# DETERMINATION OF HEAT TREATMENT REQUIREMENTS OF WELDED PRESSURE VESSELS BY FRACTURE MECHANICS ANALYSIS

K. Kálna*

In the paper results from the tests of two model pressure vessels 1200 and 1500 mm in diameter, about 3 m in length and 45 mm in wall thickness are analysed. The vessels were fabricated of Fe 510E steel and were not annealed after welding. Residual stresses in welded joints after welding and after the tests of the vessels were compared. Growth of fatigue crack and critical crack length calculated from the data of laboratory tests were compared with the data from the tests of model vessels.

## INTRODUCTION

Large diameter pressure vessels and storage tanks are fabricated by welding of pre-shaped parts. Bent plates or stamped segments for spherical storage tanks are joined into larger parts on a positioner using SA welding. Larger parts are joined on-site in various positions by MMA welding or welding in gas shielding.

Relaxation heat treatment of these large bodies or local heat treatment of welded joints is difficult and expensive. Therefore the volume of storage tanks depends most frequently on the wall thickness to which unannealed welded joints can be used. The wall thickness of pressure vessels and storage tanks is directly proportional to diameter and pressure and inversely proportional to allowable stress and/or yield point of a steel.

* Welding Research Institute, Bratislava, CSSR

The limit thickness of the welded joint from the aspect of the need of relaxation heat treatment depends on:

- steel type and welding consumables as well as yield point of a steel
- the lowest working temperature of the vessel with regard to the danger of brittle failure
- the effect of environment with regard to the danger of stress corrosion cracking.

Thus a complex of mutually connected problems has to be concerned. Optimum selection of parameters of unannealed large diameter vessels requires an engineering solution.

At present mostly CMn microalloyed steels with up to 350 MPa yield point are used in the world for the fabrication of unannealed welded storage tanks.

## EXPERIMENTAL PROGRAM

Electromelted heat of Fe 510E steel was used for the experimental program. Plates were 45 mm in thickness. The program included the study of technological conditions for welding, measurement of residual stresses in welded joints, tests of brittle-fracture characteristics of welded joints, tests of fatigue crack growth rate, tests of low-cycle fatigue of welded joints and approval tests of two model pressure vessels, Jesensky et al. (1), Jesensky and Kalna (2).

The first vessel was 1500 mm in outer diameter and it had two small nozzles, 45 mm in inner diameter, for the inlet and outlet of cooling and pressurized media. The second vessel was 1200 mm in diameter and besides two small nozzles H2 and H3 it had a manhole nozzle H1 460 mm in inner diameter, see figure 1. The nozzle H3 was welded to the place of measuring residual stresses in a longitudinal welded joint of the vessel A. To measure the stress state of the vessels electric resistance strain gauges were mounted.

The first pressure test of the vessels was carried out at +33°C. The temperature was estimated according to the transition temperature of TDTE welded joints and was elevated by the thickness effect (from 16 to 45 mm) and by effects of residual stresses and stress concentration. Test pressure was 1.2 and/or 1.5 times higher than the working pressure and 8 and/or 10 loading cycles were made. According to the data from strain gauges mounted on welded joints, residual stresses in the joints decreased more in circumferential and less in axial directions. Residual strains expressed in fictive stresses $S_r = E \cdot e_r$ were 110-195 MPa in circumferential direction and 50-90 MPa in axial direction.

Notches, V1 - in the base metal, V2 - in the longitudinal welded joint and V3 - in the connecting weld of the manhole, were made in the vessel walls. To initiate a fatigue crack, the vessels were loaded repeatedly at +10 up to +16 °C ambient temperature. The first vessel with N = 5756 cycles, the second one with N = 2845. At repeated loading of the second vessel and at this number of cycles a fatigue crack through the whole wall was formed in the connecting weld of the manhole and caused leakage. This crack was formed from a defect in the weld on opposite side from the notch V3.

The test up to failure of the first vessel was carried out at a temperature of -34 °C, using 22.2 MPa pressure, corresponding to a circumferential stress $S_t$ = 348 MPa. The second vessel was tested at -44 to -47 °C and 24.3 MPa pressure, corresponding to a circumferential stress $S_t$ = 293 MPa.

From non-damaged parts of the vessels test pieces were prepared for additional fracture-mechanical tests and for measurement of residual stresses in welded joints.

