346. Vibratory stress relieving – It's advantages as an alternative to thermal treatment

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Abstract. The aim of this study was to investigate the use of vibration to reduce the residual stress resulting from the welding process. Butt weld joints were subjected to vibration immediately after welding. The existing methods for relieving residual stress from welds are: mechanical, heat and electromagnetic. The mechanical method may be performed by hammering or vibration. The heat method consists of heating the whole welded piece or each weld, one by one. The electromagnetic method uses the electromagnetic hammer technique. In the heat treatment the part is heated until the yield point is reduced to less than the residual stress, which in turn causes local plastic distortion, decrease of the residual stress intensity and reduction of hardness. The vibration method introduces energy into the part by means of vibrations. For the stressed atomic structure there is no difference between the energy introduced through heat and the energy introduced through vibrations. The applied energy reorganizes the crystalline structure, relieving stress and stabilizing the piece, without distortion [1].

The article deals with reducement of welding stresses with the help of vibration treatment and to compare it with the classical heat treatment. The experiments were performed by a welding of structural low-alloy steel 16GS plates. Therefore the result is submitted by the mechanical tests and metal magnetic memory control.

Several specimens, after welding and vibrotreatment, were cut off the welded plates and submitted for tensile, impact, hardness tests and metallographic analysis.

The specimens, which were treated by vibration treatment, had strength and elasticity properties changed similarly as after the heat treatment. The metal magnetic memory test shows that this control method is suitable for evaluation of residual welding stresses variations after the weldment's treatment.

***Keywords*:** welded joints, residual stresses, vibratory stress relief, thermal treatment.

INTRODUCTION

Thermal stress relief, however, can have certain adverse effects such as scaling, discoloration, distortion, metallurgical changes in the microstructure, etc. It is also, time consuming and, with increasing energy costs very expensive. Since residual stresses are developed to some degree in every machining operation, there are many situations where it would be advantageous to stabilize the part at several stages of fabrication. Thermal cycling would be impractical in these cases. Also, large components like oil storage tanks, bridge structures, and similar structures are impossible or impractical to stress relieve by thermal treatments. In this background, an alternative technique of stress relief that employs mechanical vibration has emerged. This process is called vibratory stress relief (VSR) [2].

The major interest in vibration stress relief has been its relative simplicity compared with thermal stress relief. For instance, compared with thermal stress relief equipment commercially available, vibratory stress relief equipment is far less expensive, requires considerably less time for the stress relief treatment, is more portable, generally occupies less floor space, and causes no oxide scale formation. However, there is little experience in predicting the effectiveness of the treatment and there is little quantitative information on the method effectiveness or magnitude of any effects and the mechanism involved. In the absence of such quantitative information, it is difficult to determine when and where vibratory stress relief may be effectively applied, particularly in massive complex fabrications.

The present study was undertaken to provide some quantitative data on the vibratory stress relief process applied to 16GS mild steel butt welds. The various phases of this study focused on the analysis of vibration, residual stress analysis using metal magnetic storage techniques, and the effect of vibration on the mechanical properties of the weldments. This comprehensive study is unique in that it combines vibration methodology, thermal methodology, residual stress analysis, microstructural analysis, mechanical testing and metal magnetic storage.

The VSR depend on following circumstances [3]:

a) Vibration energy is induced into and absorbed by the metal at a frequency just below the peak. This is the proper frequency for best results. Vibrating at the peak amplitude frequency causes plastic deformation and fatigue. In Fig. 1, the straight line (E) represents the constant rise in vibrational energy output as the frequency of vibration increases. The curved line (A) represents the amplitude profile of a metal component vibrating at the same frequencies. At certain frequency the vibration amplitude rapidly increases or "jumps" and create a harmonic (resonant) condition. The maximum differential of energy output to work done (amplitude) is at a frequency immediately before the harmonic (X). That frequency will be used to determine the dwell time.
b) This principle was developed to determine how long conditioning time is required to provided sufficient treatment. The required conditioning (dwell) time is defined as time is needed for the harmonic peak frequency to relocate and stabilize.

$$Frequency = \frac{SS \cdot S \cdot E}{\dfrac{VW + EW}{VL} \cdot L}; \qquad (1)$$

there SS – supporting system; S – strength; E – elasticity; VW – vibrating weight; EW – eccentric weight; VL – vibrating location; L – length.

