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EFFECT OF VIBRATION ON THE VARIATION OF RESIDUAL STRESSES AND IMPACT ENERGY IN BUTT-WELDED JOINTS

UTICAJ VIBRACIJA NA PROMENU ZAOSTALIH NAPONA I ENERGIJE UDARA KOD SUČEONO ZAVARENIH SPOJEVA

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Keywords
- welding
- residual stresses
- vibration
- impact energy

Abstract

The effect of vibration on the variation of residual stresses in butt-welded steel plates and on the impact energy in characteristic zones of a welded joint is analysed in this paper. An important segment occurring as a result of welding is the phenomenon of residual stresses in the welded joint zone. Residual stress measurements are conducted both on butt-welded plates that were not vibrated during welding and on plates simultaneously welded and vibrated. It is concluded that the vibration process noticeably decreases the level of stresses in the zone of the butt weld, i.e. the result is relaxation and plane stress state. Impact energy tests have shown that vibration favourably affects the total impact energy by increasing it both in specimens notched in the weld metal (WM) and in the heat-affected zone (HAZ). It is also concluded that the correlation between the distribution of crack initiation- and crack propagation energy, as vital components in the assessment of welded joint ductility, is improved.

Ključne reči
- zavarivanje
- zaostali naponi
- vibracije
- energija udara

Izvod

Istraživanje uticaja vibracija na promenu zaostalih napona kod sučeono zavarenih čeličnih ploča i promena energije udara u karakterističnim zonama zavarenog spoja analizirana je u ovom radu. Bitan segment, koji se javlja kao posledica zavarivanja, je pojava zaostalih napona u zoni zavarenog spoja. Merenje zaostalih napona je rađeno na sučeono zavarenim pločama koje nisu vibrirane u toku zavarivanja i kod ploča koje su istovremeno zavarivane i vibrirane. Uočeno je da proces vibracija znatno smanjuje nivo zaostalih napona u zoni sučeono zavarenog spoja, odnosno, dolazi do relaksacije i uravnoteženja stanja napona. Ispitivanja energije udara su pokazala da vibracije pozitivno utiču na povećanje ukupne energije udara i kod epruveta sa zarezom u metalu šava i u zoni uticaja toplote. Uočen je i bolji odnos raspodele energije stvaranja i energije širenja prsline, kao važnih komponenti u oceni plastičnosti zavarenog spoja.

INTRODUCTION

It is generally known that high input heat and the molten metal in welded joints induce high residual tensile stresses, often accompanied by unfavourable modifications in the HAZ structure. The separation of effects of certain factors, e.g. two unfavourable effects in particular – residual stresses and modification of microstructure on the fracture resistance of a welded structure becomes increasingly important. In order to reduce residual stresses, welded joints should be heat treated after welding. This rule dates back to more than half a century, and it is not entirely applicable to newly produced steel grades and modern welding technologies. More precisely, the post-weld heat treatment relaxation of residual stresses has some negative effects due to metallurgical modifications that disrupt fracture and fatigue behaviour of a welded structure. The behaviour of an untreated welded joint is unpredictable. It is not only because of the quantity of residual stresses whose maximal values are almost equal to yield stress, $R_{p0.2}$, but also because of the distribution of residual stresses depending on numerous factors: base and filler metal properties, notch shape, number of passes of input heat, presence of defects and HAZ properties. Through control of residual stresses, one can affect the behaviour and exploitation life of materials, especially if exposed to effects of varied loading, /1/.

The main purpose of vibration tests of a welded structure is to decrease the effect of residual stresses and to improve the quality of their redistribution in the welded joint zone. In many papers, the benefit of vibrations during welding has been discussed, but the effects of vibration on impact energy, the material properties defining quality selection of the material, material ductility, and hence, structural safety, /2, 3/, has rarely been taken into consideration.

EXPERIMENTS

The equipment for vibro-relaxation (type of vibrator, measuring equipment for control of operating parameters, measuring equipment for control of stress states induced by vibrations) should be selected based on the parameters of the technology. The plan of relaxation defines the complete technology of relaxation for each stage in the fabrication of the structure.

