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Life and operational safety of power systems and chemical plants

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Analysis and modelling

ABSTRACT

Purpose: The problem addressed in the paper is the description of an effort and durability of components under the conditions of mechanical and thermal interactions. The problems of proper material testing methods have been shown as the important part of the components life assessment methodology.
Design/methodology/approach: The FEM modelling has been used to determine the stress and strain fields in the components and to describe their behaviour under mechanical and thermal loading.
Findings: An appropriate models description has been developed. So far, experimental verification of the usefulness of the model description to determine the stress and strain patterns in particular object and for chosen operation conditions has been made.
Research limitations/implications: The developed description should be useful in problems of behaviour predictions of high temperature components and their durability assessment under different mechanical and thermal loadings in industry practical applications.
Originality/value: The method, which more precise description of power industry components behaviour makes possible have been shown in the work. The work is addressed to researchers interested in problems of component behaviour prediction under different loadings that we can meet in the operation practice and to power industry engineering maintenance staff.
Keywords: Numerical techniques; Residual life analysis; Applied mechanics

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1. Introduction

Power and chemical plants subjected to simultaneous mechanical and thermal impacts, despite their simple geometrical structure and relatively fixed conditions of service, are still devices for which many of the processes responsible for the degradation of their operating properties have not been described in terms of the practical needs of users. These devices require particularly careful verification and supervision, as they may, in fact, be the cause of many serious accidents in the operating conditions of complex structures in the power and chemical industries. Steam pipelines are among the most crucial devices in the power unit, among others, due to the safety of their operation. Similarly, the issue of operational safety is one of the key problems related the systems operating in the chemical industry. Such structures, which were usually built more than a dozen or even several decades ago in the Polish energy and chemical industry, require re-evaluation of their effort and the forecast for continued safe operation.

It is possible nowadays. During the last twenty years, significant progress in technical sciences has taken place, as regards the achievements of electronics and common use of computers in the design, management and control of technological processes of production. The hardware and software currently available, among others, provide much more efficient construction, allowing to analyse a broad range of possible solutions in a relatively short time. This includes assessing the strength and life of structures being designed. Today, it would be difficult to imagine complex calculations without using numerical methods, such as the finite element method or boundary element method.

Along with the progress in the field of electronics and information technology, the development of new technologies based on the materials science takes place. Changes within the structure of materials, in their manufacturing processes and conditions of use are being currently investigated. New research equipment is created, which can be used to simulate the operating processes. The achievements in the fracture mechanics allow a more precise definition of conditions for the failure of materials and machine parts and equipment.

The knowledge acquired and new technical measures also create a basis for accurate strength analysis of technical structures after many years of service. Such units usually adequately meet their assumed purpose, although, in some cases, the period of a smooth and trouble-free operation has already expired, as defined in the design prepared many years before. In the national power sector, there are many power units that have exceeded the so-called "designed operating time". Currently, actions are undertaken, aimed at assessing their current technical condition. The ultimate goal of those activities is to ensure the operational safety by creating opportunities of the current technical supervision of pipelines. There are, however, no universally accepted, uniform and generally approved procedures for such assessment which, in many practical cases, is a complex technical issue.

The lack of a set of uniform procedures for assessing the equipment condition, after many years of service, in terms of mechanical and thermal impacts, results from the limited data from the industrial practice, in relation to the interactions between the factors determining the condition of the structures in the power and chemical industry, in conjunction with the factors to be monitored and supervised in terms of use. Thus, it seems necessary at this stage to undertake elementary research, in connection with the research into the facilities operating in the industrial conditions, in order to develop methodological assumptions for such procedures. Diagnostic tests are required in this case.

The results of tests carried out in many national and international research centres show the advisability of adjustments of the traditional approach to the design of objects subjected to mechanical and thermal impacts, including the pipelines. Considering the issue of life, there is a need for a more precise recognition of the phenomena of initiation and growth of cracks in the whole complex system of interdependence between the geometrical features, time dependent material properties and thermal and mechanical loads. The data regarding the current strength of power and chemical plants in the operating conditions is, therefore, essential for security reasons, and provide information enabling, in many cases, the formulation of general conclusions, which contribute to the new approach to component design methodology.

The paper includes, among others, problems of strength calculations of selected systems, discusses their design standards and focuses on methodological issues regarding the assessment of the current strength of components. Examples of pipelines operating in Polish power and chemical industries are provided. The methodology of testing the facilities after many years of operation has been developed, and a method to assess the condition of pipelines based on a study of their workload, variable as a function of time, as well as changing material characteristics has been proposed.

In the Polish technical literature, there is an excellent book by Wiesław Bęczkowski, titled „"Power pipelines”. The second edition of the book covers Part I, "The structure and calculations," and Part II, "The resilience and strength of the systems". The book, in an exhaustive manner, presents the classic methods for calculation of strength of materials and theory of elasticity, as applied to the design of power pipelines, and discusses their design features and materials used for pipelines. Guidance is given on the design and operation of those complex structures, including many practical aspects of their conditions of use, and presenting a number of technical examples.

