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Fatigue aspects of an evaluation of the operational safety of components working in creep conditions

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Analysis and modelling

ABSTRACT

Purpose: The main purpose is the method of the description of the thermo-mechanical fatigue process of power plant components working under mechanical and thermal loading. The work focuses on the chosen component strain-stress characteristics and their strength. The paper discusses the issue of modelling the heating and cooling processes of components in a power plants in the start-up and shut-down conditions of a boiler.
Design/methodology/approach: The FEM modelling has been used to describe the local stress-strain behaviour of the chosen component.
Findings: The calculations of stress distribution on the chosen component surface show that the internal pressure induces considerably smaller values of stresses and strains in comparison with the same stresses specified for thermal loads. However, it should be noted that the impact of temperature gradients and thermal stresses is usually short-lived, therefore, its influence on creep processes is less significant in comparison to pressure load. Material fatigue is mainly the effect of thermal stresses. Thus, thermal impacts are responsible for cracks initiation and growth in areas of the greatest intensity of damage accumulation.
Research limitations/implications: The presented analysis is the part of the complex investigation method which main purpose is increasing the accuracy of the TMF process description and thermo-mechanical life assessment. The possibility of applying the fatigue durability criteria currently assumed in standards still requires justification and confirmation in laboratory and industrial conditions to be closer to the real components behaviour. In such situation the industrial investigations curried out in the work give the model approach and data for the comparison the real behaviour with the predictions.
Practical implications: The method of stress-strain behaviour analysis used in the paper could be useful in the practical cases when the real components mechanical behaviour would be analysed.
Originality/value: The main value of this paper is the own method of the mechanical behaviour analysis of the power plant component. This method includes the temperature fields analysis taking into account the boundary conditions based on the operation parameter data and the thermoplastic material model. The material stress-strain behaviour has been treated as the local phenomenon, that could be modelled by FEM.
Keywords: Applied mechanics; Numerical techniques; Fatigue; Computational mechanics

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1. Introduction

Creep is the basic process determining the strength and durability of the power equipment components, which is especially important for materials working at elevated temperatures. The process is treated as such by the standards and procedures used by designers and users of power generation unit equipment, including pipelines, steam superheaters, boiler drums and other pressure vessels. Most often, the creep phenomenon is examined on the assumption of homogeneity of components in terms of the materials used and the stationary operating conditions, i.e. a constant operating temperature and the pressure of the medium filling or flowing through the vessels.

In the case of some components, apart from creep, the loads caused by a changing temperature during unsteady operation of a boiler, i.e. during its start-up and shut-down [1,2], are taken into account as well. In such a case, the average rate at which temperature increases or decreases is taken into account. The rate of temperature changes is related to its gradients on the section of thick-walled vessels which determine the value of strains and thermal stresses resulting in material fatigue processes caused by successive start-ups, shut-downs or changes in parameters for boiler work. The fatigue processes induced by so defined interactions, as taken into account while designing an installation, in most cases are not a threat to the components of a properly designed and operated power unit. It should be noted, however, that in both transient and steady operating conditions of an installation, states diverging from those assumed in the calculations may occur. Sudden changes in temperature and medium pressure connected with power unit control including short-term and repetitive cooling induced by the work of injection attemperators are an example. Given the rate of temperature changes within short periods of time, in such cases stresses exceed significantly the values considered in calculation procedures [3].

Cracks formed most often on the inner surface of thick-walled components may be the effect of repeated thermal impacts. The cracks are also often present in material as a result of the manufacturing process of the considered components. In particular, it applies to components made or assembled with the use of welding technologies. The cracks may grow during operation with its both variable and fixed parameters. In the latter case, rheological processes are most often the cause of crack growth.

Until recently, the regulations of pressure equipment use had not allowed for further operation of the components with defects. Currently, such a possibility is taken into account. However, the degree of threat associated with the possibility of unstable growth of crack length needs to be assessed in each case. In some of the European Union states [4,5], there are national standards and procedures for the evaluation of strength and durability of components with cracks are applied. In Poland, the standards of the European Union are applied, which at the moment still do not include the procedures to be followed during the assessment of the strength and durability of the components with cracks. However, in connection with the European Commission research programs, actions aiming at the standardization of methods of strength calculations in the considered range of applications are carried out. They include the participation in the SINTAP and FITNET programs and the application of their results in industrial practice [6-9].

In studies resulting from the above-mentioned programs, the tests carried out by the countries which had adopted the standards based on the laws of fracture mechanics have been considered. They include the tests carried out by Nuclear Electric Ltd [10,11].

