A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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P. SĘDEK*, P. GOTKOWSKI*, J. BRÓZDA*

APPLICATION OF ACOUSTIC EMISSION TO MONITOR THE COURSE OF PLASTIC STRAIN IN MECHANICAL STRESS RELIEVED WELDED JOINTS

WYKORZYSTANIE ZJAWISKA EMISJI AKUSTYCZNEJ DO MONITOROWANIA PRZEBIEGU ODKSZTAŁCANIA PLASTYCZNEGO PRZY MECHANICZNYM ODPRĘŻANIU POŁĄCZEŃ SPAWANYCH

The paper describes the process of reduction of welding residual stresses by the application of a pressure test at which acoustic emission (AE) pulses are recorded to monitor the plasticization of the material, which guarantees the proper reduction of stresses after unloading of the vessel. Specimens with deposited welds were tensile loaded, strains were measured and AE pulses recorded. Tests have also been performed on pressure vessels with remelted zones on their shells with simultaneous recording of pressure, hoop strain and AE signals. The results confirmed that the RMS value of AE can be used for monitoring of the mechanical stress relieving process, as it sharply increases when reaching by the vessel material the 0.5 % plasticization.
Keywords: Residual stresses; Mechanical stress relief; Stress measurement; Acoustic emission

W artykule opisano proces redukcji naprężeń spawalniczych występujących w zbiornikach poprzez wykorzystanie próby ciśnieniowej. Zastosowano emisję akustyczną do monitorowania stanu plastycznego materiału jako czynnika warunkującego stopień redukcji naprężeń spawalniczych. Wstępne badania przeprowadzono na płaskich elementach spawanych, które obciążano różnymi siłami rozciągającymi i jednocześnie rejestrowano przebieg odkształceń i występującą emisję akustyczną. Badania weryfikowano na rzeczywistych zbiornikach, w których naprężenia technologiczne wywołano przez odpowiednie przetopienie ścianki. Naprężenia wywołano przez powolne zwiększanie ciśnienia wewnątrz zbiorników. Rejestrowano: przebieg ciśnienia., odkształcenia przy pomocy tensometrów oporowych oraz mierzono zmiany emisji akustycznej. Stwierdzono, że najskuteczniej przebieg odkształcania plastycznego mierzy się poprzez wyznaczenie wartości skutecznej impulsów emisji akustycznej (RMS). Stwierdzono wyraźne zmiany przebiegu RMS podczas osiągnięcia granicy plastyczności stali w ściankach zbiornika. (odkształcenie plastyczne 0.5%), przez co pomiary RMS można zastosować do monitorowania procesu odprężania mechanicznego.

1. Introduction

Welding residual stresses may reduce the operating properties of the construction. In pressure vessels they lower in certain cases the brittle fracture resistance. To eliminate that in-convenience most commonly residual stresses are reduced by heat treatment. That kind of treatment is, however, very energy and time consuming. It can be replaced by mechanical stress relieving (MSR), which depends on the application of a pressure test at special selected parameters. The requirement for the reduction of the welding stresses is plasticization of the vessel walls under the action of the inner pressure. The reduction of residual stresses is so large, that it fully preserves the required service properties. In practice, however, application of that technique is limited due to the fear, that in the stress concentration areas (boiler heads, stub pipes, decanters, pipe fittings etc.) excessive plastic strains may occur and lower the brittle fracture resistance. On the other hand it is known, that for constructional steels plastic strains up to the value of 2 % do not lower the parameters, which decide on the brittle fracture resistance. A tool has to be therefore developed for the effective monitoring of the MSR process, in such a way, that the critical state would be signalled and the process could be interrupted. Investigations performed up to now have shown, that the acoustic emission (AE) effect is connected with the kinetics of plastic straining, and at stresses on the yield point value the acoustic activity of the metal increases.

* INSTITUTE OF WELDING, 44-100 GLIWICE, 16-18 BŁ. CZESŁAWA STR., POLAND

2. Mechanical stress relieving

Residual stresses can be reduced by proper application of an external load to the welded construction. That procedure, called mechanical stress relieving, consists in producing an additional stress state, which by summing up with the residual stresses causes plastic straining. A condition must be satisfied, that the sum of stresses from external loading and residual stresses will reach the yield point of the material. At the assumption, that the material of the construction and weld metal are of ideal elastic-plastic type, the MSR process can be described by the relationship [1]:

$$\sigma_w + \sigma_o \leqslant R_e \qquad (1)$$

where: σ_w – welding residual stresses,
σ_o – stresses from external loading,
R_e – yield point.

In Fig. 1 the affect of the summation principle of residual stresses with stresses from external loading is presented in a graphic form.

Constructional steels intended for welding should be characterized by a high plasticity due to the required service properties of welded joints, and especially the brittle fracture resistance. For those steels the elastic-plastic model (Fig. 2) can by applied with a sufficient accuracy. The feature of the model consists in the fact, that after reaching the yield strength plasticization takes place. By continuation of loading plastic strain increases without stress increasing up to the initiation of the strain hardening effect. The precondition of an effective MSR, i.e. the reduction of residual stresses without deterioration of plastic properties, is its implementation at the plasticization state without reaching the strain hardening state. The reduction of residual stresses, however, is not complete, as expected from equation (1), it reaches up to 80 % of the initial value of stresses along the weld axis [2, 3, 4, 5, 6, 7]. Moreover, the effectiveness of the MSR depends also on the orientation of the applied external load in relation to the direction of residual stresses. The best effectiveness is achieved when the directions of residual stresses and stresses from the external load are consistent (Fig. 1).