However, forty years have passed since the last edition of the book by W. Bęczkowski [1]. The approach to the design of objects subjected to mechanical and thermal impacts has evolved. Studies are undertaken to develop new design standards, taking into account the life assessment of the structures. In view of those issues, it seems appropriate to try a new approach to the issues of lifetime prediction and assessment of technical condition of the pipelines, benefiting on the new developments in the field of computer simulation methods for their operating conditions and methods of experimental research, to assess the material properties varying in time.

The present paper, at its current stage, is a synthetic attempt to systematize the knowledge on how to assess the life of the systems operating under mechanical and thermal loads. The issues covered herein require a more in-depth insight and more detailed discussion for their practical applications. Such approach can be found in the respective references listed at the end of this paper. Currently, the main focus is on the methodical approach that will provide the basis for the preparation of a monograph providing a detailed discussion of the presented problems, with special attention to its application aspects, related to the use of high-temperature systems.

2. Life criteria

The criteria for life of machines and equipment may vary and depend on the conditions of their functioning, the degree of responsibility, the risks they may pose to the operation and the environment. The process equipment operating in the power and chemical industries is subject to the influence of high temperature, time-varying loads of a mechanical and thermal character. Media transported by the systems in those industries may aggressively act on the surface of the material from which such systems are made. The impact of the media may also have erosive nature. Items of the equipment, as a result of those impacts, change their properties. The degree of degradation of the usability properties, which disqualifies those elements can be evaluated based on multiple criteria. The key criteria are:

- failure as a result of cracking or plastic deformation,
- creation of a crack with length taken as critical;
- change of material properties;
- presence of defects inside the material structure;
- material loses due to erosion or corrosion.

Those criteria enable the assessment of the effects of the processes occurring in materials of industrial systems. These are mainly the processes of creep and fatigue, and the coexistent aging, diffusion and surface chemical reactions, including oxidation, and nitriding, carbonation and hydrogen corrosion.

The criteria, based on which the usefulness of the material for use at elevated temperatures are evaluated, are the resistance to creep and basic mechanical properties, determined in tests carried out at temperatures in which the components made of such material are used [2-10]. Most of the standards under which the items of the power units were designed, including for example drums, superheaters and steam pipelines, present calculation procedures based primarily on the results of creep tests. The life of the parts is also evaluated based on that. The conventional laboratory tests necessary to determine the strength properties of the material to work under the influence of elevated temperature, are based on measuring the deformation of samples being heated and subjected to constant loads. This way, the creep curves in a form of graphs shown in figure 1 are determined. Three characteristic stages can be distinguished in the creep curves: stage I, in which the creep rate decreases with time, stage II, referred to as the fixed stage of creep, where creep rate is constant, and stage III, characterized by an increase in the creep rate. The final result of stage III is the specimen rupture. The creep in different periods depends on the stress and temperature, and is grounded in the phenomena that take place in the dislocation structure of metal alloys. The strength calculations of items of equipment as a criterion for the failure, the stress is assumed, among others, for which, at the assumed temperature and time, the deformation reaches the assumed value. This is referred to as the *temporary creep limit* or *creep limit* [2], which corresponds to one of the material strength properties. Material properties at elevated temperatures are also characterized by the magnitude of stress known as the *allowable creep stress*, based on which the calculation of the so-called "degree of damage" and "accounting period of work" is made. Appropriate procedures for the calculation can be found in the standards TRD 301, TRD 508, as well as in EN 13480-3:2002 (E), valid in Poland since 2004 [11]. The design lifetime of a structure operating in the creep conditions is defined as the time, which was taken into account in the strength calculations, assuming the creep resistance values in accordance with the standards [1, 4, 5].

Taking into account the creep resistance, a simplified classification of materials operating at elevated temperatures can be made. Figure 2 provides a schematic approach to the range of uses of different types of metal alloys, including those which are used in power generation and chemical industry [2].

In the devices of today's design, there is a trend of continuous increase in the operating temperatures. Therefore, new materials of increasingly better properties are designed.

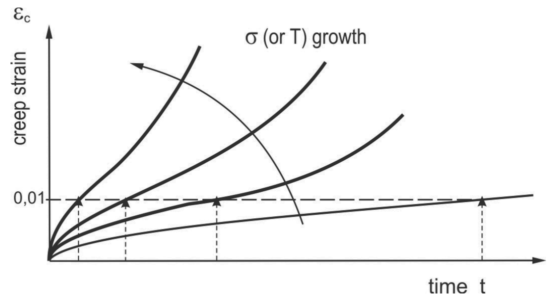

Fig. 1. Creep curves with schematically marked method for determining the temporary creep limit for the creep strain of 1 %

Understanding their behaviour in the long-term use, however, requires also long life tests and research in the field. In the devices of today's design, there is a trend of continuous increase in the operating temperatures.