## EVALUATION OF EXPERIMENTAL DATA

Mechanical characteristics of steel and welded joints of the vessels are given in table 1. Comparison of the distribution of residual stresses along thickness of the longitudinal as-welded joint and the joint after tests can be seen in figure 2, as a and b respectively. Maximum residual surface stresses $S_{rx}$ and $S_{ry}$ in longitudinal welded joints of the vessels decreased in dependence of the number of loading cycles and relative stress by 80-90% and remained on the level up to 110 MPa.

The static fracture toughness $K_{CJ}$ of steel and unannealed weld metals of joints was determined on test pieces types A20 x 40 and CT45 x 100. The temperature dependence of $K_{CJ}$ of a submerged arc welded joint fabricated by A 234 wire (2% Ni) and F 205 flux is shown in figure 3. Light symbols illustrate the data from reference plates, dark symbols the data from residues of damaged vessels, Polak (3).

The fatigue crack growth rate was determined on the test pieces CT20 x 100, cut of the damaged vessels (at r = 0.1, 0.3 and 0.5) and on the pieces with a surface notch 45 x 80 mm in cross-section, cut from the reference plates (at r = 0.1). The results are presented in the research report by Ulrich (4) and data used for the calculation of crack growth in the vessels are given in table 1.

## COMPARISON OF THE CONDITIONS OF PRESSURE VESSEL FAILURE

### Test on 1500 mm diameter vessels

The test up to failure of the vessel 1500 mm in diameter was carried out at a temperature of -34 °C. The vessel failed at a pressure $P_C$ = 22.2 MPa, corresponding to a circumferential stress $S_t$ = 348 MPa.

A brittle failure was formed from the notch located in a longitudinal submerged arc welded joint, about 7 mm beneath the surface. Fracture toughness of the steel at -34 °C is $K_{CJ}$ = 310 MPa $\sqrt{m}$, that of the weld metal is $K_{CJ}$ = 160 ± 46 MPa $\sqrt{m}$. Dependence of critical crack length $a_C$ on relative stress is shown in figure 4a. The data $a_C$ were calculated with a crack shape factor Y = 1.0. The data for the vessel failure at two stresses are plotted also in the diagram: $S_{C1}$ = 348 - 25 = 323 MPa, i.e. $S_{ry}$ = -25 MPa, $S_{C2}$ = 348 MPa for $S_{ry}$ = 0. Then there are the data for two methods of notch evaluation:

1. for surface crack: $C_C$ = 33 mm, $2\ell$ = 122 mm, Y = 1.3

2. for the through-thickness crack: $2a_C$ = 120 mm, Y = 1.0

The data for vessel failure lay in the scatterband of $a_C$ values calculated on the basis of results from laboratory tests of fracture toughness.

### Test on 1200 mm diameter vessel

The test to failure of the vessel 1200 mm in diameter was carried out at a temperature ranging from -44 °C to -47 °C. In the vicinity of notches in the shell the temperature was -44 °C, in the vicinity of the manhole welding the temperature was -47 °C. The vessel failed at 24.3 MPa pressure, corresponding to a circumferential stress $S_t$ = 293 MPa.

A brittle crack was formed from a fatigue crack in the connecting welded joint of the manhole. The fatigue crack was formed from included slag 10 x 18 mm in dimension at repeated loading of the vessel. The fatigue crack passed through shell thickness and its length was $2a_C$ = 34 mm. Stress concentration factor, according to tensometric measurement, is about k = 2.0. Stress intensity factor at failure is:

$S_{rx}$ = (0.2 - 0.4) $R_e$ = 114 - 228 MPa, $K_C$ = 151 - 168 MPa $\sqrt{m}$.

Fracture toughness of the weld metal of MMA welded joint faricated by E-B 235 electrode at -47 °C is $K_{CJ}$ = 200 ± 70 MPa √m. Dependence of critical crack length on relative strain $e/e_e$ is shown in figure 4b. The values of $a_C$ for the vessel failure are also plotted. The data lay in the scatter field of $a_C$ values calculated from the results of laboratory tests of fracture toughness.

Inspection of brittle failure from the notch in the steel of the vessel shell revealed:

- crack dimensions: $C_C$ = 25.5 mm, 2ℓ = 110 mm
- crack shape factor according to ASME Boiler and Pressure Vessel Code (5) Y = 1.08
- $K_C$ = 90 MPa √m < $K_{CJ}$ = 310 MPa √m

Brittle failure was not formed from the notch.