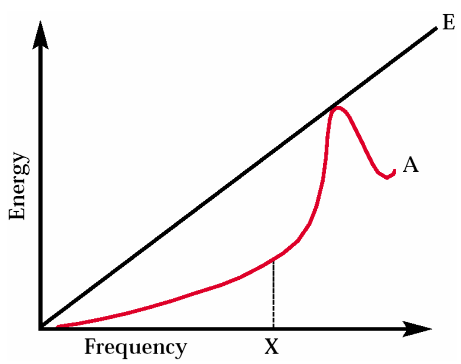

Fig. 1 Plot of the frequency vs. transmitted vibration energy [3]

The vibrators generally used have a frequency band of 0 to 200 Hz. They are connected to the structure, which should be supported on rubber blocks. Frequency is gradually increased until the first resonance is reached. This resonance is maintained for a specific period of time and then the frequency is increased again until the second resonance is reached and so on [3].

MATERIALS

For experiment was chosen hot rolled plates (thickness 30 mm) low-alloy structural steel 16GS [4]. 16GS grade steel is used for substantial structures, which work till minus 70°C temperature, for pipe system elements, which work from minus 40° to 475°C temperature, also this steel is used in nuclear power stations. The European pressure vessels and piping design and construction codes required, that stress relief of welds be done by heating, then thickness of welded joint is more then 35 mm.

The chemical and mechanical properties of 16GS grade steel plates (150x150x30) are presented in Table 1 and 2.

Specimens from 16GS grade steel were welded by using manual arc welding process (111 processes LST EN 24063). BÖHLER FOX EV50 electrode LST EN 499: E42 5 B 4 2 H5 type was used. Chemical composition as well as mechanical properties of the weld metal are presented in Tables 3 and 4.

Table 1. Chemical composition of steel specimens (manufacturer's data)

Steel grade	Composition (mass), %						
	C	Si	Mn	Cr	Ni	S	P
16GS	0.16	0.55	1.1	0.22	0.15	0.015	0.02

Table 2. Mechanical properties of steel specimens (manufacturer's data)

Steel grade	Tensile strength, R_m, MPa	Yield strength, R_e, MPa	Elongation, A_5, %	Impact work ISO-V KV, J/cm^2
16GS	530	390	24	120 (20°C)

Table 3. Chemical composition of the weld metal

Electrode	Composition (mass), %						
	C	Si	Mn	Cr	Ni	S	P
FOX EV50	0.077	0.52	1.16	0.15	0.1	0.015	0.01

Table 4. Mechanical properties of the weld metal

Electrode	Tensile strength, R_m, MPa	Yield strength, $R_{0,2}$, MPa	Elongation, A_5, %	Impact work ISO-V KV,J/cm^2
FOX EV50	515	420	22	150 (20°C)

RESEARCH TECHNIQUE

All specimens from 16GS steel were welded at the same position (PA - ISO 6947, horizontal weld) and by the same welding method. After welding one specimen was heat treated. Heat treatment mode for low-alloy steel (1.2 group CEN ISO/TR 15608:2005 [7]) sample was selected from the EN 13480-4:2005 [8]. For the sample annealing temperature was 650°C, exposure time – 60 min., after specimen was cooled to 300°C (cooling rate 150°C/h). For another sample after each pass of multilayer weld was made vibratory stress relief (Fig. 2). VSR mode was selected from Fig. 1 and basic formula (1). Third sample was welded for comparison of previous results. VSR mode for specimen was following: frequency – 100 Hz; vibrating weight - 5 kg; dwell time – 200 s (or treatment speed 1,5 cm/s).