The methods of assessing the strength and durability of the components with cracks were discussed in detail in the book by Webster and Ainsworth [11], which had been first published in 1994. The book contains the theoretical basis for methods of forecasting the crack growth in components subjected to elevated temperatures and mechanical loads. It discusses issues related to the importance of fatigue impacts and the correlation of fatigue and creep processes for cases where repetitive, long-term periods of steady load occur alternately with short-term intervals associated with loading and unloading of an installation, which intervals are connected with cyclical start-up and shut-down of power engineering equipment, to which the book is largely devoted. The study also contains the material characteristics of selected steels, necessary for the practical applications of the methodology described in it. Due to the considered in the paper nature of the impacts causing the material fatigue, the values of the extreme stresses in the fatigue cycle are the same or slightly different from the values taken into account during the analysis of the creep process. In assessing the values of loads, thermal stresses are most often disregarded or a steady rate of temperature changes of the medium is taken into account while determining them during heating and cooling. Such a way of calculating stresses is in compliance with the EN 12952-3:2001 (E) standard [2]. However, it should be noted that constant speeds of the heating and cooling process during start-up and shut-down occur extremely rarely.

Usually, in transient states of an installation operation, short-term periods of intense heating and cooling occur, which are connected with the control of the operating parameters of the boiler. The speed of temperature changes in these time periods sometimes exceeds considerably the average values established by the standards and assumed in design calculations, which is often unavoidable due to the way of "maintaining a power unit". The control of temperature in transient states is handled through changing the speed and pressure of steam as well as through starting up and shutting down the cooling elements, the latter being the above-mentioned injection attemperators. It is usually impossible to regard steam temperature changes and installation temperature changes related to them as steady, especially in start-up conditions, which results from both the ways of control and the level of the complexity of installations subject to control.

2. The influence of abrupt changes in temperature on the stresses and strains in thick-walled components

Changes in the state of a medium flowing through an installation induce oscillations of both its temperature and heat transfer coefficient. Abrupt changes in the temperature of the internal surface of thick-walled components including pipes, pipe tees and steam superheater chambers are the effect of such impacts. In their case, thermal stresses exceed considerably the values of stresses induced by internal pressure.

Quantitative characteristics of local thermal impacts are usually difficult to specify since temperature and pressure measurements are conducted in selected areas of power installations. They are not always the places of the highest intensity of destruction processes occurring in materials. Given the applied in industry methods of the control with power unit work, the characteristics of thermal loads are usually of random nature. In many cases, the speed of the changes in temperature measured at selected points of an installation reaches high values. Taking into account the possibility of the occurrence of such impacts, it seems necessary to pay more attention to their relation to the durability of power engineering equipment components. It concerns especially processes for the initiation of cracks on the inner surface of pressure vessels subjected to the impact of abrupt changes in temperature.

The values of stresses caused by the changes in temperature have been compared in the paper with the values of stresses caused by internal pressure. The question has been presented on the example of a steam superheater chamber. A selected device whose geometric characteristics were reproduced while building a model comprising the fragment of the object (Fig. 1) has been subjected to an analysis. The model was isolated by means of intersections method taking into account the symmetry planes of the considered installation component. The results of the steam temperature and pressure measures in this component in the industrial conditions have been shown in the Fig. 2.

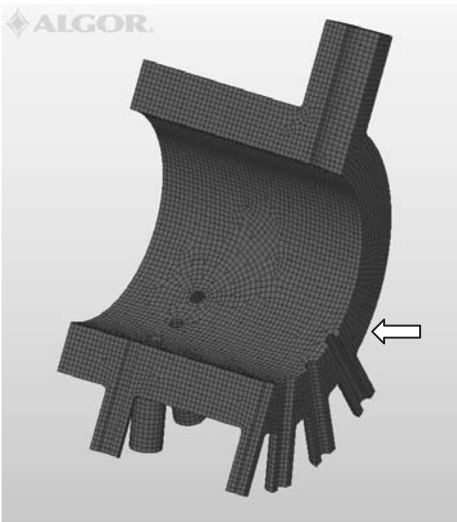


Fig. 1. Model of the part of the steam superheater chamber

For this component the temperature field has been determined as the function of the time and after that the strain and stress fields changing in time. The heat transfer coefficient has been assumed in the first step as constant. The example of the influence of mechanical and thermal loads on the stresses and strains in the volume of a steam superheater has been shown in the Fig. 3. The characteristics in this Fig. 3 represent the stress and strain changes in the selected point on the superheater header surface (Fig. 1).