For realisation of the exciting force, pneumatic vibrators with a rotating ring are practical as they cover a wide range of pulsing forces (0.105–20.0 kN) and operating frequencies (20–400 Hz). Control of operating pressure and air flow, as well as varying the ring mass, ensure necessary operating parameters of excitation.

Relaxation time is defined depending on the aim aspired to – attainment of imposed level of residual stresses. As a rule, during the whole process of relaxation, the values of relaxation of the stress-strain state and possible fatigue of the structure should be under strict control. Former experiences have shown that, due to the character of the process, vibration treatment lasting too long has little effect on the relaxation of residual stresses, but its effect on the dynamic fatigue of the structure is essential.

Material and welding technology

The material under consideration is a common structural steel S235JR of tensile strength $R_m = 420$ MPa and yield limit $R_{p0,2} = 337$ MPa, /1/.

Basic data on the selection of the welding technology:

- automatic, CO_2-gas shield;
- flow: 12–17 l/min;
- wire diameter: 0.8–1.2 mm;
- current: 125–300 A;
- welding rate: 0.35–0.55 m/min.;
- voltage: 18–22 V;
- distance between gas nozzle and work piece: 12–14 mm.

During the welding process the plate is exposed to vibration treatment with an amplitude of 0.5 mm and frequency of 64 Hz. Vibration relaxation developed both during the process of welding and during the process of plate cooling to ambient temperature, /1/.

Determination of residual strain-stress state

Effects of residual stresses may be both useful and detrimental, depending on the grain size and distribution of the stresses relative to stresses induced by in-service loading. Residual stresses are often detrimental, and there are numerous case studies where these stresses were a decisive factor contributing to material fatigue and the failure of structures. Particularly, an important aspect of residual stresses is that one cannot recognize their presence and, until recently, there were no methods for measuring residual stresses without the complete destruction of a structural part or the whole structure, /4/.

A most often used and most reliable modern technique for measuring residual stresses is the “hole drilling” method /5/. The hole drilling method belongs to the category of semi-destructive methods, as in most cases a small hole cannot noticeably weaken the structural integrity. The hole diameter is usually 1.5–3.0 mm, and the same as its depth. The drilled hole may be blocked after measuring residual stresses. Drilling of the hole (even of a very small diameter) in the material having residual stresses releases stress in the zone of measurement, because the stress that is normal to a certain free surface (in this case, the hole surface) must be zero. Elimination of the normal stress at the hole boundary reduces the stress in the nearby surrounding region, inducing variation of local-surface strain. Measurement of strains induced by stress release provides the data necessary for calculating the initial residual stress states in the measurement zone, /6/.

Strain gauges, rosettes with a hole 1.5/120 RY 61 are used for determining residual (individual) strains and the stress state in steel plates with welded joints located at the centre. Compensation of temperature variations is made using three strain gauges 6/120 LY 11. The rosettes are glued as shown in Figs 1 and 2. Residual stresses are determined experimentally in the region of longitudinal welded joint, using the standard hole-drilling method for central-hole drilling (ASTM E837), /5/. For data acquisition, the Spider 8 device was used.

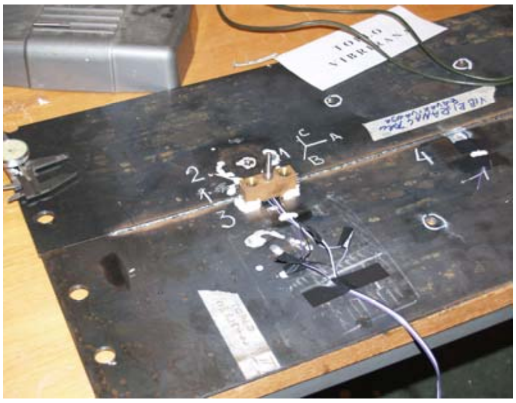

Figure 1. Welded plate, vibrated during welding.
Slika 1. Zavarena ploča, obrađena vibracijama pri zavarivanju

Figure 2. Non-vibrated welded plate.
Slika 2. Ploča zavarena bez vibracija

Upon gluing of hole-provided rosettes and connecting to the Spider 8 electronic device, the holes are drilled in order to register residual (individual) strains. First, the centring tool of a special drill is fitted, and the hole is drilled. After drilling the holes, the strain state is registered with all rosettes: $\Delta\varepsilon_a$, $\Delta\varepsilon_b$, and $\Delta\varepsilon_c$.

