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COMPARISON OF TWO METHODS FOR MEASURING RESIDUAL STRESSES IN WELDMENTS

POREĐENJE DVE METODE MERENJA ZAOSTALIH NAPONA U ZAVARENIM SPOJEVIMA

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- hole drilling method
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Abstract

The article describes two methods for measuring residual stresses that differ in the method of measurement. The first method, a method of energy X-ray diffraction, uses atomic planes as measurement sheets and it operates based on the principle of X-ray diffraction. The second method, the hole drilling method, measures residual stresses with resistance strain gauges which are glued onto the surface of the measured sample. Measurements are made on two different welded joints: Niomol 490 K steel and aluminium alloy 7049A. The steel welded joint is made by submerged arc welding (SAW). The aluminium alloy welded joint is made by friction stir welding (FSW). Measurements show good matching in areas where stresses are equally distributed in the thickness, despite the application of different measurement methods.

Ključne reči
- merenje zaostalih napona
- metoda bušenja otvora
- metoda energetske rentgenske difrakcije

Izvod

U članku su opisane dve različite metode za merenje zaostalih napona, koje se razlikuju po načinu merenja. Prva metoda, metoda energetske rentgenske difrakcije, upotrebljava atomske ravni kao merne ravnine i deluje po principu odbijanja rentgenskog zračenja. Druga metoda, metoda bušenja rupe, meri zaostale napone sa mernim trakama, koje se lepe na površinu mernog uzorka. Merenja su izvedena na dva različita zavarena spoja: čelik Niomol 490 K i legura aluminijuma 7049A. Zavareni spoj na čeliku je izveden elektrolučnim postupkom zavarivanja pod praškom (EPP). Zavareni spoj na leguri aluminijuma je izveden postupkom zavarivanja trenjem i mešanjem (FSW). Merenja su pokazala prilično dobro podudaranje u područjima jednake raspodele napona po debljini, uprkos različitim metodama merenja.

INTRODUCTION

Residual stresses are stresses contained in the material when no external load is applied on it, /1-2/. They arise as a result of limited local plastic deformation in the material which can be a result of the manufacturing method or the manufacturing process itself. Most often are the processes that use heat as an energy source, such as: welding, heat cutting, annealing, and other various types of heat treatment. They can also be pure mechanical manufacturing processes, for example: drawing, pressing, bending, mechanical cutting, grinding, sandblasting, etc. A high level of residual stresses may occur often and can easily approach the yield stress of the material. In the case when the residual stress exceeds the yield stress of the material, plastic deformation occurs, so residual stresses relax for the exceeded yield stress in the material. In welded joints these stresses most often adversely affect the welded structure itself and the weldments. Since they reduce the load capacity of the welded structure, they affect the fatigue strength of the weldments, they open the defects that occur in the weld heat affected zone (HAZ) and cause elastic deformation of the weld and the onset crack growth from the defects in aforementioned areas. Materials subjected to alternating service loads or corrosive environments can fail due to residual stresses, /7/. Knowledge of the size and distribution of residual stresses that superimpose with work stresses, makes it crucial for determining and extending the life of welded structures. Often, because we have to decide for reduction of residual stresses, which can be relaxed by annealing so to eliminate residual stresses or some other process, such as overloading, pressure testing or vibrations during and after welding.

Different methods are used for measuring residual stresses based on different principles, /1-5/:

- methods that use strain gauges (hole drilling method, circular groove method, method for removing small surface layers and cutting methods),
- diffraction methods (angular dispersive X-ray diffraction method, energy X-ray diffraction method, neutron diffraction method),
- magnetic methods (magneto-acoustic emission method, induced magnetic anisotropy method, Barkhausen emission method, method of induced velocity changes),
- acoustic-ultrasonic methods, using different waves, namely: longitudinal, transverse and Rayleigh surface waves,
- optical methods.

The article focuses on the application of energy X-ray diffraction method and the hole drilling method, which are used on two different welded joints.

