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Study and Design of Spherical Gasometers

Etude et projet de gazomètres sphériques

Untersuchung und Bemessung von Kugelgasbehältern

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SUMMARY

The results of experimental investigations of two pilot spherical gasometers carried out with the aim of determining the actual life of similar structures are considered. The mechanism of fatigue crack initiation and development in the zones of stress concentration was found on the basis of which the criteria which apply for the limit states of the gasometers were determined.

RÉSUMÉ

La communication présente les résultats d'études expérimentales sur deux gazomètres sphériques, réalisées afin de déterminer la durée de vie réelle de structures analogues. On a défini la loi d'amorçage et de propagation des fissures de fatigue dans des zones de concentration des contraintes, dont on a tenu compte lors de la détermination de l'état-limite des gazomètres.

ZUSAMMENFASSUNG

Es werden Ergebnisse komplexer experimenteller Untersuchungen an zwei kugelförmigen Gasbehältern vorgestellt, die zur Bestimmung der tatsächlichen Lebensdauer dieser Art von konstruktionen durchgeführt wurden. Es werden Gesetzmässigkeiten der Dauerrissbildung und -entwicklung in Bereichen der konstruktiven und technologischen Spannungskonzentration dargestellt, die bei der Bestimmung der Grenzzustandskriterien der Gasbehälter berücksichtigt wurden.

INTRODUCTION

Ball gas-holders of a volume up to 2000 m^3, made of low-alloy steel of 09Г2С mark, with a shell 17÷36 mm thick and an internal pressure about 0.5÷1.2 MPa are widely used in various industrial fields. A repeated-statical character of loading as well as low temperature climatic conditions influence alongside with structural stress concentrators and such inner welds imperfections as lack of penetration, pore chains, slag inclusions, etc. may contribute, under certain conditions, to premature failure of these structures. Their useful life may be determined on the basis of complex experimental-and-theoretical investigations, including:

- an experimental investigation of stress-strain conditions in the zones of stress concentrators (such as zones of supporting straps and branch pipes reinforcement connections with the gas-holder shell) with regard for its kinetics in the process of cyclic loading;
- full-scale hydrostatic tests of pilot ball gas-holders under static and repeatedly-static loading conditions with ultrasonic control at inner defects development in field butt joints with the successive revealing of all zones of possible failure of the structure shell;
- analysis of the physical and mechanical characteristics at static and cyclic loading, including the crack resistance properties of steel and welded joints of the gas-holder;
- analysis of the work loading spectrum of the conventional gas-holders;
- fatigue life and crack resistance analysis.

Investigations according to the above-mentioned programme were carried out on ball gas-holders of 2000 m^3 volume, with shell thickness 36 mm, fabricated of steel of 09Г2С mark.

1. GAS-HOLDERS FULL-SCALE TESTING PROCEDURE

Experimental investigations were carried out on two gas-holders loaded by internal excessive pressure created by water pouring; loading conditions are as follows: repeated-static loading with frequency 15÷20 cycles per hour and an asymmetry $\rho \approx 0.1$; maximum pressure at the loading cycle was P_{max} = 1.6 MPa and that 30% exceeded the admissible level of operating loading.

At the first stage of testing, using a method of strain measurement, a character of stresses distribution in the zones of supporting straps and branch pipes connections with the shell in the initial and the subsequent loading cycles (up to the 100th) was investigated. For this purpose chains of transverse-and-longitudinal metal-film 2 mm-base resistance strain gauges were used. In order to measure the level of residual welding stresses in the above-mentioned zones, by a method of a local surface off-loading, 0.5 mm-base resistance strain gauges were used.

It was found out as a result of strain measurement investigations that the maximum level of stress concentration didn't exceed the value of $K_\sigma^* = 3.4$, which is characteristic for the cases of an abrupt transition of a fillet weld to base metal and shallow undercuts (up to 0.5 mm) along the bead of the weld. In the course of the structure testing, repeated elastic-plastic deformations took place in the local zones of the structure, which range of values practically didn't change (a condition of the material rigid loading).

Maximum level of residual welding stresses in the above-mentioned zones of the structure before its loading σ_{w_0} didn't exceed $0.65\sigma_{0,2}$, where $\sigma_{0,2}$ is the shell material yield point. However, during the first loading cycles a considerable reduction of σ_{w_0} took place with the subsequent stabilization at the level $\sigma_w = 0.25 \div 0.5\sigma_{0,2}$, depending on the level of stress concentration, K_σ^*, as well as a nominal stress in the shell.

Before the excessive pressure loading of the gas-holders a random ultrasonic non-destructive inspection of field butt joints was carried out. As a result, some continuous technological defects such as pours chains, slag inclusions, lack of weld root penetration were detected, the sizes of these defects exceeded the admissible level specified in the technical requirements for the structures fabrication.

