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Acceptability of Residual Stresses Measurement Methods of Butt Weldments and Repairs

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The joints made by fusion of materials are exposed to the influence of residual stresses induced by welding thermal cycles. Residual stresses were measured on butt welded plates made of NIOMOL 490K, before and after reparation. The objective of this paper is to compare three methods of residual stress measurement (hole-drilling method, x-ray diffraction and directional effective permeability) induced by two welding processes (Submerge Arc Welding and Transferred Ionized Molten Energy) of V-butt welded plates. The residual stresses values are higher after reparation than before reparation of welded joints.

Keywords

Residual stresses
Residual stresses measurement
SAW welding
Stress distribution
T.I.M.E. welding

Ključne riječi

Mjerenje zaostalih naprezanja
Raspodjela zaostalih naprezanja
T.I.M.E. zavarivanje
Zaostala naprezanja
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Prihvatljivost različitih metoda za mjerenje zaostalih naprezanja na sučeonim zavarenim spojevima i reparaturama

Izvornoznanstveni članak

Spojevi koji su zavareni taljenjem materijala izloženi su zaostalim naprezanjima, koja nastaju zbog toplinskog ciklusa zavarivanja. Zaostala naprezanja su mjerena na sučeonim zavarenim pločama iz čelika NIOMOL 490 K, prije i poslije reparature. Cilj ovog rada je usporediti tri različite metode za mjerenje zaostalih naprezanja (metoda bušenja rupice, metoda rendgenske difrakcije i metoda usmjerene efektivne permeabilnosti) na V – sučeono zavarenim spojevima zavarenim s dva različita postupka (zavarivanje pod praškom i Transferred Ionized Molten Energy). Vrijednosti zaostalih naprezanja na zavarenim spojevima poslije reparature su veće nego prije reparature.

1. Introduction

Nowadays, there are no industrial structures without welds and no welds without damage risks. One of the main damage causes is the welding residual stress. For the design and fabrication of stable welded structures, the effects of residual stresses need to be estimated. The welded joints may have complex shapes, and the welding residual stresses also have complex three-dimensional distributions.

Welding residual stresses have an effect on many aspects of the integrity of structures but are normally one of the largest unknown stresses; they are difficult to measure and to estimate theoretically but are often significant when compared with the service stresses on which they superimpose. High tensile residual stresses can reach yield strength of the material and therefore lead to loss of performance in corrosion, fatigue and fracture.

Examples given in this paper are of residual stress distributions in plate butt welds.

The plates are made of micro-alloyed steel NIOMOL 490K and are welded by SAW welding method and also by high productive MAG process-the Transferred Ionized Molten Energy (T.I.M.E.). After

Symbols/Oznake

α	- angle of the principal stresses direction, ° - pravac djelovanja glavnih naprezanja
$\varepsilon_i(z)$	- strains in strain gauges, μm/m - deformacije u mjernim trakama
λ	- X-ray of wavelength, μm - valna duljina rendgenskih zraka
σ_1, σ_2	- surface principal residual stresses, MPa - glavna zaostala naprezanja na površini
θ	- diffraction angle at X-ray diffraction method, ° - difrakcijski kut kod rendgenske difrakcijske metode
A, B	- calibration coefficients at hole drilling method - kalibracijski koeficijenti kod metode bušenja
A_5	- elongation, % - izduženje
d	- atomic inter-planar spacing, μm - udaljenost između atomskih ravnina
E	- Young modulus, MPa - Youngov modul elastičnosti, MPa
R_m	- ultimate tensile strength, MPa - rastezna čvrstoća
R_{p02}	- yield stress, MPa - granica tečenja

welding, the residual stresses were measured using three different methods. The most appropriate method for this example was used on repaired welded joint.

2. Review of several measurement methods of residual stresses

A measurement of residual stresses is expensive and takes time. Main methods for characterization of residual stresses in industrial engineering structures are: (1) strain gauging, (2) diffraction, (3) acoustic and (4) magnetic. Before deciding which method is the most appropriate, it is important to consider the advantages and limitations of those techniques.

The application of the measurement techniques depends on: the kind of residual stresses (first, second, third and fourth), material properties and manufacture, structural geometry [1], fabrication procedure, welding procedure, post weld treatments, speed and cost of measurements, accuracy of method, sensitivity of method, portability of equipment, ability to operate in confined spaces etc, [2].

The objective of this paper is to compare three measurement methods of residual stresses induced by two welding processes of V-butt welded plates:

1. Hole-drilling method (HD)
2. X-ray diffraction (XRD) and
3. Directional effective permeability (DEP).

The hole-drilling method is a semi-destructive technique with a small to negligible effect on the components in which the stresses are measured. HD method is one of strain gauge techniques so called stress relief technique where the residual stress is relieved by the removal of the material.