ENERGY X-RAY DIFFRACTION METHOD

The non-destructive measurement of residual stresses is based on the basics of X-ray wave front interaction in the crystal lattice, as shown in Fig. 1a.

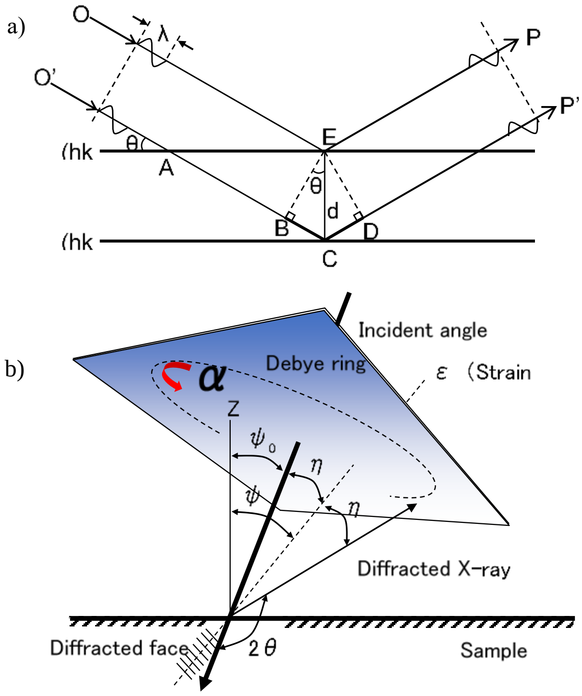

Figure 1. a) X-ray wave front interaction in the crystal lattice, b) incident X-ray diffracted in the form of cone (360°) due to the polycrystalline material, where the incident X-ray forms an angle with the diffracted X-ray.

Measurements with energy X-ray diffraction (EXRD) are based on the Bragg law, according to the equation

$$n\lambda = 2d\sin\theta\,, \tag{1}$$

where: n is the whole number of lines of reflection; λ is X-ray wavelength; d is the interplanar spacing of the crystal lattice; and θ is angle of incidence which equals to the diffraction angle.

Different crystalline planes diffract X-rays of different strength. Each crystal grid has its own spectrum of diffracted X-rays relative to the incident angle 2θ (Fig. 1b). Steel at room temperature usually has a body-centred cubic lattice (α-Fe). The strongest diffraction of X-rays is obtained for crystal plane (211) at an angle of 156.37°. To determine one value of residual stresses, we must obtain at the same point two diagrams of functions and determine the maximum of diffracted beams from the angle 2θ, and namely for two different symmetrical angles of the metering position $\psi_1 = 0°$ and $\psi_1 = 45°$. In that way the function is defined for different spacing d between the group of planes (211) from which we determine normals with respect to angle 2θ. From the phase lag between these normals, with respect to the expected peak of the group of planes (211) for α-Fe, the value of residual stresses is obtained.

The Pulstec μ-X360 portable X-ray analyzer is used (Fig. 3a) and diffraction method $\cos\alpha$ for determining the values of residual stresses. Residual stresses can also be measured by the $\sin^2\psi$ method. In the $\sin^2\psi$ method the variation of the lattice interplanar spacing is detected by changing the angle of incident X-rays (ψ_0). (In the standard XRD measurement, 7 different angular measurements are recommended). Because of the restrictions of the device, the $\sin^2\psi$ method is used in the laboratory only. The $\cos\alpha$ method enables high precision measurements also for samples with a certain degree of crystal deformation. In order to avoid the influence of crystal orientation, the $\sin^2\psi$ method can be used. The $\sin^2\psi$ method has a disadvantage: the penetration depth of X-ray radiation varies during the experiment when the ψ angle changes, /10/. The $\cos\alpha$ method, via the 2D detector, has shown better measurement repeatability than $\sin^2\psi$ via the line detector, /10/. Figure 2a presents the linear dependence of 2 theta peak position upon $\sin^2\psi$, where the slope represents the residual stress. In Fig. 2b is an example of a data analysis graph related to residual stresses after using the $\cos\alpha$ method with Pulstec μ-X360 on Niomol 490 K. The approximation straight line is calculated from the graph. The residual stress value is determined from the slope of the approximation straight line. Residual stress is calculated by an elastic coefficient. The less there is separation between the approximation straight line and plot data means higher measurement precision.

