoj (najmanje 150–250 mm) fiksnoj udaljenosti od uzorka i pruža veliku prostornu rezoluciju duž pravca upadajućeg neutronskog snopa (0,5–2 mm).

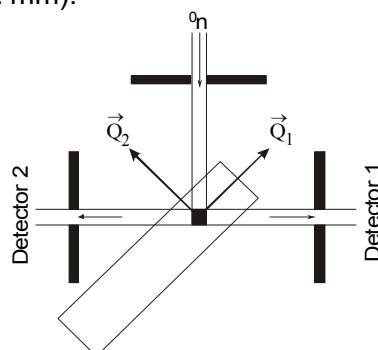


Figure 2. Schematic of the experimental design for determining internal stresses in a bulk object. Incident and scattered (at angles $2\theta = \pm 90^\circ$) neutron beams are restricted by diaphragms shaping a gauge volume within the specimen. Measurement of neutron diffraction patterns by $\pm 90^\circ$ 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 $2\theta = \pm 90^\circ$) neutronski zraci ograničeni su dijafragmama koje oblikuju merač zapremine unutar uzorka. Merenje uzoraka difrakcije neutrona detektorom od $\pm 90^\circ$ omogućava istovremeno određivanje deformacijaa u dva međusobno normalna pravca.

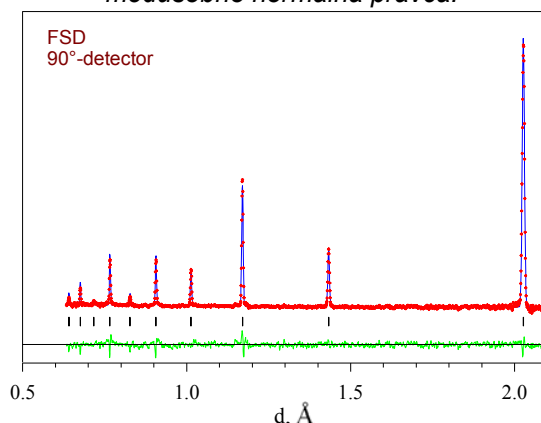


Figure 3. Part of the diffraction spectrum of the α -Fe reference specimen, measured on the FSD neutron diffractometer in the high-resolution mode using 90° -detector. The experimental points, the profile curve calculated by the Rietveld method and difference curve are shown. Bars indicate diffraction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

$$2d_{hkl} \sin \theta = \lambda \quad (2)$$

where λ is the neutron wavelength, d_{hkl} is the interplanar spacing, and θ 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

$$2d_{hkl} \sin \theta = \lambda \quad (2)$$

gde je λ talasna dužina neutrona, d_{hkl} je interplanarni razmak, a θ je Bragg-ov ugao. Metoda difrakcije neutrona veoma je slična tehnicu rendgenskih zraka. 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 its 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]:

$$t = \frac{L}{v} = \frac{\lambda mL}{h} = \frac{2mLd_{hkl} \sin \theta}{h} \quad (3)$$

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

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

$$\varepsilon_{hkl} = \frac{(d_{hkl} - d_{hkl}^0)}{d_{hkl}^0} = \frac{\Delta t}{t} \quad (4)$$

where d_{hkl} and d_{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],

$$W^2 = C_1 + C_2 d^2 + C_3 d^2 + C_4 d^4 \quad (1)$$

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 $\Delta d/d \approx 2 \div 4 \times 10^{-3}$.

