Achievements in Mechanical and Materials Engineering

COMMENT Worldwide Congress on Materials and Manufacturing Engineering and Technology

16th - 19th May 2005
Gliwice-Wisła, Poland

COMMITTEE OF MATERIALS SCIENCE OF THE POLISH ACADEMY OF SCIENCES, KATOWICE, POLAND
INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS OF THE SILESIAN UNIVERSITY OF TECHNOLOGY, GLIWICE, POLAND
ASSOCIATION OF THE ALUMNI OF THE SILESIAN UNIVERSITY OF TECHNOLOGY, MATERIALS ENGINEERING CIRCLE, GLIWICE, POLAND

13th INTERNATIONAL SCIENTIFIC CONFERENCE
ON ACHIEVEMENTS IN MECHANICAL AND MATERIALS ENGINEERING

Chemical pipelines material fatigue

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Abstract: The paper presents several aspects of the technical state assessment problem of the chemical industry pipelines working under mechanical and thermal loading. The material fatigue process in the chosen object have been discussed The following methodical problems have been presented: methods of mechanical behaviour investigation of materials in specific operating conditions, modelling the object from the point of view of solids mechanics using FEM, structure of materials changes under mechanical and thermal loading. Models of the pipeline have been worked out. Areas of the maximal effort have been determined in this pipeline. Characteristics of the stress cycles in pipeline elements have been assigned. The mechanical conditions of the material fatigue process have been described.

Keywords: Chemical pipeline; Fatigue; Structure changes; Fracture;

1. INTRODUCTION

In this paper, an example is shown, which illustrates some elements of an integral approach to the evaluation of the condition of a synthesis gas pipeline working in one of chemical plants.

In a course of time an engineering pipeline changes its material and geometrical conditions; characteristics of its supports change as well. One of the most frequently used methods of supporting power industry pipelines is “constant load” support. In this case it is assumed that reaction in the support point is constant, but the pipeline can displace freely. In the initial stage, support is consistent with a design.

An example of an object working in the chemical industry is a pipeline of 1st degree methane conversion, which connects a preheater with the reactor in an installation producing ammonia. Via the pipeline, a so-called “reactor gas” being a mixture of steam and methane is transported under 3,2 MPa pressure at temperature of 550°C. The pipeline is made of austenitic steel of the following chemical composition: C = 0,04 ÷ 0,1 %, Cr = 15 ÷17 %, Ni = 12 ÷ 14 %, Nb $\cong$ 10 $\times$ C (however, not less than 1,2%) and Mn < 1,5 %.

The object is supported in 13 points. In the section under internal pressure (points 1÷ 125) (Table 1), the pipeline is made of seamless pipes of the following dimensions in mm: 323,9 $\times$ 14,2; 273 $\times$ 12,5 and 219,1 $\times$ 10. Throughout its length, the object is insulated with a 160 mm thick mineral wool layer covered with 1 mm thick aluminium sheathing.

Suspension types and their elastic characteristics, design for the pipeline, were necessary to describe the boundary condition of the model.

In the case of a chemical pipeline, the start-up time and outage time are so short that changes in temperature in transient states may significantly influence its instantaneous effort.

During the examination of the pipeline the cracks in the joints of welded T-pipes, tube reducers and arcs were observed. T-pipes very often cracked too.

An influence of a non-uniform temperature distribution along the pipeline length on effort of the object was taken into consideration in the analysis of the pipeline behaviour. For this purpose, thermocouples were installed in selected points of the pipeline.

Continuous registration of the temperature was conducted during the start-up in a steady state and during shutting down the installation.

Thus obtained characteristics enabled the determination of variable in time distributions of temperature along the pipeline axis, which distributions were defined for selected instants: tI, tII, tIII, tIV. The temperature distributions were approximated between measuring points by means of straight-line equations. The following instants of time were selected as representative: tI – the pipeline in a cold condition, loaded with its dead-weight only, tII – the instant in which the greatest diversity of temperatures was observed in individual lines of the pipeline, tII – the instant of greates temperature in the start-up pipe and tIV – an instant corresponding to the stabilised process.

In the case of elastic supports present in chemical pipelines, the operation process leads to the growing with time probability of blocking their free shifting as well as to the occurrence of additional frictional resistance connected with the wear of rolling elements, which ensure freedom of shifting in a plane perpendicular to the spring axis. In such case, evaluation of the existing pipeline effort requires determining the degree of wear of individual supports as well as determining their current characteristics. To define the real pipeline service conditions, a review (stock-taking) of the supports was made. As a result of measurements and examinations of the supports, significant discrepancies were found between their current characteristics and the characteristics in a state consistent with the design. A juxtaposition of present characteristics of the supports was made, along with the method of the degree of freedom reduction and elastic constants of the supports after long operating period.

