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Thermo-mechanical fatigue conditions of power plant components

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Analysis and modelling

ABSTRACT

Purpose: The main purpose of this work is the description of the mechanical behaviour of power plant components working under mechanical and thermal loading that cause the thermo-mechanical fatigue fracture in selected areas of the component surfaces.

Design/methodology/approach: The computer modelling has been used to describe the local stress-strain behaviour of the chosen component.

Findings: The values of variable in time temperature strains and stresses in selected points of the power plant header were determined. The points were located at the edges of holes through which water steam is supplied and carried away, where under use conditions the presence of cracks can be observed. That stresses and mechanical strains caused by the influence of a non-uniform temperature field may be significantly higher in comparison with the stresses and strains caused by the pressure inside the analysed component. Tensile thermal stresses of high values are created especially under conditions of sudden cooling during unsteady work of a power unit.

Research limitations/implications: The possibility of applying the 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 presented analysis is the part of the complex investigation method which main purpose is increasing accuracy of the TMF process description and thermo-mechanical life assessment.

Practical implications: The calculations carried out may constitute a basis for developing a material test parameters which would bring closer the fatigue conditions appearing locally in the analysed components. 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; Computational material science and mechanics; Fatigue; Metallic alloys

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1. Introduction

The development of new methods of material studies and computer techniques changes the methods of constructing the components of technical devices. This concerns all fields of technology. However, the pace of changes differs in individual fields, which results from the complexity degree of both, the objects being examined and the phenomena occurring in them.

Application of computer methods of strength calculation of elements is not troublesome in cases where it is possible to define the conditions of their use in a simple and explicit way. Then, a skilled application of the finite element method or the boundary element method usually enhances the precision of calculations and provides better possibilities in the scope of geometrical and material optimization. Serious problems appear when there is a link between the conditions of use and constructional features of complex objects or their elements and it is not possible to define the external influences explicitly. Such cases often occur in components of those power engineering devices whose geometric features determine, among others, the conditions of heat exchange, which in turn, determine the values of thermal interactions.

The problem gets even more complicated since over time, a possibility appears of changing the material properties which determine the devices' behaviour, including the values of interactions of both, mechanical and thermal nature. In such situation, the proper selection of constructional features depends on the ability to foresee the behaviour of the objects being designed in the period of their use, which requires appropriate material data and properly-developed computer calculation models. Nowadays, the designers of power engineering devices distinguish two ways of approaching the design problem [1].

First of them, called ”design by rules” [1-3], is based on direct determination of the geometrical and material features from the assumed values of interactions. Formulas and procedures compliant with the material strength principles, construction and operational experience, which are contained in appropriate standards, are used then.

Another method consists of designing based on the method of analysis of the examined component's behaviour – “design by analysis”. This method is based on R5 and R6 procedures, on British standards [4, 5] and new European procedures of SINTAP and FITNET, which are the subject of European projects aimed at elaborating new drafts of standards [6, 7].

Very often, the first of them consists of initial preparation of a project which can subsequently be subject to an analysis with taking into account the various conditions of operation and possible links between the geometrical, material and dynamic features, understood as the value of interactions. This approach is indispensable in case of facilities after many years of operation, in which the evaluation of the actual material and dynamic features constitutes a serious problem.

Methods used by the designers change together with the development of available bases of material properties. The conviction that the strength of elements of power engineering devices is their actual property, variable in time and dependable on the history of use, is more and more common. The material bases being created and new calculation methods offer possibilities of evaluating the actual strength. Simultaneously there appears a need to develop procedures and methods for assessing the state and residual life of objects after many years of use when the load history and material is known. Procedures of this type are called “assessment”. Most often, the designing methods based on an analysis and evaluation of the condition of objects complement each other and have the same basis from the fields of mechanics and materials science.

Introduction of new ways of constructing and examining objects results in changes in standards. These changes, however, run slowly, which is justified mainly with safety issues and the necessity to verify the new methods and principles in practice.

In this context, the paper concentrates on the issue of thermo-mechanical fatigue in the perspective of valid European standards, simultaneously trying to evaluate the possibilities of describing in a more accurate way the strength and durability of elements subject to this fatigue process, based on new strength analysis methods, which take into consideration previously developed new methods of examining the fatigue characteristics of materials.

2. Thermo-mechanical fatigue from the perspective of EN 12952 standard

The commonly applied standards for designing elements of power engineering devices, subject to mechanical and thermal interactions are based on properties determined in creep tests. This concerns both, the basic standards used by the designers while ”designing by rules” and the procedures which do not have the rank of a standard, such as the R5 procedure used in “design by analysis" methods, which take into consideration the presence of cracks in devices' elements and then, describe their development under creep conditions. In case there is a necessity to take into consideration the fatigue phenomenon, the standards and procedures are based on fatigue characteristics, determined in constant temperatures. It results, among others, from the lack of uniform standards which would describe the conditions of carrying out fatigue tests at a temperature variable in time and the resultant lack of appropriate material characteristics. Methods of calculating stresses and strains under the conditions of thermo mechanical fatigue are based on many simplifications; hence difficulties appear when they are to be applied in the issues of analysis and optimisation process of constructional features of elements being constructed.