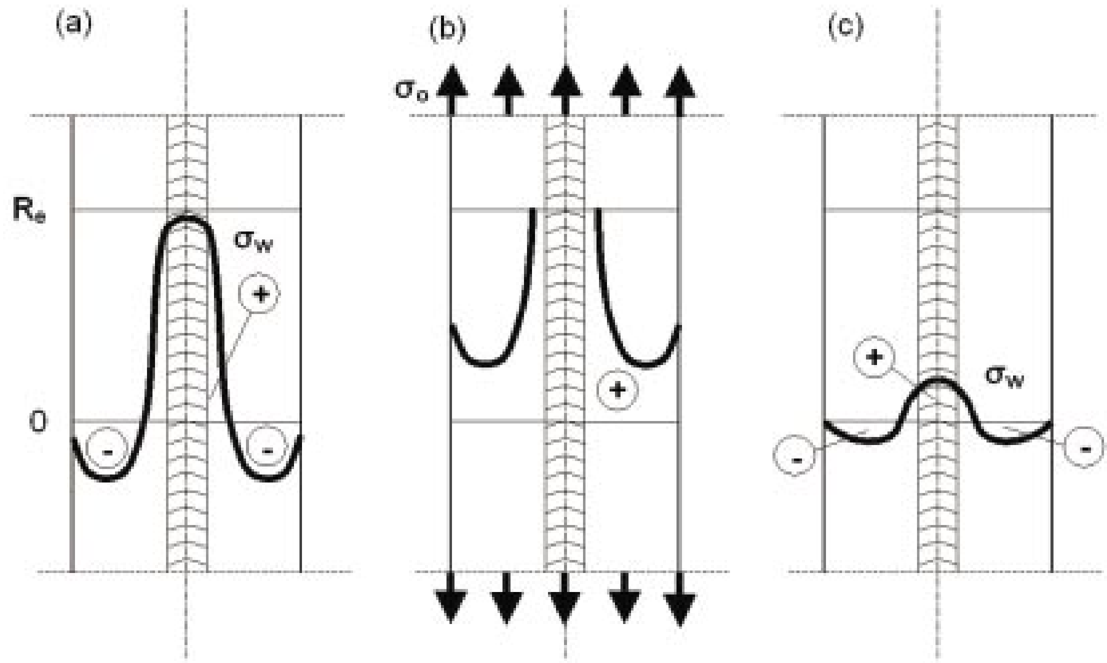

Fig. 1. Scheme of the stress summation principle
a) Residual stress distribution in as welded element
b) Stress state after external load application
c) Distribution of residual stresses in the element after unloading