It represents a surface measurement method applicable to most materials by drilling blind holes and measuring the residual stresses of isotropic, linear-elastic materials, [3]. Although this quantitative method is used mainly on flat machine parts it can be used also for grooves and welds [4].

The residual principal stresses depending on hole depth z, $\sigma_1(z)$ and $\sigma_2(z)$, can be calculated from equations involving measured values of strains, $\varepsilon_i(z)$, and the calibrated correlation coefficients obtained for each depth increment. These coefficients depend of the hole geometry (diameter and depth), strain gauge location and material properties. Their calibration is developed by several authors [5].

X-ray diffraction is the most widely used non-destructive method for evaluating residual stresses. It allows the study and separation of three kinds of residual stresses. This method is based on the fact that X-ray of wavelength λ strikes a polycrystalline material at an angle θ and the grains with interplanar spacing d diffract intensity at the same angle where $\lambda=2d\cdot\sin\theta$. The principal stresses σ_1 and σ_2 are obtained from the strain with formulas usually derived from linear isotropic elasticity theory [5].

Directional effective permeability technique is a magnetic technique which uses the magnetic anisotropy to measure the stress present in a magnetic material. The magnetic anisotropy induced by stress will result in the rotation of an induced magnetic field away from the direction in which it is applied. This difference in direction, so called rotation of magnetisation, is the basis of DEP technique for stress measurements. When the applied magnetic field is oriented at 45° to the tensile stress direction, the maximum rotation occurs; in the case when the magnetic field and stress axes are parallel or orthogonal, there is no rotation [5].

The comparison of used residual stresses measurements methods is shown in Table 1, while the advantages and disadvantages of these techniques are shown in Table 2.

3. Experimental work

Experimental investigations are carried out on welded joints of micro-alloyed steel NIOMOL 490 K, at room temperature. The steel was produced in the plant

Table 1. The comparison of residual stresses measurements methods [5]

Tablica 1. Usporedba različitih metoda za mjerenje zaostalih naprezanja

	Hole-drilling method / Metoda bušenja rupice (HD)	X-ray diffraction / Metoda rendgenske difrakcije (XRD)	Directional effective permeability / Metoda usmjerene permeabilnosti (DEP)
Principle of the measurement / Princip mjerenja	Strain changes caused by the hole drilling measured using standard three element rosette / Promjena deformacija uzrokovana bušenjem rupice i mjerenjem standardnom rozetom koja se sastoji od tri mjerne trake	Interplanar spacing of grains obtained from the angular spectrum of Bragg diffraction pattern / Rastojanje među ravninama atoma u zrnima dobivena iz oblika Braggovog difrakcijskog spektra	The stress induced magnetic anisotropy recorded as a function of magnetic field rotation angle / Inducirana naprezanja zbog magnetne anizotropije koja je zabilježena kao funkcija kuta rotacije magnetskog polja
Data and calibration requirements / Podaci i potrebni kalibracijski uvjeti	Calibration data for coefficients *A* and *B* which depend on Young modulus *E*, and Poisson ratio *v* and diameters of the strain gauge rosette and the drilled hole / Kalibracijski podaci za koeficijente *A* i *B* koji zavise od Youngovog modula *E*, Poissonovog faktora *v*, promjera rozete od mjernih traka i promjera izbušene rupice	Calibration required on the microstructural same material to obtain material elastic constants measured by X-ray / Nužno potrebna kalibracija na materijalu sa istom mikrostrukturom, da se dobiju elastične konstante materijala, mjerene pomoću X-zraka	Calibration required on the microstructural same material to generate calibration curves / Nužno potrebna kalibracija na istom materijalu da se naprave kalibracijske krivulje
Measured data / Izmjereni podaci	Principal residual stresses σ_1 and σ_2 / Glavna zaostala naprezanja σ_1 i σ_2 Angle of the principal stresses direction α / Kut glavnih zaostalih naprezanja α	Residual stress in measured direction / Zaostalo naprezanje u pravcu mjerenja	Difference of the residual principal stresses σ_1 - σ_2 / Razlika glavnih zaostalih naprezanja σ_1 - σ_2 Angle of the principal stresses direction α / Kut glavnih zaostalih naprezanja α
Stress measurement accuracy / Preciznost mjerenja zaostalih naprezanja	Better than ±10 MPa in the region below 70 % of the yield stress and up to 70 % of the yield stress needed additional calibration / Bolja od ±10 MPa u području ispod 70 % granice tečenja, a za područje iznad 70 % granice tečenja potrebna je dodatna kalibracija	Better than ±10 MPa in homogeneous materials, for better accuracy in heterogeneous materials is needed additional calibration / Bolja od ±10 MPa za homogen materijal, za bolju preciznost na heterogenom materijalu potrebna je dodatna kalibracija	±20 MPa with calibration / ±20 MPa s kalibracijom
Measurement depth / Dubina mjerenja	Smaller than the drilled hole diameter (i.e. 2 mm) / Manje od promjera izbušene rupice (otprilike 2 mm)	Only 0.05÷0.1 mm / Samo 0,05÷0,1 mm	Only up to 2 mm / Samo iznad 2 mm
Stress averaging area / Područje osrednjavanja naprezanja	1÷2 mm diameter and 1÷2 mm deep / 1÷2 mm promjera i 1÷2 mm u dubinu	0.1÷1 mm^2 and 0.05÷0.1 mm deep / 0,1÷1 mm^2 i 0,05÷0,1 mm u dubinu	5×5 mm
Degree of destruction / Stupanj razaranja	Semi-destructive / Polu razarajuća	Non-destructive / Bez razaranja	Non-destructive / Bez razaranja