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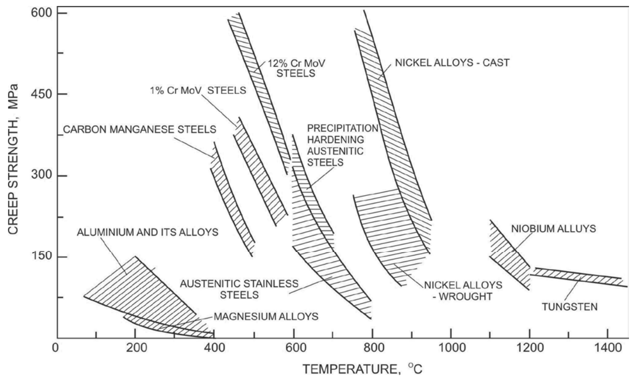


Fig. 2. Scopes of use of various materials designed for elevated temperatures (Webster, G.A., Ainsworth, R.A. [2])

The use of materials of improving properties is one way to improve the performance of the components. Another method is the selection of design features to ensure reduction of workload through the use of design methods based on computer simulation of the system operation. Along with the increase of permanent strain in creep conditions inside the structure of the material, defects may occur. For technical applications the structure classes, corresponding to the level of its degradation, have been developed [2, 7, 8, 12]. Based on the operating experience, the necessary actions have been determined, which need to be taken by the user, after finding a certain degree of the structure defect. Figure 3 provides a schematic presentation of images of structures, representing the class used in the evaluation of high temperature components, included, among others, in the German and British standards [2, 7, 8, 12].

Figure 3 shows also the schematic approach to damage in fatigue conditions. Damage of this type occurs mainly on the surface of the material. In the physical sense, the creep and fatigue are two different processes whose course is determined by the structure of the material. The process of fatigue is often of the surface nature, and is caused by the formation of micro cracks on the surface of the elements and samples. Formation of the micro cracks is preceded by the change of surface topography, apparent as the intrusion and extrusion (Fig. 3b) [2, 13-15]. The intensity and extent of the structural changes are determined, as in the case of creep, by the load size and temperature value. There are specific stages in this process distinguished, which differ as to the type and extent of microstructural phenomena determining the growth of fatigue crack [16-18]. The creep and fatigue processes occur usually simultaneously, and the formation of cracks is the result of summing up their microstructural effects.

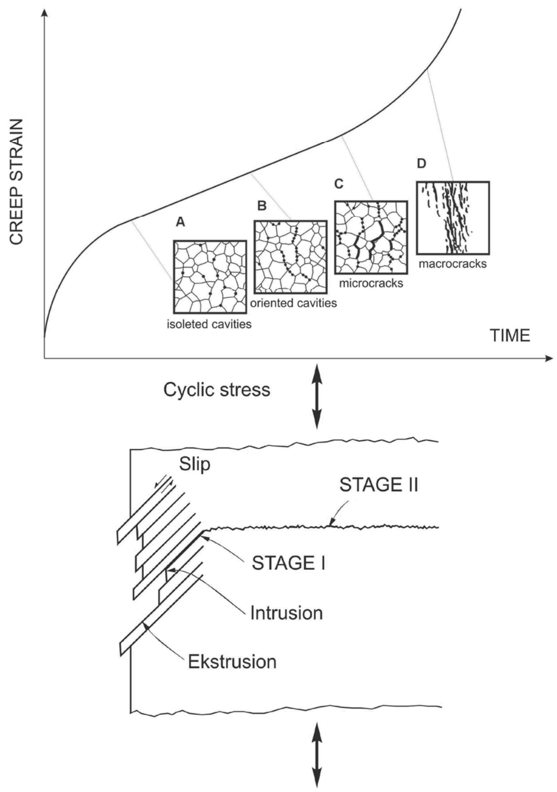


Fig. 3. Formation of microstructure defects: (a) – classes of various material defects due to creeping (Hernas A., Dobrzański J. [7]), (b) – schematic presentation of the intrusion and extrusion process formation (Webster, G.A., Ainsworth, R.A. [2])

The cracking processes depend crucially on the degree of stress. Efforts are therefore taken to study the creep and fatigue in complex stress conditions, in order to reflect the actual conditions of the structure service in the laboratory. Characteristics of the materials subjected to creeping are then presented in the form of models that recognize the links between components of the stress and strain tensor, and the temperature and time. Creep theories are formulated which, due to the limited possibility of practical laboratory tests, are then verified in specific cases only. Those theories are aimed to provide a basis for the modelling and forecasting the effects of creep processes, and are based on hypotheses related to the material properties [19-21]. The potential of the creep rate is, among others, assumed [20]. At this stage, a general approach, allowing a description of the behaviour of materials in a variety of conditions, determined by state of stress, temperature and the type of material, does not seem possible yet. Thus, the inclusion of material properties in creep conditions is mostly phenomenological in nature.

Creep tests involving the study of material behaviour the material during long-term static loads do not provide results that would allow a sufficiently precise description of its properties under the influence of cyclically variable loads. To some extent, the impact of cyclical effects on the properties of the material is included, in fact, in vibrocreep tests, the scope of application of their results, however, is limited to structures subjected to cyclic loads with high average values and low amplitude.