Inspection of brittle failure from the notch in longitudinal submerged arc welded joint of the vessel shell revealed:

- crack dimensions: $C_C$ = 27 mm, 2ℓ = 102 mm
- crack shape factor according to (5) Y = 1.12
- $S_C = S_t + S_{ry}$ = 293 + 100 = 393 MPa
- $K_C$ = 128 MPa √m ≤ $K_{CJ}$ = 132 ± 22 MPa √m

Brittle failure was not formed from the notch.

## CONCLUSIONS

a. Good agreement between the results of laboratory tests on welded joints in reference plates and tests on model vessels was established. Fracture mechanics approaches can be used to evaluate brittle failure resistance, applicability of unannealed welded joints, defect tolerance, etc.

b. Experimentally it was proven that residual stresses in welded joints can be decreased significantly to the level of about 100 MPa by repeated warm pressure tests.

c. It was proven that pressure vessels and storage tanks, about 50 mm in wall thickness, can be fabricated with unannealed welded joints and be resistant to brittle failure when using a suitable steel and suitable welding consumables as low as -50 °C.

d. On the basis of results from experimental works technical delivery conditions were proposed for the fabrication of thick-walled (up to 50 mm) unannealed pressure vessels and storage tanks operating at temperatures down to -50 °C.

## SYMBOLS USED

| | |
|---|---|
| a | = crack length (mm) |
| $K_{CJ}$ | = fracture toughness determined by $J_{IC}$ method (MPa √m) |
| S, $S_r$ | = stress, residual stress (MPa) |
| T40J | = transition temperature after KV = 40 J (°C) |
| T50% | = transition temperature after 50% plastic fracture surface appearance (°C) |
| TDTE | = transition temperature after DT test, $1/2E_{max}$ (°C) |

## REFERENCES


(1) Jesenský, M. et al. "VITKOVICE model pressure vessel testing", Research Report VÚZ Bratislava, 1585/4/206, 6, 1985 (in Slovak).

(2) Jesenský, M. and Kálna, K., "KS Brno model pressure vessel testing", Research Report VÚZ Bratislava, 1585/4/206, 7, 1985 (in Slovak).

(3) Polák, P., "Static and dynamic brittle-fracture characteristics determination of welded joints", Research Report VÚZ Bratislava, 1585/3/205, 10, 1985 (in Slovak).

(4) Ulrich, K., "Surface fatigue crack growth rate in welded joints", Research Report VÚZ Bratislava, 1584/4/205, 9, 1985 (in Slovak).

(5) ASME Boiler and Pressure Vessel Code, Section XI, A-3000, 1977.

TABLE 1 - Mechanical Properties of Materials tested

| Vessel D/h | | | 1500/45 | | 1200/46 | | |
|---|---|---|---|---|---|---|---|
| Material | | | Fe 510 E | 121 A234 + F205 | Fe 510 E | 121 A234 + N70 | 111 E-B 235 |
| $R_e$ | +20°C | MPa | 400 | 510 | 420 | 570 | 570 |
| $R_m$ | | MPa | 550 | 620 | 560 | 665 | 670 |
| $A_5$ | | % | 30 | 24 | 29 | 23 | 20 |
| Z | | % | 73 | 72 | 72 | 57 | 63 |
| KV | | J | 155 | 105 | 140 | 120 | 140 |
| m | | - | 2.30 | 2.43 | 2.33 | 3.02 | 3.02 |
| C | | x | $7.9 \cdot 10^{-5}$ | $5.6 \cdot 10^{-5}$ | $5.7 \cdot 10^{-5}$ | $4.3 \cdot 10^{-6}$ | $6.4 \cdot 10^{-6}$ |
| T40J | | °C | -70 | -55 | -52 | -50 | -52 |
| T50% | | °C | -35 | ± 0 | -43 | -45 | -33 |
| TDTE | | °C | -18 | +13 | - | -35 | + 4 |
| t | | °C | -34 | | -44 | | -47 |
| KV | | J | 105 | 60 | 95 | 46 | 50 |
| $K_{CJ}$ | | $MPa\sqrt{m}$ | 310 | 160±36 | 310 | 132±22 | 200±70 |

x mm/k cycl, $MPa\sqrt{m}$

TABLE 2 - **Comparison of calculated and real Fatigue Crack Growth Values Δa after repeated Loading of Vessels**