"Železarna ACRONI", Jesenice. It has a minimum yield stress 490 MPa and guaranteed brittle transition temperature of -60 °C.

Table 2. Advantages and disadvantages of residual stresses measurement techniques [3]

Tablica 2. Prednosti i mane različitih tehnika za mjerenje zaostalih naprezanja [3]

	Advantages / Prednosti	Disadvantages / Mane
HD	- Simple / Jednostavna - Quick / Brza - Portable / Prenošljiva - Biaxial measurements / Dvoosna mjerenja	- Interpretation of data / Interpretacija rezultata - Semi-destructive / Polu razarajuća - Limited strain sensitivity and resolution / Ograničena osjetljivost na deformacije i rezolucija
XRD	- Non-destructive / Bez razaranja - Useful on wide range of materials / Upotrebljiva na različitim vrstama materijala - Biaxial measurements / Dvoosna mjerenja	- Basic measurements / Osnovna mjerenja - Surface measurements / Površinska mjerenja - Electropolishing required / Potrebno elektropoliranje
DEP	- Simple / Jednostavna - Quick / Brza - Portable / Prenošljiva	- Magnetic material only / Samo za magnetičan materijal - Calibration required / Potrebna kalibracija - Demagnetization requir. / Potrebna demagnetizacija

The investigation was conducted using a 200×200×12 mm three-pass V-butt welded plate. Keeping in mind the type of the steel (high strength micro-alloyed steel) and technical and technological regulations that need to be complied with, half of those welded plates is welded by SAW with a filled wire FILTUB 128 (wire diameter ϕ4 mm) according to A-5.23 standard and agglomerated welding flux FB TT according to EN 760 standard, all produced in the plant Elektrode Jesenice. The remaining half of plates is welded by T.I.M.E. with a NiMo 1-IG wire of diameter ϕ 1,2 mm produced by Böhler.

The chemical composition of the steel BM and the filler materials is given in Table 3. The tensile properties of the steel BM and the filler materials along with impact energy values are given in Table 4. After that we performed hardness measurements.

Three welding conditions of welded plates were examined: (1) as welded plates, (2) post weld heat treated plates (PWHT) and (3) vibrated plates during welding. On such prepared welded plates we measured their residual stresses using three methods that we already mentioned: HD, XRD and DEP. Figure 1 (a) shows measurement places on investigated plates.

After that, on a plate of the same dimensions (200×200 ×12 mm) we did the multi-pass repair welding (with seven-pass, 100 mm long welded joint), by SMAW process using consumable material EVB NiMo of chemical composition given in Table 4. Figure 1 (b) shows measurement places, position of the repair weld in the plate and its length.

We measured the hardness of the repaired welded joint and, by HD method, which showed the best results for these plates, measured the residual stresses. Both measurements were performed especially at the beginning and at the end of welded joint where we expected the highest values.

4. Results and discussion

The hardness profiles across the welded joints are given in Figure 2 for SAW and in Figure 3 for T.I.M.E. welding process for three different welding conditions (as welded, PWHT and vibrated during welding). and were measured on the weld cap, the root and WM. In welded joints performed by SAW, the hardness were higher than those in joints welded by T.I.M.E. process.

The residual stress measurements that we performed in these investigations are not mutually comparable because they give different output data.

HD and XRD methods are compared due to the longitudinal and transverse residual stress components (Figure 4 and Figure 5), while all three methods, HD, XRD and DEP, are compared due to the differential values of principal residual stresses (Figure 6 and Figure 7).

The highest residual stresses were measured in the welded condition; the stress values were close to yield stress of the base material. The heat input during welding was equal in SAW and T.I.M.E. processes. However, in welded joints performed by SAW, the residual stresses were a fraction higher than those in joints welded by T.I.M.E. process.

