

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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EFFECT OF VIBRATORY TREATMENT ON RESIDUAL STRESSES IN STRUCTURAL STEEL WELDMENTS

SUMMARY OF DOCTORAL DISSERTATION

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Introduction

The rapid expansion of the industrial construction has increased the demand for steel structures and their workability requirements. There is a particular need to optimize the material use and to assess more accurately the structural resistance to dynamic loads and the corrosive effect. Most structures are joined by welding. Industrial structures such as tanks, bridges, pressure vessels, piping and other similar installations are made of 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. 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. However the practical problem arises when there is a need to assess the change in residual stresses in a real structure after applying vibratory stress relief 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 structure.

This dissertation deals with the effect of vibration energy application to residual welding stresses relief and to the weld metal structure itself. The aim of this study is to find the residual welding stresses assessment method that could be applied under field conditions.

Research object. The effect of the vibratory treatment on residual welding stresses in a structural steel and application of non-destructive control methods for residual stresses at the manufacturing or assembly site.

Aim and tasks of the work. The main aim of this work is to investigate the effectiveness of vibratory treatment method for reduction of residual welding stresses in a structure and to find the best non-destructive control method of residual stresses from the following methods: the magnetic metal memory, ultrasonic wave propagation, X-Ray diffraction, neutron diffraction and hole drilling technique. It is also necessary to evaluate the practical application of these methods at the manufacturing and assembly site.

This dissertation intends to examine the vibratory treatment application for

residual welding stress relief in order to highlight advantages of the method. The problem solving process is based on non-destructive control methods used for the identification of changes in residual welding stresses or their concentration areas after the vibratory treatment.

The dissertation also aims to identify the relationship between the mechanical properties of structural steel weldments and various technologies enabling the reduction of residual welding stresses.

The following tasks were set in order to achieve thesis objectives:

1. To investigate the effect of the vibratory treatment of weldment to residual stresses in steel weldments and possibilities to use different non-destructive stress measurement methods.
2. To suggest residual welding stress control methods to be used at the manufacturing or assembly site and to create an algorithm for the its implementation.
3. To indentify the distribution of residual welding stresses in the specimen section using numerical methods.
4. To examine the influence the vibration energy on steel weldability and to suggest operation modes in order to improve the welding technological properties.
5. To examine the change in mechanical properties and a microstructure after the vibratory treatment of weldments.

Methodology of research. Analytical and experimental methods of research as well as comparative analysis were applied in this dissertation. During the experiments the change of residual stresses and mechanical properties was examined using different techniques. The following modern methods were used in the research: X-Ray diffraction, neutron diffraction, magnetic metal memory, ultrasonic wave propagation, hole drilling, digital point pattern interferometry, optical microscopy, radiographic control and classical methods used for determination of mechanical properties.

Scientific novelty. The following scientific novelties were disclosed in the course of writing this thesis:

1. Interdependence between the ultrasonic surface wave propagation speed and stresses have been examined in a structural steel weldment and in a basic metal; the ultrasonic surface wave method application for measuring residual stresses after vibratory treatment has been investigated. The proposed stress measurement algorithm enables evaluation of the effect of vibration on residual stresses at the manufacturing or assembly site, where there are no possibilities to use other assessment methods.

2. Interdependence between mechanical properties of structural steel weldments and different technologies of the residual welding stress relief has been identified; effect of the vibration energy on technological weldability of structural steel has been investigated and operating modes improving technological properties of weldability during the vibratory treatment have been suggested.

Practical value. The vibratory treatment used for welding reduces residual welding stresses in a joint to the point which could be achieved only by applying thermal treatment. Due to the effect of vibratory treatment the weldment metal becomes softer and does not lose its strength and hardness.

Results of the ultrasonic research and the proposed stress measurement algorithm allow the assessment of the change in residual welding stresses after the vibratory treatment at the manufacturing or assembly site.

It is possible to determine the stress level of structural steel by using the magnetic metal memory method and to identify the change in concentration of residual welding stresses after the vibratory treatment.

Research has helped to determine the most appropriate modes for the vibratory treatment and welding. The application helps to improve the technological weldability of a structural steel and to effectively relieve residual welding stresses.

Based on the research results the vibratory treatment method could be suggested to the European Committee for Standardization for *inclusion in normative documents* describing production of steel constructions as an analogue to the thermal treatment method.

