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Fatigue properties of weld joint of gas pipelines

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Abstract

Pipeline systems as well as pressure vessels under operation, possess some sections or junctions in which the operation conditions are different to those which were considered during the design stage. These places are usually booster pump stations or compressor stations where there are dynamical effects which are added to a pressure loading of piping systems. The most loaded sections are weld joints. Fatigue properties were measured on the specimens from the original weld joints of the pipelines. Together with the multiannual monitoring of loading pipelines at the compressor station it is possible to estimate the real fatigue strength and lifetime of welded pipelines.

Keywords: fatigue; pipeline; weld joints; vibrations

1. Introduction

Regulations and standards determining the conditions for the design and construction of pressure pipelines intended for the transport and storage of natural gas (and other media) presuppose constant pressure values and thus constant values of stresses in pipeline and their welds (Restrepo et al. 2001, Nanney 2012). During the transport and

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storage of hydrocarbons and other media, there are operating conditions where the internal pressure and the external load changes dynamically. Typical examples are excited pressure pulsations in side-branches and bypasses, operation of pipelines near compressors, etc. (Wachal et al. 1991, Radavich et al. 2001). This kind of operation increases the frequency of changes in mechanical stresses in the pipe and their welds. Therefore, in addition to static pressure safety, it is necessary to monitor and evaluate the cyclic (fatigue) strength of the pipeline. The place where the fatigue damage accumulates the fastest in the material due to the cyclic nature of stress is determined by the value of two parameters:

- the highest level of stress amplitude
- the lowest level of cyclic properties of the material

The geometry of pipelines usually does not create places with a significant concentration of stress. The critical point in terms of the accumulation of fatigue damage is thus determined by the second factor - the level of cyclic properties of the material. The lowest level of these properties is achieved in the localities of welded joints, because during their creation melting, crystallization and the formation of an area with a different chemical composition and microstructure in comparison with the basic material take place. Cyclic properties of the so-called heat-affected zones of the weld are significantly lower due to the result of these processes compared to the base material.

Nomenclature

σ_a	stress amplitude
σ_f'	fatigue strength coefficient
b	fatigue ductility exponent
X52 X60	designation of piping materials according to the American Petroleum Institute standard

2. Long-term monitoring of stresses during operation of pipelines

Valid values of stress waveforms in pressure pipes during real operation can be obtained only by their direct measurement. Several measurement methodologies and complex monitoring systems developed and operated by STU in Bratislava and which were published by Chmelko (2015, 2020) are based on continuous sensing of the deformation state of the pipeline in selected cross-sections (Glisic 2019), recorded and evaluated stress values during several years of operation. The obtained data in the form of time records of stresses are a valuable basis for creating an idea of the long-term behaviour of stress of these types of pipes. As an example, in Fig.1 there is output from such a monitoring system deployed to monitor the increased dynamics of operation at the compressor site when pushing gas into underground storage tanks. The long-term development of mechanical stresses was obtained near the weld in the place of the T-fitting of the bypass at the compressor. The course of the maximum values of equivalent stresses was calculated from the measured data in the form of daily maxima and minima in one year using the methodology detailed Chmelko (216, 2020). Stress peaks represent start-ups and subsequent work of the compressor up to its depressurization. Smaller stress amplitudes throughout the year are caused by the vibration of the subsoil from the work of the surrounding compressor units or other units at the compressor station.