The most useful technique for reducing of residual stresses is PWHT. Two hours of post weld heat treatment at temperature of 580 °C relax residual stresses the best. There are some materials that do not allow such high temperature during PWHT reducing the effect of relaxation.

Plate's vibration during welding reduces residual stresses mostly in the WM and HAZ region of the welded joint. Even though the PWHT relaxation method is more effective in reducing residual stresses, there are some advantages in applying plates vibration: the

Charpy toughness of the WM and the HAZ is higher and dimension stability is better [6-8].

Measurements of the residual stresses in WM and HAZ have some specifics because of materials microstructural changes and high residual stress gradients which appeared during cooling after welding.

X-ray diffraction and DEP methods are very sensitive to microstructural changes. As such they are prone to higher errors during measurement of the residual stresses. DEP method is particularly sensitive for measuring in WM or HAZ. In order to prevent higher measurement errors, additional calibration is required utilising same material like the one being investigated.

In the region of WM and HAZ, the stress gradient is high and it affects significantly the accuracy of measurement. The smaller the measuring surface, the higher the accuracy of measurement. In order to increase precision and to decrease the noise during measurement, very small three element strain gauge rosettes are used when performing HD method of residual stress measurement.

X-ray diffraction method is not suitable for residual stress measurement of welded joints, especially in HAZ region for at least two reasons: (1) XRD is very sensitive to high stress gradients and this is why the measurement area has to be small and (2) in HAZ region, there are a lot of different microstructures so the measured area has to be bigger in order to get the signal. As those two demands are contradictory, the calibration of the instrument is obligatory to be done for almost every measuring place, which prolonged the time for measurement. That's why it is better to use another method for measuring welded joints residual stresses.

When DEP method is used in the welded joint more additional problems appear [9]. The diameter of the magnetic sensor is large in comparison with the width of the weld seam. Therefore a special calibration test on similar weld of the same material is required for every measuring place in WM and HAZ. Also, while being welded, material is becoming magnetised as a consequence of the high welding current. Demagnetization has to be performed before measurements especially in WM and HAZ region. Other two disadvantages of the DEP method are: (1) it gives only differential value of the principal residual stresses and value for the angle from the near principal stress, and (2) the DEP method is only applicable on magnetic materials.

Table 3. Chemical composition of the base metal and filler materials (weight %)

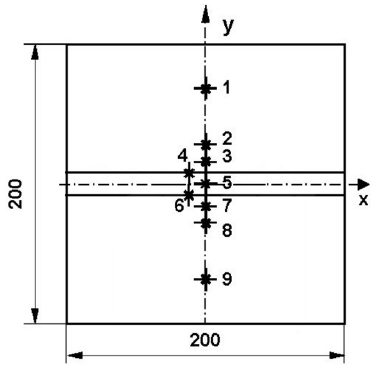
Tablica 3. Kemijski sastav osnovnog materijala i dodatnih materijala (mas. %)

Material / Materijal	C	Si	Mn	P	S	Cr	Ni	Mo	Nb
Steel base metal / Osnovni materijal	0,06	0,34	0,41	0,01	0,004	0,73	0,27	0,36	0,051
Filler / Dodatni materijal FILTUB 128	0,05	0,20	1,40	-	-	-	1,20	0,40	-
Filler / Dodatni materijal NiMo1	0,09	0,62	1,77	0,011	0,003	-	0,95	0,31	-
Filler / Dodatni materijal EVB NiMo	0,06	0,40	0,90	-	-	-	1,10	0,30	-

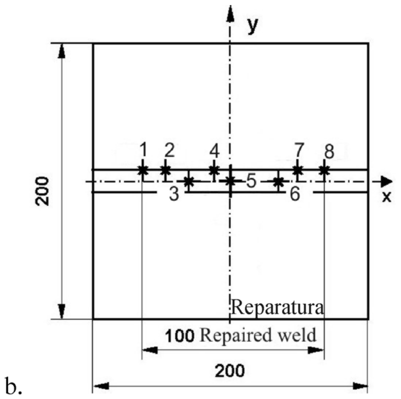
Table 4. Tensile properties of the base metal and filler materials (room temperature) and impact energy values

Tablica 4. Svojstva na zatezanje osnovnog i dodatnih materijala (pri sobnoj temperaturi) i vrijednosti Charpy energije