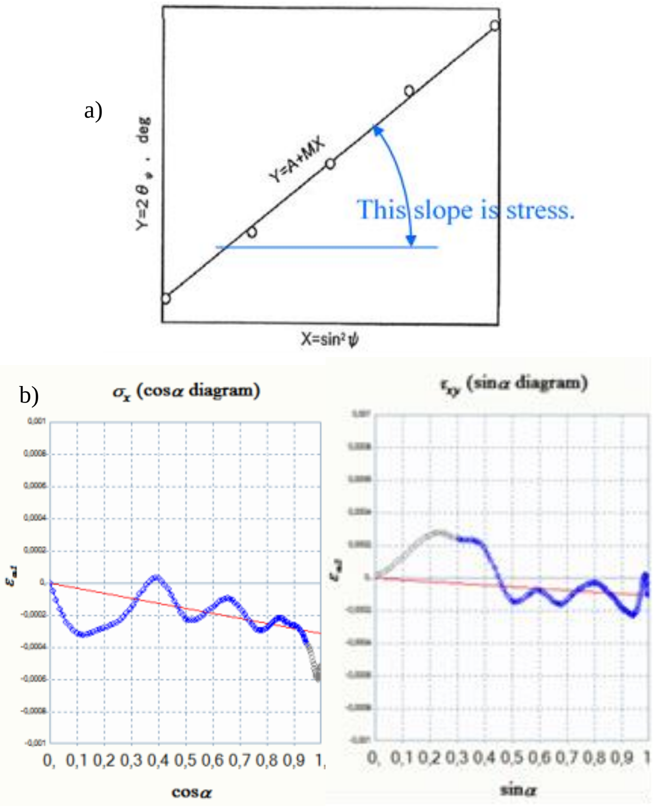

Figure 2. a) Linear dependence of 2 theta peak position upon $\sin^2\psi$; b) data analysis graph related to residual stresses ($\cos\alpha$ method) in Niomol 490 K (20 mm in transverse direction).

Deformation in the crystal lattice is measured during the measurement of residual stresses with EXRD X-rays. Therefore, crystal lattice deformation can be measured by comparison of the interplanar spacing value of the intact lattice with the size of the deformed crystal lattice due to residual stresses. The residual stress is determined from the elastic constants assuming linear elastic behaviour of the corresponding planes of the crystal lattice. A wrong value of X-ray elastic constant may introduce a large bias in the measured stress, /11/. Due to the radiation of the selected surface of the sample, several appropriately oriented crystalline grains are added to the measurement, the number of which depends on the material on which measurements are performed.

The diffraction method is a non-destructive method and it can be used on polycrystalline materials that have relatively small crystal grain. Most often, the size of crystalline grains of metal materials is between 10 μm and 100 μm, which is favourable for residual stress measurements with the EXRD method /6/. A larger grain would be problematic, because in the irradiated extent only a few grains contribute to the diffraction peak (intensity is lower). The Cr tube is recommended for measuring residual stresses in ferritic steel alloys, aluminium alloys, nickel (pure), nickel alloys, austenitic steel, cobalt-chromium alloys, neodymium and zirconium. Any suitable flat surface should be selected for measuring residual stresses. The shape and size of the sample is not critical because there is no upper limit for transmission systems in residual stress measurements. Curved patterns can also be measured if the size of X-rays is smaller than the curvature of the sample. The temperature during the measurement must be constant in order to avoid further changes in network parameters due to thermal expansion. Calibration is needed for accurate measurement, and ferritic powder provided by Pulstec is used for calibration.