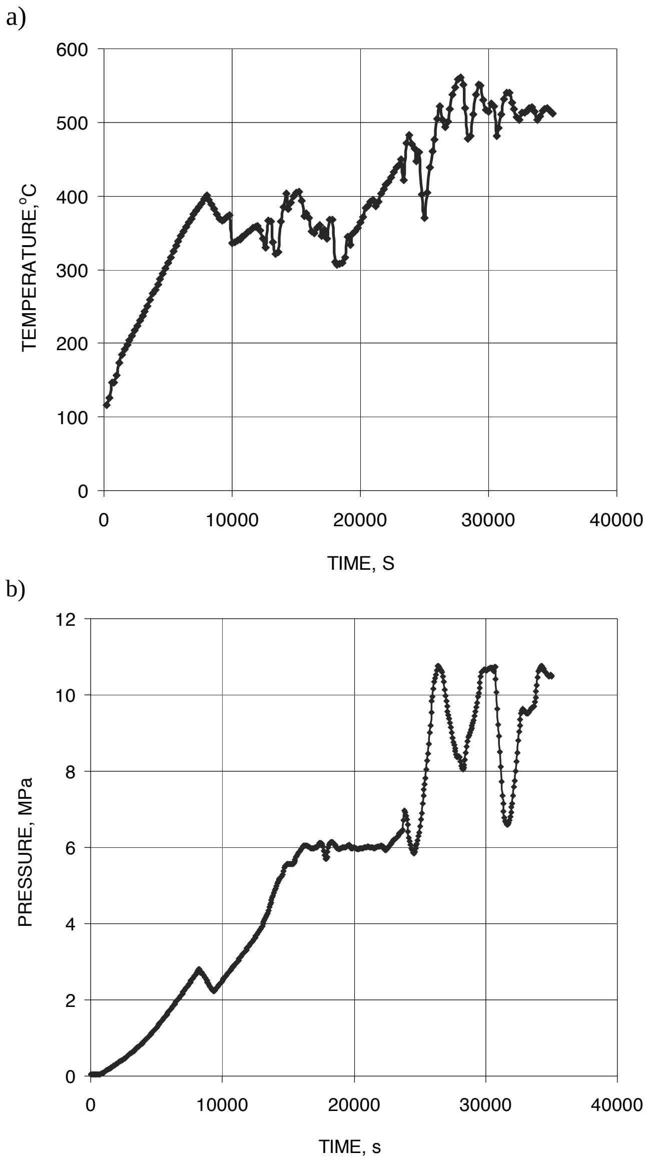
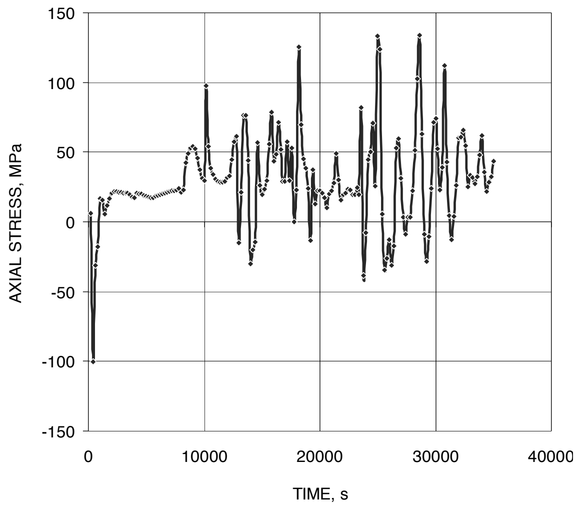


Fig. 2. Characteristics of changes in the temperature - a) and pressure - b) of the medium flowing through the chamber in time

We can observe the strong influence of the temperature changes on the strain and stress values. However taking into account complicated characteristics of the temperature and pressure changes in time, as have been shown in the Fig. 2, it is difficult to assess the regularities of the influence of the possible operation parameters on the stress and strain fields. It is difficult as well to assess the differences in the influence of the temperature and pressure on the stress and strain state. In such a case the chosen idealized characteristics could be used. These characteristics should represent the possible typical or extreme parameters of the operation. Such analysis has been done and will be presented in the paper. It was assumed that at the initial moment, the chamber is heated to the temperature of steady work of the boiler. Next, it is loaded with internal pressure equal to the working pressure (Fig. 4). The loading is taking place at a rate low enough to disregard the influence of inertial forces on the values of stresses and strains. A steady state of work of the installation is achieved in this way. It was also assumed that abrupt changes in temperature of a medium may occur in the conditions of control of the operation of a power generation unit. Steam superheater chambers in the vicinity of injection attemperators are especially exposed to such impacts way. The introduction of water to superheated steam causes abrupt changes in the state of the medium, the conditions of heat exchange and pressure as well. The description of this phenomenon is a separate problem which requires a diagnosis and tests.

a)



b)