Defended propositions

1. The best method for measuring the change in residual welding stresses of structural steel joint after the vibratory treatment at the manufacturing or assembly site is the recording and analysis of the ultrasonic surface longitudinal wave propagation in the metal.
2. Different methods of residual welding stress relief in a joint determine mechanical properties and residual stress levels in weldments.
3. Defects occurring as a result of a simultaneous welding and vibratory treatment can be avoided by applying technological welding process measures.
4. Vibratory treatment can be applied to unlimited-size welding structures made of structural or clad steel.

The scope of the scientific work. The dissertation consists of an introduction, 4 chapters, conclusions, bibliography, list of publications and appendices.

The scope of the study – a total of 122 pages (without annexes), 94 figures and 9 tables. There are 7 annexes. The bibliography includes 57 sources.

1. Residual stresses, their relief and measurement techniques

The first chapter contains the reference literature review. This chapter provides an overview of residual welding stresses, their effect on a construction, stress reduction techniques and identification methods. The study focuses on the reduction of residual welding stresses using vibration energy and on the methods of stress change analysis; the dissertation aim is to assess practical applications on real industrial objects.

2. Experimental research methodology

The second chapter presents the research methodology. The experiments and their application is described, the layout of the instruments and their mode of operation, tests and treatment methods are presented.

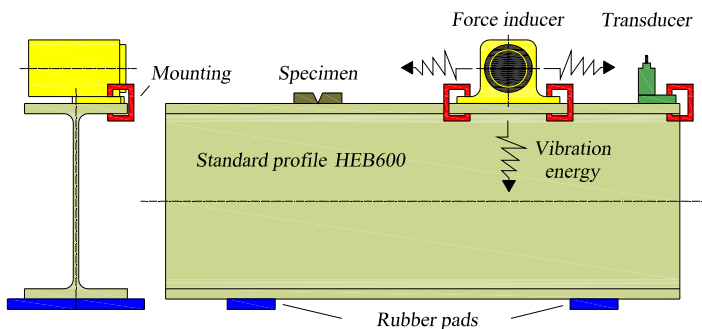


Fig. 1. Work-desk for vibratory treatment

The specimens were produced from S355J2 (LST EN 10025-2:2005) 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. 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: magnetic metal memory, ultrasonic wave propagation (UT), X-Ray diffraction (XRD), neutron diffraction (ND), hole drilling (HD/DSPI) and numerical (FEM).

3. Analysis of residual stress measurements

Metal magnetic memory analysis. The analysis of the results of the experiment has shown that the gradient of the magnetic field strength and stresses are related by the linear dependence. It was found that the greatest drop of the magnetic field strength gradient was in a metal yield strength zone. It suggests that this magnetic parameter can be used to diagnose the stressed and/or the destructive state of a metal.

The application of the metal magnetic memory method has shown that the vibration treatment after welding reduces the concentration of residual stresses by approx. 35%. The thermal treatment reduces the concentration of residual stresses by approx. 70%. The practical application of the metal magnetic memory method shows that the change of magnetic field strength in a structure before and after vibration treatment occurs, i.e. the concentration of residual welding stresses decreases. However, it is difficult to measure the level and direction of residual welding stresses by this method. Therefore, its application at the production or assembly sites is limited, because the obtained change does not confirm a specific effectiveness of the VSR.

Ultrasonic wave propagation analysis. The ultrasonic method (UT) 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 $K_{PM} = -1.377 \times 10^{-5} \text{ MPa}^{-1}$, for a weld metal $K_{SZ} = -1.616 \times 10^{-5} \text{ MPa}^{-1}$. The surface longitudinal wave method is sensitive for sensor pressing, therefore a weldment

was levelled to the original metal surface prior the measurement of residual welding stresses.

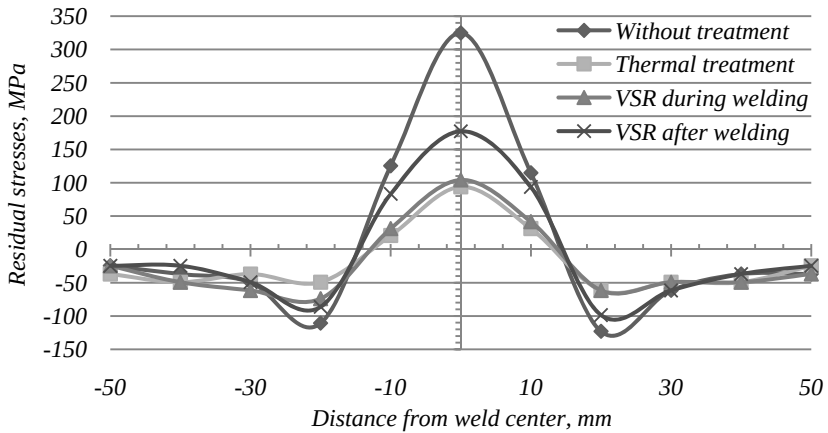


Fig. 2. Distribution of longitudinal residual stresses in specimens by ultrasonic technique