The dependencies based on which elements of power engineering devices subject to thermo mechanical fatigue are designed, result, in accordance with the EN 12952 standard, from a simple adding up of stresses determined for thin-walled vessels loaded by the internal pressure and thermal stresses, estimated based on simplified dependencies. Therefore, the thermal stresses in elements of power engineering devices are examined in accordance with the EN 12952 standard only with temperature gradients in unsteady states during heating and cooling. The material characteristics determined during isothermal uniaxial fatigue tests are used in this standard. This is the approximate method which doesn't take into consideration the influence of the concurrent temperature and strain changes on the material properties. Most often, it is not possible to apply the characteristics determined in static tensile tests to describe the deformation process of a material in conditions where temperature and stresses change simultaneously. Such influence is taken into account in thermo mechanical tests [8-10].

3. The characteristic of the object

It is necessary to keep in mind that the way of determining stresses compliant with the standards does not take into consideration many possible states which appear during the power unit operation. This refers in particular to sudden temperature changes resulting from the control process both under the conditions of start-up and shut-down and correcting work parameters of the power unit. The necessity to introduce locally a cooling medium in a form of water mist results in sudden, local cooling down caused by water evaporation. This concerns escpecially elements located in the proximity of the so-called injection attemperators, such as superheater chambers. Cyclic nature of attemperators' work is the reason of high temperature gradients, developing and disappearing on the surface of the discussed elements. Frequency of changes in thermal load and the rate of temperature changes is in such cases a few hundred times higher than the frequency of the power units' start-up and shut-down. This effect is caused by the action of water coming from the spray water system [11]. Its effect on thermal load is nowadays the subject of discussions in the circles of power engineers, in particular with reference to those cases, where the power units work in a cyclic system, where the frequency of start-ups and shut-downs is significantly higher in comparison with the operation conditions of conventional power units. The presented study is intended to make a contribution to the discussion.

4. Modelling the process of thermo-mechanical fatigue

Steam superheater systems include the superheater chambers consisting of thick-walled pipes connecting their individual levels. Steam is supplied to the chambers, i.e. collectors of coil pipes, through a system of "inlet" pipes and it is carried away from them through an "outlet" piping system. Systems of pipes of smaller diameters are welded to the thick-walled pipes with use of appropriate ferrules. A fragment of one of the superheater chambers used in Polish power stations is shown in Figure 1. Figure 1 presents a geometrical model of a pipe together with ferrules and a system of inner holes, through which water steam passes. The model of this header was built with use of Alibre Design programme. The FEM model was prepared with use of FEM Algor programme, which was used for calculating temperature, stresses and strain fields variable in time.

The thermal influences have been taken into account. In the calculations the surface film conductance values presented in Table 1 were assumed. The boundary coefficients were adopted based on a handbook by Zbigniew Orłoś entitled "Thermal Stresses" [12], thus assuming intensive heat exchange both under heating conditions, in contact of the inner surface with superheated steam, and in cooling conditions, in contact of the inner surface with water mist. On the external surface, heat exchange was assumed for a case of contact with air of a room temperature. The cycle which contains the 10 second period of cooling and 30 second period of heating was assumed.

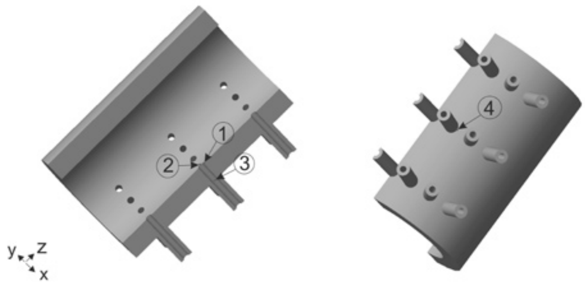


Fig. 1. Models for the analysis of heat flow and calculating the distribution of stresses and strains variable in time

Table 1.
Surface film conductance

Superheated steam	a_w=0.001 W/mm^2 °C
Water - boiling	a_w=0.01 W/mm^2 °C
Air	a_z=0.000001 W/mm^2 °C

It was assumed that before cyclical changes of the temperature the chamber is subjected to heating by the superheated steam with a temperature of 540ºC, until the moment of equalization of temperature distribution on the chamber's section. The material model has been assumed with linear hardening at constant temperature. In the model the Young modulus and coefficient of hardening depended on the temperature.