Material / Materijal	Direction / Smjer	Yield stress / Granica tečenja $R_{p0,2}$, MPa	Ultimate tensile strength / Rastezna čvrstoća R_m, MPa	Elongation / Istezanje A, %	Total impact energy at - 60 °C/ Ukupna energija kod Charpy ispitivanja pri - 60 °C J
Steel base metal / Osnovni materijal	L – T	544	601	23	289
Filler / Dodatni materijal FILTUB 128		>550	630-730	>20 %	>60
Filler / Dodatni materijal NiMo 1		>550	650-800	>20 %	>47
Filler / Dodatni materijal EVB NiMo		>510	580-710	>22%	>27



	x	y
1	0	-75
2	0	-30
3	0	-15
4	-10	-8
5	0	0
6	-10	8
7	0	15
8	0	30
9	0	75



	x	y
1	-50	8
2	-30	8
3	-20	0
4	- 10	8
5	0	0
6	20	0
7	30	8
8	50	8

Figure 1. Location of the residual stresses measurements on the welded plates, (a) for three different welding conditions and (b) for repair welding

Slika 1. Lokacija mjerenja zaostalih naprezanja na zavarenim pločama, (a) za tri različita stanja zavarivanja i (b) za reparaturno zavarivanje

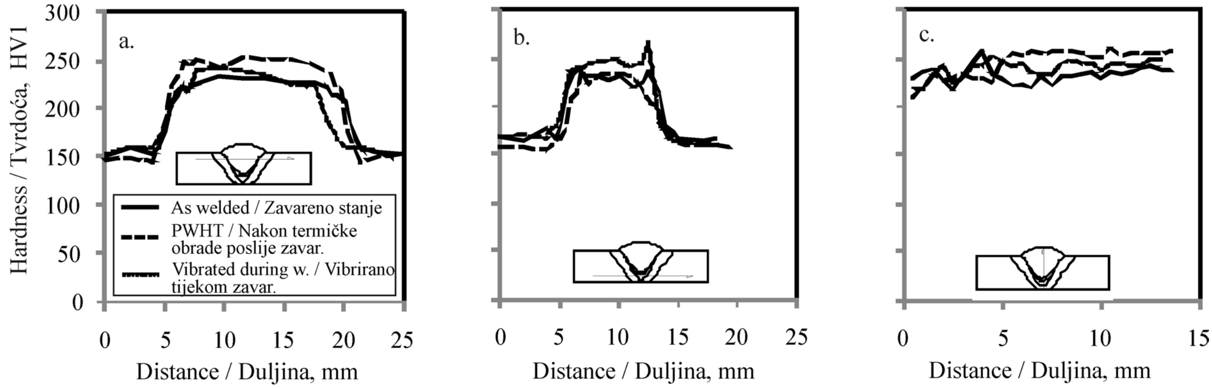


Figure 2. Comparison of Vicker's hardness profile on the SAW welded joints in three different conditions (as welded, PWHT and vibrated during welding) (a) weld cap, (b) root, (c) WM

Slika 2. Usporedba Vickersovih profila tvrdoće na spoju zavarenim pod praškom u tri različita stanja (zavareno, nakon toplinske obrade poslije zavarivanja i vibrirano tijekom zavarivanja) (a) tjeme, (b) korijen, (c) metal zavara

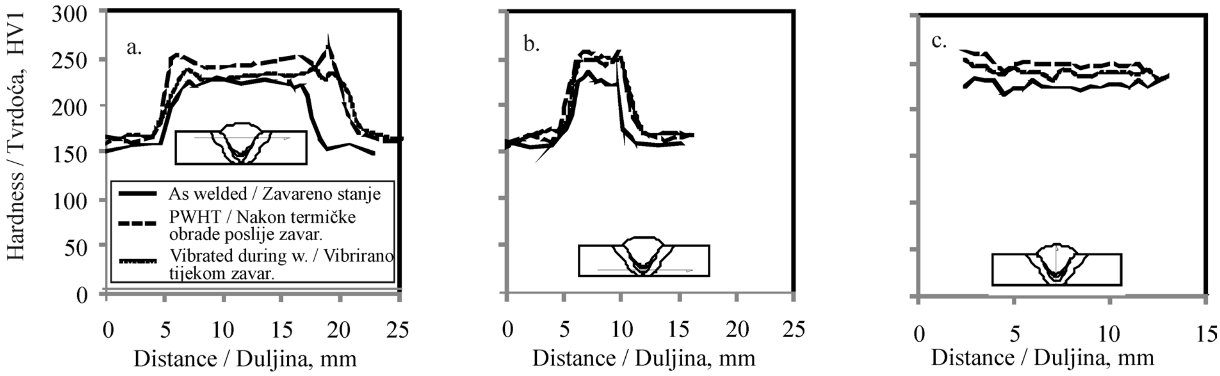


Figure 3. Comparison of Vicker's hardness profile on the T.I.M.E. welded joints in three different conditions (as welded, PWHT and vibrated during welding) (a) weld cap, (b) root, (c) WM