During the experiment on the FSD neutron diffractometer a small scattering volume (gauge volume) of the size of $2 \times 2 \times 24$ 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

energija neutron, koristeći vreme leta tokom eksperimenta na impulsnom izvoru neutrona. Kada se koristi difrakciona metoda TOF na izvoru impulsa neutrona, naprežanje se određuje relativnom promenom vremena leta neutrona $\Delta t/t$. Zavisno od talasne dužine neutrona, položaj vrha na vremenskoj skali je definisan uslovom (vidi 3):

$$t = \frac{L}{v} = \frac{\lambda mL}{h} = \frac{2mLd_{hkl} \sin \theta}{h} \quad (3)$$

gde je L ukupna dužina leta od izvora neutrona do detektora, v je brzina neutrona, λ je talasna dužina neutrona, m je masa neutrona, h je Plankova konstanta, d_{hkl} je interplanarni razmak, a θ je Bragg-ov ugao

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

$$\varepsilon_{hkl} = \frac{(d_{hkl} - d_{hkl}^0)}{d_{hkl}^0} = \frac{\Delta t}{t} \quad (4)$$

gde su d_{hkl} i d_{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 izobličenjima rešetke 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],

$$W^2 = C_1 + C_2 d^2 + C_3 d^2 + C_4 d^4 \quad (2)$$

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 naprežanja u različitim industrijskim komponentama i novim naprednim materijalima. Specijalna tehnika korelacije - brza Fourierov-a seckalica za modulaciju intenziteta primarnog snopa neutrona i RTOF metoda za prikupljanje podataka - omogućava dobijanje spektra difrakcije neutrona $\Delta d/d \approx 2 \div 4 \times 10^{-3}$ visoke rezolucije.

Tokom eksperimenta na FSD neutronsom difraktometru, određeni su mali volumeni raspršivanja (zapreminska vrednost) veličine $2 \times 2 \times 24$ mm za EBW uzorak pomoću radialnih 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.

debljine uzorka. Orijentišući uzorak na određeni način, merene su glavne komponente zaostalog naprezanja u tri međusobno normalna smera (u odnosu na smer vektora raspršivanja neutrona Q).

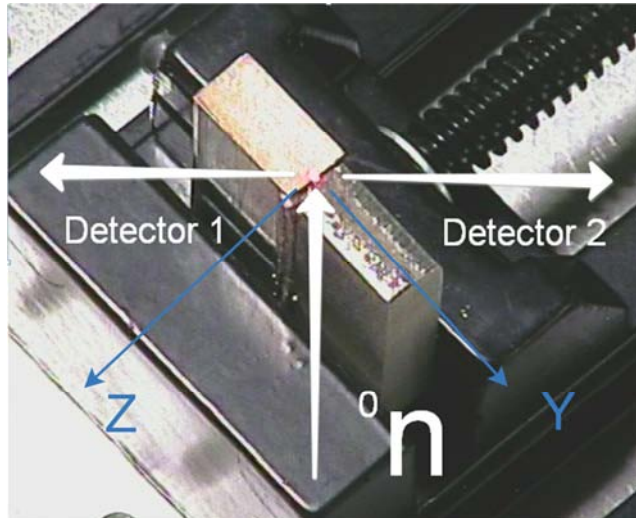


Figure 4. Photograph of the sample during the experiment on the FSD instrument.
Slika 4. Fotografija uzorka tokom eksperimenta na FSD instrumentu.

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 toplote 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.

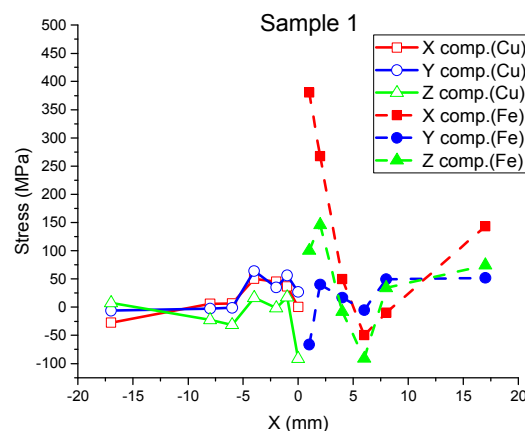


Figure 5. Residual stress in the studied EBW specimen No. 1. ($I = 50$ mA)
Slika 5. Zaostali naponi na proučavanom uzorku EWB Br. 1. ($I = 50$ mA)



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.