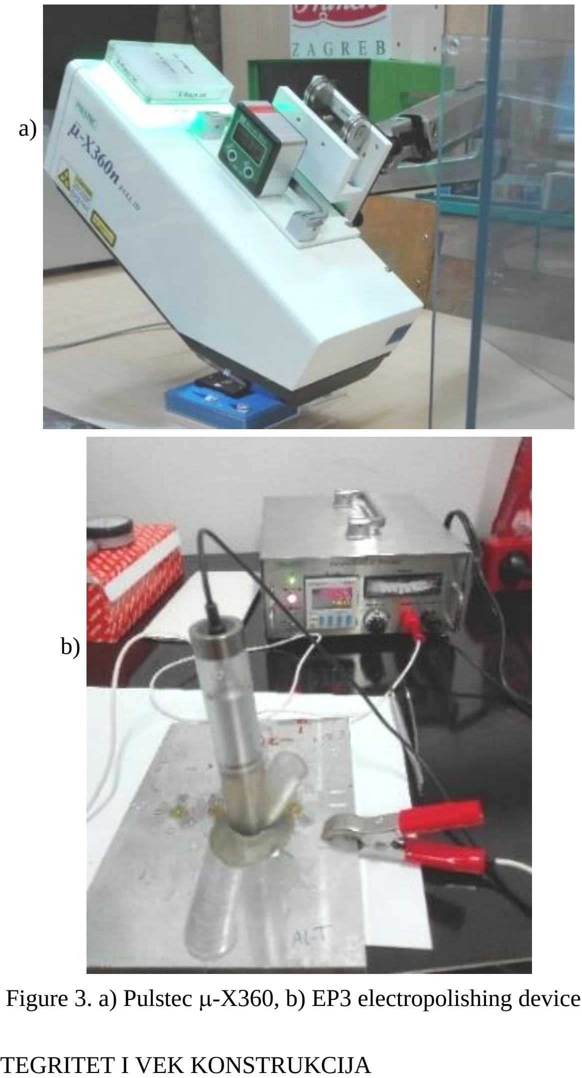

Figure 3. a) Pulstec μ-X360, b) EP3 electropolishing device.

The EXRD method uses a fixed angle of incident X-rays. The device for measuring residual stresses, the Pulstec μ-X360 has a circular mask for X-rays – a collimator that limits the irradiated surface on which the measurement is performed. The device has a laser pointer which allows to determine the measured surface in the sample and the distance between the device and sample. Most portable devices for measuring residual stresses have 2 detectors /5/. All diffracted X-rays from the Pulstec μ-X360 source of X-rays of are assembled in a two-dimensional detector during only a single irradiation, enabling the image of the entire Debye-Scherrer ring (in 125 points) from which the final value of residual stresses is automatically determined in the direction of measurement.

Many metallic materials strongly absorb X-rays, so the intensity of the incident X-rays is greatly reduced with depth, so measurements are limited to a very small thickness of the surface. The intensity of the incident X-rays thus decreases exponentially with the depth of the material. Consequently, most of the diffracted X-rays originate from a thin surface layer, so residual stress measurements correspond only to that material layer. The presence of a colour layer in coloured materials can result in a decrease in the intensity of diffracted X-rays, therefore the colour must be removed. In order to be able to easily measure residual stress values, it is essential to remove the layer of material by electropolishing, which is easily very localized, /5/.

The key to successful electropolishing is the right choice of electrolytes and electropolishing parameters. The device EP3 was used for electropolishing (Fig. 3b). The anode (+) for electropolishing is actually a magnet that is placed on the surface of the specimen that we want to electropolish. The cathode (–) represents the electrode of the EP3 device. The electrolyte closes the current loop between electrodes mentioned previously. The electropolishing depth depends on the state of the surface and material, and is about 50-200 μm. The total electropolishing depth depends on the electropolished area of the material, since lack of data can occur because of the absorbed scattered X-rays towards the sensor from the material that is not electropolished. If a lack of the Debye-Scherrer ring has been observed in the measurement result of the electrochemical polishing point, the polishing area can be increased, and the distance from the sample or incident angle can be changed, /8/. If the surface of the material may be grinded together with electropolishing, the residual stress can be measured at greater depths.