| Vessel | Notch | Δp MPa | N – | ΔS MPa | a mm | ΔK MPa $\sqrt{m}$ | Δa mm |
|---|---|---|---|---|---|---|---|
| 1500/45 | Fe 510 E | 13 | 2000 | 204 | 22.0 | 54.4 | 1.55 |
| | | 16 | 3756 | 251 | 23.6 | 71.6 | 5.47 |
| | | Total N = 5756 | | | Calculated Δa = 7.02<br>Real value Δa ~ 7.00 | | |
| | A 234 + F 205 | 13 | 2000 | 204 | 24.0 | 56.9 | 2.04 |
| | | 16 | 3756 | 251 | 26.0 | 75.7 | 7.67 |
| | | Total N = 5756 | | | Calculated Δa = 9.71<br>Real value Δa ~ 9.00 | | |
| 1200/46 | Fe 510 E | 16 | 2000 | 193 | 23 | 52.6 | 1.17 |
| | | 19 | 845 | 229 | 24.2 | 63.5 | 0.77 |
| | | Total N = 2845 | | | Calculated Δa = 1.94<br>Real value Δa ~ 2.5 | | |
| | A 234 + N70 | 16 | 2000 | 193 | 23.5 | 53.1 | 1.38 |
| | | 19 | 845 | 229 | 24.9 | 64.6 | 1.05 |
| | | Total N = 2845 | | | Calculated Δa = 2.43<br>Real value Δa ~ 3.5 | | |