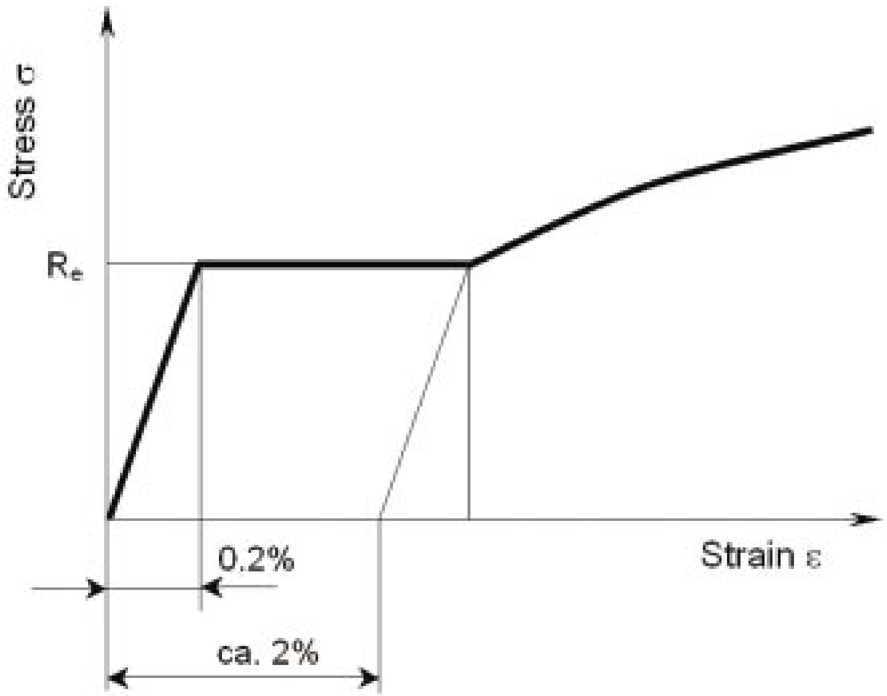

Fig. 2. Model of the assumed elastic-plastic material

3. Generation of acoustic emission

Acoustic emission (AE) is the result of elastic propagation of waves, which are generated in a material by rapid release of accumulated energy. It may be the result of processes accompanying different phenomena, beginning from effects taking place in sub microscopic scale, as for example jumps (diffusion) of atoms into the adjacent location in the crystal lattice, and ending on the macroscopic scale of catastrophic damage of a complete construction [11]. Intensive AE takes place during plastic straining, which is directly connected with dislocation movements, dependent in turn on the metal microstructure. Of essential meaning are factors that influence the dislocation displacement, such as grain size, density of already existing dislocations as well as the size and distribution of foreign phase particles. Important is also the fact, whether the material was previously strained and to what extend. In general, the acoustic effect does not occur or is weaker until the external stress reaches the previous level (Kaiser effect). Dependent on the load magnitude, different dislocation velocities are achieved. When a mobile dislocation is suddenly arrested on various obstacles during plastic straining, its kinetic energy on a very short stopping distance (order of tens of lattice parameters) considerably increases the energy of atoms by increasing their vibration amplitude. Those vibrations propagate in the form of elastic waves. A correlation has also been discovered between AE rate (number of AE pulses) and the change of mobile dislocation density, and it has been found that AE takes place due to the release of pinned dislocations and their multiplication [8]. There is also an opinion, that at loads below the yield strength AE is generated mainly by activation of dislocations due to their unpinning from point type obstacles, and at stresses exceeding the yield strength – by a rapid increase of dislocation density [9, 10].

4. Examination of acoustic emission during mechanical stress relieving

The influence of the MSR process on the intensity of AE phenomenon has been examined. To get possible high welding residual stresses, test plates, made of S235 steel 15 mm in thickness, were prepared with milled groves in which welds were deposited in three layers by submerged arc welding. The view of the test plate is shown in Fig. 3.

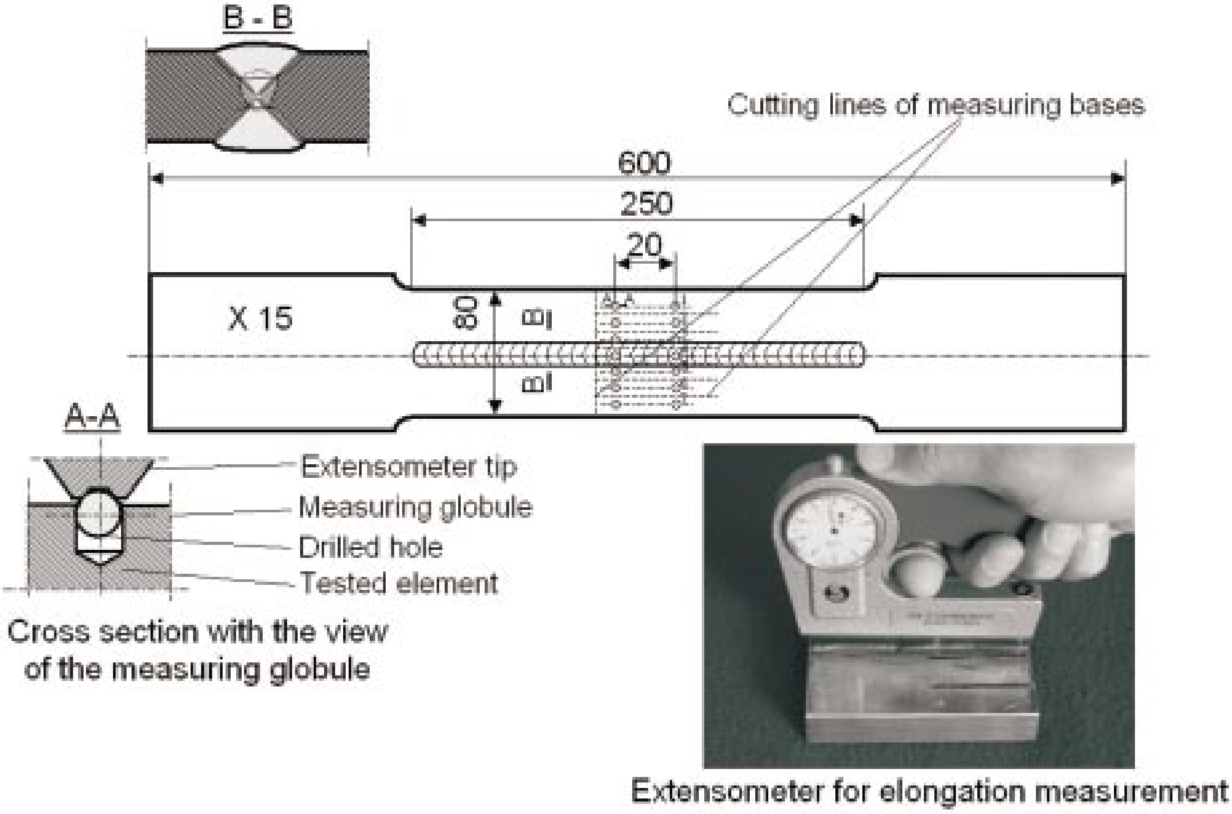

Fig. 3. Geometry of welded test plate for tensile testing with bases for welding residual stress measurement and extensometer

The test plates were loaded by tensile forces in an automated materials testing machine at the simultaneous recording of AE pulses by the AUDIMAT apparatus. The experimental stand is shown in Fig. 4.