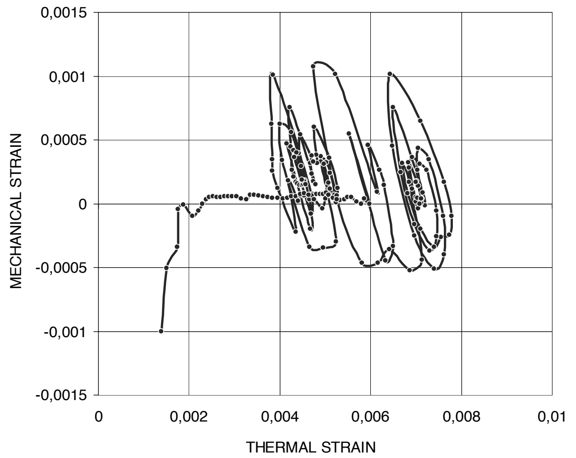
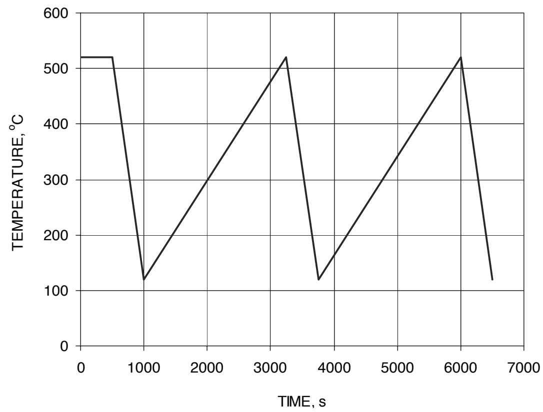


Fig. 3. Characteristics of changes in the axial stress in point shown in the Fig. 1 as the time function - a) and the mechanical strain versus thermal strain characteristic determined for the same point - b)

a)



b)

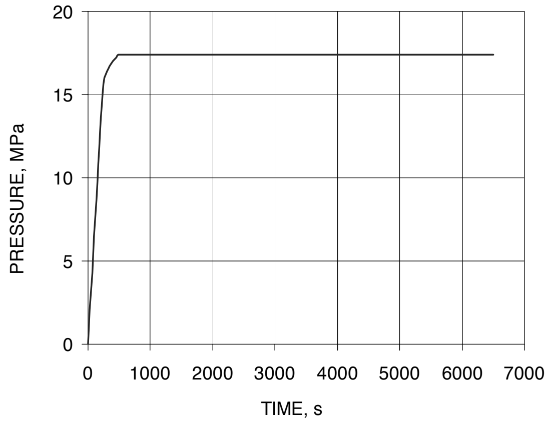
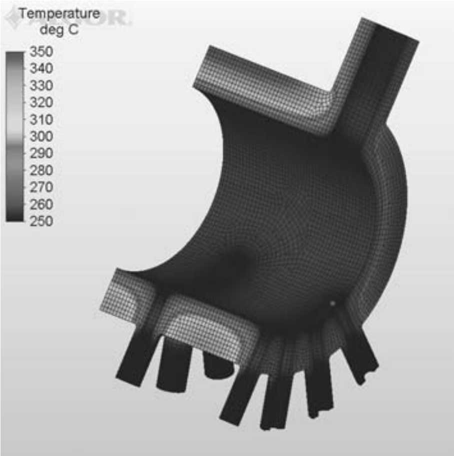


Fig. 4. The assumed characteristics of changes in the temperature - a) and pressure - b) of the medium flowing through the chamber as a time function

At this stage, the attention was focused on the elaboration of heat flow process in the material of a superheater chamber induced by the oscillations of the temperature of a medium. It was assumed that steam cooling in short periods of time during the control with power unit may be characterized with cyclical courses of changes in its temperature. The course of changes in temperature of the considered medium at the time in the form presented in Fig. 4a was assumed. The first period of time (500 s) corresponds to loading with internal pressure. The length of this period is not connected in any way with the actual length of time of loading but it results solely from the stress calculation method by the means of the software used in the calculations. This period was introduced in order to compare the stresses caused by pressure with the stresses caused by uneven temperature field. It was assumed that later the temperature course would have a cyclical form. The changes occur in the range of maximum temperature - 520°C to a minimum one - 120°C. The value of the minimum temperature slightly above the water boiling point was assumed in this case. Heat transfer coefficient equal to 0.01 $J/^{o}C \cdot s \cdot mm^2$ [12] was initially assumed. Such an assumed value was taken from the range which corresponds to an intensive heat exchange occurring during the cooling which takes into account the state of water drops boiling as well as during the contact of a chamber with steam in the state of bubble condensation. The temperature varying in time was specified for the assumed boundary conditions. Examples of temperature distributions on the inner surface and the chamber sections are shown in Fig. 5.

a)



b)

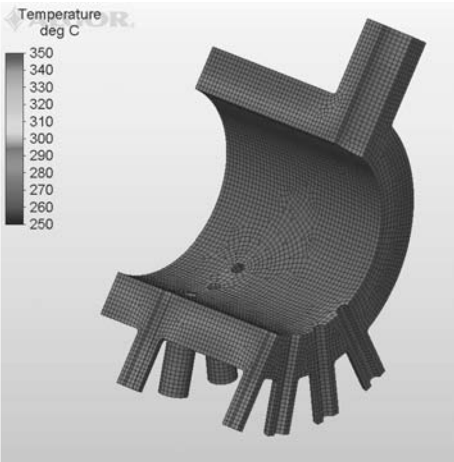


Fig. 5. Temperature distributions on the inner surface and chamber sections at selected moments of time: a) 850 s (cooling), b) 2000 s (heating)

Pressure and temperature field constituted the load of the considered device. Assuming distributions of temperature corresponding to the successive moments of time, stress fields varying in time were specified in the next turn.