HOLE DRILLING METHOD

The hole drilling method is a method for measuring residual stresses standardized according to ASTM E837 - 13a. The method is able to measure uniform and non-uniform residual stresses if the in-plane stress gradients are small, /7/. The method is applied in cases where material behaviour is linear elastic and uses a three-element strain gauge rosette for measuring residual stresses, which contains three resistance strain gauges. They are located at angles 0°, 45°, 90° or 0°, 90°, 225° (Fig. 4a). The strain gauge rosette is glued onto the surface of the sample prior to measurements. The method is, by principle, half-destructive, meaning that residual stresses must be relaxed during measurement. This is done by drilling a hole of diameter equal to 1.6 mm in the middle of strain gauge rosette. The hole can be easily blind (depth up to 2 mm) or through the material, which depends on the thickness of the material.

It is necessary to centre the drilling tool before drilling - turbine drill and the centre of strain gauge rosette. Before drilling, the strain gauge rosette is set to zero, and changes in deformation are measured around the drilled hole during the test. The measured deformations are a consequence of relaxed residual stresses due to hole drilling. Measurements are usually performed in steps with a progressive drilling of 0.1 mm in depth. Deformations around the drilled hole up to the final depth of drilling are measured the whole time. This is followed by an evaluation phase, that is carried out in accordance with ASTM E837 - 13a standard. Values and directions of principal stresses can be easily calculated from measured deformations of individual strain gauges,

$$\sigma_{x,y} = \frac{\varepsilon_1+\varepsilon_3}{4A} \pm \frac{1}{4B}\sqrt{(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2}\ , \qquad (2)$$

$$\tan\alpha = \frac{\varepsilon_1-2\varepsilon_2+\varepsilon_3}{\varepsilon_3-\varepsilon_1}\ , \qquad (3)$$

where: $\sigma_{x,y}$ are principal stresses; α is the angle of principal stresses; ε_1, ε_2 and ε_3 measured deformations in individual strain gauges; A, B are material constants (Fig. 4b and 4c).

Table 1 gives a comparison of methods used for measuring residual stresses. Both methods are suitable residual stress measurements in welded joints.

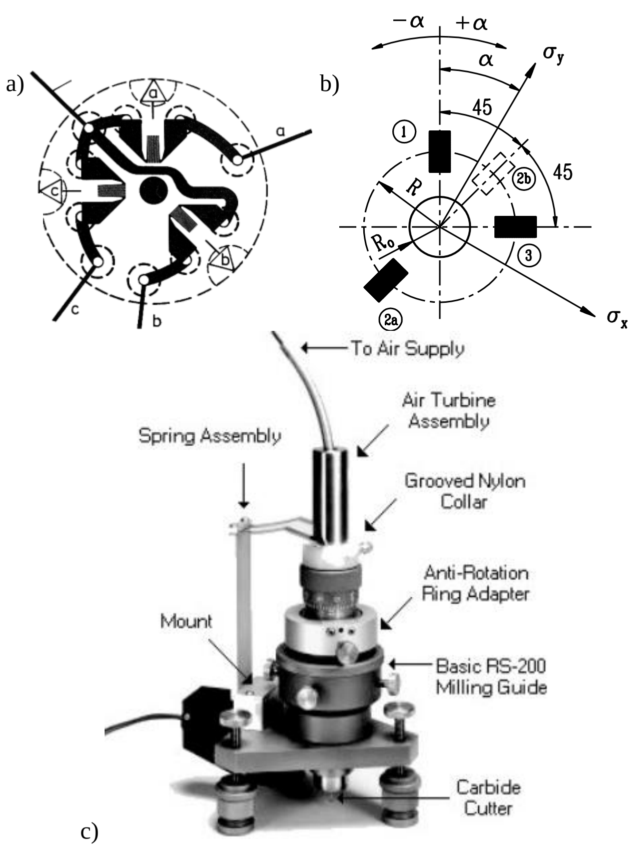

Figure 4. a) Resistance strain gauge; b) evaluation of residual stresses; c) Vishay device, /12/.

