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INFLUENCE OF VIBRATORY STRESS RELIEF ON RESIDUAL STRESSES IN BRIDGE STRUCTURAL MEMBERS WELDMENTS

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Abstract. The welding process can join two similar materials with a bond that has mechanical properties comparable to the original material. Unfortunately, this process induces residual stresses in the weldment, which, if left untreated, can cause distortion of the part, premature fatigue failure or cracking along the weld. In a cases of cracking in steel bridge structural members were attributed to metal fatigue. The majority of these fatigue cracks are initiated adjacent to a weld. A post-weld heat treatment is the traditional method of relieving these stresses, but is costly and a time consuming process. Heat treatment is required for weldments, which have heavy fatigue loading since the post-weld heat treatment reduces the residual stresses in the weldment and generates more uniform mechanical properties. Vibratory stress relief techniques could be used to substitute the heat treatment for these types of weldments and save time and money. The purpose of this paper is to provide a brief overview of the generation, measurement, and reduction of residual stresses. Residual stresses in the weld bead were measured by means of X-ray diffraction, neutron diffraction, ultrasonic technique, hole drilling and numerical methods. In addition, welded specimens were subjected to mechanical testing with purpose of determination of VSR effect on weld and heat-affected zone metal.

Keywords: vibration stress relief, residual stresses, ultrasonic stress measurement, high resolution X-ray diffraction, neutron diffraction, hole-drilling method.

1. Introduction

The rapid expansion of the industrial steel constructions, steel bridges, etc. has increased the demand for steel structures workability requirements. Most structures are joined by welding. Industrial structures such as bridges, tanks, pressure vessels, piping and other similar installations are made of low carbon or low carbon low alloy structural steel. As a result of a welding process residual welding stresses are close to or even exceeding a material yield point. According to the recommendations of the industrial construction standards when welding objects are thicker than 35 mm, such residual stresses shall be thermally relieved. Thermal treatment process involves maintaining the high temperature in a structure followed by a slow cooling and a resulting reduction of residual stresses (According ASM Handbook 2002; Žiliukas, Surantas 2010). A vibratory stress relief (VSR) technique for the relief of residual welding stresses has been successfully applied worldwide for over 30 years. This method, compared to the thermal treatment, is much less energy, labour and time consuming intensive (Aoki *et al.* 2005; Wang *et al.* 2008). However the practical problem arises when there is a need to assess the change in residual stresses in a real structure after applying VSR method. Accurate residual stress measurement methods, such as X-ray or neutron diffraction, can show the distribution of stresses only under laboratory conditions and when applied to limited-size products. Therefore, many difficulties arise when assessing the effect of vibration energy to residual stresses in a real bridge structural member or other structure.

2. Stress relief by thermal and vibration energy

Thermal Stress Relief (TSR). Depending on the shape and size of the piece, the residual stress relief by the heat treatment can be carried out by:

- heating the entire piece, or parts of it, in a furnace;
- installing a temporary burner into work piece;
- treating the welds one by one by pass of electric current (resistance heating).

Heating by exothermic kits, which enjoyed some popularity in the sixties and seventies, was abandoned because it did not produce the expected results (Radaj 2003).