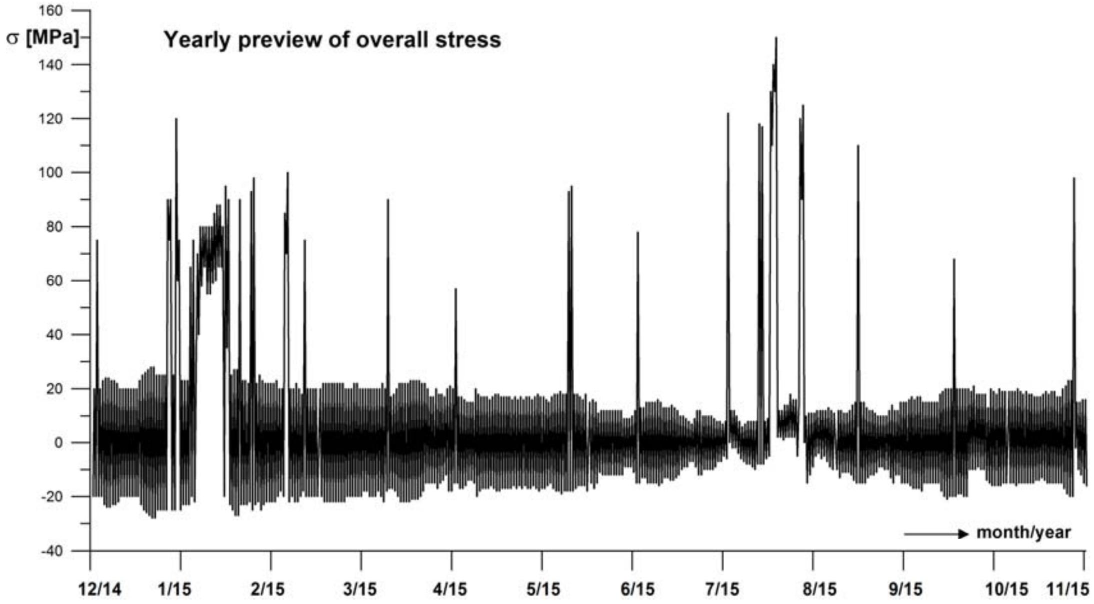

Fig. 1. Daily maximal and minimal values of equivalent stresses in the location of the T-fitting at the discharge of the turbocharger at the gas storage during the period from December 2014 to November 2015.

3. Cyclic tests of weld joint

To assess the fatigue strength, i.e. resistance to fatigue fracture, it is necessary to know the cyclic properties of the material. As no significant dynamics in operation loading were expected at the pipeline design stage, these properties were not determined or measured. From the point of view of material fatigue due to cyclic stress, the most critical place is the welded joint of the pipeline, in which different materials meet, more precisely, there are areas with different microstructure: the basic material of the tube, the weld metal and the transition area (so-called heat-affected zone). Each of these materials has different cyclic properties due to their different internal structure. In order to determine the fatigue properties of the relevant material a weld of two short sections of pipe was made using the same technology as used in pipe construction. The welded pipes were ϕ 508x20 in diameter made of S355J2G3 material (manufacturer: Chomutov-Mannesman), which is close to standard X52 pipe steel. Test specimens were taken from the welded piece of pipe around the circumference by mechanical cutting so that the weld was in the middle of the specimen (Fig. 2).

Fig. 2 Cutting specimens from welded pipes, their final shape and specimens after the cyclic tests.

Cyclic tests of the samples described above were performed in a test frame on an electrohydraulic pulsator Inova EDYZ 6 in the laboratories of the Faculty of Mechanical Engineering STU in Bratislava. The cyclic tests consisted of loading the specimens with an alternating tensile-pressure cycle up to fracture. The load amplitude levels were chosen to include, in particular, the area around the fatigue limit ($N_f \approx 10^6$) and the life until the fracture range of the order of 10^4 cycles, which represents the actual required life of the pipe collectors. The results of cyclic tests are in Fig.3.

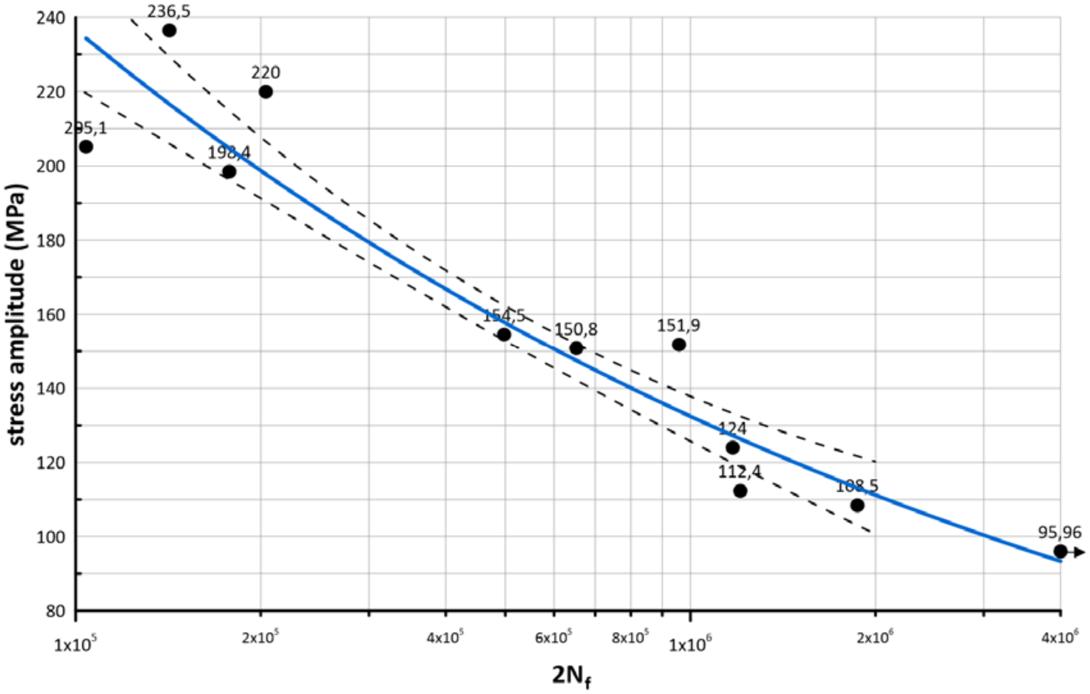

Fig. 3. Basquin curve of the test specimens from welded pipe (95% confidence interval).