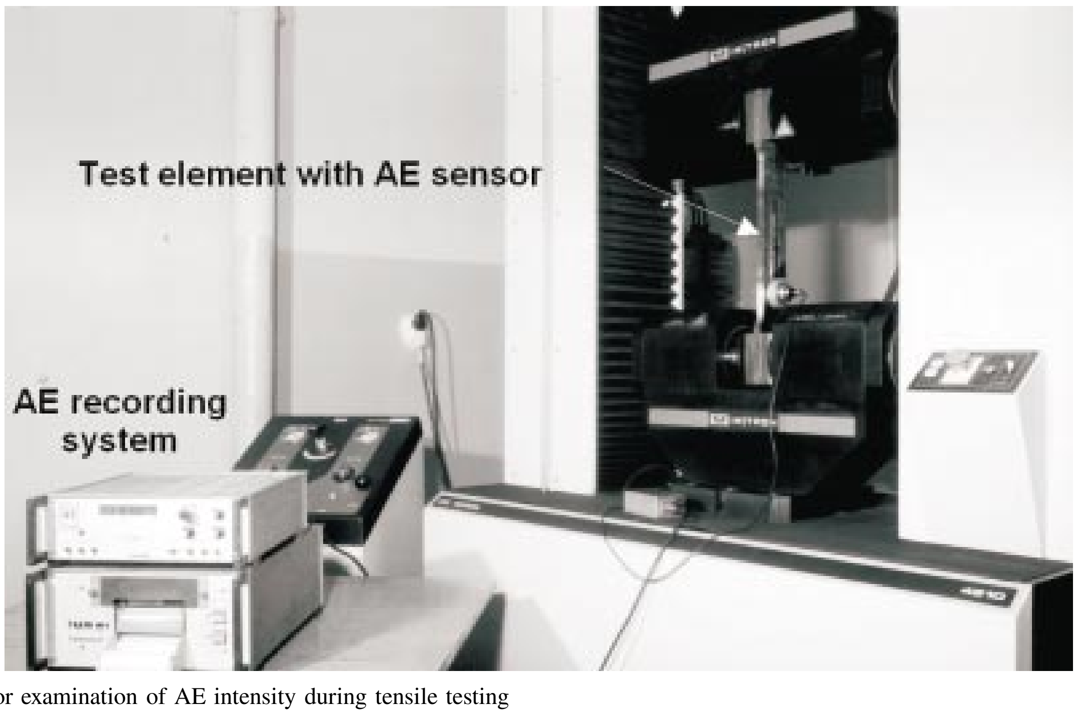

Fig. 4. Stand for examination of AE intensity during tensile testing

The test plates were tensioned to reach the plastic strain. After the tests the plastic strain has been measured on bases shown in Fig. 3. As the next step welding residual stresses were determined by trepanning [2, 3]. The dissecting lines for the individual measuring bases are shown in Fig. 3. Results of AE and welding residual stress measurements are presented in Fig. 5. The plate with measured residual stresses just after welding, shown at position a), was used as the datum feature. At position b) the course of tensile test with AE pulse number measurements is presented. The specimen straining under load was 1.1 % and after unloading the plastic strain reached the value of 0.33 %, which is close to the strain corresponding to the proof stress. The number of AE pulses in a given strain interval during the tensile test, presented in Fig. 5 by bars, increases distinctly. The applied parameters: loading and strain have confirmed the effectiveness of the MSR process, the reduction of welding residual stresses is evident (above 50 %). Ad positions c) and d) the tensile tests have been performed at higher parameters, which resulted in a much higher AE intensity and a more intensive reduction of welding residual stresses. Attention has to be paid to the fact, that when during the tensile test a 1.5 % strain under load is reached, the most intensive AE is observed, which is than lowered at the subsequent straining (Fig. 5d). Of such behaviour of the steel under loading advantage can by taken for the monitoring of the MSR process and its interruption at the proper moment. It is well known, that continuation of the steel straining is not beneficial, because strains over 2 % cause strain hardening and lowering of the brittle fracture resistance.