The analysis of ultrasonic wave propagation speed (Fig. 2) has shown that the maximum tensile stresses at the centre of a joint in specimens without application of any treatment were 324 MPa. The maximum 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) 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 load-

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

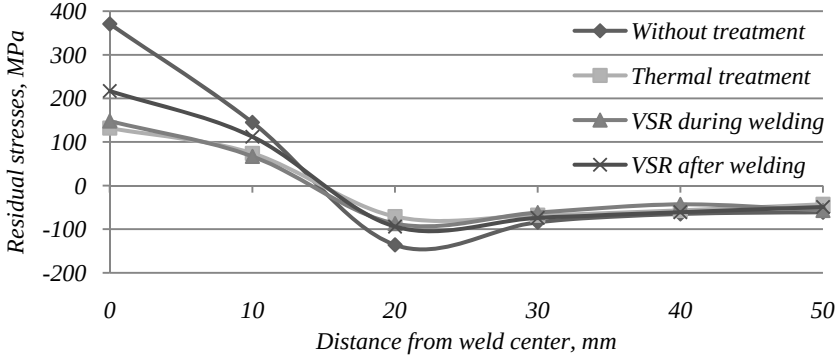


Fig. 3. Distribution of longitudinal residual stresses in specimens

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. Figure 4 illus-

trates the *von Mises* stresses fields of the butt joint after the entire specimen welding.

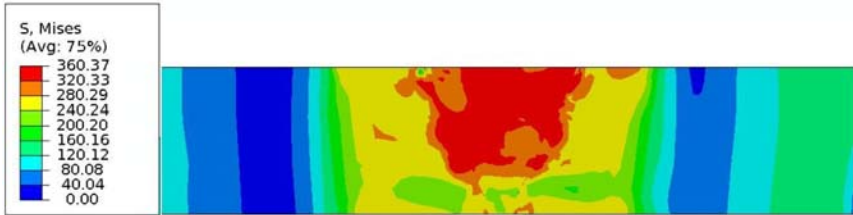


Fig. 4. Distribution of *von Mises* stresses, MPa

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 μm on the specimen surface.

The neutron diffraction measurements were made using the (211) reflection, at the detector angle, 2θ , of approximately 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 (FEM) and experimental analysis (UT, HD/DSPI) results (Fig. 5).

Common residual stress analysis comparison. Based on the comparison of peak points of residual welding stresses (Fig. 5), we can argue 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 sug-

gested for application at the production or assembly sites is the ultrasonic method.

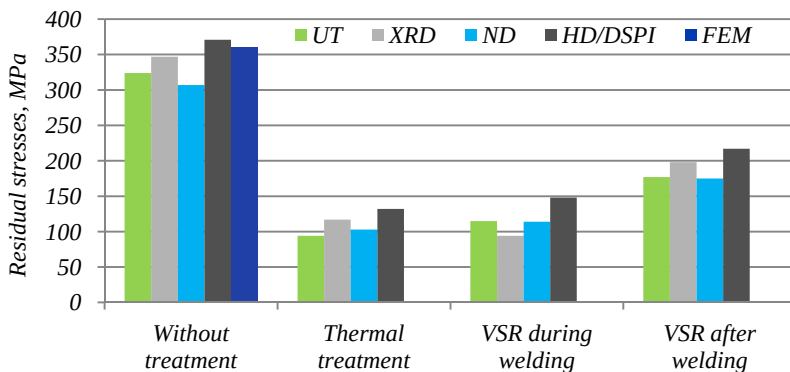


Fig. 5. Peak of longitudinal residual stresses in welded specimens, using different measurement techniques

4. 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. Analysis of the mechanical properties indicates that the VSR treatment does not have negative effect on the joint strength, in contrast to the thermal stress relief (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 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 minimum value of impact strength (33.8 J/cm^2) according LST EN 10025-2:2005 standard, 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.