Having all above-mentioned in mind, fatigue cracks were expected to develop at full-scale cyclic tests in the zones of structural stress concentration and in the zones of welded butt joints where continuous technological effects were observed, that's why a periodic ultrasonic inspection of these zones was performed. When a through crack developed in the shell, which could be discovered from the appearing a slight water spurt, the gas-holder testing was stopped, the water drained and a sealing cover plate 3 mm thick was placed from the inner side of the damaged place of the shell and welded with a fillet weld along the perimeter. Then the gas-holder was refilled with water and cyclic testing continued up to the moment of through cracks development in other zones of the shell. Simultaneously, the growth of through cracks in the zone of sealing cover plates (their length allowed the development of fatigue cracks up to the critical level) was measured. Special displacement gauges were used for determining stress intensity factors in the tip of the developing cracks.

In such a way, the reliable results were obtained for the zones of the most probable failure of the gas-holder shell and the characteristics of the cyclic crack resistance of the structural material were estimated.

2. DISCUSSION OF THE RESULTS

The full-scale test results showed that the zones of the most probable failure of the ball gas-holder are, first of all, butt welds with long inner defects such as pour chains, slag inclusions, lack of penetration, etc. As a rule, these welds were performed by a manual arc method in a vertical or overhead position. Initially, at the cyclic loading of the structure the process of merging of separate closely adjoining defects into one of a considerable length took place, further this defect developed up to the moment of the shell depressurization. The four observed cases of the gas-holder shell failure in the zone of butt welds allowed to find out that at a through crack formation its dimensions on the inner surface of the gas-holder shell are about 90÷130 mm, and at the outside surface - about 15÷20 mm, and this is likely to be characteristic of the given type of the stressed state, the shell thickness and welding defects which are near to the inner surface of the shell.

The other zones of the possible gas-holders failure are the zones of junction of the bottom reinforcement (the inner ring strap) in the zone of the gas inlet pipe and the supporting straps on the gas-holder shell. All cracks initiated near the bead of the fillet weld. This type of the failure is of a multi-nucleative character. For example, in one case a through crack initiated in the shell in the zone of its junction to the inner ring strap. Its length at the inner surface of the gas-holder along the fillet weld bead was 150 mm. Besides, 5 surface cracks in the immediate vicinity of each other were found along the perimeter of this junction, one of the cracks, as it was discovered after examination of the fatigue fracture, was nearly half of the thickness of the gas-holder shell. It should be noted that a multi-nucleative initiation of cracks in the zones of structural stress concentration of ball gas-holders with their subsequent merging in the process of the structure cyclic loading, may lead, under certain conditions, to the shell fracture and depressurization and, as a result, to even more serious consequences.

Having in mind all above-mentioned and with regard for the found out mechanism of fatigue cracks in a gas-holder shell initiation and development, the following marginal state criteria were accepted:

- development of a through fatigue crack in the zone of butt welded joints;
- development of a long surface crack in the zones of junction of branch pipes reinforcement and supporting straps with the gas-holder shell.

The full-scale testing results showed that the shell maintained its load-carrying capacity at the presence of through cracks in butt welds and long surface cracks in the zones of structural stress concentration until the temperature of testing was not lower than +10C and at nominal stresses 30% exceeding the maximum working stresses. To find out the critical crack dimensions margins and to make account of the lowered up to -40C operating temperature, the experimental investigation of characteristics of a crack-resistant steel and welded joints on metal, cut of the gas-holder shell after completion of endurance tests were performed. Static cracking tests were performed at axial tension of large-scale specimens of a real thickness with through cracks and surface long cracks in the temperature range from +20C to -100C.

Experimental results for the specimens with surface cracks are given in the fracture graphs, Fig. 1, as the relationships used for the evaluation of the surface crack, in the gas-holder shell, critical depth with regard for the maximum operational stresses and stress concentration influence. The results of the strength analysis, taking into account the experimentally found characteristics of the static crack resistance for the near-weld zone of the welded joint at minimum operating temperature $T = -40C$ showed that at development of long surface fatigue cracks ~ 4 mm deep in the gas-holder shell the load-carrying capacity margin at max. working pressure 1.2 MPa was $n_\sigma = 1.75$ and the critical crack depth margin was $n_a = 2.0$.

The design evaluation of the fracture resistance of the gas-holder shell with a through crack in the butt weld was carried out using a critical stress intensity factor K_c as a strength criterion for the weld metal. The above-mentioned margins of the critical stress intensity factors and crack lengths are ensured at max. working internal pressure up to 1,2 MPa and climate temperatures up to -25C. At lowering the temperature to -40C the working pressure in the gas-holder should also be lowered to 0.8 MPa in order to ensure the corresponding crack resistance margins.