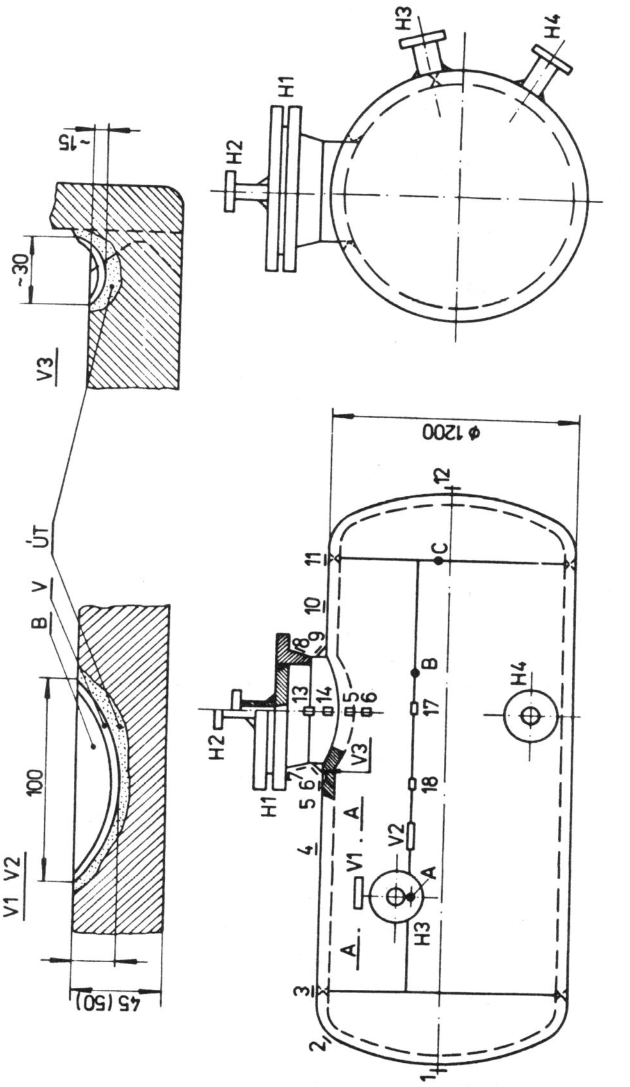


**Figure 1** The sketch of the model pressure vessel with manhole nozzle

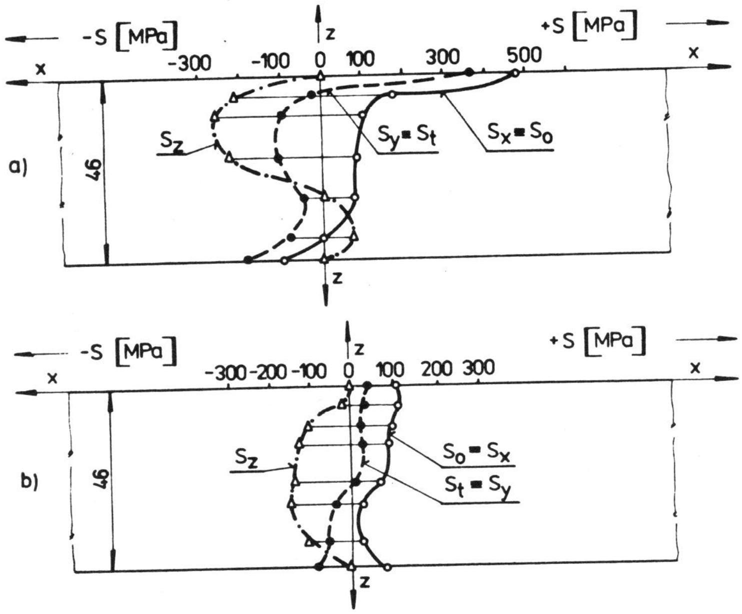


Figure 2 Distribution of residual stresses along the thickness of the longitudinal joint weld metal, a - after welding, b - after testing of vessel

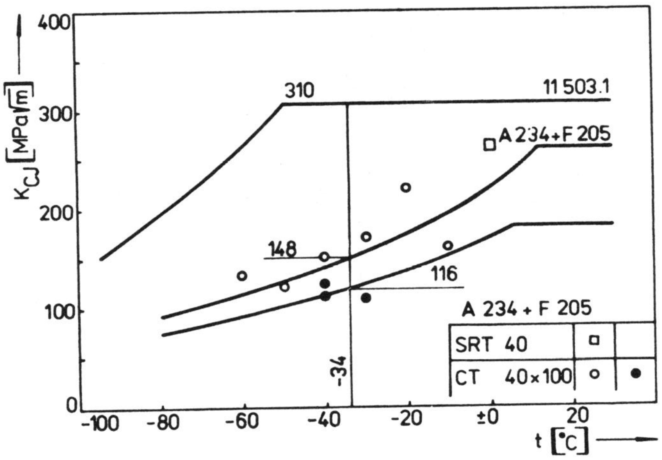


Figure 3 Temperature dependence of fracture toughness of A234 + F205 weld metal

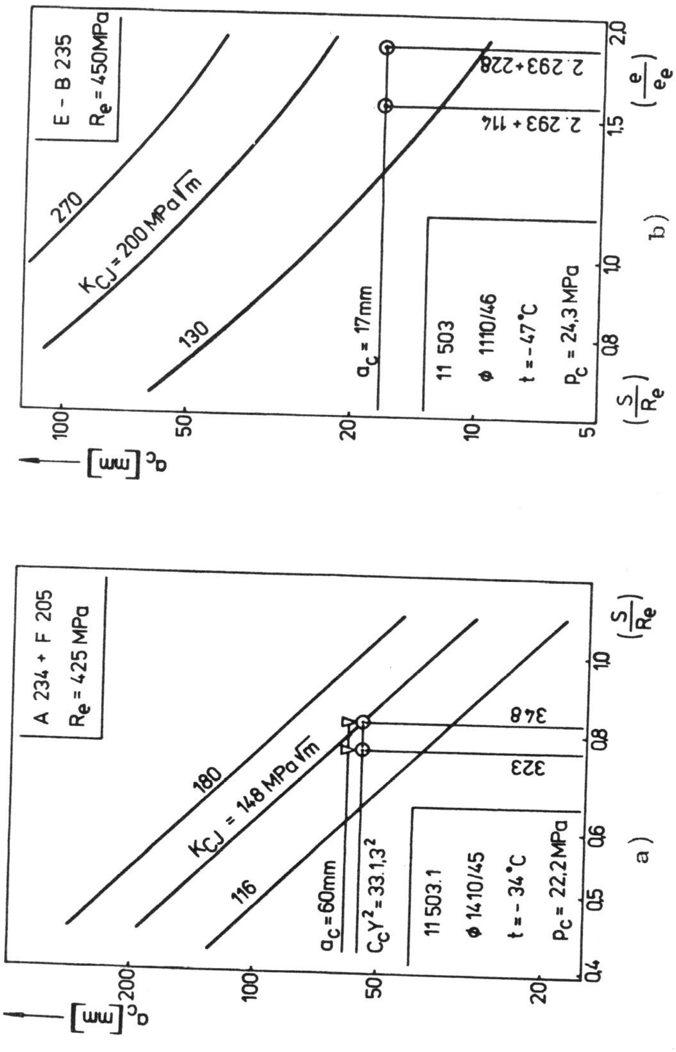


Figure 4 The dependence of critical crack length $a_C$ on the stress ratio in a - SA (A234 + F205) and b - MMA (E-B 235) weld metals