Slika 3. Usporedba Vickersovih profila tvrdoće na spoju zavarenim s T.I.M.E. postupkom u tri različita stanja (zavareno, nakon toplinske obrade poslije zavarivanja i vibrirano tijekom zavarivanja) (a) tjeme, (b) korijen, (c) metal zavara

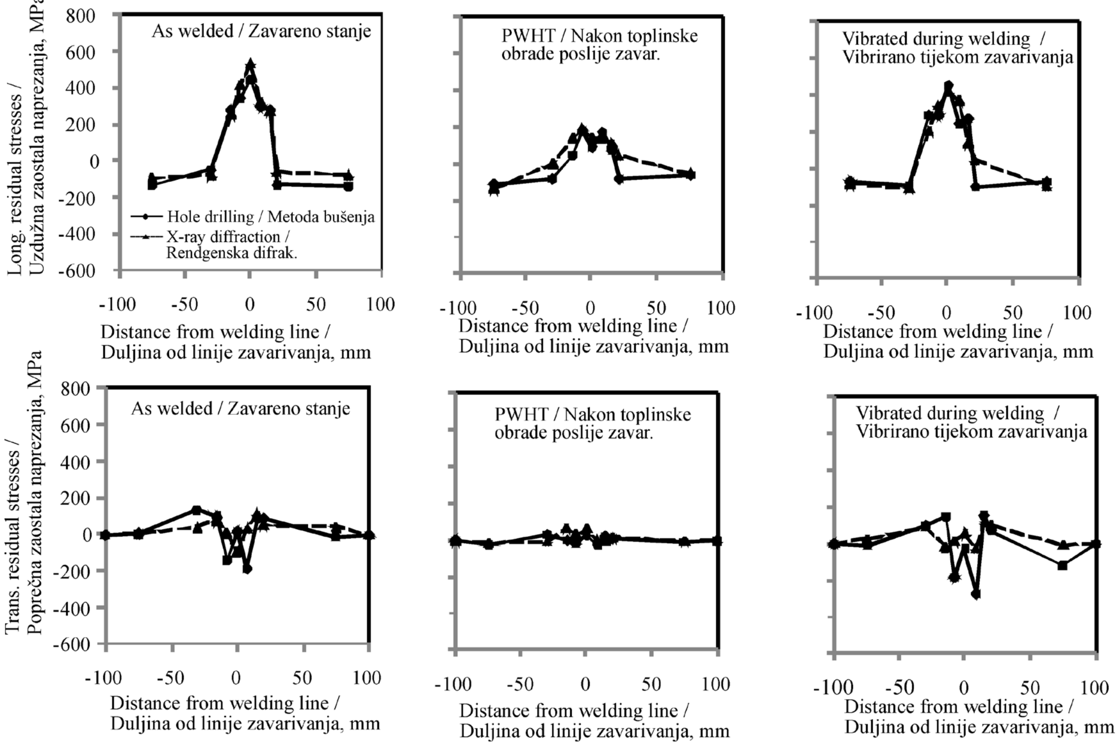


Figure 4. Comparison of the hole drilling and X-ray diffraction method using longitudinal and transverse residual stresses on the SAW welded joints in three different conditions

Slika 4. Usporedba metode bušenja rupice, metode rendgenske difrakcije na osnovi uzdužnih i poprečnih zaostalih naprezanja na zavarenom spoju zavarenom pod praškom za tri različita stanja