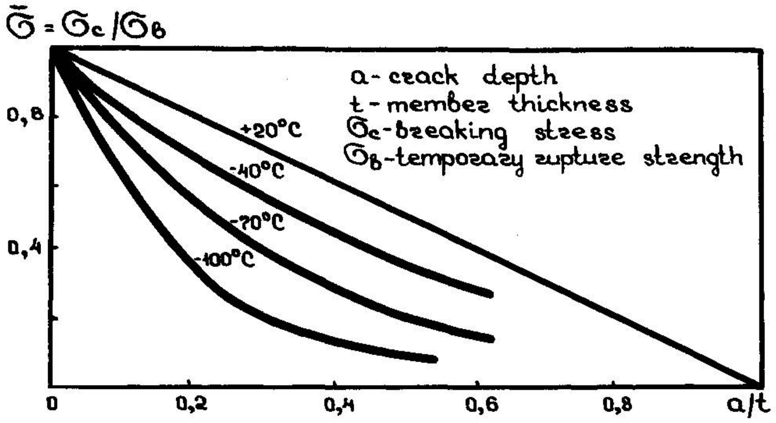

Fig. 1 Fracture curves for the specimens with surface cracks in the near-weld zone of the welded joint

The results obtained were used at the evaluation of the gas-holder useful life, considering cracks dimensions in the shell.

3. THE USEFUL LIFE EVALUATION

The useful life evaluation was performed with regard for 2 criteria of the structure limiting state:

- development of long surface cracks approximately 4 mm deep in the zones of structural stress concentration, which guarantee the absence of the brittle fracture of the shell at minimum operating temperature T = -40C;
- depressurization of the shell as a result of fatigue cracks development initiated from large inner imperfections in welded joints.

At the evaluation of the useful life based on the criterion of surface cracks development the design fatigue curve found on the basis of the experimental data was used, which connected the amplitude of local stresses σ_a^* in the zones of structural and the admissible number of stresses [N]; the safety factors for stresses n_σ and durability n_N being equal to 1.25 and 3.0, respectively (Fig. 2a).

At the determination of local stresses the highest level of structural stress concentration $K_\sigma^* = 3.4$ was considered. The range of operational loading corresponded to the real one for the group of gas-holders with capacity 2000 m^3.

As a result of calculations made with a regard for a rule of linear summation of fatigue damages, it was found out that the useful life of gas-holders according to the criteria of cracks of a critical size development in the zones of a structural stress concentration was 44 years.

At calculation of the useful life according to the criteria of a shell depressurization the fatigue curve was used (Fig. 2b), which characterized the relationship of the admissible number of the loading cycles to the range of nominal stresses in the structure $\Delta\sigma$ and corresponding to the lower envelope of the experimental data according to the moment of through cracks development in ball gas-holders, as well as models of welded joints with the similar weld imperfections at the above-mentioned safety factors according to stresses and durability.

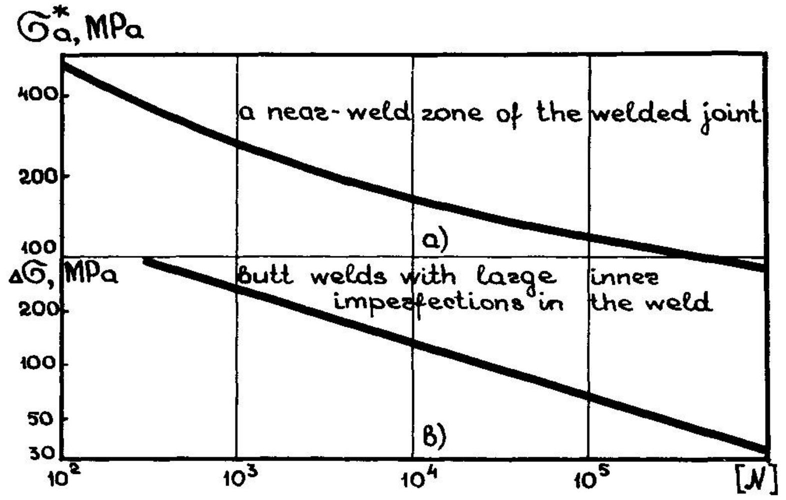

Fig. 2 Fatigue curves for the evaluation of the useful life: a) according to the criterion of surface cracks development, b) according to the criterion of the shell depressurization

The calculation of the useful life was also carried out on the basis of the rule of linear summation of damages without taking into account those amplitudes of nominal stresses at which fatigue cracks had no growth; the largest imperfection found at a random ultrasonic non-destructive testing in one of the gas-holders (lack of penetration of 450x8 mm size) being taken as an initial imperfection. As a result, it was found out that the useful life of a battery of ball gas-holders according to the criterion of the shell depressurization caused by fatigue cracks development from long inner defects in butt field welded joints was 34 years.

In such a way, the factor limiting the structure useful life was the presence of long inner defects in butt welded joints, the elimination of these defects would increase the durability of ball gas-holders up to 44 years.