Based on these values, we are able to calculate the principle normal stresses, σ_1 and σ_2. The stresses are calculated according to:

$$\sigma_{1,2} = -A^*(\Delta\varepsilon_a + \Delta\varepsilon_c) \pm \\ \pm B^* \sqrt{(\Delta\varepsilon_a + \Delta\varepsilon_c - 2\cdot\Delta\varepsilon_b)^2 + (\Delta\varepsilon_c - \Delta\varepsilon_a)^2} \tag{1}$$

Values A^* and B^* can be found in literature for various elastic modules, E, and Poisson's coefficients. These values relate to geometric parameters of the rosette RY 61, strain gauge 1, Fig. 3, taken as a reference direction. The principle direction 1 can be found after calculating the angle of orientation in the mathematically positive direction of movement relative to the referential direction. Principle direction 2 is normal to principle direction 1.

The angle of orientation φ is calculated according to:

$$tg2\theta = \frac{\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b}{\Delta\varepsilon_c - \Delta\varepsilon_a} \tag{2}$$

$$\theta = \frac{1}{2}\arctan\frac{\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b}{\Delta\varepsilon_c - \Delta\varepsilon_a} \tag{3}$$

The results of measurement are given in Tables 1 and 2, where the angle of maximal principle residual stress is denoted by θ.

Data from test locations 1 and 2 were taken when the plates were in the tool, so that bending was also present which was noticeable when the screws holding the plate were released and the plate had deformed (see in Figs).

Table 1. Results of measurement of residual (individual) stresses – non-vibrated.
Tabela 1. Rezultati merenja zaostalih napona – bez vibracija

Test location	Strain gage 1, ε_a	Strain gage 2, ε_b	Strain gage 3, ε_c	Voltage σ_1	Voltage σ_2	Angle θ_1
1	-199	-165	-91	283.0	211.7	10.2
2	-178	-165	-88	261.0	192.7	17.7
3	-155	-111	-81	224.6	178.0	-5.4
4	-203	-154	-45	263.8	159.2	10.4

Table 2. Results of measurement of residual (individual) stresses – vibrated.
Tabela 2. Rezultati merenja zaostalih napona – sa vibracijama

Test location	Strain gage 1, ε_a	Strain gage 2, ε_b	Strain gage 3, ε_c	Voltage σ_1	Voltage σ_2	Angle θ_1
5	-159	-155	-32	216.7	109.1	21.6
6	-158	-144	-51	219.4	137.1	18.2

Based on results obtained and relevant analysis, one can conclude that the values of residual (individual) stresses obtained are very high. Residual (individual) stresses are lower in the case of the vibrated plate than in the case of the non-vibrated plate. This means that residual stresses induced during welding are noticeably lower if the structure in the welding process is exposed to certain modes of vibration, as in that way better redistribution (relaxation) of individual stresses already present in the material and stresses induced during welding is attained.

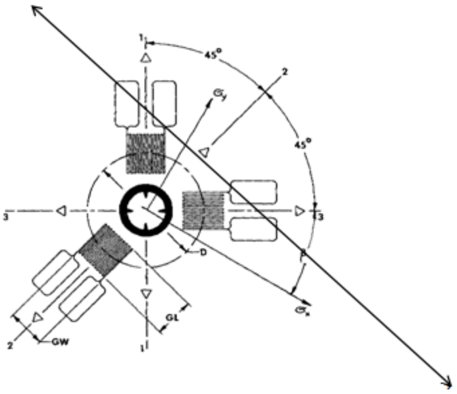

Figure 3. Scheme of the rosette strain gauges, 6/120 RY 11, /7/.
Slika 3. Shema merne rozete 6/120 RY 11, /7/

Determination of impact energy

Testing by bending induced by the impact effect of force on a notched specimen can provide an explanation of material behaviour for disrupted strain, i.e. at volumetric stress rate. Determination of the operation leading to fracture under established test conditions is most frequently used for the current control of the quality and homogeneity of the material, as well as of its treatment. This test procedure provides the possibility to establish susceptibility to brittle fracture, i.e. susceptibility to the increase of brittleness during exploitation (aging).