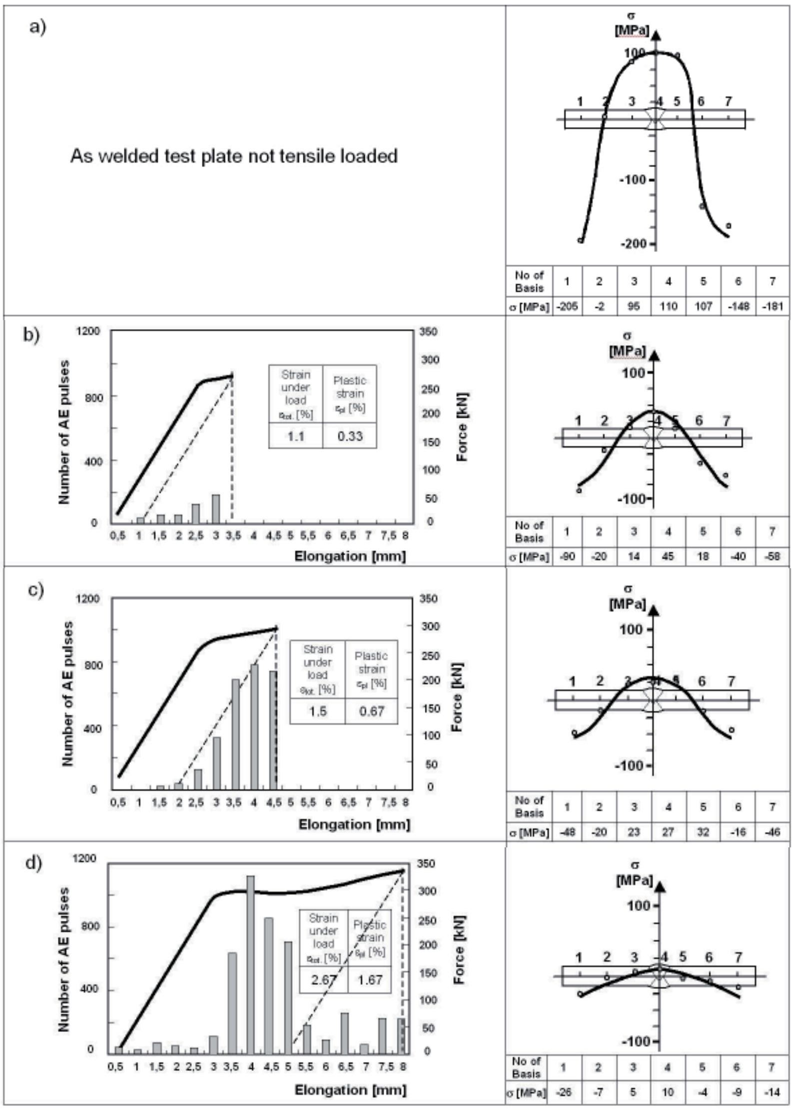

Fig. 5. Statement of tensile test results with AE pulses recording

5. Tests performed on real pressure vessels

MSR tests have been performed on typical pressure vessels made of S235 steel, used in electrical boiler fabrication, with dimensions: length 470 mm, diameter 240 mm, wall thickness 2.5 mm [12]. During the pressure test AE parameters were recorded. For experimental reasons additional welding residual stresses were incorporated by remelting the vessel shell using TIG (nonconsumable tungsten electrode inert gas arc) welding. The application of TIG remelting was the most effective means to incorporate residual stresses, because submerged arc welding, which has been used for the preparation of tensile test samples, was not possible due to low wall thickness (2,5 mm) of the pressure vessel. A general view of the test vessel is shown in Fig. 6 with bases for residual stress measurements from remelted regions.

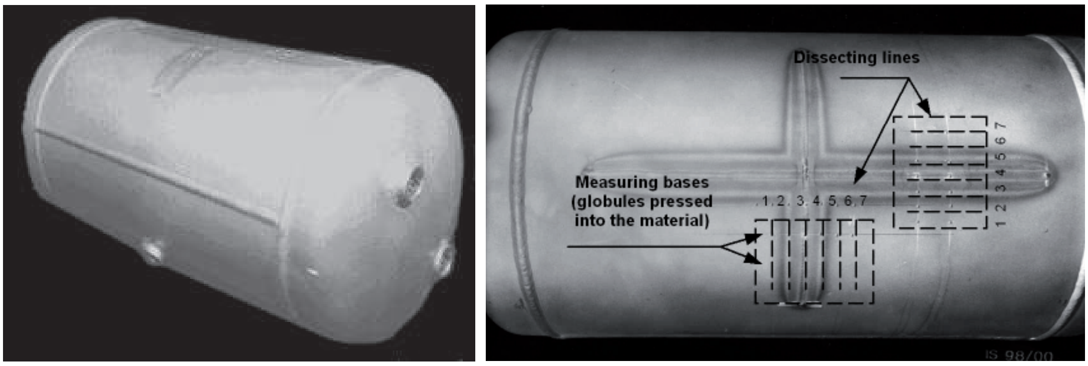

Fig. 6. General view of the test vessel and distribution of bases for measurements of residual stresses from remelted regions

The condition for an effective MSR process of the vessel is such a loading by inner pressure to reach in the walls stresses of the yield point. The test pressure 5.5 MPa was calculated acc. to the moment-free theory for cylindrical vessels.

The MSR tests have been performed on the experimental stand shown in Fig. 7. The test vessel with an additional stress state, produced by TIG melting of the shell, has plugged connector pipes with the exception of one connected to the water pressure pipe. On the connector pipe an electronic pressure gauge AR007/10MPa was mounted, which was connected to the pressure transducer. The manual hydraulic pump with a maximum pressure of 40 MPa was connected to the tested pressure vessel by a copper pipe. On the vessel walls AE sensors were placed as shown in Fig. 7.