The points in which the stresses reach the highest values were selected on the chamber inner surface. In accordance with the operating tests, they are also places in which the formation and development of cracks in operating conditions were observed [13,14]. A thermo-elastic-plastic model of material was adopted (Fig. 6). In the points defined in Fig. 7, the characteristics of changes at time of the components of the state of stress (Fig. 8) and strain were specified.

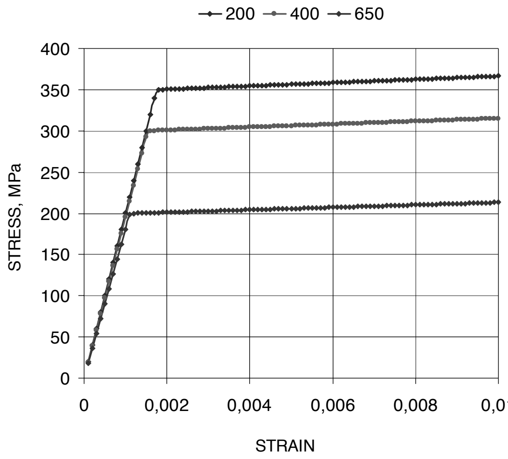


Fig. 6. Graphs presenting the relation between strains and stresses for the thermo-elastic-plastic model of material assumed in the calculation

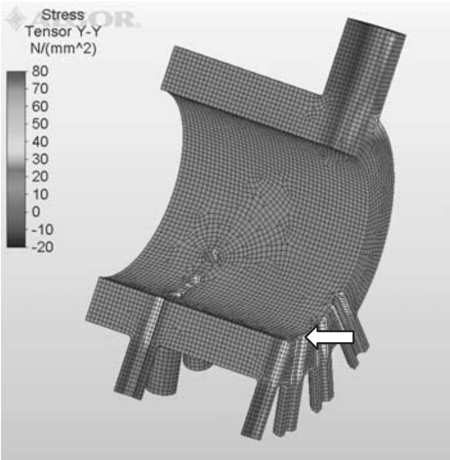


Fig. 7. Model of the part of the steam superheater chamber (stress distribution at 550 s) with point in which stress and strain characteristics (Fig. 8) have been determined

Two characteristic points (A and B) on the header surface have been defined (Fig. 9). These points have been used in order to compare the values of hoop and axial stresses.

In Figure 8, the periods of time at which the stress values exceed the yield point can be observed, which causes the formation of plastic deformations in subsequent cycles of changes in temperature. This type of local behavior of the material is characteristic for the thermo-mechanical fatigue processes [15-20]. With the aim of presenting a quantitative perspective of the intensity of this process, the relations between the components of the state of stress and strain have been determined in the form of a hysteresis loop - $\sigma(\varepsilon)$ (stress as a function of mechanical strain), as well as the relations between mechanical and thermal strains (Figs. 8d, 8c, 11).