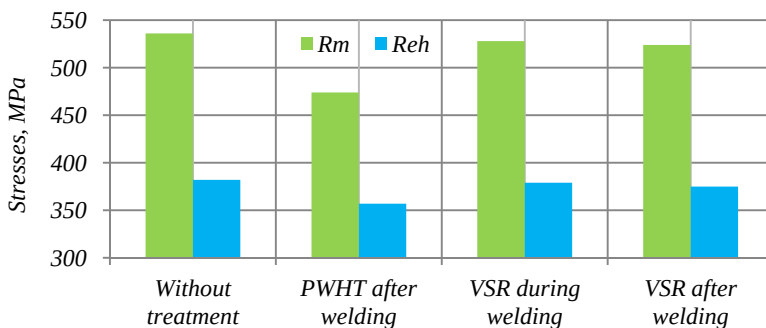


Fig. 6. The tensile test results

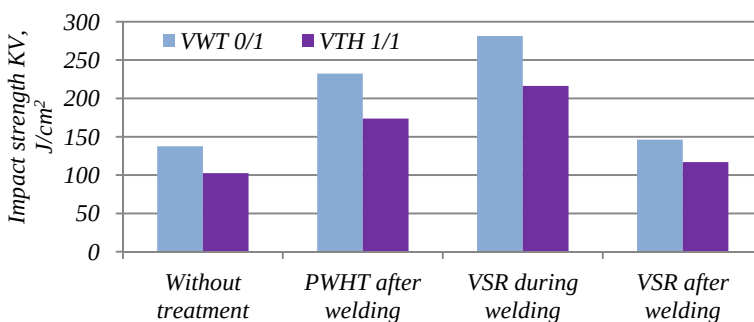


Fig. 7. The impact strength test results

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. 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. Maximum hardness value in HAZ near the melting line was 200 HV. The minimum hardness values estimated in welded metal was about 175 HV. Thermal stress relieve reduced the hardness of the weld significantly. Minimum 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 weld-

ing (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.

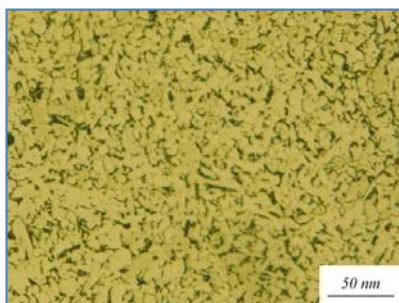


Fig. 8. Microstructure of welded metal (without treatment), zoom 1000×

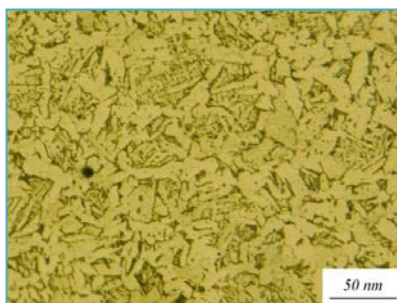


Fig. 9. Microstructure of welded metal (VSR during welding), zoom 1000×

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 we can argue 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 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%.

General conclusions

1. 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.

2. The research revealed that the magnetic field strength gradient and tensile stresses are related by the linear dependence, thus this metal magnetic memory method can be used when diagnosing the stressed state of a metal. The magnetic parameter expresses the concentration of residual welding stresses with a sudden change of the magnetic parameter at the peak of residual stress concentration. However, it is difficult to measure the level and direction of residual welding stresses using this method. Therefore, its application on the production or assembly site is limited, because the measurement results obtained change does not confirm the specific effectiveness of VSR.

3. 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 $K_{PM} = -1.377 \times 10^{-5} \text{ MPa}^{-1}$, for a joint metal $K_{SZ} = -1.616 \times 10^{-5} \text{ MPa}^{-1}$. 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 hole drilling method. The depth of the surface wave propagation along the surface of the specimen reaches 2.5–3 mm. The algorithm designed for ultrasonic measurement of the residual stress can be easily applied at production and assembly sites.

4. The research shows that the X-ray diffraction analysis allows for identification of surface residual stresses only in the depth of 50–100 μm . 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.

5. 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.

6. 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.

7. The distribution of residual stresses in the specimen section determined using the numerical method correlates with the results of experimental methods (UT, XRD, ND, HD/DSPI). The maximum tensile stresses on the surface of the weldment reached 360 MPa.