The isotropic material hardening model has been taken into account during calculations (Fig. 2). For the such model of material for different strain, temperature "paths" (Fig. 3) the examples of stress-strain-temperature characteristics in the uniaxial tension conditions have been calculated to show the behaviour of this thermoplastic material (Fig. 4).

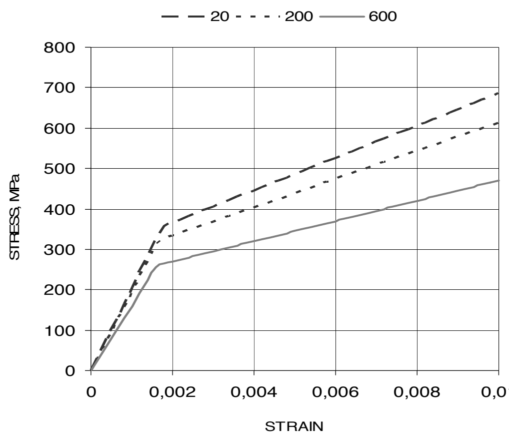


Fig. 2. Stress-strain curves for different temperatures (20^{o}C, 200^{o}C, 600^{o}C) used to define material model

The material characteristics presented in the Figure 3 shows the large variety of the material behaviour dependent on the relationships between mechanical strain and temperature. This has an influence on the local stress-strain bahaviour in thermo-mechanical processes of components, that operate under mechanical and thermal loading.

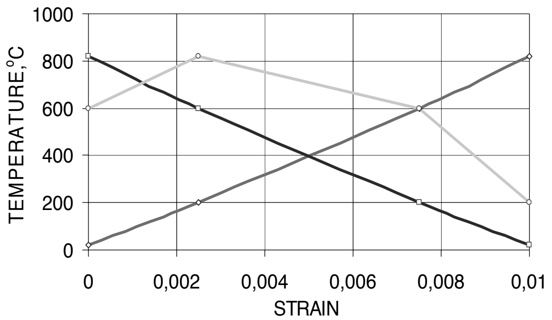


Fig. 3. The example of the characteristic of temperature changes with strain (temperature strain "paths")

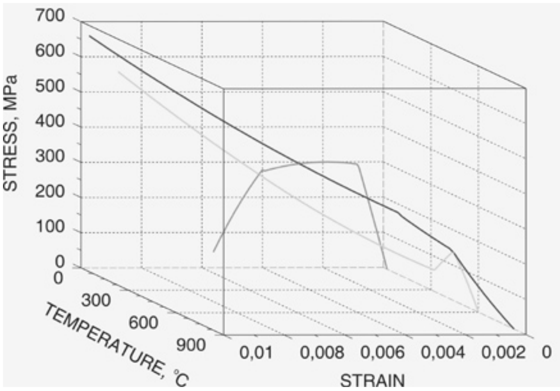


Fig. 4. The stress-strain- temperature characteristics determined for the thermo-plastic material model from the Figure 2 for different strain-temperature paths characterized by the curves shown in the Fig. 3

Calculations were carried out, based on which the distributions were calculated and the value of variable in time temperature in selected points of chamber was determined. The points were located near the holes through which water steam is supplied and carried away (Fig. 1), which are places where under use conditions, the presence of cracks can be observed. Cracks often appear between holes in planes perpendicular to chamber's axis. They start to be created on the holes' edges. For these conditions distributions of stresses and strains were determined for thermal loading. The distributions of the temperature and stresses were determined for previously defined moments of time. The examples are shown in the Figures 5-7 and 8-10.

Values of total, mechanical and thermal strains variable in time, and the dependency between temperature and mechanical strains, computed for different points (Fig. 1) are shown in the Figures 11-14.

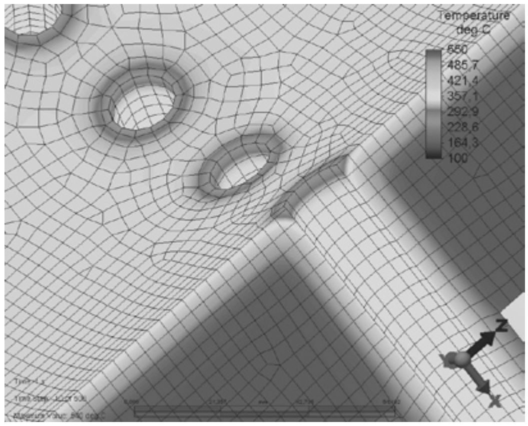


Fig. 5. Temperature distributions in the chamber, determined for its model under cooling and heating conditions determined for chosen instants of the time (1 s)