VSR technique, based on the weight of the piece, introduces into it high amplitude and low frequency vibrations for a given period of time. This relieves residual stress without distortion or alteration of tensile strength, yield point or resistance to fatigue, and the static equilibrium is restored (Hebel 2001). The most efficient vibrations are the resonant ones, because in the resonance frequency vibrations stress is better distributed, if compared with subresonant frequency. Low frequency vibrations carry high amplitude energy and are very efficient in the significant decrease of peak residual stress in parent metal and welds. The equipment usually employed consists of a sturdy vibrator of variable speed, which is attached to the piece and an electronic control panel. Both are mounted into a portable cabinet. Also attached to the piece is an accelerometer that detects vibrations and transmits a signal to the control panel. The resonance point is then determined and displayed on a dial. If the vibrator is equipped with a recorder, a chart can also be obtained. The point of resonance is attained by varying the frequency of the vibrator until the proper one is reached. Two minutes is the average time required to reach the resonance frequency. At this point, vibration is maintained for a given time, depending on the weight of the piece and its intended application. The time may range from 10 min to an hour or more, but if it is exceeded, the piece will not suffer any damage due to fatigue or loss of tensile strength. If structures are very big, long or have open spaces, it may be necessary to apply the procedure in several points. Some equipment carries out the vibration process automatically. Vibration is maintained for 15 min, in a sequence of three different selected frequencies, each lasting 5 min. This setting is efficient to treat pieces weighing up to 10 t. For pieces weighing more than 10 t two consecutive 15 min periods can be used, without the piece suffering any harm (Hebel 2001). Two simple rules should be followed for all applications:

– support the piece in the best possible manner, isolating it from the floor or rigid structures, thus leaving it free to vibrate;
– the vibrator should be directly connected to the piece, in order to transfer the entire vibratory energy generated.

The method can be used on a wide range of ferrous and nonferrous metals, including carbon and stainless steel, cast iron, aluminum, titanium etc., in a large variety of shapes. Sizes can vary from small welded parts, shafts and gears, to large welded and machined steel structures. However, it presents some limitations: it is not efficient for extruded, cold worked and precipitation hardened materials.

One of the most important benefits of the use of the VSR method is its capacity to relieve stress at any point of the manufacturing process, such as after machining, snagging, drilling or grinding. In welded parts, stress relief can be performed during welding, which is very useful to prevent concentration of residual stress that may cause warping of the piece. The method is especially compatible with MMA, MAG, MIG and TIG welding. With other welding processes some logistical problems may arise.

3. Techniques for measurement of residual stress

Residual stress measurement techniques of different materials can be broadly classified into 3 types: destructive method, semi-destructive method and non-destructive methods (Withers, Bhadeshia 2001).

In destructive method a portion of the residually-stressed body is cut away and the resulting deformation of the body is carefully measured with the help of strain gages, then the residual stresses, which existed at the freshly exposed surfaces, before they were thus exposed, can be calculated. This technique, referred to as dissection method, is old but still powerful. The disadvantages of this technique are: the method is very tedious and painstaking, theoretical analysis is difficult and the method is unable to detect residual micro-stresses (Withers, Bhadeshia 2001).

Semi-destructive hole-drilling method is a widely used method for measuring residual stress. It involves drilling of a hole on the surface of the object being examined, and measurement of strain redistribution that takes place on the surface as a result of the hole (Baldi 2005). Elasticity theory is used to calculate the residual stresses that existed prior to the drilling. The strains may be measured with strain gages or with photo-elastic coatings mounted on the surface before drilling (Lord *et al.* 2008).

Non-destructive methods come in three basic types:

1. X-ray diffraction method is the most common non-destructive method for evaluating residual stresses. It is based on lattice strains, the changes in the spacing between crystallographic lattice planes, which are caused by stress. The disadvantages of this method are: as the volume of surface material interrogated by X-ray beam is small, and the lattice strain which is measured reflects the combined influence of both micro- and macro-residual stresses acting at that location (Monin *et al.* 2009). In materials having high variation of micro-stress gradients the evaluation of macro-residual stress is not proper. The elastic constants of crystals vary with their orientation so that their calculated values differ substantially from the measured values; measured values are not always available.

2. Neutron diffraction method. Like X-ray diffraction technique neutron diffraction relies on elastic deformations within a polycrystalline material that cause changes in the spacing of the lattice planes from their stress free value. Measurements are carried out in much the same way as with X-ray diffraction, with a detector moving around the sample, locating the positions of high intensity diffracted beams. The greatest advantage that neutrons have over X-rays is the very large penetration depths that neutrons can obtain, which makes them capable of measuring at near surface depths of around 0.2 mm down to through-thickness measurements of up to 30 mm in steel. With high spatial resolution, neutron diffraction can provide complete three-dimensional strain maps of engineered components.