In order to determine the total impact energy, impact testing of specimens V-2 notched in the weld metal (WM) and the heat-affected zone (HAZ) is conducted according to standards EN 10045-1, /8/, and ASTM E23-01, /9/, respectively, with specimen geometry and appearance as shown in Fig. 4. As a rule, the notch is made by milling in order to avoid modification of the material state during the treatment. No visible traces of machining are allowed at the base of the notch.

The fracture energy is determined as an integral (magnitude) by testing the bending induced in impact loading. Thus, the determined fracture energy provides no possibility to separate the material resistance to crack initiation from the resistance to crack propagation. To make it possible, the impact force and time should be continuously registered during the test, which can be attained by instrumentation of the pendulum. Instrumentation of the pendulum includes the connection of the force meter installed in the pendulum hammer, a fracture-time detector and a strain meter through an amplifier with ultra high-speed A/D card. As the specimen fracture induced by impact is a short-time phenomenon (0.5–12 ms), the role of the amplifier with ultra high-speed A/D card is to make registered signals visible.

Tests on the instrumented pendulum with an oscilloscope provided force–time and energy–time diagrams, enabling analysis of test results - the assessment of the effects of V-2 notching on the total impact energy, A_t, and its components, crack initiation energy, A_i, and crack propagation energy, A_p, in the first place.

Impact tests of specimens sampled from welded plates of S235JR steel, first one non-vibrated and the second a vibrated specimen, are conducted at 20°C. The testing itself is conducted on the instrumented SCHENCK TREBEL 150 J Charpy pendulum. Two groups of specimens are tested, depending on the location of the V-2 notches as follows:

– I group, specimens with V-2 notches in the weld metal,
– II group, specimens with V-2 notches in the HAZ.

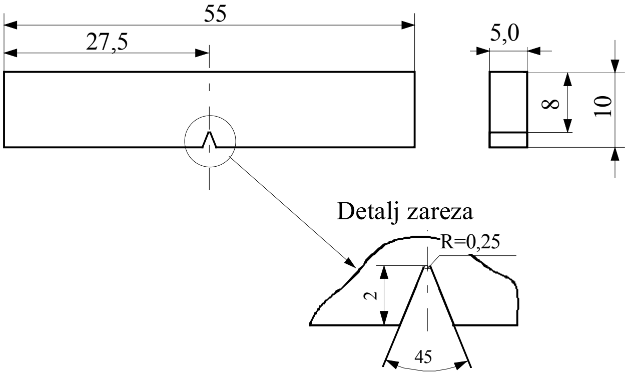

Figure 4. Shape and dimensions of standard specimen for Charpy pendulum impact testing of V-notched specimens.
Slika 4. Oblik i dimenzije standardne epruvete za Šarpi udarno ispitivanje epruveta sa V zarezom

Results of impact tests are presented in Table 3 for specimens sampled from the non-vibrated plate, and in Table 4 for specimens sampled from the vibrated plate.