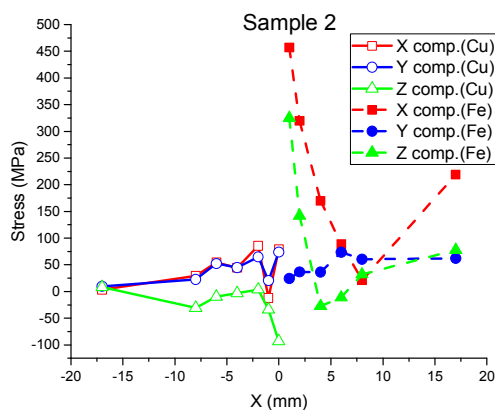


Figure 6. Residual stress in the studied EBW specimen No. 2. ($I = 60 \text{ mA}$)
Slika 6. Zaostali naponi na proučavanom uzorku EWB Br. 2. ($I = 60 \text{ mA}$)

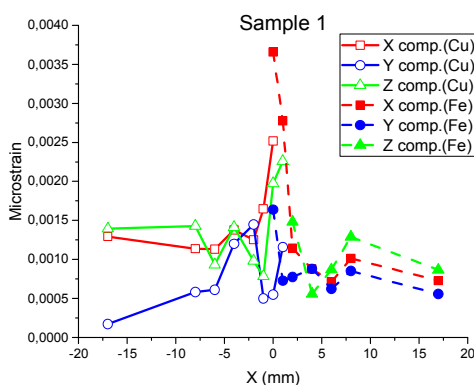


Figure 7. Residual microstrain in the studied specimen No. 1. ($I = 50 \text{ mA}$)
Slika 7. Zaostali naponi na proučavanom uzorku Br. 1. ($I = 50 \text{ mA}$)

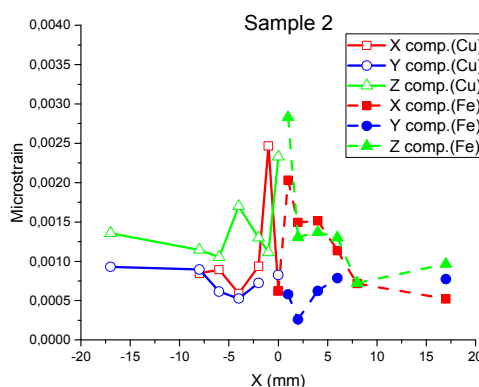


Figure 8. Residual microstrain in the studied specimen No. 2. ($I = 60 \text{ mA}$)
Slika 8. Zaostali naponi na proučavanom uzorku Br. 2. ($I = 60 \text{ mA}$)



Microstrains grow in the region of thermal influence in the X and Y component of copper and the X component of steel. Z components also vary in both materials, but less than in other components. Microstrains in the second sample differ significantly from the first. Z component practically does not change. The X component in the welding location has a dip almost to zero.

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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Mikrodeformacije rastu u području toplotnog uticaja u komponentama X i Y kod bakra i X komponenti kod čelika. Z komponente se takođe razlikuju u oba materijala, ali manje nego u ostalim komponentama. Mikrodeformacije u drugom uzorku značajno se razlikuju od prvog. Z komponenta se praktično ne menja. X komponenta na mestu zavarivanja ima pad skoro do nule.

5. Zaključci

Istraživani su zaostali naponi u različitim spojevima između bakra i nehrđajućeg čelika tipa 304 zavarenih elektronskim snopom pri različitim strujama snopa. Bakar i čelik imaju veoma različita mehanička i fizička svojstva. Ove karakteristike imale su veliki uticaj na raspodelu napona u zavarenim uzorcima. Preostali naponi u bakaru ne prelaze 100 MPa u oba uzorka. Maksimalni naponi se primećuju u zoni toplotnog uticaja kod čelika u X komponenti - 450 MPa. Što je veća struja snopa, veći su zaostali naponi.

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