3. Ultrasonic method for evaluating residual stresses is based upon the changes in the velocities of ultrasonic waves due to stress. The disadvantage of this method is:

higher order elastic constants are generally required in order to relate ultrasonic velocities to residual stress (Sajauskas 2004). These constants which are also dependent on the metallurgical texture must be experimentally determined for a particular material being examined. This method has a limited capability for detecting sharp stress gradients and it has little use for determining residual stress in materials such as plastics, composites and certain non-metallic materials (Tanala *et al.* 1994).

4. Materials and methods

The specimens were produced from S355J2 (*LST EN 10025-2:2005 "Hot Rolled Products of Structural Steels-Part 2: Technical Delivery Conditions for Non-alloy Structural Steels"*) hot-rolled steel plate of cross-section 140×140×30 mm. The specimen size was selected according to limitation of the used measurements technique.

Several series of specimens were welded: the first series contain no treatment; heat treatment was performed after welding on the second series; the third series of specimen was treated applying VSR during welding and in the fourth series VSR was applied after welding (Jurčius *et al.* 2008). VSR treatment was carried out on a special work-desk (Fig. 1).

Vibrational conditioning relaxation process uses a sinusoidal vibration waveform. Force inducer induces energy to create vibration amplitude that is below the harmonic amplitude. A dwell time and working frequency depending on the component's strength, elastic modulus, and size, is maintained to allow internal stresses to redistribute and balance themselves.

The change in residual stresses was measured using the following methods: ultrasonic wave propagation (UT), high resolution X-ray diffraction, neutron diffraction (ND), hole drilling (HD/DSPI) and numerical (FEM).

5. Analysis of residual stress measurements

Ultrasonic wave propagation analysis. The ultrasonic wave propagation (UT) method of stress measurement is based on the acoustic-elasticity effect, when the velocity of elastic wave propagation in solids is dependent on mechanical stresses. This technique takes into account the effect of the microstructure through the application of coefficients of corrections to the measurements carried out in the melted zone and parent metal.

During the tensile test the interdependency of the speed of surface ultrasonic longitudinal wave propagation and stresses was identified, i.e. constants of structural steel acoustic elasticity were determined: for a basic metal $K_{PM} = -1.377 \times 10^{-5}$ MPa^{-1}, for a weld metal $K_{SZ} = -1.616 \times 10^{-5}$ MPa^{-1}. The surface longitudinal wave method is sensitive for sensor pressing, therefore a weldment was leveled to the original metal surface prior the measurement of residual welding stresses.

The analysis of ultrasonic wave propagation speed (Fig. 2) has shown that the max tensile stresses at the centre of a joint in specimens without application of any treatment were 324 MPa. The max compressive stresses in the same series of specimen reached 123 MPa. During the application of the VSR treatment the peak of longitudinal residual stresses in specimen was reduced by approx 65%. The VSR treatment after welding reduced the peak of residual stresses on average by approx 47%. The thermal treatment reduced residual stresses of the B2 series specimens by approx 71%. It was noted that residual stresses of all specimens at the heat action zone were close or equal to zero. The method of ultrasonic surface longitudinal wave propagation speed for the measurement of residual stresses (up to the depth of 3 mm) is a practical and easily applicable at the production or assembly sites. Structural steel acousto-elastic constants identified during the research can be used in the ultrasonic analysis of residual stresses for the same steel group. Ultrasonic measurements correlate with the results obtained by diffraction, hole drilling and FEM methods.