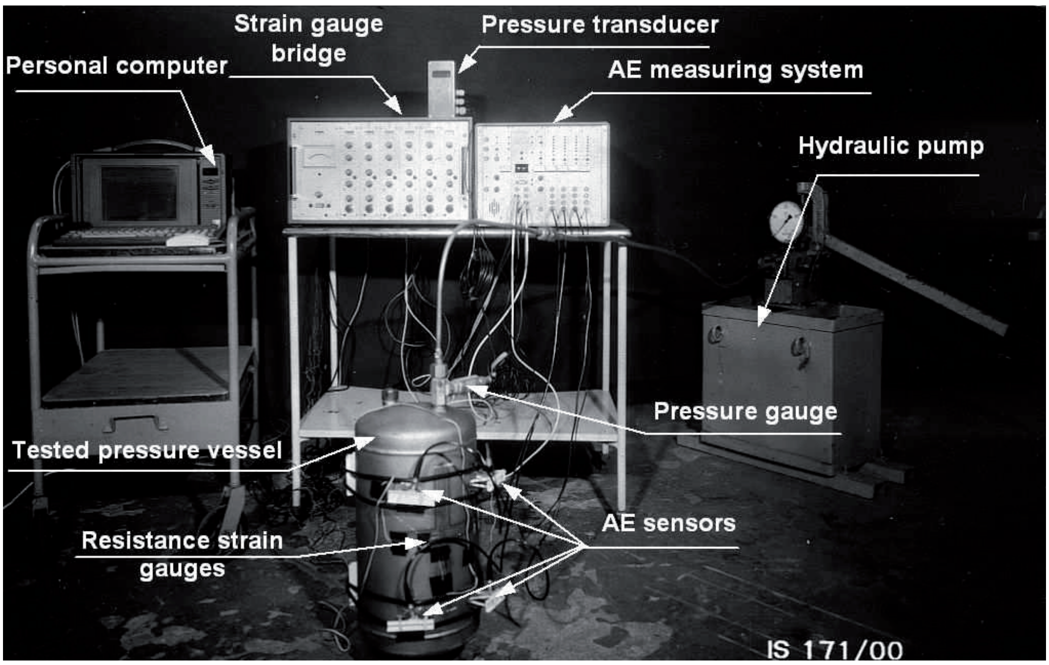

Fig. 7. View of the test stand

To control the stress state during the pressure test, on the walls of the vessels resistance strain gauges were glued. Their distribution is shown in Fig. 8. The AE sensors were connected to the AMS3 measuring system and the resistance strain gauges to the KWSA bridge. To determine the effectiveness of MSR of the tested vessels, residual stresses were measured at the regions of remelted vessel walls. The measurements were performed on a not MSR vessel and on the vessel after MSR, on circumferential and longitudinal bases. The measuring bases and dissecting lines are shown in Fig. 6. In Table 1 residual stress values are presented for the vessel in the as welded condition and the vessel after MSR. The distribution of residual stresses in tested vessels is shown in Fig. 8.

TABLE 1

Residual stresses measured in the tested pressure vessels

No of basis	As welded vessel		Vessel after MSR	
	Hoop stress [MPa]	Longitudinal stress [MPa]	Hoop stress [MPa]	Longitudinal stress [MPa]
1	- 81	- 70	- 46	- 25
2	- 52	- 37	- 77	- 43
3	66	51	88	10
4	238	218	52	62
5	83	10	70	52
6	- 40	- 15	- 53	- 56
7	- 46	- 46	- 39	- 20