Table 1. Comparison of methods for measuring residual stresses.

	EXRD method	Hole drilling method
Type of stresses measured	I + II order of residual stresses	I order of residual stresses
Result of measurement	Normal and shear component of residual stresses on the surface in the direction of measurement	Principal stresses and their direction on the surface up to 1.6 mm in depth
Method precision	depends on the measured material	± 10 %
Requirements before measurement	Electropolishing	Bonding of the strain gauge rosette
Time needed for measurement	15 min	1 hour
Measurement depth	< 10 μm	2 mm
Measuring surface	∅ 2 mm	∅ 5.13 mm (rosette diameter)
Damage on the material after measurement	Non-destructive method (after electropolishing up to 200 μm)	Half-destructive method (hole 1.6 mm, depth 2 mm)
Materials that can be measured	Polycrystalline metal and ceramic materials	All metallic materials
Power source	230 V to power the device and computer	230 V for supplying the measuring system + compressed air
Weakness of the method	Influence of microstructure, directed microstructure	Measurements with the large gradients of residual stresses
Difficulties in measurements on welded joints	Microstructural changes in HAZ and weld, calibration needed	Performance of measurements with large gradients of residual stresses
Protective measures	Protection against radiation from X-rays (up to 3 m without protection, up to 1.5 m with protection)	(no restrictions)

RESULTS OF MEASURED RESIDUAL STRESSES

Measurements were carried out on two different welded joints. The first welded joint was welded on a 12 mm thick steel sheet from Niomol 490 K by submerged arc welding with filled wire. Filled wire FILTUB 128 with 4 mm diameter was used as filler material and welding powder FB TT. The welding parameters were welding current 530 A, welding voltage 30 V and welding speed 60 cm/min. Welding was performed in three passes.

Residual stresses were measured at two points in the transversal direction at 20 mm and 70 mm distance from the centre of the weld (Fig. 7a). Before the measurement of residual stresses with EXRD method, measurement points were electropolished with a 10% NaCl solution in water by a current of 0.6 A for 2 min. and additionally 3 min. with a solution from Pulstec manufacturer at 200 μm depth.

Figure 5a shows the Debye 3D ring (left) and distortion (right) from Niomol 490 K at 20 mm distance from the centre of the weld in the transversal direction, and Fig. 5b shows the Debye 3D ring (left) and distortion (right) from Niomol 490 K at 70 mm distance from the weld centre in the transversal direction.

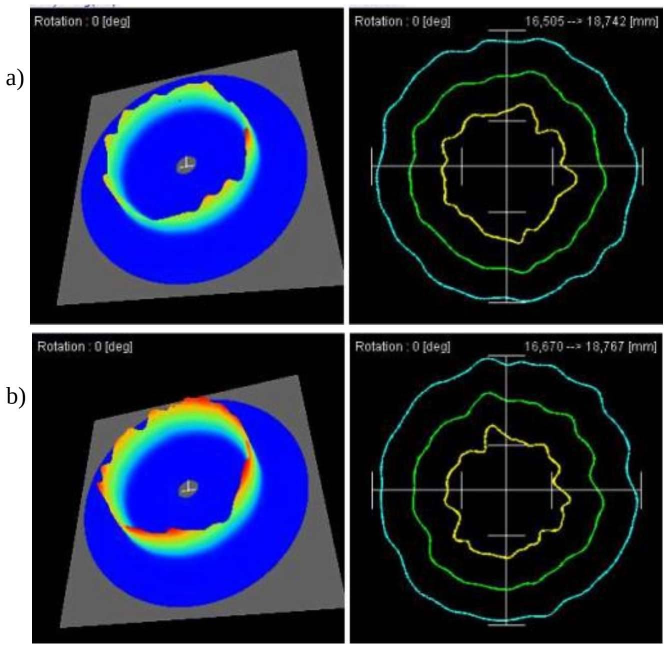

Figure 5. Debye 3D ring (left) and distortion (right) from Niomol 490 K in the transversal direction at: (a) 20 mm and (b) 70 mm distance from weld centre.