8. The vibration stress relief *after welding* has no substantial effect on the strength, hardness and plasticity of the material. The thermal stress relief 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.

9. 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 centres formed in the liquid metal bulk.

10. 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%.

List of publications on the dissertation topic in the peer-reviewed scientific journals

Jurčius, A.; Valiulis, A. V.; Černašėjus, O.; Kurzydowski, K. J.; Jaskiewicz, A.; Lech-Grega, M. 2010. Influence of vibratory stress relief on residual stresses in weldments and mechanical properties of structural steel joint, *Journal of Vibroengineering* 12(1): 133–141. ISSN 1392-8716 (Thomson ISI Web of Science).

Jurčius, A.; Valiulis, A. V.; Kumšlytis, V. 2008. Vibratory stress relieving – it's advantages as an alternative to thermal treatment, *Journal of Vibroengineering* 10(1): 123–127. ISSN 1392-8716 (Thomson ISI Web of Science).

In the other editions

Jurčius, A.; Valiulis, A. V.; Černašėjus, O. 2009. Effects of vibration energy input on stress concentration in weld and heat-affected zone of s355J2 steel, in *The 5th International Conference Mechatronic Systems and Materials MSM2009*, Vilnius, Lithuania, 2009. Solid state phenomena (Scopus), (accepted).

Jurčius, A.; Valiulis, A. V. 2009. Effects of vibration energy input on stress concentration in weld and heat-affected zone, in *Proc. of 14th International Conference Mechanika 2009, Kaunas, Lithuania, 2009*. Kaunas: Technologija, 171–177. ISSN 1822-2951 (Inspec).

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KONSTRUKCINIO PLIENO LIEKAMŲJŲ SUVIRINIMO ĮTEMPIŲ VIBRACINIO ATLEIDIMO TYRIMAI

Mokslo problemos aktualumas. Sparčiai augant plieninių konstrukcijų poreikiui, didėja joms keliami reikalavimai. Projektuojant konstrukcijas, siekiama kuo tiksliau nustatyti reikiamą metalo storį, įvertinti konstrukcijos elementų atsparumą apkrovoms bei aplinkos poveikiui. Pramoninės konstrukcijos, tokios kaip rezervuarai, tiltai, slėginiai indai, vamzdynai ir kiti panašūs įrenginiai gaminami iš konstrukcinio plieno. Šio plieno suvirinimo metu, ypač virinant daugiasluoksnes storasienių elementų siūles, sukeliami liekamieji suvirinimo įtempiai, kurie dažnai siekia arba net viršija medžiagos takumo ribą. Šiuos liekamuosius įtempius plieninių konstrukcijų gamybos standartai rekomenduoja termiškai atleisti, kai suvirinamos storesnės kaip 35 mm jungtys. Klasikinis, laiko patikrintas atleidimo metodas, yra terminis apdorojimas. Šio proceso metu palaikoma aukšta konstrukcijos temperatūra, po to lėtai aušinant pasiekiamas liekamųjų įtempių sumažėjimas. Yra žinoma, kad liekamuosius įtempius konstrukcijoje galima sumažinti ne tik terminiu būdu. Pasaulyje vibracinis metodas liekamųjų suvirinimo įtempių atleidimui sėkmingai taikomas daugiau kaip 30 metų. Šis metodas, lyginant su klasikiniu atleidimo metodu, pasižymi labai mažomis energijos, darbo ir laiko sąnaudomis. Tačiau po vibracinio apdorojimo būtina nustatyti liekamųjų įtempių pokytį konstrukcijoje. Tiksliais liekamųjų įtempių kontrolės metodais, tokiais kaip rentgeno spindulių ar neutronų difrakcija, galima išmatuoti įtempių pokytį konstrukcijoje tik laboratorijos sąlygomis. Todėl kyla sunkumų, norint įvertinti vibracijos energijos poveikį liekamiesiems suvirinimo įtempiams konstrukcijos gamybos ar surinkimo aikštelėje.

Disertacijoje nagrinėjamas vibracijos energijos poveikis liekamiesiems suvirinimo įtempiams ir konstrukcijos virintinėms jungtims. Siekiama rasti tinkamiausią liekamųjų suvirinimo įtempių įvertinimo metodą, kurį būtų galima taikyti lauko sąlygomis.