In power generating equipment and chemical plants, during the start-up and shutdown, as well as in emergencies, the overloads may occur. Plastic deformation occurs in the components of that equipment, which usually involves areas of stress contrentiation areas, and are the result of mechanical or heat impact. In most cases, it appears that the plastic deformation associated with a single crossing of the yield stress caused by loads or stress attributable to uneven temperature field do not pose a threat to components made of plastic materials. The multiple loads and cyclic changes of temperature fields may lead to failure. It can be assumed that, if each cycle exceeds the yield strength, after a specified number of impact cycles, the component will be destroyed. This is the fatigue in the range of a low number of cycles, referred to as low-cycle fatigue (Fig. 4).

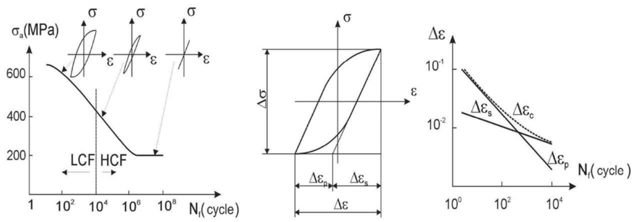


Fig. 4. Fatigue characteristics: (a) - fill Wöhler plot taking into account the range of low number of cycles , (b) - hysteresis loop with marked characteristic values of the deformation range, (c) - fatigue plot determined in the low-cycle fatigue tests

Due to the local values of stress above the yield strength, the components subjected to the low-cycle fatigue, have a limited life, for the steel of not more than 10^5 cycles. The basic strength, elasticity and fatigue properties, as well as the creep characteristics are not sufficient in this case for the evaluation of materials. It is necessary to use such methods of testing the material properties which would simulate the processes of cyclic elastic-plastic deformation. In terms of mechanical impacts, tests of this type are the fatigue tests for stress or deformation control, carried out at room temperature and elevated temperatures.

In many studies on the processes of cracking of materials subjected to mechanical and thermal impacts, attempts have been made to find a generally useful size criteria values, characterizing those processes in such a way that they can provide a basis for estimating the life of samples and structures. The life was presented in the form of criteria for which, in some cases, it was possible to assign physical meaning. For the criteria adopted, the laboratory tests were presented in different ways, by proposing mathematic models for material characteristics. The criteria, in most cases, are of hypothetic character, and relate to specific conditions of cracking. One of the first attempts to formulate the criterion of stability under the low-cycle fatigue was that presented by Manson [22, 23]. He suggested the relationship between the number of cycles to failure - N_z and the range of plastic deformation - $\Delta\varepsilon_p$:

$$\Delta\varepsilon_p \cdot N_z^{\alpha} = C, \qquad (1)$$

in which C and α are the material constants.

Experimental tests and an attempt to interpret the formula (1), with the power generating approach, would allow Coffin [24, 25] to present it as follows:

$$\Delta\varepsilon_p \cdot N_z^{1/2} = C \qquad (2)$$

The power generating criteria represent the group of relations between the fatigue components and number of load cycles, most commonly used to describe the life. Typically, they rely on identifying the work of plastic strain based on the course of the hysteresis loop. Feltner and Morrow [26] assumed that the failure occurs when the work of plastic deformation, measured as the surface area of the hysteresis loop under cyclic load, reaches the value of energy dissipated in the material during the trial of static tensioning.

Extending the scope of research to the value of the number of cycles to failure $N_z > 10^4$, Manson proposes the approximation of the fatigue plot with the equation:

$$\Delta\varepsilon = \Delta\varepsilon_p + \Delta\varepsilon_s = M \cdot N_z^{-z'} + \frac{A'}{E} N_z^{-\gamma} \qquad (3)$$

The M and A' constants are determined [13,23] from the static tensile test.

Coffin [27] proposed the dependency taking into account the effect of load frequency - ω:

$$\Delta\varepsilon = \frac{C}{\left(N_z \cdot \omega^{k-1}\right)^{\alpha}} + \frac{A \cdot C^n}{E \cdot N_z^{\alpha \cdot n}} \omega^{n \cdot \alpha(1-k)+k_1}, \qquad (4)$$

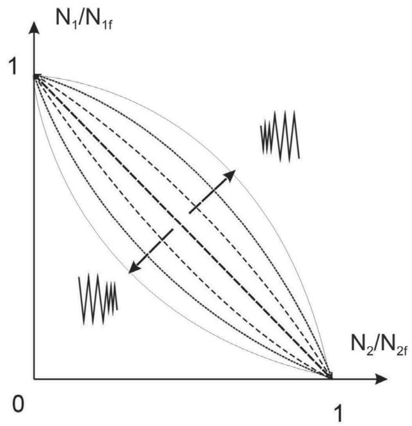
where A, C, k, α, n, k_1 are the constants depending on the temperature and material type.