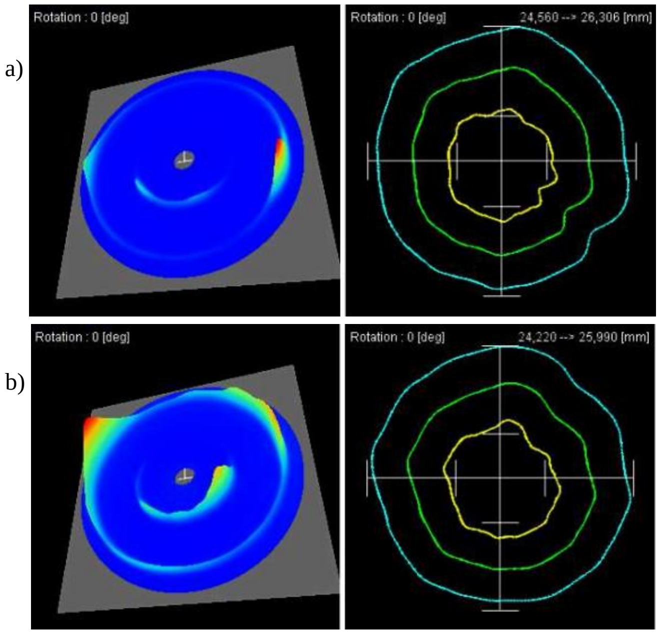

Figure 6. Debye 3D ring (left) and distortion (right) from aluminium alloy 7049A at 30 mm from weld centre in the: (a) transversal direction; (b) longitudinal direction.

The second welded joint is made by friction stir welding of 6 mm thick aluminium alloy 7049A. Welding parameters were: rotational speed of the spindle 800 min^{-1}, welding speed 70 mm/min, tool tilt 1° and tilt of tool cone 5°. The measuring position was 30 mm from the weld centre. Residual stresses were measured longitudinally and transversally to the welding direction (Fig. 7b). Before residual stress measurements with EXRD method, the measurement point was electropolished with a 10% NaCl water solution with a current 0.6 A for 2 min at depth of 110 μm.

In Fig. 6a are presented the Debye 3D ring (left) and distortion (right) from aluminium alloy 7049A at 30 mm from the centre of the weld in the transversal direction. In Fig. 6b are presented Debye 3D ring (left) and distortion (right) from aluminium alloy 7049A at 30 mm distance from the centre of the weld in the longitudinal direction.

Measurement results of both methods are presented in Table 2. Measured residual stresses values on Niomol 490K in the transversal direction at 20 mm and 70 mm distance from the centre of the weld is presented in Fig. 8. The measured values of residual stresses on aluminium alloy 7049A at 30 mm from the weld centre in both transversal and longitudinal direction are presented in Fig. 9. Residual stress results are also important for simulation, /13/.

Table 2. Results of residual stress measurements.

method	Niomol 490 K		7049A	
	20 mm, transversal	70 mm, transversal	30 mm, transversal	30 mm, longitudinal
EXRD	+145±55 MPa at depth 200 μm	+125±64 MPa at depth 200 μm	-8±13 MPa at depth 110 μm	+19±15 MPa at depth 110 μm
Hole drilling	+130±13 MPa at depth 1.6 mm	+5±0.5 MPa at depth 1.6 mm	-11±1.0 MPa at depth 1.6 mm	+54±5.4 MPa at depth 1.6 mm