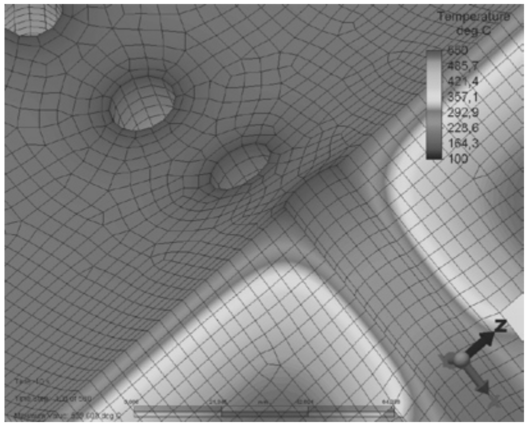


Fig. 6. Temperature distributions in the chamber, determined for its model under cooling and heating conditions determined for chosen instants of the time (10 s)

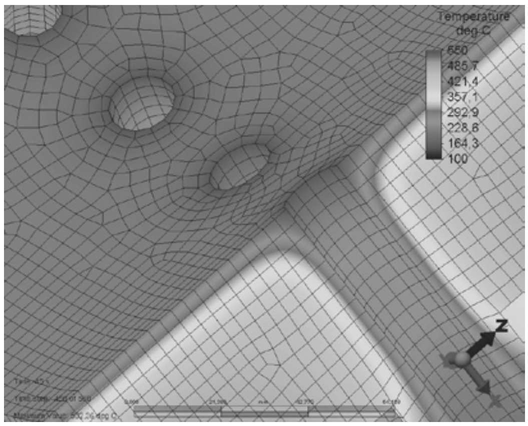


Fig. 7. Temperature distributions in the chamber, determined for its model under cooling and heating conditions determined for chosen instants of the time (45 s)

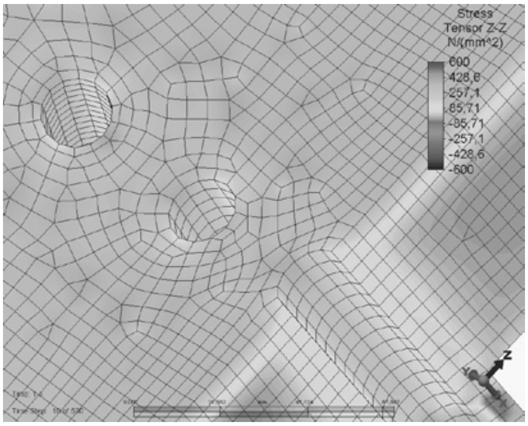


Fig. 8. Distributions of axial stresses caused by thermal loads determined for chosen instants of the time (1 s)

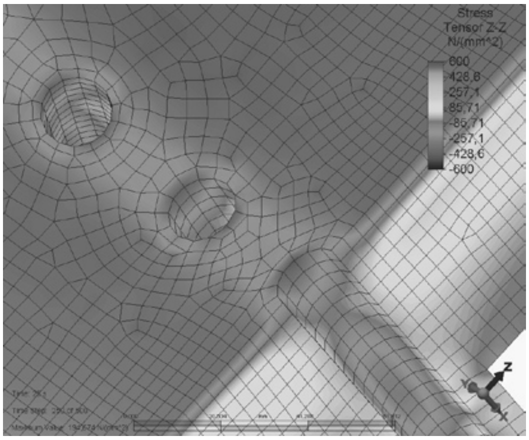


Fig. 9. Distributions of axial stresses caused by thermal loads determined for chosen instants of the time (25 s)

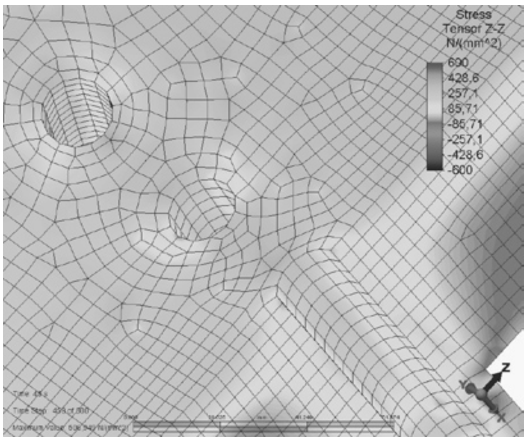
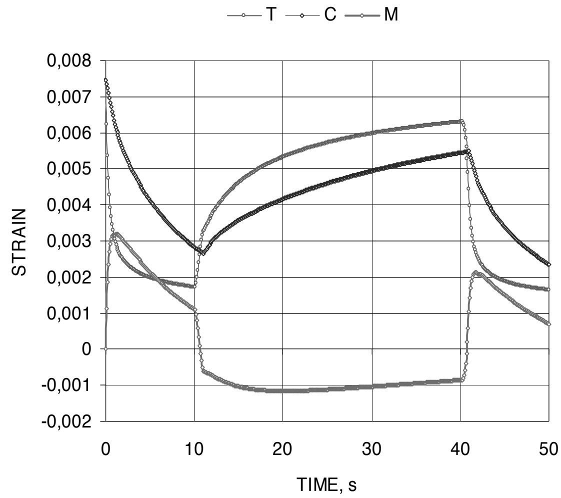
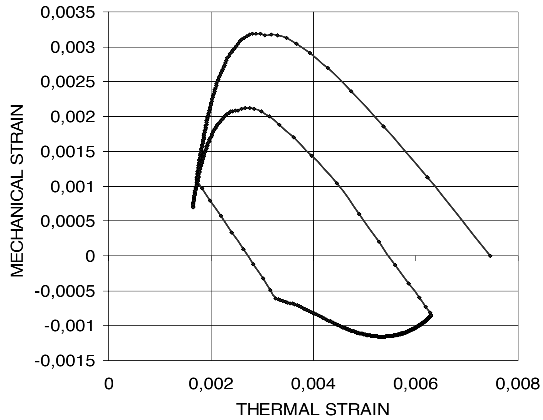