By statistical processing of the results using the Basquin formula (Basquin 1910) in the form

$$\sigma_a = \sigma_f'\left(2N_f\right)^b \tag{1}$$

it is possible to determine the value of the maximum permissible amplitude of the alternating cycle for the 95% confidence interval for 1.10^6 cycles per value

$$\sigma_a = 101.5 MPa \tag{2}$$

The critical point in terms of fatigue life is the root of the weld on the inner surface of the pipe, from where all fatigue fractures spread (Fig. 2). All fractures started to propagate in the heat-affected zone of the weld material because this zone affected by welding has the worst internal structure after recrystallization due to the cyclic properties of the material.

The same character of results was obtained for the pipeline material used in the construction of the transit gas pipeline (manufacturer: Salzgitter Mannesmann Line Pipe). This material (sometimes referred to as X60) is practically identical to S355J0 steel in its chemical composition and mechanical properties (see Pereira et al. 2020). The section of the welded pipeline used for the production of specimens for cyclic tests was selected directly from the cut sections of the real pipeline used in the construction of the transit gas pipeline with dimensions ∅700x20. Specimens of the welded pipe material were obtained by the same production process as in the case of the previous material. Cyclic tests were performed on an identical electrohydraulic pulsator. A comparison of the fatigue curves of both steels is shown in Fig.4.

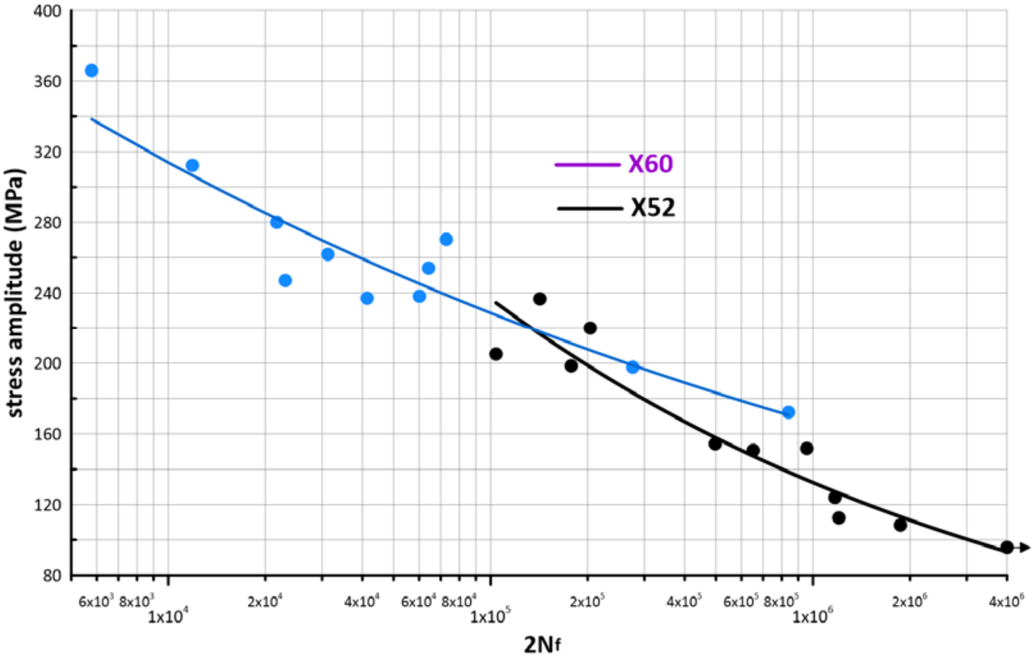

Fig. 4. Comparison of Basquin fatigue life curves of welded pipe material – steel X52 and X60.

4. Conclusions

Based on the analysis of the operating stress of pressure pipes in the vicinity of compressors through multi-year stresses monitored directly during operation and through experimental tests of welded pipe specimens on the electrohydraulic pulsator we came to the following conclusions:

- in the operation of pipelines near compressors, it is necessary to record the cycles from pressure starts and shutdowns, vibrations of pipelines under certain conditions may not contribute to the fatigue process in the pipeline material (Chmelko 2014)

- the fatigue limit of the welded joint of the pipeline for the alternated tensile-pressure cycle is 101.5 MPa (95% confidence interval) for the material S355J2G3 (≈X52), resp. 135.6 MPa for material X60

- number of cycles approx. 58000 (representing 80 years of operation with two daily start-up and shutdown cycles) allows the stress amplitude in operation up to 190MPa for material S355J2G3 (≈X52)

- at the same value of internal pressure, the weld of material X52 has sufficient fatigue strength up to a diameter of 700 mm. Pipe diameters above 700 mm require a material with a higher level of cyclic properties, e.g. X60 or X70

- the critical point of the welded joint is the heat affected zone at the point of elevation from the weld root at the inner surface due to the notch effect and the deteriorated internal structure of the material (Kliman 2015).

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