Tyrimo objektas – vibracinio apdorojimo poveikis konstrukcinio plieno suvirinimo liekamiesiems įtempiams bei neardomieji liekamųjų įtempių matavimo metodai, jų taikymas konstrukcijos gamybos ar surinkimo aikštelėje.

Darbo tikslas ir uždaviniai. Šio darbo pagrindinis tikslas yra ištirti kaip galima sumažinti liekamuosius suvirinimo įtempius konstrukcijoje vibraciniu būdu, tyrimus atliekant neardomosios kontrolės metodais: magnetinės metalo atminties, ultragarso bangos sklaidimo, rentgeno spindulių difrakcijos, neutronų difrakcijos, skylės gręžimo. Taip pat siekiama įvertinti tyrimui naudojamų metodų praktinį pritaikymą konstrukcijos gamybos ar surinkimo aikštelėje.

Disertacijoje numatoma nagrinėti vibracinio apdorojimo taikymo liekamųjų suvirinimo įtempių atleidimui problemą, siekiant atskleisti vibracijos energijos poveikį ir šio metodo teikiamus privalumus. Problemos sprendimas grindžiamas neardomosios kontrolės metodais, skirtais liekamųjų suvirinimo įtempių ar jų koncentracijos sričių pokyčio nustatymui, po vibracinio apdorojimo. Taip pat disertacijoje siekiama nustatyti konstrukcinio plieno suvirintų jungčių mechaninių savybių ir liekamųjų suvirinimo įtempių atleidimo technologijų tarpusavio priklausomybę.

Darbo tikslui pasiekti reikia spręsti šiuos uždavinius:

1. Įvairiais neardomais įtempių matavimo metodais, ištirti vibracinio apdorojimo poveikį liekamiesiems suvirinimo įtempiams konstrukcijoje.
2. Pasiūlyti konstrukcijos gamybos ar surinkimo aikštelėje tinkamą naudoti liekamųjų suvirinimo įtempių kontrolės metodiką bei sudaryti jos įgyvendinimo algoritmą.
3. Skaitiniu metodu nustatyti liekamųjų suvirinimo įtempių pasiskirstymą bandinio pjūvyje.
4. Ištirti vibracijos energijos poveikį suvirinamumui bei pasiūlyti technologines suvirinamumo savybes gerinančius darbo režimus.
5. Ištirti suvirintos jungties mechaninių savybių bei mikrostruktūros pokytį, kai suvirinimo jungtis apdorojama vibraciniu būdu.

Tyrimų metodika. Disertacijoje taikomi eksperimentiniai, skaitiniai bei lyginamieji tyrimo metodai. Eksperimentų metu buvo tiriami liekamųjų įtempių bei mechaninių savybių pokyčiai, taikant skirtingas įtempių atleidimo technologijas. Tyrimams buvo panaudoti šiuolaikiški metodai: rentgeno spindulių difrakcijos, neutronų difrakcijos, magnetinės metalo atminties, ultragarso, skylės gręžimo, skaitmeninio taško šablono interferometrijos, optinės mikroskopijos, radiografinės kontrolės bei klasikiniai mechaninių savybių nustatymo metodai.

Mokslinis naujumas. Rengiant disertaciją buvo gauti šie mechanikos inžinerijos mokslui nauji rezultatai:

1. Ištirta ultragarso paviršinės išilginės bangos sklaidimo greičio ir įtempių priklausomybė konstrukcinio plieno suvirinimo siūlėje bei pagrindiniame metalo; ištirtas ultragarso paviršinės išilginės bangos metodo taikymas liekamųjų įtempių įvertinimui po vibracinio apdorojimo. Taikant pasiūlytą įtempių matavimo algoritmą, galima įvertinti vibracijos poveikį liekamiesiems įtempiams konstrukcijos gamybos ar surinkimo aikštelėje, kuomet nėra galimybės taikyti kitų įvertinimo metodų.
2. Nustatyta konstrukcinio plieno suvirintų jungčių mechaninių savybių ir skirtingų atleidimo technologijų tarpusavio priklausomybė; ištirtas vibraci-

jos energijos poveikis konstrukcinio plieno suvirinamumui bei pasiūlyti darbo režimai, gerinantys technologines suvirinamumo savybes VSR metu.

Praktinė vertė. Vibracinis apdorojimas suvirinimo metu sumažina liekamuosius įtempius jungtyje iki lygio, pasiekiamo taikant terminį poveikį. Dėl vibracinio poveikio suvirinimo jungtis tampa plastiškesnė, nepraranda stiprumo bei kietumo.