Having the support characteristics, distributions of reduced stresses were determined in a pipeline with support features changed as a result of a long-term service.

Models enabling the determination of stress distribution, taking into account, changeable in time, boundary conditions, material characteristics and geometrical features of the objects, were elaborated. Basing on the analysis of operating conditions and technical documentation assumptions the data for computational models were determined. These data included: pipe diameters - length, radius, wall thickness, arc radius; characteristics of fittings - diameters, weight, material characteristics - grade, physical and mechanical properties; features of thermal isolation - thickness, specific gravity.

Calculations were done for variants of thermal loading that differed in temperature distribution along the pipeline. One of temperature variants was connected with starting the pipeline and featured temperature diversification along its axis. The next variant covered steady state. In the next one higher temperatures occurred along the pipeline axis, but temperature diversification along the pipeline axis was smaller.

The stress distributions along the pipeline axis were determined in the chosen (tII, tIV) instants of the temperature cycle. Calculations showed a significant influence of temperature distribution along the pipeline axis on reduced stress distribution. It was found that the maximal effort takes place in the T-pipe 64T, on which inside the surface cracks occur.

To determine the influence of the support characteristics changes on the material effort the equivalent stress distribution has been determined for two stages of support e.g. state which agree with project of the pipeline and the state after long (about 20 years) operating period. The ratio of reduced stresses σ_a (actual state) and σ_d (designed features of the object) has been calculated for the chosen points of pipeline. The changes in support state can cause few times greater stresses than these calculated for the design state. The maximal value of the ratio σ_a / σ_d has been found in the T-pipe 64T case.

In order to determine, in global formulation, stress in such elements as T-pipe or arc stress concentration coefficient was assumed. It is an approximate method. Precise characteristic of the objects requires more sophisticated method of component damage process analysis. Coefficients of stress concentration, taken for calculations, do not give sufficient information for the precise analysis of local deformation processes in areas of the maximal effort, in which the processes of crack initiation and growth can take place. The analysis of local strain processes requires the application of computer methods - finite element methods for instance.

2. LOCAL BEHAVIOUR ANALYSIS

From those T-pipe regions, which were under the greatest effort, picked based on calculations, samples were taken for metallographic investigations. Next, transverse and longitudinal microsections were made, which were then etched in Villel's reagent. Microscopic observations were performed using a light Reichert microscope.

The research carried out revealed that thermal and mechanic strain of close-to-surface regions as well as the action of an aggressive environment (steam, methane) lead to cracking of protective, passive oxide layers, in consequence of which a local corrosion attack occurs.

Based on the metallographic observations, it was found out that those particularly degraded and showing the strongest traces of wear are the close-to-surface regions which reach ca. 0.5 mm deep. The microscopic observations show considerable defects of these regions resulting from the plastic strain that takes place during sliding and twinning that is presented in Figure 8. Simultaneously, in the investigated steel, despite its stabilising with niobium in the quantity of 0.5%, aggressive intercrystalline corrosion is observed. It is the most dangerous case of austenitic steels corrosion, which in particular attacks steel along grain boundaries, practically without any noticeable influence on the grain matrix. In consequence, the aggressive environment upsets the coherence between individual grains, which in effect leads to nucleation of microcracks and their gradual growth. This process intensifies especially where variable force and temperature fields are present under the operating conditions of this fragment of the pipeline. The corrosion processes as well as high thermal and mechanic load augment the process of cracks nucleation and propagation. In the Figere 8a we can see the cracks, which show a course characteristic of cracking under thermal fatigue conditions.

When we want to assess the fatigue life it is necessary first of all to determine conditions of the fatigue process e.g.: temperature, stress and strain fields in areas of the maximal effort. The local approach of the component model has to be used for this purpose. The global analysis gives data for such aim.

In the earlier applied methods of calculations of elements of a complex shape, provided for by standards, these elements are treated in a simplified way in relation to their geometry and loads. An evaluation of the condition of a pipeline from the point of view of its properties under the conditions of changeable in time loads requires a more precise approach to the state of stress and strain in those elements which are subjected mostly to fatigue. An analysis in a global approach enables the formulation of boundary conditions for a local approach, the latter referring to areas of the highest effort. Only such local approach ensures the determination of local characterisations of damage conditions, which reflect the relations between the components of stress and strain tensor and the temperature and time, necessary for durability forecasts. One of important elements of the local approach is the defining of load conditions at the boundaries of selected pipeline areas. A shift from a global-holistic approach to a local one necessitates acceptance of a different object model for the discussion. A model of the analysed fragment, which, in a global approach, is a spatial frame, in local approach is substituted with a solid. Such model of T-pipe 64T is presented in the Figure 9. In this case, it is important that external load be distributed on parting planes. The distribution would be consistent with the distribution of stresses induced by a defined type of internal interaction.