Table 3. Results of impact tests of specimens sampled from the non-vibrated plate.
Tabela 3. Rezultati ispitivanja udarom za epruvete uzete iz ploče bez vibracija

Specimen designation	Total impact energy, A_t, J	Crack initiation energy, A_I, J	Crack propagation energy, A_P, J
WM-1n	21	10	11
WM-2n	17	10	7
VM-3n	18	10	8
HAZ-1n	49	16	33
HAZ-2n	46	15	31
HAZ-3n	43	15	28

Table 4. Results of impact tests of specimens sampled from the vibrated plate.
Tabela 4. Rezultati ispitivanja udarom za epruvete uzete iz ploče sa vibracijama

Specimen designation	Total impact energy, A_t, J	Crack initiation energy, A_I, J	Crack propagation energy, A_P, J
WM-1v	26	10	16
WM-2v	24	9	15
WM-3v	28	10	18
HAZ-1v	52	15	37
HAZ-2v	55	16	39
HAZ-3v	56	16	40

The Charpy pendulum impact test with an oscilloscope provided two types of diagrams as follows: force–time and energy–time. Characteristic diagrams obtained by testing specimens with V-2 notch in WM, sampled from both non-vibrated and vibrated plates, are shown in Figs. 5 and 6, respectively. Diagrams obtained by testing specimens with the V-2 notch in HAZ, sampled from both non-vibrated and vibrated plates are shown in Figs. 7 and 8, respectively. Other diagrams are not presented as they indicate the same character of behaviour of the tested specimens.

Values obtained for total impact energy depend on the notch location, and on whether the plate from which the specimens are sampled has been vibrated or not. The effect of the vibration process is favourable, as values obtained for total impact energy are higher by almost by 30% for specimens with a notch in the WM and by approx. 18% for specimens with a notch in the HAZ, /10/.

It is particularly important to emphasize the correlation between the components of the total impact energy, i.e. the crack-initiation- and crack-propagation energy. The process of vibration improves the correlation between the crack-propagation- and crack-initiation energies in favour of the crack-propagation energy as a ductile component of fracture. We have a case study where the values of the crack-initiation energy obtained, i.e. brittle fracture components, are almost identical for both groups of specimens, while the values of the crack-propagation energy, i.e. ductile fracture components, are noticeably higher for specimens sampled from vibrated plates.

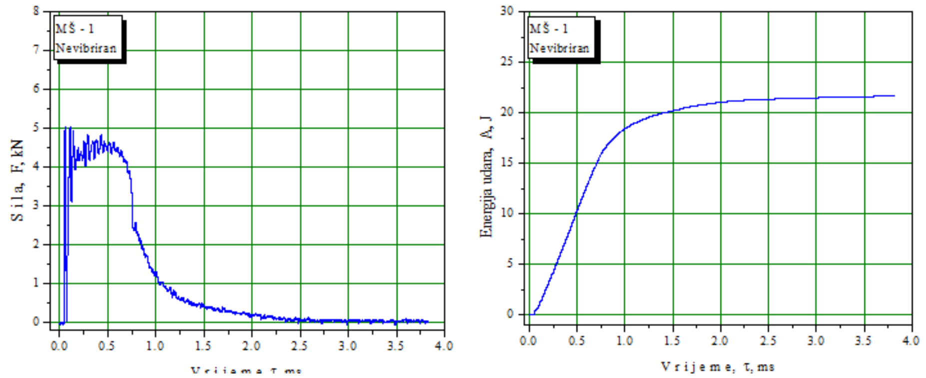

Figure 5. Diagrams obtained by impact test of specimen WM-1n.
Slika 5. Dijagrami ispitivanja udarom za uzorak WM-1n

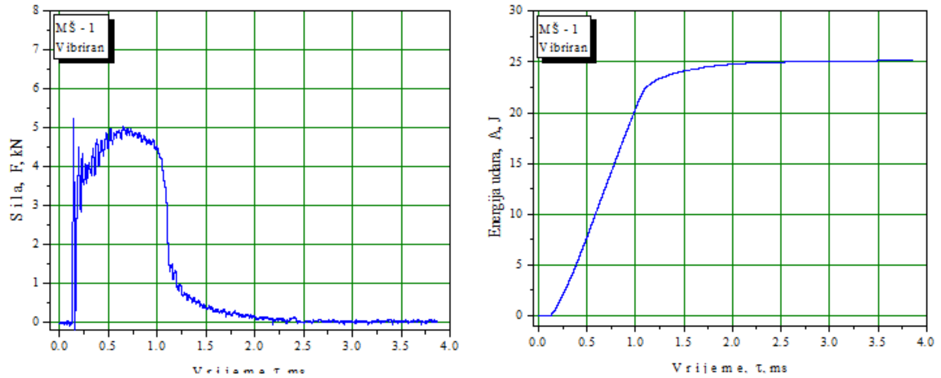

Figure 6. Diagrams obtained by impact test of specimen WM-1v.
Slika 6. Dijagrami ispitivanja udarom za uzorak WM-1v