Fig. 10. Distributions of axial stresses caused by thermal loads determined for chosen instants of the time (45 s)

a)



b)



c)

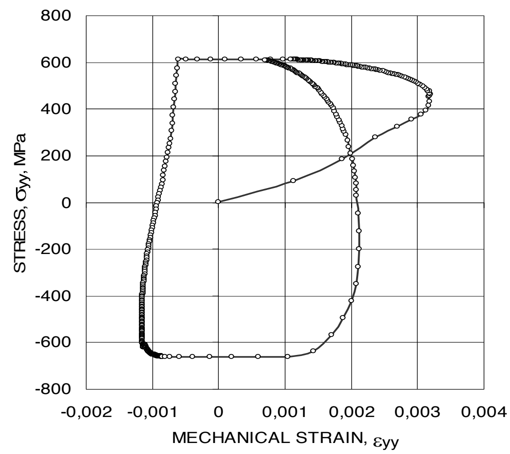


Fig. 11. Total - C, thermal -T and mechanical - M strains versus time characteristics - (a), mechanical strain versus thermal strain - (b) and interdependencies between mechanical strain and stress - (c); in the point 1, y direction

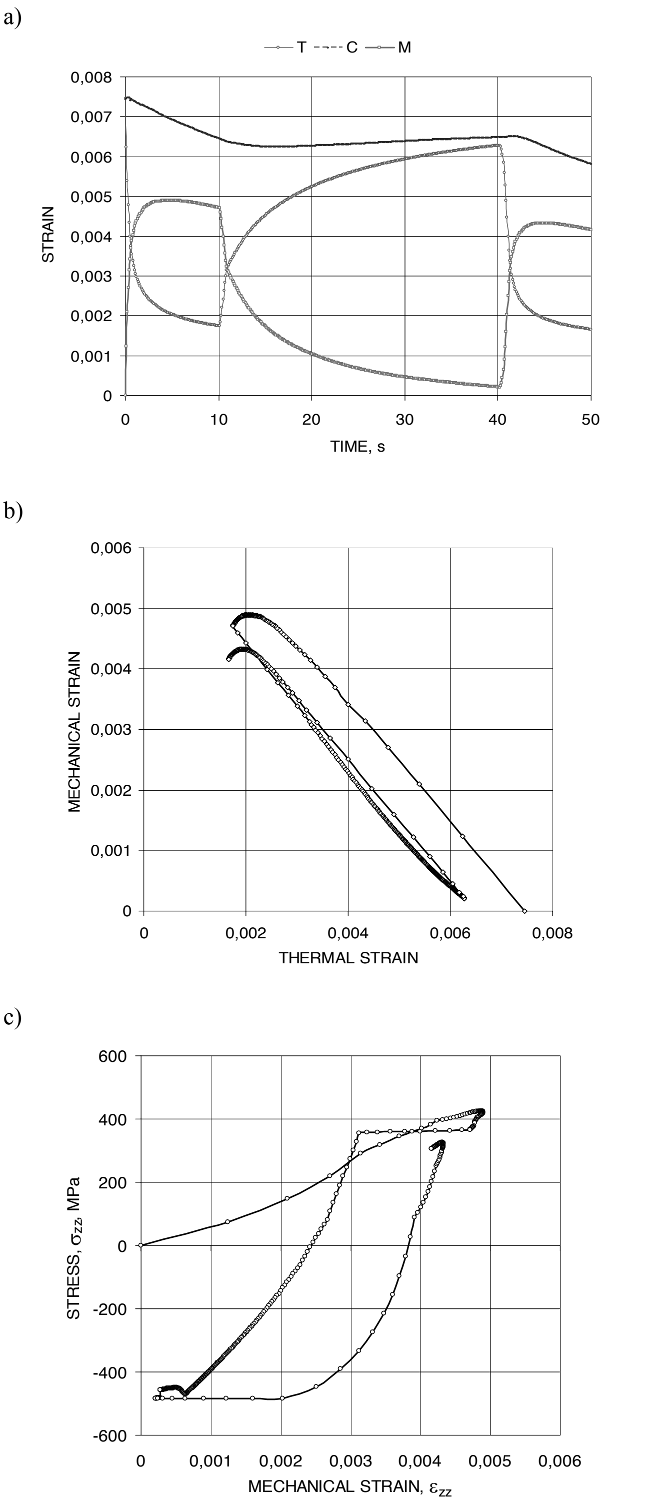


Fig. 12. Total - C, thermal -T and mechanical - M strains versus time characteristics – (a), mechanical strain versus thermal strain - (b) and interdependencies between mechanical strain and stress - (c); in the point 2, z direction