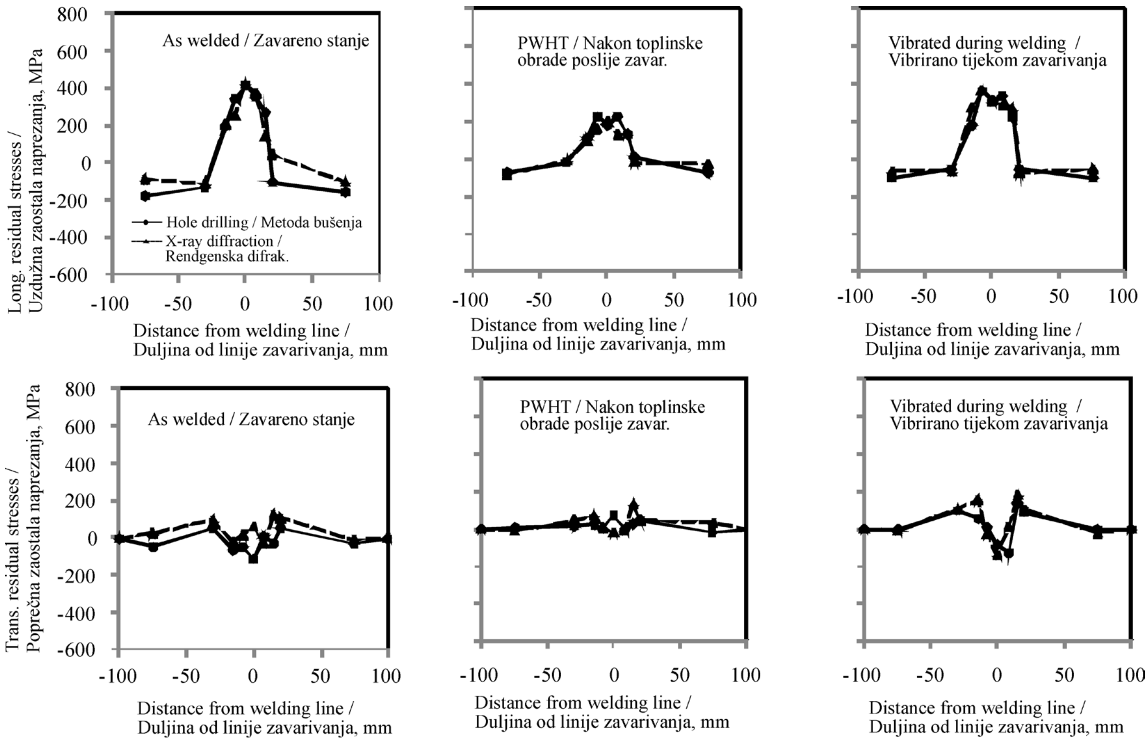


Figure 5. Comparison of the hole drilling and X-ray diffraction method using longitudinal and transverse residual stresses on the T.I.M.E. welded joints in three different conditions

Slika 5. Usporedba metode bušenja rupice, metode rendgenske difrakcije na osnovi uzdužnih i poprečnih zaostalih naprezanja na zavarenom spoju zavarenom sa T.I.M.E. postupkom za tri različita stanja

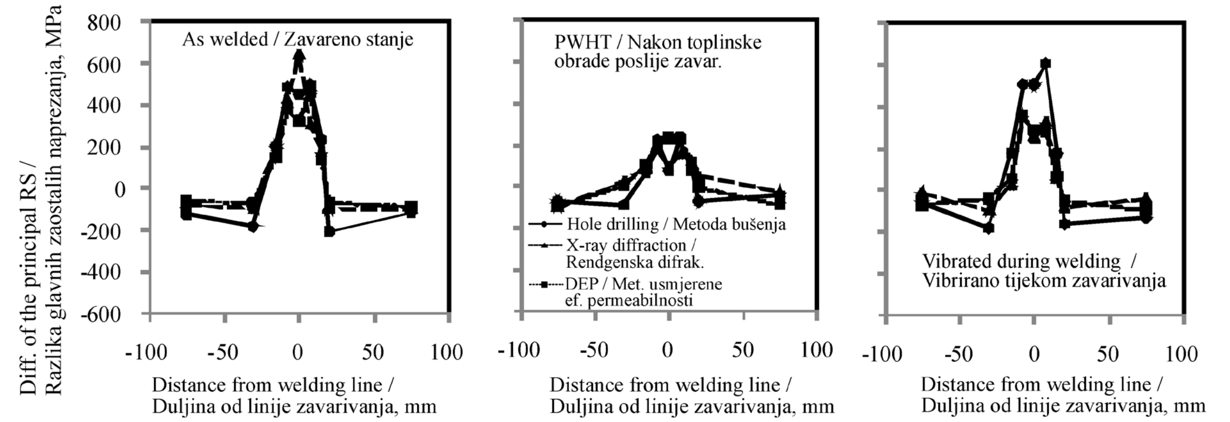


Figure 6. Comparison of the hole drilling, X-ray diffraction and DEP method using differences of the principal residual stresses on the SAW weld joints in three different conditions

Slika 6. Usporedba metoda bušenja rupice, rendgenske difrakcije i DEP na osnovu razlike glavnih zaostalih naprezanja na zavarenom spoju zavarenom pod praškom u tri različita stanja