Hole drilling method analysis. Hole drilling (HD) and digital speckle pattern interferometry (DSPI) method (HD/DSPI) has been successfully used for several years in many applications in the area of experimental mechanics for measurements of mechanical stresses. Two sets of images are captured, one at the reference loading stage and the other at the final relaxing stage. A phase pattern is computed for each stage and the phase difference is calculated for each pixel of the image. After some image processing, the displacement field between the two loading configurations

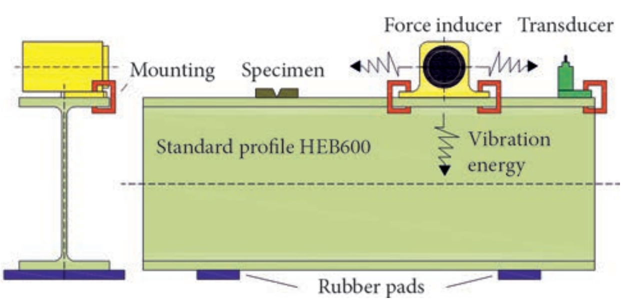

Fig. 1. Work-desk for vibratory treatment

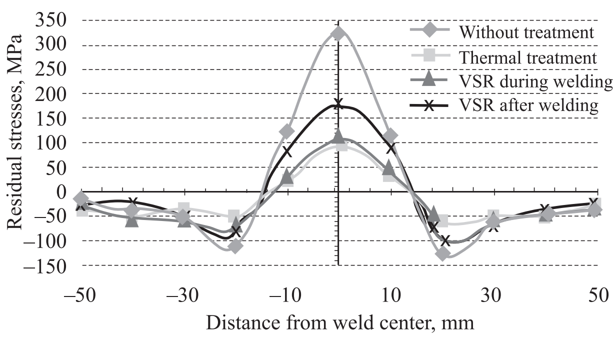

Fig. 2. Distribution of longitudinal residual stresses in specimens by ultrasonic technique

is computed for the whole image. From spatial derivatives of that, the strains can be computed and then, the stresses can be determined.

Under the laboratory conditions HD/DSPI device was very practical and easy to use. The time necessary to measure residual stresses is about ten times faster than what is required when strain gauges rosettes are used. Almost no surface preparation is required. The acquisition and processing time is very short. However, some experience and measurement skills are necessary at the current development stage to successfully measure residual stresses.

Research performed by using combinative HD/DSPI technique demonstrates that maximal residual stresses relieve was higher than normal steel S355J2 yield stresses (Fig. 3). It was also found that vibration energy applied during welding reduces maximal stresses more than 2.5 times. VSR after welding resulted in maximal stress reduction of about 42%.

Numerical analysis of residual stress. The same model was used for both thermal and structural analysis, but element type differed. The conventional quiet elements technique was chosen for the modeling of filler material and was implemented by using an element birth and death feature. For thermal analysis, total welding time of the complete all weld, i.e. 1399 s was divided into 28 equally spaced solution steps, further divided into three sub-steps. Load step time in structural analysis was kept equal to thermal analysis. Fig. 4 illustrates the *von Mises* stresses fields of the butt joint after the entire specimen welding.