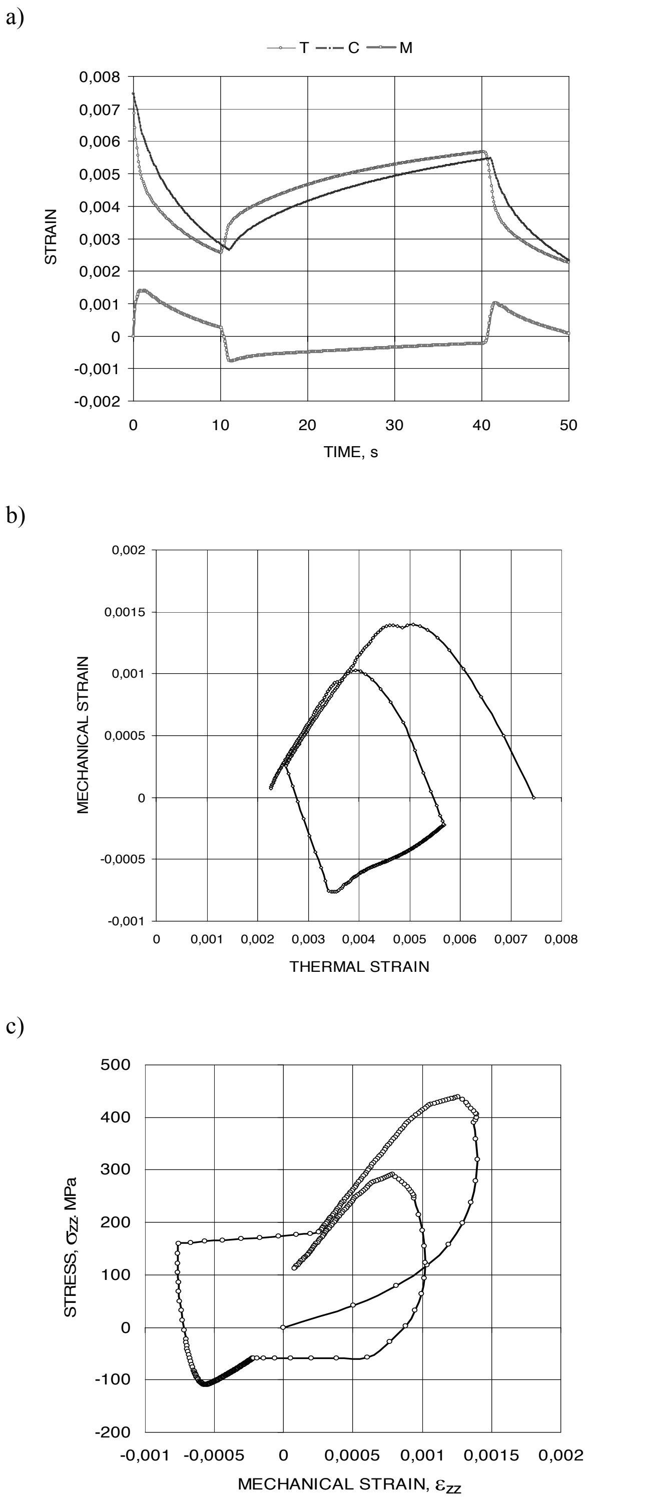
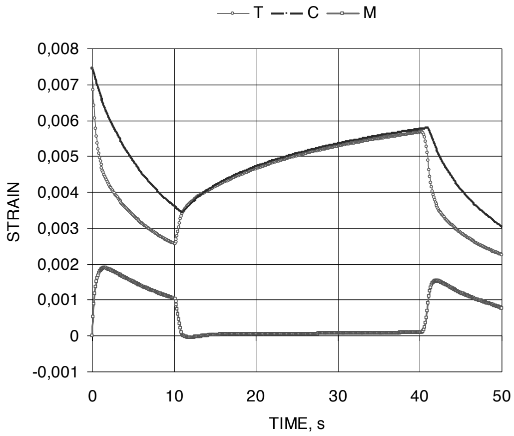
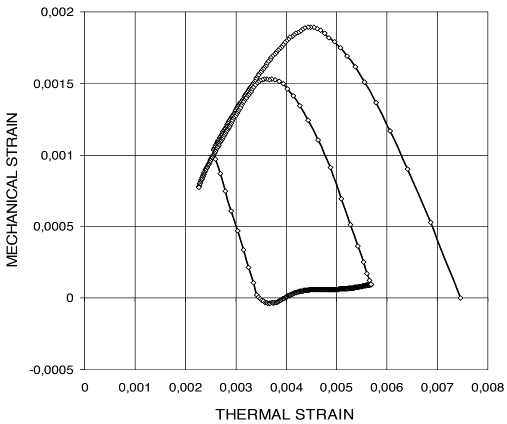