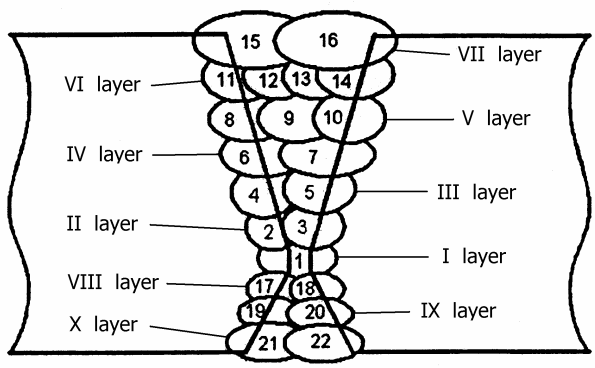

Fig. 2 Runs and layers of multilayer weld

After welding and treatment process, the following analyses of welded specimens were carried out:

1. To check the quality of the weld the radiographic X-rays analysis was used (level B) [9]. The analysis was performed using X-ray generator *ERESCO 42MF2*.
2. To check the tensile properties of specimens the cross-tensile test [10, 11] was used. Specimens were cut mechanically. 3 specimens were cut out of each welded joint. The tensile test was carried out in a *MIRI-500K* tensile machine.
3. Strength properties were evaluated by impact strength test [12, 13]. 4 specimens were cut out of each welded joint. Specimen type - KVWS 0/1 (Charpy pendulum V-notch, weld-metal notch, notched surface parallel to the specimens surface, notch over central area of weld).
4. Vickers hardness was measured on the three areas: weld, interface and heat affected zone. All hardness tests were carried out according to Standard [14]. The analysis was performed using *Krautkramer TIV* measurement equipment.
5. Metallographic test was done for all specimens.
6. Residual stresses relieve were test with magnetic metal memory method [6]. Measurements were made before welding, after welding and after treatment. The analysis was performed using *Energo Diagnostika TSCM-2F* measurement equipment.

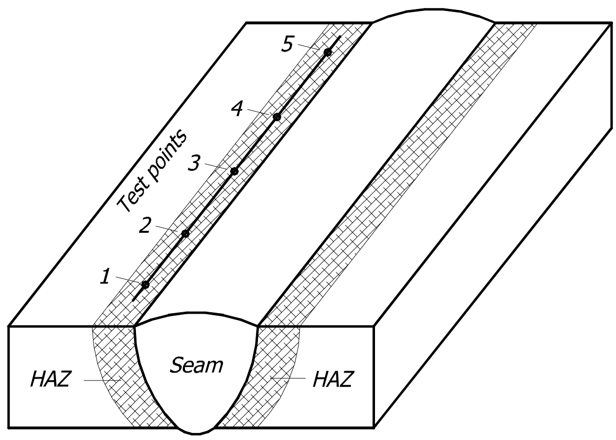

Fig. 3 Test points of magnetic metal memory control

For metal magnetic memory control, on the each specimen's surface were selected 5 points (Fig. 3). Parameters of residual magnetic field were measured several times on the same points (before welding, after welding and after treatment).

RESULTATS AND DISCUSSION

Table 5. Mechanical properties of welded samples

Specimens	Tensile strength, R_m, MPa	Elongation, A_5, %	Impact work ISO-V KV, J/cm^2		Hardness, HV		
			Seam	HAZ	Weld zone	Fusion zone	HAZ
After VSR	482	25	155	202	163	156	156
After PWHT	443	28	188	240	155	149	149
Without treatment	471	24	145	112	179	166	168

The X-rays analyses disclose that all welded joints confirm to technical requirements. Any defects influencing the results were not detected. All results of mechanical testing are presented in the Table 5.

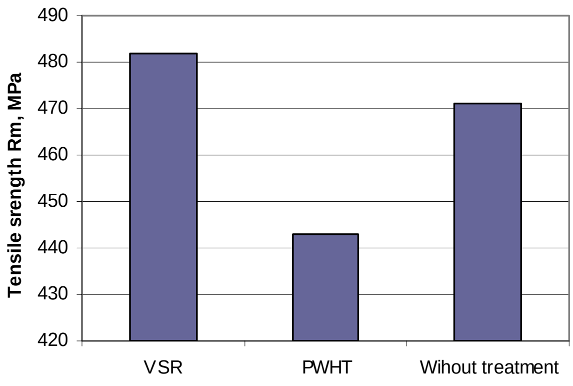

Fig. 3 Chart of Tensile strength

Three specimens were cut from each welded specimens, having the dimensions indicated the Standard [11]. The specimens were clamped in the MIRI-500K machine loading them to rupture. The loading rate was 500 N/s (~50 kgf/s). In all cases rupture occurred in the base metal and not in the welds or HAZ. Table 5 shows the information resulting from the tests. Minimal requirement of tensile strength is $R_m \geq 450$ MPa.