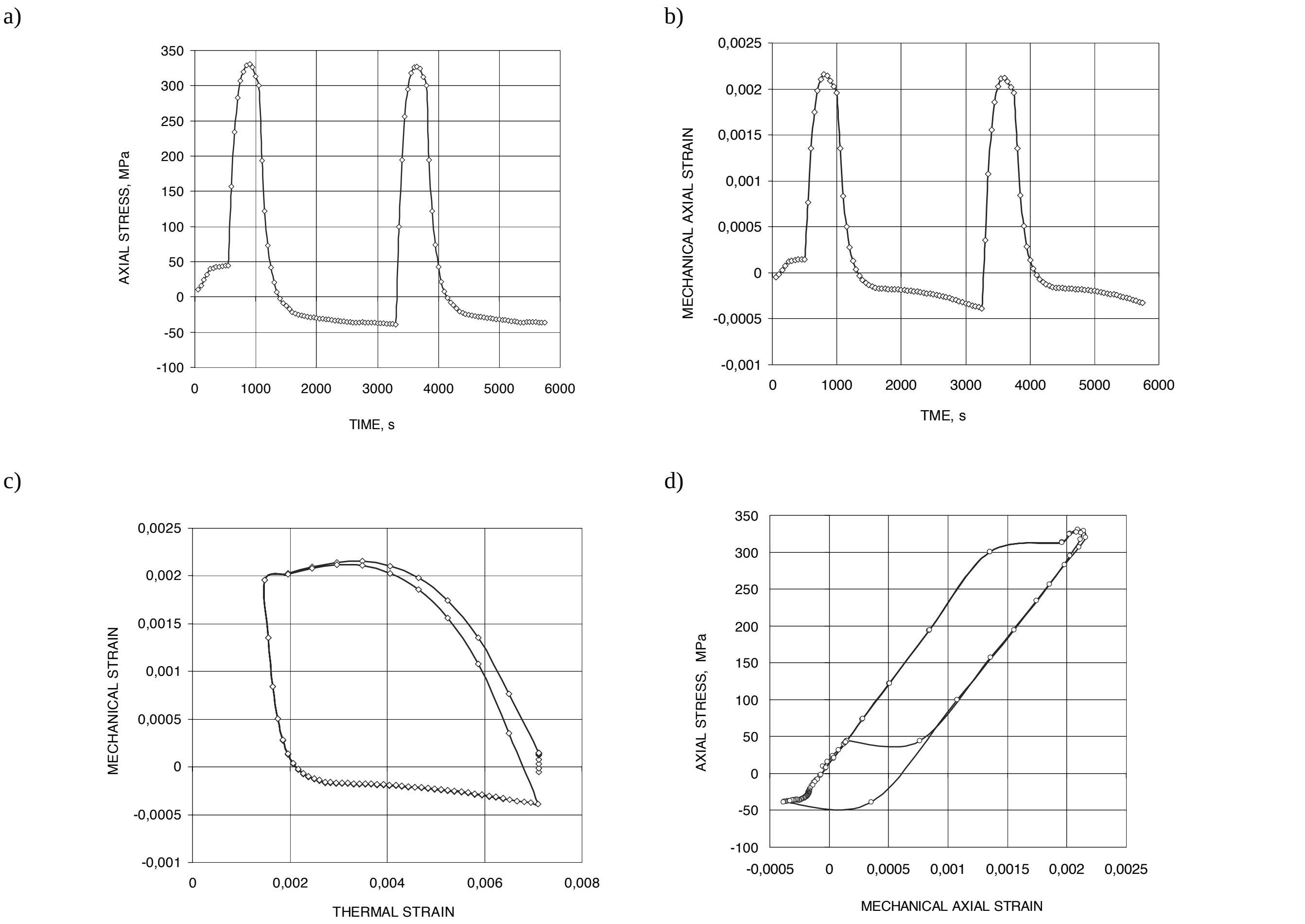


Fig. 8. The characteristics of the stress - a) and strain - b) changes in time; the relation between thermal strain and mechanical strain - c) and strain-stress hysteresis loop - d) specified for the point shown in Fig. 7

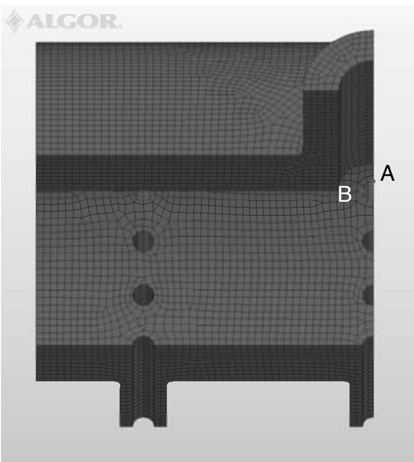


Fig. 9. The model of a chamber with marked points in which the characteristics of the mechanical behaviour of material were specified.

Relation courses presented by the figures enable the specification of the type of thermo-mechanical fatigue process and the parameters which may form the basis for assessing the fatigue life regarded as the number of cycles or time for the formation of a cracks in the considered place.

3. Calculation results analysis

The calculations of stress distribution on the surface of a superheater chamber show that loading it with internal pressure induces considerably smaller values of the components of stress state in comparison with the same values specified for thermal loads. However, it should be noted that the impact of transient field of temperature and thermal stresses is usually short-lived, therefore, its influence on creep processes is less significant in comparison to pressure load. Material fatigue is mainly the effect of thermal stresses. Thus, thermal impacts are responsible for the formation and to some extent for the development of cracks in areas of the greatest intensity of damage accumulation. However, while the stresses induced by pressure remain within the elastic range, which is safe owing to the possibility of rapid material decohesion, their long-term impact is the potential cause of the development of cracks, both those that may be present in the material after the technological process of their manufacturing and those which are induced by fatigue during the use of an installation.

a)

b)