Fig. 13. Total - C, thermal -T and mechanical – M strains versus time characteristics – (a), mechanical strain versus thermal strain - (b) and interdependencies between mechanical strain and stress - (c); in the point 3, z direction

a)



b)



c)

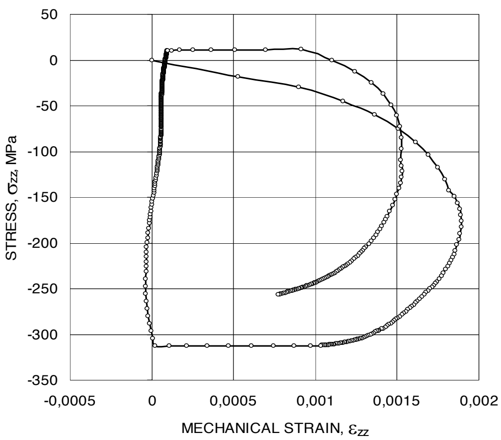
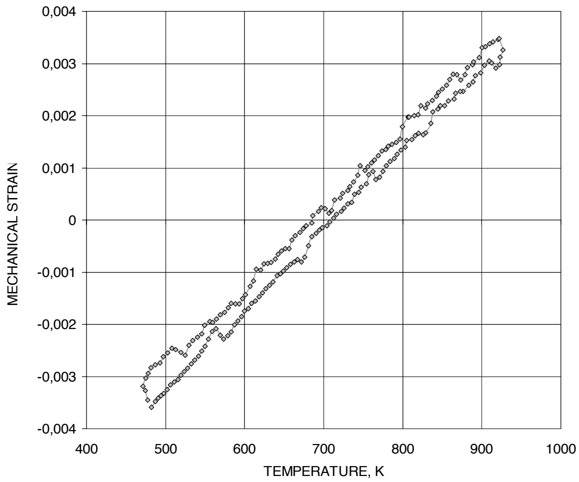


Fig. 14. Total - C, thermal -T and mechanical - M strains versus time characteristics – (a), mechanical strain versus thermal strain - (b) and interdependencies between mechanical strain and stress -(c); in the point 4, z direction

The temperature fields show the high temperature gradients particularly in the areas near the holes in the inside surface of the header during the cooling period of the cycle (Figs. 5-7). This influences on the high thermal stresses around the holes (Figs. 8-10). The areas of high stresses unite with themselves that gives the good circumstances for the initiation of the cracks and their growth between the holes perpendicularly to the header axis ”z”.

Such cracks are observed during operation of described superheater header [13]. Comparison of Figures 11-14 enables evaluation of the nature of the phenomenon of thermo-mechanical fatigue which is presented by the behaviour description of the model. The comparison is possible as well of this approach with results obtained from the specimens tested in typical laboratory conditions (Figs. 15 and 16) [14-16].

a)



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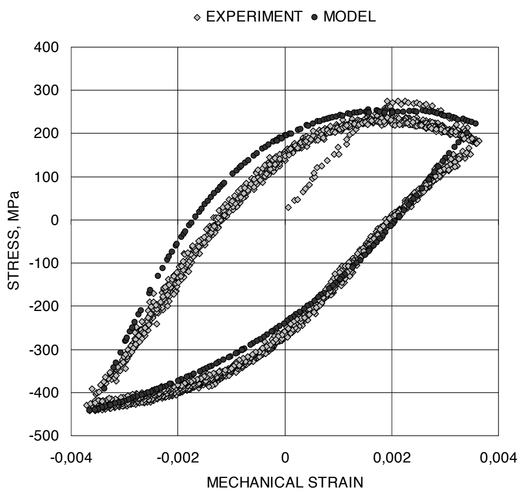
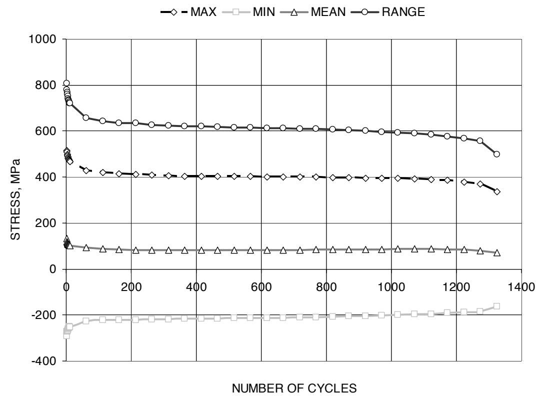