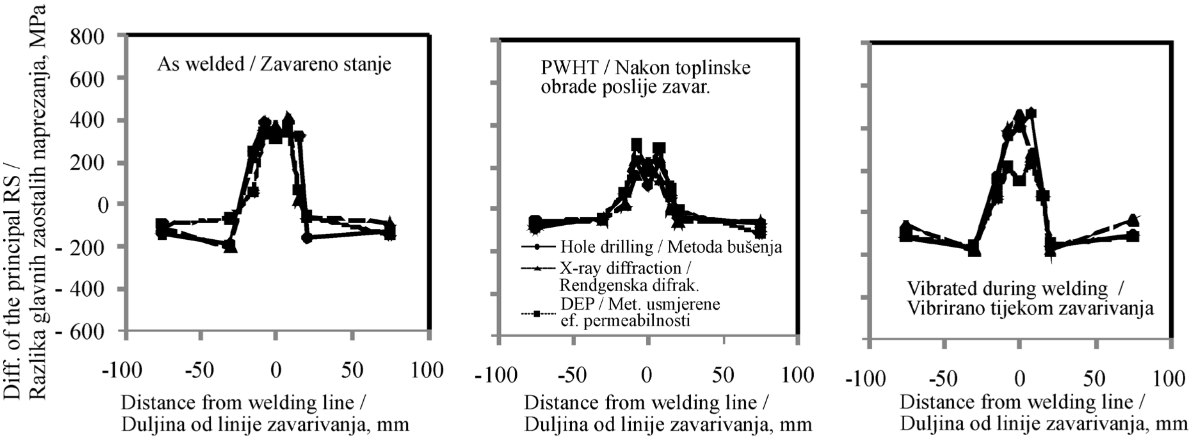


Figure 7. Comparison of the hole drilling, X-ray diffraction and DEP method using differences of the principal residual stresses on the T.I.M.E. weld joints in three different conditions

Slika 7. Usporedba metoda bušenja rupice, rendgenske difrakcije i usmjerene ef. permeabilnosti na osnovu razlike glavnih zaostalih naprezanja na zavarenom spoju zavarenom sa T.I.M.E. postupkom u tri različita stanja (zavareno, nakon toplinske obrade poslije zavarivanja i vibrirano tijekom zavarivanja)

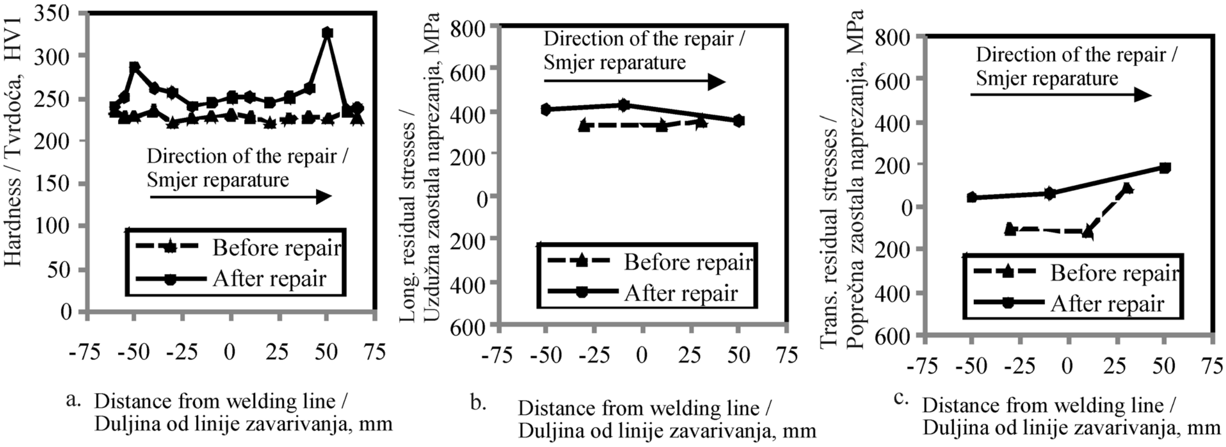


Figure 8. Results of hardness and residual stress measurement (a) Hardness, (b) Longitudinal residual stresses (c) Transverse residual stresses

Slika 8. Rezultati mjerenja tvrdoće i mjerenja zaostalih naprezanja (a) tvrdoća, (b) uzdužna zaostala naprezanja, (c) poprečna zaostala naprezanja

Figure 8 (a) shown hardness values measured on the repaired welded joint before and after repair. Maximum hardness values were measured at the beginning and at the end of the repair welded joint.

Longitudinal and transverse residual stresses before and after repair welding are shown in Figure 8 (b) and 8 (c). It can be seen that the values of stresses are higher after the repair welding. Also, from Figure 8 we can conclude that a lot of flaws can occur at the beginning and at the end of repair welded joint because of higher values of measured hardness and residual stresses [10, 11]. These places need devote special attention during planning of the repair welding technology and during repair welding.

5. Conclusions

Comparing three different methods for residual stress measurements in welded joints, we can conclude:

- hole drilling method is the most appropriate method for measurements of residual stresses in welded joints especially out of laboratory.
- X–ray diffraction method is laboratory method which gives good results in base material for a short measurement time, while for measurements in WM and HAZ it requires additional calibration and longer time for measurements.
- directional effective permeability method is very simple and useful in real structure but results are less reliable in welded joints especially if demagnetization is not performed in a proper way.

Higher values of residual stresses were measured on the repaired welded joint because of rigidity of the nearby remaining material which disables the narrowing of joint during the welding process [10, 11].

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