Based on the criterion of Coffin, Moskwitin [28] attempts a more general approach to the life in conditions of complex stress. Monographs [29, 30] provide an analysis of a series of life criteria in relation to the thermal and mechanical fatigue. The phenomenological description of test results proposed in this paper, however, requires further experimental verification and physical interpretation.

The life criteria mentioned offer the possibility of its assessment in the case of fixed parameters of external loads. However, taking into account the operating conditions of power units and process systems in the chemical industry, it must be assumed that the materials of which the components of those objects are made, are very rarely subjected to the impacts of relatively fixed effects. Their loads are variable in time, temperature, and consequently the local distributions, changes globally. The parameters of load and temperature cycles vary. Under those conditions, the assessment of cumulative effects of time-varying interactions requires the use of appropriate methods, which are based on assumptions regarding the mechanisms of damage accumulation.

The failure of the material operating under the influence of elevated temperature and varying loads is a very complex process, which is due to the simultaneous action of two factors affecting the stability, i.e., creep and fatigue. It is extremely difficult to separate those phenomena and to determine their role in the process of material failure, as it depends on the external conditions, in which the given material operates and on the properties of the material itself. This issue is a problem that has not yet been fully resolved.

a)



b)

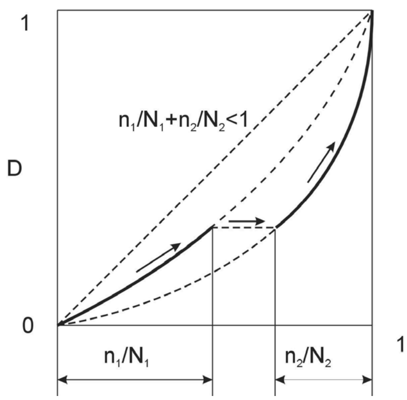


Fig. 5. Characteristics presenting the effects of load sequence on the fatigue resistance of the material: a) - according to K.J. Miller [33], b) - according to J. Schijve [34]

Considering the issues of life prediction of materials subjected to fatigue and creep, the most commonly method used is the linear hypothesis of damage summation [2, 31, 32]. The law describing the accumulation of damage in this case can be expressed in a form of the dependencies:

$$\sum_{i=1}^{N}\frac{t_i}{t_{zi}}+\sum_{i=1}^{K}\frac{N_i}{N_{fi}}=1\ , \tag{5}$$

where: t_i – duration of load action on a given level;
t_{zi} – failure time in the conditions in which the t_i was determined;
N_i – the number of cycles at a given stress amplitude;
N_{fi} – number of cycles to failure in conditions in which the N_i was determined.

The criterion (5) was successfully applied in many cases. There were, however, such cases where significant differences were obtained between the experimental results and the forecasted life on the basis of the dependency (5). Research is also conducted into the fatigue damage accumulation process, including the impact of load sequence on the fatigue resistance of the materials [33-35] (Fig. 5). Such works were also carried out in the Department of Mechanics of Materials of Silesian University of Technology.

The aim of the study was to attempt a physical interpretation of damage accumulation under fatigue with variable load amplitude [35]. The interpretation was based on the energy approach to the process in which the free energy released at the time of the formation of cracks was adopted as the size criterion. The problem of damage accumulation for graduated load is one of the key issues in assessing the life of equipment subjected to mechanical and thermal impacts.

The hypothesis of linear damage summation (5) assumes that there is a possibility of separating periods during which the creep processes occur from the load spectrum, and the periods in which the material is subjected to fatigue. The life is assessed on the basis of the characteristics identified in the classical creep tests and fatigue tests carried out for the fixed parameters of load cycles. In most cases, however, the creep phenomena occur in each load cycle of the power unit components, and they locally occur in line with different sequences, depending on the operating conditions of a specific component - the size of load, temperature, rate of their changes and constraints. Among the various courses of load changes, among others, the following can be distinguished: the characteristic course of the fatigue load, sinusoidal pendulum cycle, one-sided sinusoidal courses, with a large share of the average stress, one-sided trapezoidal cycle, in which there are periods of time corresponding to the variable and constant stress. The role of fatigue and creep processes will differ for each of the runs mentioned.

Depending on the length of each time period, the local deformation process will proceed in a different way, which can be characterized by the course of the hysteresis loop in the stress – strain coordinates. Coffin [36] and Manson [37] have distinguished four basic types of load cycles. They also proposed a method of estimating the life, involving the separation of the time intervals which can relate to the basis cycles in case of any load. For any cycle strain ranges can be distinguished, in which the tensile creep, compression, fatigue during tensing and fatigue during compression is involved. The sum of those ranges is defined as the equivalent strain range. In carrying out the fatigue tests for the basic cycles, the life of complex courses of load is estimated based on the hypothesis of damage summation.