Fig. 15. Diagrams describing the TMF IP test results (P91 steel): a) - mechanical strain versus temperature – eighth cycle of the in phase test, b) - hysteresis loops determined for in phase test [15]

a)



b)

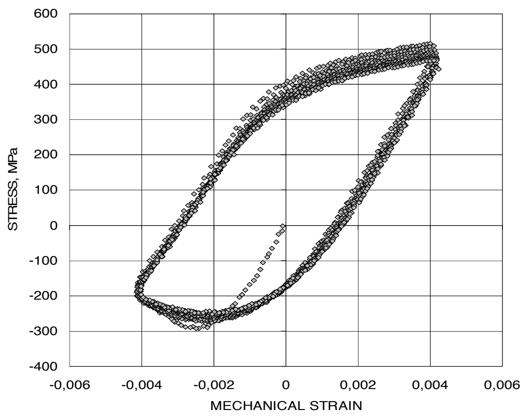


Fig. 16. Characteristics of a thermo-mechanical fatigue test (P92 steel): a) - maximal, minimal, mean stress and stress range as the function of the cycle number, b) - dependence of stress on mechanical stress – mechanical strain cycle is shifted in phase in relation to temperature by a 180° angle [15]

The stress-strain characteristics show the large variety. They depend on the point in which were determined and are different for the different stress and strain components.

Calculations of distribution of stresses and strains in superheater chamber have shown that stresses and mechanical strains caused by the influence of a non-uniform temperature field may be significantly higher in comparison with the stresses and strains caused by the pressure inside the chamber [13].

Some from among diagrams in the Figures 11-14 show the similarity with these typical described in the Code-of Practice [8]. The curve in the Figure 12b can be compared for instance with the linear dependence between the mechanical and thermal strains determined from the out of phase (OP) test. The diagram in the Figure 13b can be compared with the diagram describing the so called “diamond cycle”. Though that we can find the similarity between these diagrams the stress-strain curves determined for the analyzed component and from typical laboratory tests are significantly different.

Discrepancies between these two approaches is natural and have different sources. The thermoplastic model with isotropic hardening was adopted in the calculations. It is anticipated that further studies will take advantage of various material models, assuming the possibility of occurrence of plastic deformation and creep processes.

The main advantage of performed analysis is possibility to use its results to determine the local behaviour of the material. The local stress-strain characteristics could be used in the method of durability prediction in the thermo-mechanical fatigue processes. On this stage of investigation such analysis should be performed together with different thermo-mechanical tests, mathematical modelling of the material behaviour in TMF tests which should lead to the formulation of the proper constitutive equations.

5. Conclusions

Taking into account the number of parameters deciding upon material behaviour in practical applications, thermo-mechanical fatigue characteristics can show a large variety. Different sorts of stress and strain cycles we may determine for the different point of the analyzed component. Shifts in the strain cycle phase in relation to the temperature cycle are possible. The difference can also refer to the values of maximal and minimal test parameters and the periods of its individual parts.

The calculations carried out may constitute a basis for developing a material test methods which would bring closer the fatigue conditions appearing locally in the discussed element. The parameters of characteristics determined for an object based on its model approach and FEM calculations should be then compared with appropriate durability characteristics, developed based on examinations of thermo-mechanical fatigue tests.

On this stage the results should be treated as the methodical approach of the local stress-strain behaviour description of the chosen component of the power plant.

We can see that the local component characteristics differ from the typical used in the methods of material testing [7-9]. The conclusion may be justified, that the material test parameters should be closely connected with the stress strain behaviour of the material, that has the local character, when we would like to obtain the similar characteristics for a test specimen and a power plant component. It is particularly important in these cases in which the time to failure assessment is the aim of our investigation.

The calculations carried out may constitute a basis for developing a material test parameters which would bring closer the fatigue conditions appearing locally in the analysed components [18-22].

The possibility of applying the 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 presented analysis is the part of the complex investigation method which main purpose is increasing accuracy of the TMF process description and thermo-mechanical fatigue life assessment.

The problem isn’t still resolved how to use the data from laboratory tests in the design methodology. Particularly it concerns the problem of the fatigue life that is determined for the chosen types of the mechanical and temperature cycle characteristics only [15].

On this stage it is necessary to develop the material testing methods as well as to perform the proper number of material tests, from which it would be possible to work out the set of TMF data for different materials. In such situation the results presented in the paper would bring the basic information about the material behaviour in the chosen element and would be the contribution in the understanding the power plant component behaviour in the operation conditions, in which the TMF and high temperature influence play the crucial role [18-25].

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