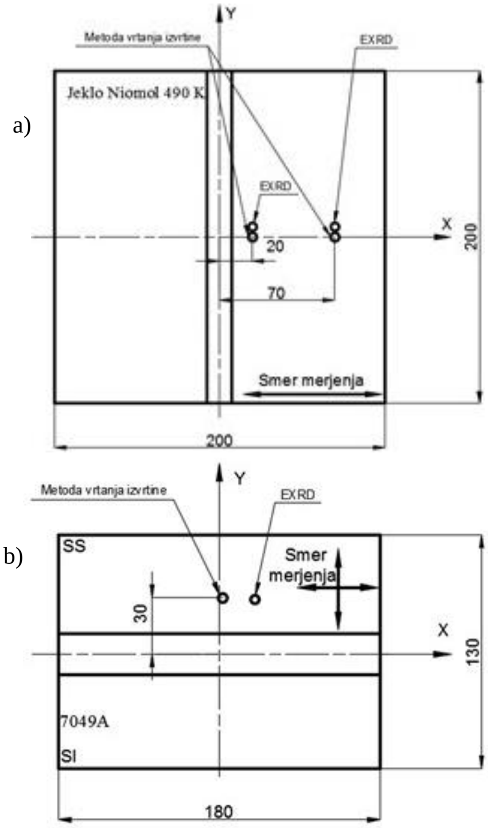

Figure 7. Position and direction of measurements on weld of: a) Niomol 490 K, b) aluminium alloy 7049A.

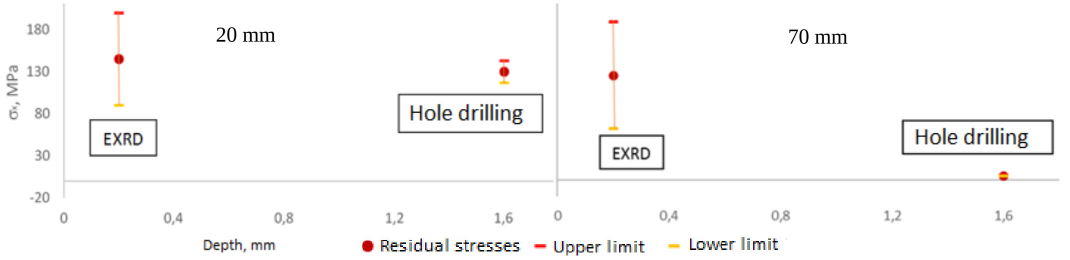

Figure 8. Residual stresses in Niomol 490K in transversal direction, 20 mm and 70 mm distance from the centre of weld.

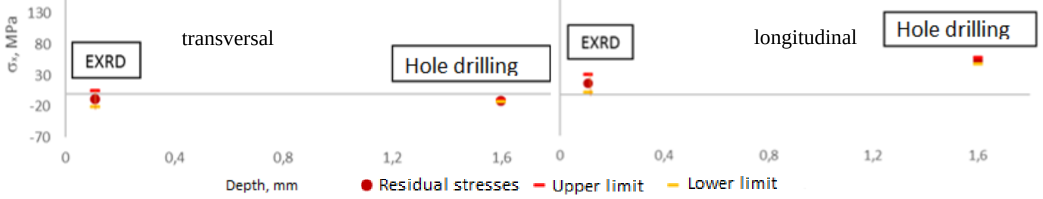

Figure 9. Residual stresses in aluminium alloy 7049A, 30 mm from the centre of the weld in both transversal and longitudinal direction.

CONCLUSION

Two different methods for measuring residual stresses are compared: the energy X-ray diffraction method (EXRD) and hole drilling method.

Residual stress measurements are made on welded joint of Niomol 490 K made by SAW process and welded joint of aluminium alloy 7049A made by friction stir welding.

Measurements of residual stresses are carried out only on base material, because the values of residual stresses do not change in depth and they can be compared. The results cannot be directly compared, since they are measured at different depths.

In the area of microstructural changes (weld metal and HAZ), the change in microstructure is affecting the residual stresses measurements by energy X-ray diffraction method. Measurements are also affected by residual stresses of II order which cannot be measured by the hole drilling method. That is the reason why direct comparison in these areas is not possible or reasonable.

A comparison of both methods, where stresses do not change in depth, show a fairly good matching.

The EXRD method and the hole drilling method should be combined, as EXRD gives results on the surface with what the results of hole drilling method are complementing.

ACKNOWLEDGEMENTS

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