Ultragarso paviršinės išilginės bangos metodas bei pasiūlytas įtempių matavimo algoritmas leidžia įvertinti liekamųjų suvirinimo įtempių pokytį po vibracinio apdorojimo konstrukcijos gamybos ar surinkimo aikštelėje.

Tyrimais nustatyti tinkamiausi vibracinio apdorojimo ir suvirinimo režimai. Juos taikant, pagerinamas konstrukcinio plieno technologinis suvirinamumas, efektyviai atleidžiami liekamieji suvirinimo įtempiai.

Remiantis tyrimų rezultatais, galima siūlyti Europos standartizacijos komisijai įtraukti vibracinio apdorojimo metodą į plieninių konstrukcijų gamybos norminius dokumentus, kaip analogą terminiam apdorojimui.

Ginamieji teiginiai

1. Patikimas būdas išmatuoti konstrukcinio plieno suvirintos jungties liekamųjų įtempių pokytį po vibracinio apdorojimo (konstrukcijos gamybos ar surinkimo aikštelėje) yra ultragarso paviršinės išilginės bangos sklaidimo metodu registravimas ir analizė.
2. Skirtingi liekamųjų suvirinimo įtempių atleidimo metodai sąlygoja plieno suvirintų jungčių mechanines savybes ir liekamųjų įtempių lygmenį.
3. Vibracinio apdorojimo suvirinimo metu sukeltų defektų galima išvengti naudojant technologines suvirinimo proceso priemones.
4. Vibracinį apdorojimą galima taikyti neribotų matmenų konstrukcijoms, pagamintoms iš paprasto ar plakiruoto konstrukcinio plieno.

Darbo apimtis. Disertaciją sudaro įvadas, 4 skyriai ir rezultatų apibendrinimas. Bendra disertacijos apimtis yra 122 puslapiai (be priedų), 94 paveikslai ir 9 lentelės. Taip pat yra 7 priedai. Rašant disertaciją buvo panaudoti 57 literatūros šaltiniai.

Pirmajame skyriuje pateikti atliktos literatūros analizės rezultatai ir suformuluoti uždaviniai. Antrajame skyriuje aprašyta bandymo metodų (VSR, terminio apdorojimo, magnetinės metalo atminties, UT, XRD, ND, HD/DSPI, FEM) esmė, taikymas, eksperimentų atlikimas bei rezultatų apdorojimas. Trečiajame skyriuje, eksperimentinėje dalyje, aprašyta vibracijos poveikio liekamiesiems suvirinimo įtempiams tyrimo eiga, gauti rezultatai ir jų analizė bei pateikti ginamųjų teiginių įrodymai. Ketvirtajame skyriuje aprašytas vibracijos

poveikis suvirintos jungties mechaninėms savybėms, mikrostruktūrai, suvirinamumui, pateikti tyrimo rezultatai ir jų analizė.

Bendrosios išvados

1. Taikant skirtingas liekamųjų įtempių matavimo technologijas, patvirtinta, kad vibracinis poveikis *suvininimo metu* mažina didžiausius liekamuosius suvininimo įtempius apie 60 %, *po suvininimo* – apie 40 %, o terminis atleidimas – apie 62 %. Tuo remiantis, klasikinis terminis įtempių atleidimo metodas konstrukcinio plieno suvirintų jungčių liekamiesiems įtempiams mažinti gali būti pakeistas vibraciniu atleidimo metodu.

2. Tyrimo metu nustatyta, kad magnetinio lauko stiprumo gradientą ir tempimo įtempius sieja tiesinė priklausomybė, todėl metalo magnetiniu atminties metodu galima nustatyti metalo įtemptą ir/arba deformuotą būvį. Magnetinis parametras liekamųjų suvininimo įtempių koncentraciją išreiškia staigiu magnetinio parametro pokyčiu ties liekamųjų įtempių koncentracijos piku. Šiuo metodu sunku įvertinti liekamųjų suvininimo įtempių dydį bei veikimo kryptį, todėl jo taikymas konstrukcijos gamybos ar surinkimo aikštelėje yra ribotas. Matavimų rezultatai nepatvirtina konkretaus VSR poveikio efektyvumo.