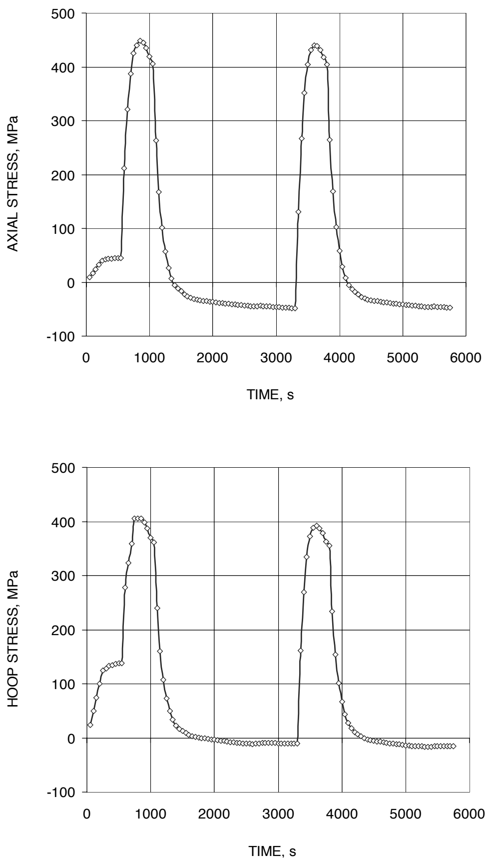


Fig. 10. A graph presenting the relation of axial stress at point A and hoop stress at point B (Fig. 9) to time

A widely known phenomenon which occurs in pressure vessels of power engineering equipment is the formation of cracks on the inner surface of the vessels [14,21-25]. In superheater chambers these cracks display hoop direction as they develop and connect the cracks perpendicular to the axis of chambers with each other. Such a process of cracks growth appears to be contrary to commonly accepted opinion on pressure vessels cracking in planes perpendicular to the direction of hoop stresses, which are twice as big as axial stresses for internal pressure loading of cylindrical thin-walled vessels.

However, the analysis of the characteristics presented by the figures (Figs. 10a and 10b) allows for other conclusions. For instance, it turns out that the hoop stresses caused by pressure and transient temperature field at point B in Figure 9 reach smaller maximal values than the axial stresses at point A of the same hole. The same finding applies to a stress range regarded as the difference between the maximal and minimal stresses in the course of the hysteresis loop (Fig. 11). If cyclically variable normal stresses are regarded as the cause of cracks development, a greater rate of the crack growth present in the point A should be expected. Thus, considering the crack growth in thermo-mechanical fatigue process, cracks perpendicular to the axis of the chamber are characterized by 'privileged' conditions for the growth of their length. The calculation results are in compliance with the observations in industrial conditions, where older types of superheater chambers cracking perpendicular to the chamber axis [13,14] are a characteristic phenomenon.

a)

b)

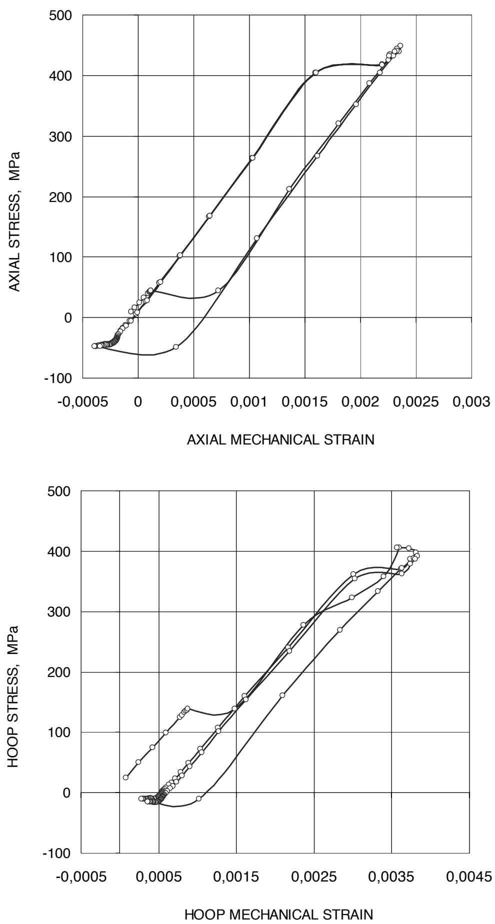


Fig. 11. Hysteresis loops specified for points A and B (Fig. 9): a) point A, axial stress, b) point B, hoop stress

The presented results were obtained for the assumed boundary conditions, which should be considered in this case as one of many possible approximations of the conditions occurring during the use of superheater chambers. Thermal loads are usually characterized by less systematic nature. However, the aim of the tests has not been to represent superheater chambers work in an accurate way, as it is the subject of separate research, but to determine the relevance of particular types of loads in the process of the degradation of the use qualities of the concerned equipment. The study illustrates also the methodology for the assessment of strength and conditions for the formation and growth of cracks in power engineering equipment components, with a particular consideration of the conditions of thermo-mechanical fatigue processes. In this perspective, this study represents one of a number of studies carried out at the Silesian University of Technology, the subject matter of which is concerned with the fatigue processes induced by mechanical and thermal factors in power engineering equipment. These processes in future should be examined with the other phenomena connected with the crack initiation and growth in the creep conditions [26,27]. In such situation the work presents the result of the investigation of the selected process - thermo-mechanical fatigue, which influence the bahaviour and the life of the high temperature components of power plants.