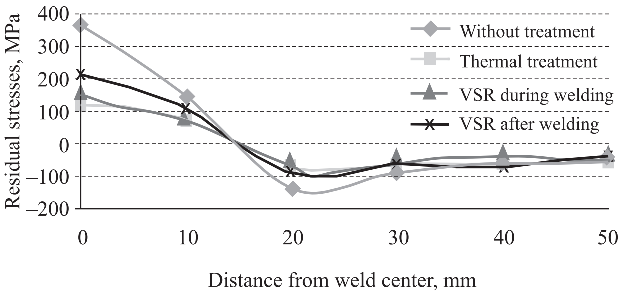

Fig. 3. Distribution of longitudinal residual stresses in specimens

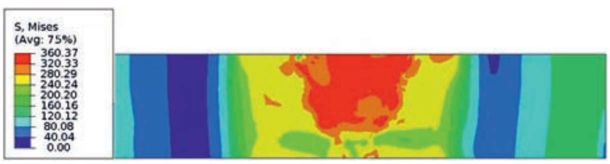

Fig. 4. Distribution of *von Mises* stresses, MPa

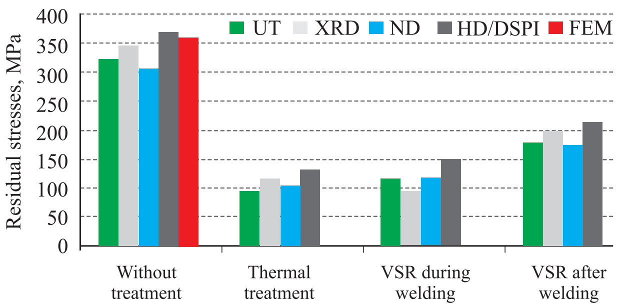

Fig. 5. Peak of longitudinal residual stresses in welded specimens, using different measurement techniques

The values of axial residual stresses calculated by the finite element method are compared with the experiments (Fig. 5). These results show that the computation finite element results are very close to the experimental results.

Diffraction analysis. X-ray diffraction measurements were conducted with a portable X-ray device *PROTO iXRD*. Cr-K_α radiation and (BCC, hkl-211) reflections were used to study residual stress distribution in weld region. The depth of the measurements was 50–100 mm on the specimen surface.

The neutron diffraction measurements were made using the (211) reflection, at the detector angle, 2θ, of approx 156°. Measurements were made with the scattering vector parallel to the three axes marked transverse, longitudinal and normal. The depth of the measurements was 5–8 mm on the specimen surface.

The analysis of X-ray and neutron diffraction indicates that the VSR treatment during welding reduced the peak of residual stresses more than 60%. It also revealed that after welding it reduced residual stresses peak more than 40% in the specimens. The results of diffraction research correlate with numerical and experimental analysis (UT, HD/DSPI methods) results (Fig. 5).

Common residual stress analysis comparison. Based on the comparison of peak points of residual welding stresses (Fig. 5), can be affirm that the vibration relief during welding reduces residual welding stresses on average by 60%, and the vibration relief after welding reduces residual welding stresses by approx 40%. The measurement results of the same point vary due to different measurement depths.

Based on the assessment of the change of residual welding stresses, measuring techniques and tools used, the residual stress measurement method suggested for application at the production or assembly sites is the ultrasonic method.

6. The effect of vibratory treatment on mechanical and technological properties of weldments

Tensile tests were performed according to requirements of standard *LST EN 895:1998 "Destructive Tests on Welds in Metallic Materials – Transverse Tensile Test"*. Analysis of the mechanical properties indicates that the VSR treatment does not have negative effect on the joint strength, in contrast to the TSR (Fig. 6). Elongation results outweigh minimal requirements by 20%. It was also established that the VSR treatment during welding increases the plasticity of the joint with no effect on strength properties.

Impact strength analysis was performed according to *LST EN 875:1998 "Destructive Tests on Welds in Metallic Materials – Impact Tests – Test Specimen Location, Notch Orientation and Examination"* recommendations for two different zones: weld metal and heat-affected zone. Temperature for all tests was –30 °C. For weld metal and HAZ impact strength study VWT 0/1 and VHT 1/1 specimen types were used respectively. Test results (Fig. 7) demonstrate that impact strength of specimens without treatment is the lowest of all specimens, but exceeds the min value of impact strength (33.8 J/cm^2) according *LST EN 10025-2:2005*, when test temperature is –30 °C. In addition, the analysis indicates that the VSR treatment after welding does not affect the weld metal and HAZ impact strength. Both the VSR treatment and thermal treatment during welding increases weld metal and HAZ impact strength.

Hardness tests. In micro-hardness tests universal *Zwick/Roell ZHU 2.5* electronic hardness tester was used, applying technique described in standard *LST EN 1043-2:1998 "Destructive Tests on Welds in Metallic Materials – Hardness Test – Part 2: Micro Hardness Testing on Welded Joints"*. Four measurement areas were made: parent metal, HAZ, weld metal and HAZ between welds. Thereby 12 measurements were carried out for each specimen. Hardness tests revealed that vibratory energy does not affect parent metal, weld and HAZ hardness. Max hardness value in HAZ near the melting line was 200 HV. The min hardness values estimated in welded metal was about 175 HV. Thermal stress relieve reduced the hardness of the weld significantly. Min hardness value in HAZ between welds was 141 HV.