3. Nustatyta, kad ultragarso paviršinės išilginės bangos sklaidimo greitį metalė ir tempimo įtempius sieja tiesinė priklausomybė. Nustatytos konstrukcinio plieno akustinio tamprumo konstantos: pagrindiniam metalui $K_{PM} = -1,377 \times 10^{-5} \text{ MPa}^{-1}$, siūlės metalui $K_{SZ} = -1,616 \times 10^{-5} \text{ MPa}^{-1}$. Paviršinės išilginės bangos metodas jautrus jutiklio prispaudimui, todėl matuojant suvininimo siūlės įtempius reikia sulyginti suvininimo siūlę su pagrindiniu metalu. Tyrimo metu ultrgarsu nustatytas liekamųjų įtempių pasiskirstymas bandiniuose koreliuoja su difrakcijos bei skylės gręžimo metodu gautu įtempių pasiskirstymu. Paviršinės ultragarso bangos sklaidimo gylis bandinio paviršiuje siekia 2,5–3 mm gyly. Sukurtas liekamųjų įtempių nustatymo ultrgarsu algoritmas lengvai taikomas konstrukcijos gamybos ir surinkimo aikštelėje.

4. Tyrimo metu nustatyta, kad rentgeno spindulių difrakcija galima išmatuoti tik paviršinius liekamuosius įtempius 50–100 μm gylyje. Ši matavimo technologija labai jautri medžiagos paviršiaus apdirbimo kokybei, be to įrangos mobilumas ribotas. Dėl šių priežasčių rentgeno spindulių difrakcijos metodo taikymas konstrukcijos gamybos ar surinkimo aikštelėje yra sudėtingas, tačiau įtempių matavimo procesas bekontakts, patikimas bei pilnai automatizuotas.

5. Neutronų difrakcijos tyrimais nustatyta, kad tūriniai (5–8 mm gylyje) liekamieji suvininimo įtempiai ~ 12 % mažesni negu įtempiai suvirintos jungties paviršiuje. Matavimo metodas yra labai tikslus, nereikalingas matuojamo pavir-

šiaus paruošimas, tačiau liekamųjų įtempių matavimai trunka labai ilgai, o tyrimai galimi tik laboratorijoje.

6. Kombinuotu HD/DSPI metodu liekamųjų įtempių matavimo gylis siekė 1,5–2,0 mm. Vieno taško matavimas truko iki 5 kartų greičiau negu matuojant rentgeno spindulių difrakcijos metodu, tačiau abiejų metodų matavimo tikslumas ir matuojamų įtempių gylis yra tapatūs. Dėl didelio jautrumo aplinkos virpesiams, HD/DSPI įtempių matavimo technologijos taikymas konstrukcijos gamybos ar surinkimo aikštelėje yra ribotas.

7. Skaitiniu būdu nustatytas liekamųjų įtempių pasiskirstymas bandinio pjūvyje koreliuoja su eksperimentinių metodų (UT, XRD, ND, HD/DSPI) gautais rezultatais. FEM analizė parodė, kad po suvirinimo maksimalūs tempimo įtempiai jungties paviršiuje siekia 360 MPa.

8. Vibracinis įtempių atleidimas *po suvirinimo* neturi esminio poveikio medžiagos stiprumui, plastiškumui bei kietumui. Terminis liekamųjų įtempių atleidimas didina suvirintos jungties plastiškumą ~70 %, tačiau mažina stiprumą ~10 % bei kietumą ~12 %. Vibracija *suvirinimo metu* didina suvirintos jungties plastiškumą 2 kartus, nekeisdama stiprumo bei kietumo, priešingai negu terminis įtempių atleidimas.

9. Vibracinis apdorojimas turi įtakos suvirinimo siūlės metalo kristalizacijai. Dėl pakitusios skysto metalo konvekcijos vonelėje kristalizuojasi stambesni ferito grūdėliai, nes nauji kristalai pradeda augti ne nuo kieto kristalizacijos fronto paviršiaus, o spontaniškai nuo savaiminių kristalizacijos centrų, susidariusių skysto metalo tūryje.

10. Tyrimo metu nustatyta, kad vibracija *suvirinimo metu* mažina įvirinimo gylį, todėl daugiasluoksnio suvirinimo metu atsiranda nesulydymo defektai. Siekiant išvengti šių defektų būtina padidinti suvirinimo srovę: PA ir PC suvirinimo padėtims 10–20 %, PF padėčiai iki 10 %.

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IN STRUCTURAL STEEL WELDMENTS

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