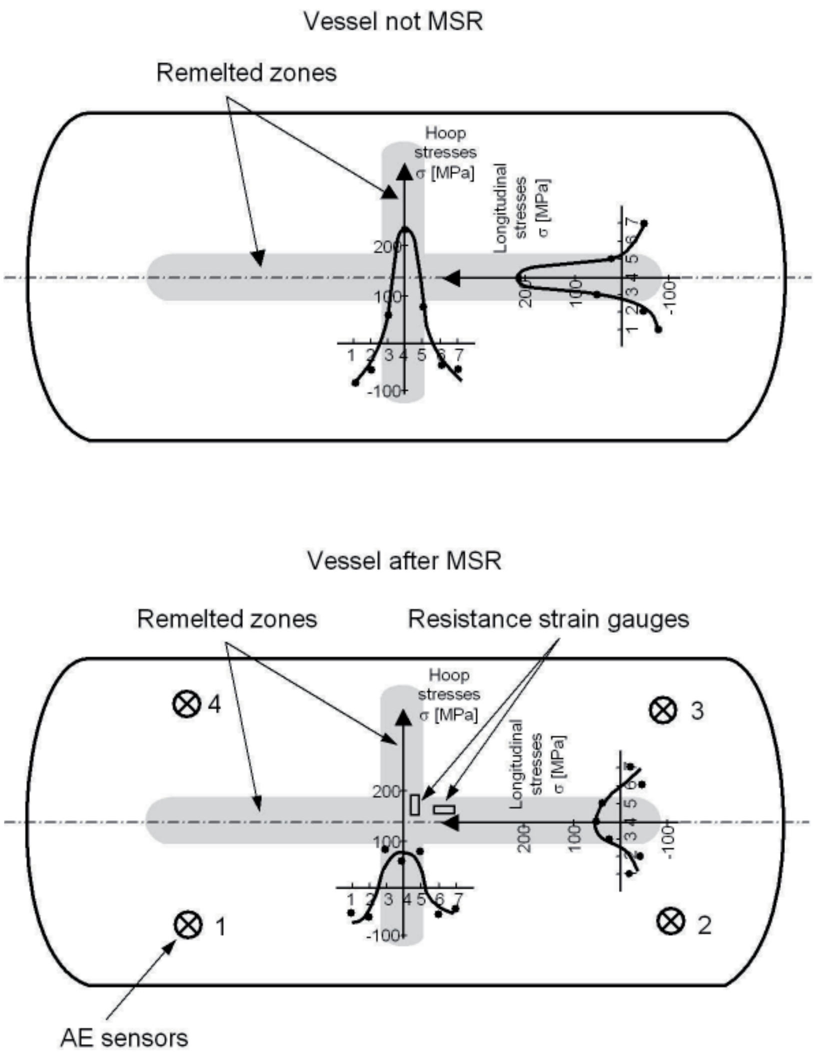

Fig. 8. Distribution of residual stresses in test vessels

In the individual windows of Fig. 9 the following output functions are presented: window 1 – course of pressure changes during the test, window 2 – cumulative plot versus time of root-mean-square (RMS) values of AE pulses for all four sensors, window 3 – distribution of AE sources on the measuring area determined by the arrangement of sensors (Fig. 8), window 4 – course of circumferential strains (measured by a resistance strain gauge) at the time of MSR process.

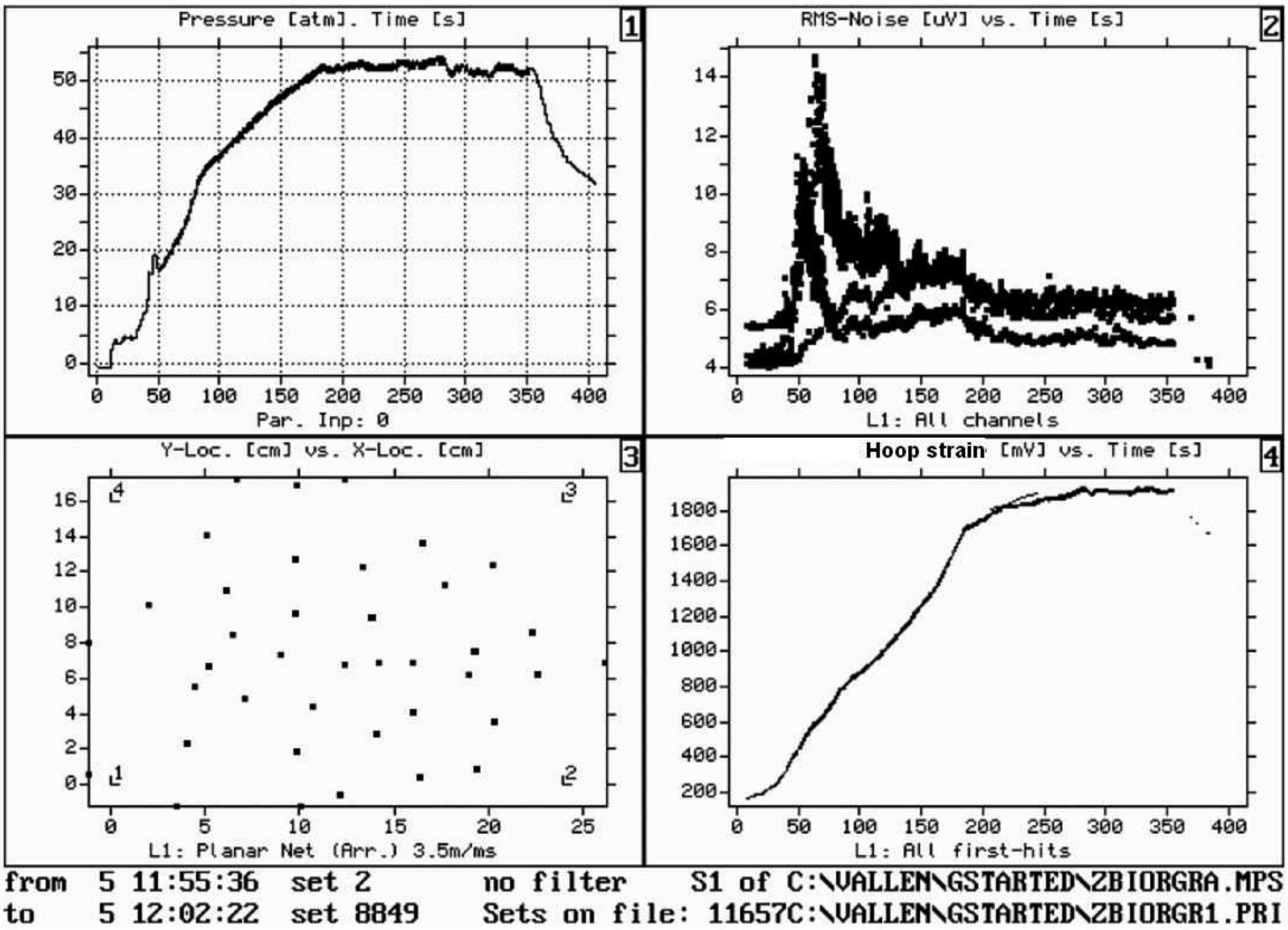

Fig. 9. Course of pressure value, RMS of AE pulses, hoop strain and distribution of AE sources during MSR of pressure vessels

It has been assumed that the water pumping was done uniformly, it means that the load increase from the applied pressure was also uniform and was constant in time. At the loading, which occurred between the 50 and 100 second of pressure build-up, a considerable increase of RMS value was noticed (window 2). In windows 1 and 4 a certain curving of the pressure and hoop strain lines can be observed which shows, that stresses on the yield stress value have been reached. The distribution of AE sources was uniform at the measuring surface without any concentrations, which means that the shape of the remelted region had no influence on it.