In large parts of power equipment cracks are very likely to occur. The cracks can be generally divided into two groups. The first one includes those that are caused by the phenomena and courses present in the manufacturing process, and the other includes those which occur during operation of the structure. Regardless of origin, the cracking during operation of the device given can increase due to the effect of the alternating field of stresses and strains. Given the need to ensure reliable and safe operation of the equipment, it is important to know the rate of cracks propagation. This is because it allows to specify the time after which the crack reaches its critical length, which also determines the life of the structure given. The measure of material resistance to crack growth may be the characteristics of the propagation determined in the conditions similar to those in service.

Experimental studies of steel grades used under the influence of elevated temperatures and static loads have shown that the crack growth characteristics are similar to a typical form of creep curve. That allowed for the creation of several mathematical models describing the process of destroying the material, similar to the formulas which describe the course of the creep phenomenon [38-41]. The most common relations result in the dependency of crack growth *da/dt* as a function of parameters such as: stress intensity factor - K, the tension before the tip of the crack - σ, the rate of crack opening displacement dv/dt, C^* parameter defined in similar way as the J integral [10].

$$\frac{da}{dt}=A\cdot(K)^m \tag{6}$$

$$\frac{da}{dt}=B\cdot\sigma^n \tag{7}$$

$$\frac{da}{dt}=C\cdot\left(\frac{dv}{dt}\right)^k \tag{8}$$

$$\frac{da}{dt}=D\cdot(C^*)^l \tag{9}$$

Integrating the above dependencies in relation to the time, the material life can be specified. The accuracy of the structure life prediction will largely depend on the proper selection of a criteria parameter, applied to appropriate material model. In more complex operating conditions of the structure, the description of the material failure process, models integrating several criteria parameters are applied. In a study of 18-8 grade steel crack rate, in creep conditions at 650° [41], a mathematical model including the effect of stress concentration factor K_σ and of the nominal stress σ_n were applied, for the crack initiation time t_i:

$$(K_\sigma\cdot\sigma_n)^{\alpha_i}\cdot t_i=C_1, \tag{10}$$

where: α_i, C_1 - material constants.
C^* is the parameter that definition take into consideration the rate of the energy density near the crack tip:

$$C^* = \int_{\Gamma} \left[W_s^* dy - T_i \left(\frac{\partial \dot{u}_i}{\partial x} \right) ds \right] \quad (11)$$

where $W_s^* = \int_0^{\varepsilon_{ij}^c} \sigma_{ij} d\varepsilon_{ij}^c$ is the rate of the energy density near the crack tip, $\dot{u}_i$ is the displacement of the point on the contour Γ in which the load equals T_i, ε_{ij}^c is the rate of creep strain component.

The life criteria mentioned do not include all mathematical models used at present. Many of them are based on the fundamental relationships of cracking mechanics, describing the process of decohesion in brittle and plastic materials [42- 48]. Those include the concept of using such parameters as the stress intensity factor K, the threshold stress intensity factor K_{th}, crack opening displacement *COD*, the extent of the integral change J – ΔJ, and other concepts based on energy balance. The relationships between the cracks growth rate and those values can be presented in the form of dependency:

$$\frac{da}{dN} = f(K, K_{th}) \quad (12)$$

$$\frac{da}{dN} = f(COD) \quad (13)$$

$$\frac{da}{dN} = f(\Delta J), \quad (14)$$

where $\frac{da}{dN}$ (fig. 6a) is the crack growth rate at cyclically changing load.

Nowadays, the dominant approach to the problem of life prediction in structures subjected to mechanical and thermal impacts is to use the multiple criteria approach [2, 40]. The currently R5 and R6 standards used in the United Kingdom, and proposals of the European standards SINTAP - *Structural Integrity Assessment Procedures [49],* describe the procedures for predicting crack development and damage criteria associated with the achievement of the limit state. The so called FAD (Failure Assessment Diagram) was introduced (fig. 6b), which is a graphic interpretation of the bicriterial boundary condition.

In the first, conservative estimate of one of the criteria is the relative fracture toughness, the second criterion are the loads causing global plasticization – of the entire (not cracked) cross-section of the element with a crack, or local plasticization of the section at one point. K_r is, in this case, the quotient of stress intensity coefficient K_I, and its critical value determined for the material K_{mat25}, and referred to the coat thickness of the sample, assumed by the standards, equal 25 mm. L_r is the ratio of the operating load to the load causing plasticization of the section. In the British standards the parameters of cracking resistance at elevated temperatures are taken into account, and the loads causing creep processes in the material [2].

The ratio of OB to OA (Fig. 6b) is called the coefficient of sensitivity, and may serve as the measure of risk posed by the presence of cracks, as it sets out the distance of the point characterizing the local "workload" (point A) from the curve describing the boundary states.