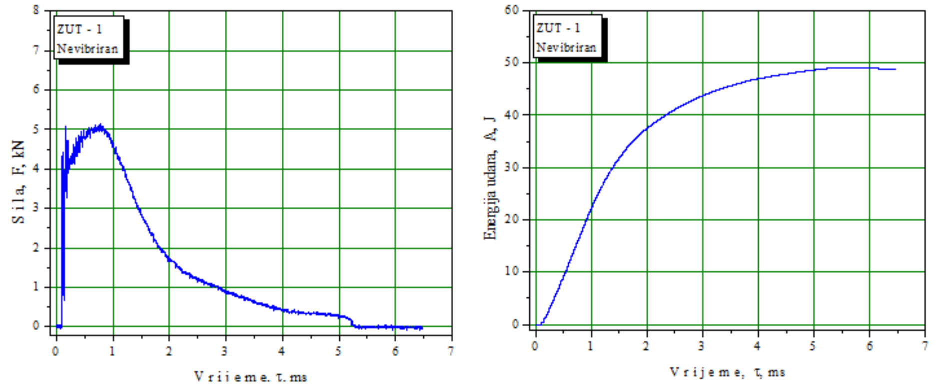

Figure 7. Diagrams obtained by impact test of specimen HAZ-1n.
Slika 7. Dijagrami ispitivanja udarom za uzorak HAZ-1n

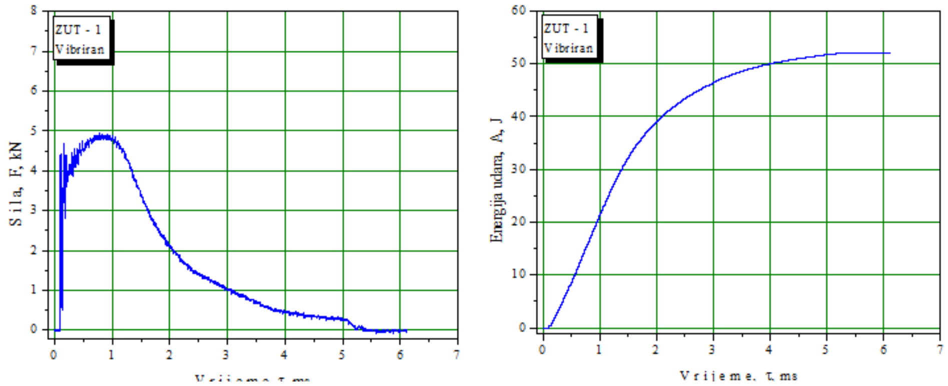

Figure 8. Diagrams obtained by impact test of specimen HAZ-1v.
Slika 8. Dijagrami ispitivanja udarom za uzorak HAZ-1v

CONCLUSION

Based on results obtained by measurements and analysis, the following can be concluded:

- Values obtained for residual stresses are very high. Residual (individual) stresses are lower in case of vibrated plate than in case of non-vibrated plate. It means that the residual stresses induced during welding are noticeably lower if the structure is vibrated in welding, as in that way a better redistribution (relaxation) of individual stresses, already present in the material and stresses induced during welding, is attained.
- Results obtained by testing the impact energy of vibrated plate in WM and HAZ are noticeably better than those for the plate that is not vibrated during welding. The process of vibration improves the correlation between the crack-propagation energy and the crack-initiation energy, in favour of the crack-propagation energy, as a ductile fracture component.

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Key Dates

Abstract submission deadline: 28 February 2013
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