In Fig. 10 are presented RMS records versus pumping time (load increase) for the individual AE sensors. It can be seen on each diagram, that in the loading range between 50 and 100 seconds of pumping time, a substantial RMS increase takes place, which lowers than at a further loading. The visible peaks in the RMS records indicate reaching by the vessel material the 0.5 % plasticization. That value is the guarantee of proper parameters for the reduction of welding residual stresses (Fig. 5). The reduction of maximum hoop stresses was 80 % and the longitudinal stresses – ca. 70 %. The examination has revealed, that the phenomenon of acoustic activity increase of a material under load can be an effective signal for MSR (reduction of welding residual stresses).

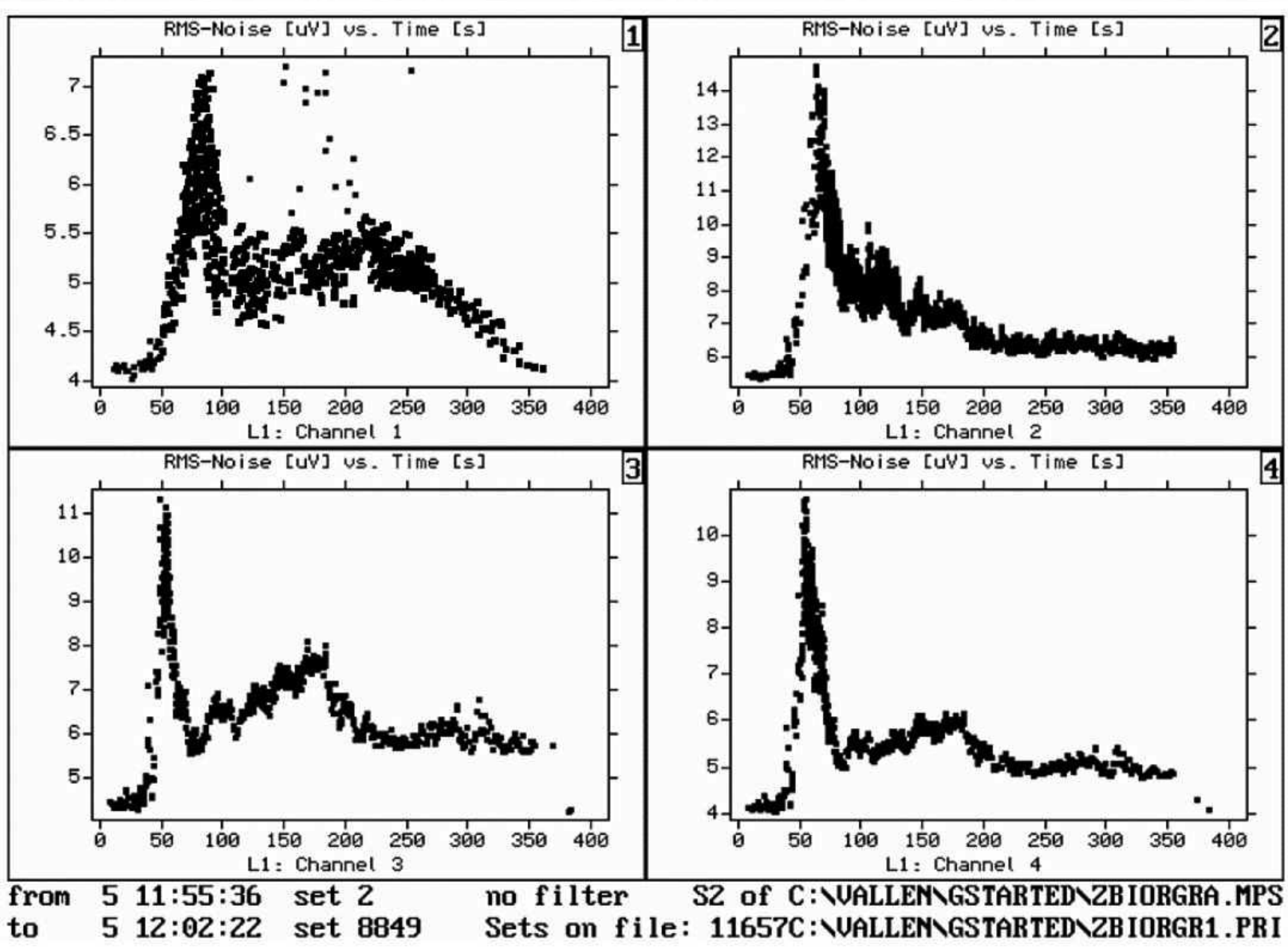

Fig. 10. RMS diagrams for the individual AE sensors arranged at the remelted area on the vessel shell

6. Conclusions

The following conclusions can be drawn

- The constructional steel S235 grade under loading at the yield point range shows a strong acoustic activity.
- In the plasticity range a reduction of welding residual stresses takes place.
- The course of the acoustic emission signal, and especially the RMS value, can be used as a convenient monitoring tool of the mechanical stress relieving process.

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