In this way, the size of the models to be discussed can be limited, which considerably shortens the time of analysis of this problem by finite element method. This problem is extremely vital where strain is of an elastic/plastic nature.

The method of stresses determination in the nodes on the finite-element lattice in the planes of partition is described separately for a bending moment and torsion moment.

The parting planes have been defined as border regions in the form of rings. The manner of external forces distribution at the partition border resulted from the method of generating the finite element lattice in solid models of complicated shape components. The method applied in the study referred to a specific case of the border region partition, where the section area is divided into concentric rings, which are next divided into elements of, most often, the same size. A similar procedure was applied for torsion moments.

Using a finite element method program, reduced stresses' distributions were determined in consecutive instants of time, characteristic of pipeline service. The presented approach allowed the localisation of areas under the highest effort. This kind of approach can be also used for the purpose of T-connection durability forecasting. It would be necessary then to determine the characteristics in the form of dependence between the components of stress and strain tensor and temperature in order to compare their parameters with the durability criteria, e.g. with Manson-Coffin's criterion.

It has been stated that the fatigue and fracture properties depend on the exploitation time of a component. It is commonly known that materials change their structure and properties in the operating condition. This is the reason why it is necessary to have material data connected with the actual material state. Sometimes it is possible to test material after long exploitation period, but this is a difficult, expensive and sometimes impossible way. Simulation technique seems to be better. In this case material testing systems are used, which give possibility to change temperature, strains and stresses in time. The cyclic stress-strain curve, has been taken as the material characteristic in presented work. This type of characteristic allows, in certain meaning, influence of loading history on the material behaviour. Results of low cycle fatigue tests could bring closer influence of the real operation condition on the changeable material features.

On the examples of the stress patterns on the T-pipe surface, the maximal stress equals 234 MPa. The place of maximal stress was located in the area of connection the main pipeline with the part connecting T- pipes 64T and 117T. The areas of maximal effort were the same as areas in which the intensive damage process occurred. On the basis of local analysis it is possible to assess the danger of non-controlled crack propagation, in case of their presence in a pipeline.

The basic material characteristic is in that case failure assessment diagram (FAD). It is also possible to determine the crack parameters that could cause the fracture of the pipeline. Whatever there is still a problem of evaluating length and depth of the crack, which should be treated as critical for given loading conditions and with a given state of the material.

Structure changes depend on material grade and history of temperature and loading. That's why the component behaviour should be analysed as the one depending on the complex material characteristics e.g. stress-strain curves, low cycle fatigue life characteristics, fatigue crack growth rate graphs, Manson-Coffin relationships and creep curves. The proper data for the chemical plant life assessment are available in the limited range.

3. FINAL REMARKS

The maintenance of plants, which work under mechanical and thermal loading e.g. pipelines in chemical or power industries has to have a special character taking into consideration the safety reasons. Some of these plants, after long operating period, need their technical state assessment. Now we can use for this purpose the new methods that differ from these used long time ego, when they were designed. These new methods gave us possibilities to determine the actual unstable effort of the complex technical structures. Now it seems to be the proper time to look for the new maintenance methodology, which could be based on the model formulation.

The paper is an attempt to describe elements of the methodology of the state assessment of the plant. The FEM model formulation is the main part of method used in the work. On the basis of analysis it was stated that there is a possible influence of stress changes in starting and switching off period conditions upon the fatigue of the pipeline material.

As the analysis shows, the state of exploited pipelines calls for the detailed information connected with temperature distribution, temperature changes in time in particular places and also characteristics of the supports. It is necessary to monitor temperature in the chosen places of the pipeline. Recording should enclose start-up and steady state conditions of the object. Performed calculation showed significant importance of load variation in time for the durability of a pipeline. It is necessary as well to determine the changeable support characteristics, which should be one of the procedure elements necessary to evaluate lifetime of examined plant components.

The presented procedure allows determining places of the highest reduced stresses, in which the material fracture can occur. Such places should be analysed, taking into account the geometrical features of components and using local description of the object.

The pipeline behaviour analysis and metallographic observations of the material after long operating period show the importance of thermo-mechanical fatigue phenomenon in damage processes of the chemical pipeline materials. These kind of fatigue is one of important problem and it is now the subject of scientific research projects.

The analysis of the support characteristics, that decide on the stress distribution in the pipeline, shows that changes in these characteristics strongly influence the object behaviour.

The uncertainties of loading prediction in supports in operating period seems to be as well important for the life and fracture prediction as the uncertainties in mechanical properties assessment. But these phenomena should be treated as the separate problem, which needs the special methodical approach