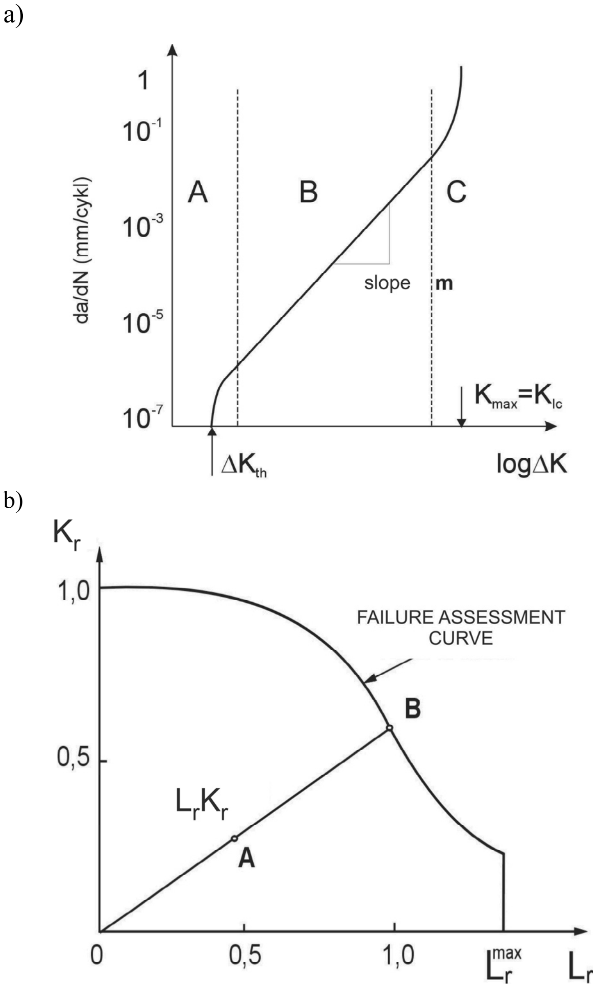


Fig. 6. Cracking resistance characteristics: a) – fatigue crack growth rate as the function of stress intensity factor range, b) – FAD curve

The FAD curve can be applied both in the evaluation of the sensitivity coefficient for the existing structures, as well as in procedures for the design of power equipment components. Given the importance of the risks due to the presence of cracks, calculation procedures, based on the FAD curve, can be regarded, at present, as the most developed methods for assessing the safety of structures subjected to mechanical and thermal impacts.

Selection of a proper criterion for assessing the life of components must be based on an analysis of the nature of the failure process, which results directly from the operating conditions. In some cases, the relevant criterion will be the parameters of fracture mechanics, and fatigue properties in others. Often, the use of a given criterion depends on the measure of material failure adopted. This is because, sometimes the first appearance of a fatigue crack should be considered as failure of a component, whereas in other cases, the existence and propagation of cracks is allowed, on condition, however, that their length is less than critical. A comprehensive characterization of the material intended to operate in conditions of cyclically changing temperature fields must therefore contain details on the critical value of K_{IC} coefficients, *COD* or J_c, fatigue crack propagation rate, creep strength, creep rate, as well as the dependencies describing the low-cycle fatigue strength at elevated temperatures. Based on that, it is possible to design a structure of the desired life.

Moving from the material to the structures on which it is applied, it should be noted, however, that the analysis of the behaviour of a given item of equipment is a much more complex issue, as it requires the consideration, in addition to material properties, also of the impact of geometric and dynamic design features on the criteria parameters of stress and strain. In many cases, the determination of material characteristics may also be a serious technical problem.

3. Equipment for testing mechanical properties of materials

The first strength testing machines were simple devices, which originally applied mechanical transmission systems for multiplication of load with appropriate weights until the failure of sample or tested component. Later solutions used electric drive with a system of mechanical gears. The progress in the investigation of material behaviour in terms of time-varying loads and prolonged loads has led to the development of new types of machines to test mechanical characteristics of materials, noticeable from the beginning of the past century. Those are the fatigue and creep testing machines. The machines for fatigue tests manufactured by the end of the 1960-ties used mainly the phenomenon of resonance. In that case, the excitation was achieved with the aid of a rotating eccentric weight or magnetic field varying in time. Design solutions of the creep test machines included a mechanical loading system composed of weights transmitting axial load on the sample through an arrangement of special levers.

In the 1960-ties, hydraulic drives in the strength testing machines began to be used. In the 1970-ties, the hydraulic drive system was used commonly in machines for mechanical tests, including the fatigue tests. Such machines were equipped with a control system based on servo-valves. The controls were initially based on analogue solutions. In early 1980-ties, servo-hydraulic machinery with digital control systems emerged.

The system for force and displacement measurement in the strength testing machines also evolved. In the oldest machinery used for evaluating the load acting on a sample, the details of the mechanical system gear ratio were sufficient, and the elongation was measured with a graduated ruler. Electrically driven machines were usually provided with a mechanical system for recording deformation plots, which reflected the relationships between the load value and displacement of specimen grips. Precise measurement of elongation was made with the aid of external tensometers (extensometers), operating on the basis of an appropriate mechanical or optical indication. Later on, external induction tensometers were used and selsyns. Such arrangements ensured processing the signal of the core displacement in an induction coil, into the rotation angle of a drum with a tape for plot recording wound on it.

In the servo-hydraulic machinery, resistance and induction displacement sensors are used. For measuring forces, measuring heads are used, the operating principle of which is based on the application of resistance tensometers.