Vickers hardness was measured on the three areas: weld, fusion zone and HAZ (Table 5). The hardness of the heat treated specimen decrease marginally.

The specimens for the impact test were cut from each welded specimens as required by Standard [12]. The four specimens were submitted to impact test in the Charpy machine, at room temperature, with a 30 kg hammer. None of the specimens was broken (Table 5). Minimal requirement of Impact work by standard is ≥ 80 J/cm^2 then testing temperature –20^{o}C.

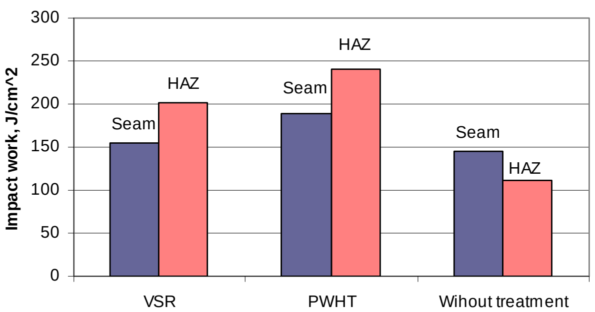

Fig. 4 Chart of impact work

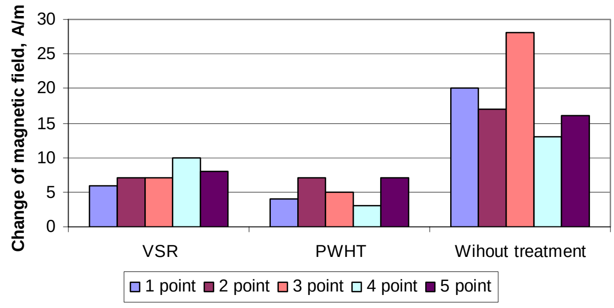

Fig. 5 Chart of magnetic metal storage

The results of metal magnetic memory test shows that after welding the residual magnetic field of specimens increase, but after the treatment the residual magnetic field become lower. As a result of changes of a magnetic field and mechanical test results we can propose that residual stresses were reduced.

After being polished, the specimens were etched with Nital and their microstructures observed in the metallographic microscope. The weld metal is mostly composed by ferrite with visible dendritic arrangement. The dark part visible in the micrographs is pearlite. On the parent metal and weld fusion interface the dark pearlite grains are visible, with ferrite grains surrounding the pearlite grains. The closer to the weld fusion interface the size of perlite grains are bigger, because they were exposed to higher temperatures than the ones farther. It was also observed that neither the vibration modes nor the heat treatment alter the original metallographic structure of the material.

CONCLUSIONS

1. None of the specimens (after VSR or after PWHT) was broken by impact test because the welded joint metal was ductile (welded metal has considerable amount of ferrite).
2. The specimens that had been heat treated showed a decrease in tensile strength and an increase in elongation, as was to be expected. The vibration treatment practically does not alter those values.
3. The decrease in hardness resulting from both treatments was similar, indicating an effective reduction in residual stress.
4. The measurement of magnetic residual field, regardless a location of a vibration energy of specimens, showed that magnetic field changes were stable.
5. The magnetic metal memory test indicates that, by help of this control method we can propose changes of residual welding stresses after the treatment.
6. VSR and PWHT treatment have not influence on the original metallographic structure of the material.
7. The implementation of VSR procedures as a replacement of stress relief annealing for the stabilization of weldments, castings and forgings leads to saving of production costs. The saving of thermal

energy has to be emphasized first of all because in the VSR procedure it does not exceed 1% of the energy required for the annealing of weldments and make in average only 0.4% of production costs.

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