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References

[1] P. Fontaine, J-F. Golopin, HRSG Optimization for cycling duty based on Euro Norm EN 12952-3, ETD Conference on Cyclic Operation of Power Plant, London, 2007.
[2] Standards EN 12952, EN 12952-3:2001 (E), EN 12952-4:2000.
[3] J. Okrajni, W. Essler, Computer models of steam pipeline components in the evaluation of their local strength, Journal of Achievements in Materials and Manufacturing Engineering 39/1 (2010) 71-78.
[4] BS 7910, Guide on methods for assessing the acceptability of flows in structures (replacing PD 6493 and PD 6539), British Standards Institution, London, 1994.
[5] Design and construction rules for mechanical components of FBR nuclear islands, RCC-MR, Appendix A16, AFCEN, Paris, 1995.
[6] S. Webster, A. Bannister, Structural Integrity Assessment Procedure for Europe - of the SINTAP programme overview, Engineering Fracture Mechanics 67/6 (2000) 481-514.
[7] Project European Thematic Network FITNET FFS-GIRT-CT-2001-05071.
[8] A. Neimitz, I. Dzioba, M. Graba, J. Okrajni, The assessment of the strength and safety of the operation high temperature components containing crack. Kielce University of Technology Publishing House, Kielce, 2008.
[9] A. Neimitz, Procedures of the strength assessment of structural components containing cracks, Kielce University of Technology Publishing House, Kielce, 2004 .
[10] Nuclear Electric Ltd, Assessment Procedure for the High Temperature Response of Structure. Proc, R5/2, UK, 1997.
[11] G.A. Webster, R.A. Ainsworth, High Temperature Component Life Assessment, Chapman & Hall, London 1994.
[12] Z. Orłoś, Thermal stresses, PWN, Warsaw, 1991 (in Polish).
[13] K. Mutwil, M. Cieśla, Factors determining the durability of steam superheater chambers, Power Engineering 14 (2007) 81-84 (in Polish).
[14] A. Hernas, J. Dobrzański, Durability and damage of steam boilers and turbines, Silesian University of Technology Publishing House, Gliwice, 2003.
[15] J. Bressers. L. Remy (eds.), Fatigue under thermal and mechanical loading, Kluwer Academic Publishers, Netherlands, 1996.
[16] P. Hähner et al., Research and development into a European code-of-practice for strain-controlled thermo-mechanical fatigue testing, International Journal of Fatigue 30/2 (2008) 372-381.
[17] H. Sehitoglu, Thermal and thermo-mechanical fatigue of structural alloys, Fatigue and Fracture, ASM Handbook 19 (1996) 527-556.
[18] J. Okrajni, Thermo-mechanical conditions of power plant components, Journal of Achievements in Materials and Manufacturing Engineering 33/1 (2009) 53-61.
[19] J. Okrajni, G. Junak. A. Marek, Modelling of the deformation process under thermo-mechanical fatigue conditions, International Journal of Fatigue 30/2 (2008) 324-329.
[20] J. Okrajni, A. Marek, G. Junak, Description of the deformation process under thermo-mechanical fatigue, Journal of Achievements in Materials and Manufacturing Engineering 21/2 (2007) 15-24.
[21] J. Okrajni, K. Mutwil, M. Cieśla, Steam pipelines’ effort and durability, Journal of Achievements in Materials and Manufacturing Engineering 22/ 2 (2007) 63-66.
[22] D. Renowicz, A. Hernas, M. Cieśla, K. Mutwil, Degradation of the cast steel parts working in power plant pipelines, Proceeding of the 15th Scientific International Conference „Achievements in Mechanical and Materials Engineering” AMME’2006, Gliwice-Wisła, 2006, 219-222.
[23] J. Okrajni, The durability of power plant pressure vessels from the point of view of obligatory standards, Power Engineering 18 (2008) 93-100 (in Polish).
[24] D. Renowicz, M. Cieśla, Crack initiation in steels parts working in boilers and steam pipelines, Journal of Achievements in Materials and Manufacturing Engineering 21/2 (2007) 49-52.
[25] J. Dobrzański, The classification method and the technical condition evaluation of the critical elements’ material of power boilers in creep service made from the 12Cr-1Mo-V, Journal of Materials Processing Technology 164-165 (2005) 785-794.
[26] A. Neimitz, I. Dzioba, M. Graba, J. Okrajni, The assessment of the strength and safety of the operation high temperature components containing crack, Kielce University of Technology Publishing House, Kielce, 2008.
[27] Project European Thematic Network FITNET FFS-GIRT-CT-2001-05071.