Microstructure analysis. For the purpose of comparison, photographs of the joint microstructure of two specimens are presented here: the first is without any treatment (Fig. 8), while the second is pictured after the VSR during welding (Fig. 9). It is noted that due to the effect of vibration the size and shape of the grain differs from that of the specimen which was not treated with any method. Vibration affected solidification process and formed larger ferrite grains, because due to the changed of weld pool metal convection grains start to grow not from the solid crystals front surface but spontaneously from the spontaneous solidification centres formed in the liquid metal bulk. The number of such solidification centres which could grow is limited, thus the larger grain structure is being formed.

The analysis of technological properties was carried out in order to ground negative changes in welding joints caused by the VSR treatment. By changing welding positions (flat position, horizontal position, vertical up position), welding current and frequency of vibratory treatment, the welding penetrate depth, the form of a weldment and defects caused by vibration were analyzed.

Based on the test results of technological properties can be affirm that the vibration effect during welding reduces the penetrate depth, thus defects occur in multilayered weldments. The adequate joint shape and penetrate depth can be achieved by increasing the welding current by 10–20%. Due to the increase of the vibration effect, the penetrate depth decreases and excess metal is formed on the outer side of a joint. This happens due to the significantly changed convection. Reduction of the vibration effect by 5% results in the identical weldment to the one obtained

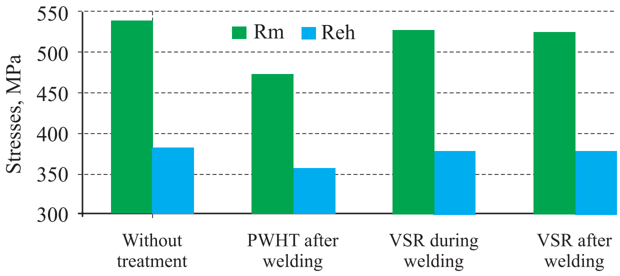

Fig. 6. The tensile test results

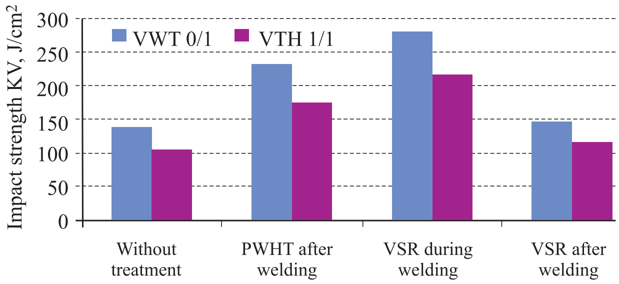

Fig. 7. The impact strength test results

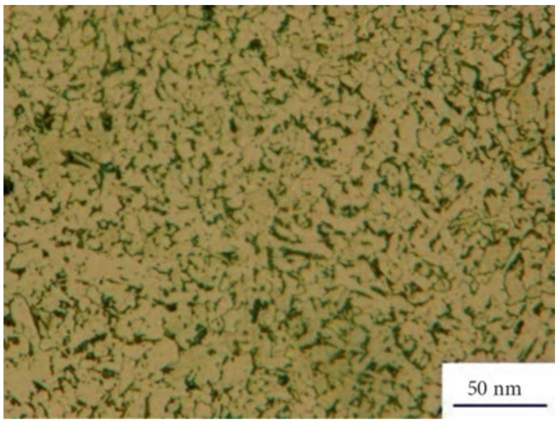

Fig. 8. Microstructure of welded metal (without treatment)

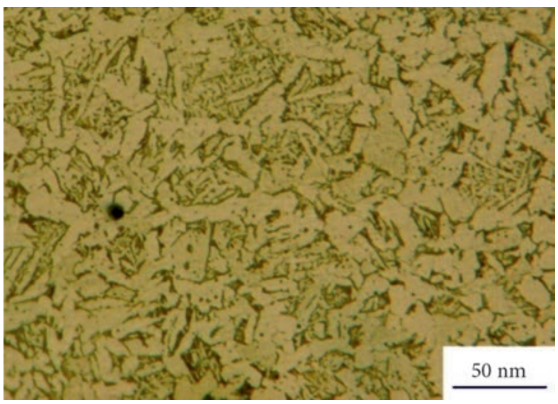

Fig. 9. Microstructure of welded metal (VSR during welding)

without vibration, but in this case residual stresses cannot be fully relieved. To avoid welding defects it is necessary to increase the welding current: for flat and horizontal welding positions – by 10–20% and for vertical up position by 10%.

7. Conclusions

Different residual stress measurement techniques confirmed that the effect of vibration *during welding* reduces peaks of residual welding stresses by approx 60%, *after welding* – approx 40%, and thermal relief reduces peaks by approx 62%. On this basis, the classical thermal method used to reduce residual welding stresses in structural steel weldments may be substituted by the VSR.

The linear dependency between surface ultrasonic longitudinal wave speed propagation and stresses was identified. The constants of structural steel acoustic elasticity were determined: for a basic metal $K_{PM} = -1.377 \times 10^{-5}$ MPa^{-1}, for a joint metal $K_{SZ} = -1.616 \times 10^{-5}$ MPa^{-1}. The surface longitudinal wave method is sensitive for probe pressing, therefore a weldment was levelled to the original metal surface prior the measurement of residual welding stresses. The distribution of residual stresses in specimens determined by ultrasonic method during the research correlates with the residual stress distribution resulting from using the diffraction and HD method. The depth of the surface wave propagation along the surface of the specimen reaches 2.5–3.0 mm. The algorithm designed for ultrasonic measurement of the residual stress can be easily applied at production and assembly sites.

The research shows that the X-ray diffraction analysis allows for identification of surface residual stresses only in the depth of 50–100 mm. This method is very sensitive to the quality of the material surface treatment and mobility of the required installations is limited. For these reasons, its application on the production or assembly sites is difficult; however the measurement process is contactless, reliable and fully automatic.

Neutron diffraction analysis shows that volumetric residual welding stresses in the depth of 5–8 mm are approx 12% lower than those at the surface of the weldment. The measurement method is characterized by a high precision level, does not require surface preparation, but is very time consuming and can be carried out under the laboratory conditions only.

The depth of residual stress measurement reached 1.5–2.0 mm when using the combined HD/DSPI method. The measurement of one point lasted up to 5 times shorter than measuring with the X-ray diffraction method, but yielded equivalent measurement precision level and depth of residual stresses. Due to the sensitivity to environmental vibrations, the application of this method at the production or assembly site is limited.

The distribution of residual stresses in the specimen section determined using the numerical method correlates with the results of experimental methods (UT, high resolution X-ray diffraction, ND, HD/DSPI methods). The max tensile stresses on the surface of the weldment reached 360 MPa.

The vibration stress relief *after welding* has no substantial effect on the strength, hardness and plasticity of the material. The TSR increases the plasticity ~70% of a welding joint, but it reduces the strength ~10% and hardness ~12%. Vibration *during welding* increases the plasticity of a weldment 2 times without changing the strength and hardness.

The vibration treatment affects the solidification of the weld pool metal. Due to the altered pool metal convection ferrite grains are larger, because they start to grow not from the solid crystals front surface but spontaneously from the spontaneous solidification centers formed in the liquid metal bulk.

The research shows that vibration reduces the penetration depth *during welding,* therefore defects are observed during the multilayer welding processes. In order to avoid welding defects it is necessary to increase the welding current: for flat and horizontal welding positions – by 10–20% and for vertical up position by 10%.

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