The main difference between the traditional and modern strength testing machines lies in the programmable control and data collection functions. Numerically controlled systems are provided with special devices to achieve that. Without them, it the fatigue tests, simulating the time runs during the actual loading, would not be possible. Neither the heat and mechanical fatigue tests would be possible. Continuous recording and numerical processing of test results is what is also required in the crack fracture mechanic tests, in which – both while performing the test, and while processing its results – a large number of variables and interrelated values, calls for a particularly careful approach to the measurement accuracy and their rapid real-time processing while performing a test.

Currently, one of the most up-to-date technical issues is the thermal and mechanical fatigue, which – due to the significance and different nature, as compared to the fatigue at constant temperatures – should be considered in a different manner. The tests for the thermal and mechanical fatigue are aimed at simulating, in laboratory conditions, the history of the thermal and mechanical load in the areas of structural parts subjected to the highest workload. That can be achieved by subjecting a specimen to synchronised, cyclical temperature variations and mechanical strains, using the predefined relations between the temperature cycle and strain.

While comparing the results of tests for the thermal and mechanical fatigue with the isothermal fatigue tests, it should be noted that the number of parameters, to be identified and determined with the thermal and mechanical fatigue tests, is much higher. It is not possible to simply apply the methodology for low-cycle fatigue tests at constant temperature in the thermal and mechanical fatigue procedure. At the same time, the thermal and mechanical fatigue tests, due to the possibility to select from a broad range of relationships between the parameter tests, allow better consistency of results with the operating conditions of the structural parts. There is, however, some difficulty involved here, related to the variety of test parameters adopted by various laboratories. This is because it is impossible, in many cases, to compare the results obtained. Therefore, recently, works aimed at working out standards covering the performance of such fatigue tests are underway.

4. Progress in the microstructural tests of material decohesion processes

The opportunity to evaluate the extent of degradation of material performance characteristics due to the combined effects of mechanical and thermal factors is associated with the development of tools used by modern materials science. Discovery of the many phenomena occurring in the structure of materials and crucial for their decohesion, for which a model approach was developed in the fifties [50, 51] of the last century, was possible with the aid of the transmission electron microscopy. In the transmission microscopes used in the late fifties and early sixties, the method of thin foil was applied. It was a laborious method, and the results obtained in the thin foil technology allowed inferences about the phenomena occurring in the structure of materials during fatigue and creep only in an indirect manner. In the late sixties in electron microscopy, a new technique was invented, known as the scanning electron microscopy. Observations conducted by this method on the surface of samples subjected to fatigue and fatigue fracture, made it possible to identify the mechanisms of formation and development of cracks [52, 53]. Research in that area was particularly intense in the seventies [54, 55]. To date, observation of fractures is one of the basic methods of determining the causes of failures of items of equipment operating under the conditions of fatigue.

The introduction of electron microscopes was a breakthrough in the field of NDT testing of the structure of components subjected to many years of service in conditions of mechanical and thermal loading. Using the replica technique, is possible to assess changes in the structure of material, using the preparations for mapping the geometry of a properly prepared outer surface of the components. The surface of the tested components, before taking the preparation, is ground, polished and etched. After removing the replica and its spraying, using an electron microscope, the structure of the material surface layer of a component can be examined. On the basis of the matrix replicas examination, the material structure state is assigned to one of four categories presented in figure 3. Depending on the category to which the structure of the material is assigned, the relevant provisions impose a further course of action, the decision is taken about the possibility of further work, the date of the next tests is set, or the component is withdrawn from service. In Poland, the relevant procedure was included, inter alia, in the instruction of the Ministry of Mines and Energy of 1986. Some Polish companies have developed their own procedures for evaluation of material structure, on the basis of years of research and accumulated databases. Such companies are RAFAKO and the Institute of Ferrous Metallurgy, using their own classification of structures, based on the study of pearlite decomposition and carbide separation processes within and at the grain boundaries [15].

5. Computer-aided methods for analysing mechanical states

Components of industrial facilities subjected to mechanical and thermal impacts, in addition to many common characteristics, resulting from the nature of those interactions, have distinguishing characteristics associated with the size of loads, their variability in time and size of structures. Pipelines which are, in any case, the basic parts of the installation of the power generating and chemical industries may be a good example of structures, which are characterized by a diversity of operating conditions and degradation of their performance characteristics. In attempts to systematize the causes of changes in the properties of such installations, it seems necessary to take into account:

- creep material straight segments and arcs;
- creep of materials in local areas, in the elements of complex shape;
- formation of cracks and their development in conditions of creep, in the welded joints of complex shape parts with sections of pipe;
- fatigue of mechanical and thermal nature of components in the local areas of complex shape parts;
- pipeline axial shift;
- changes in fastener characteristics;
- change in material properties, caused by long-term effects of loads and elevated temperatures.

Evaluation of the current state of the structure, after many years of service should take into account all the above causes. Their effect in specific conditions determines the properties of a structure which, only in some cases, may be tested in industrial conditions. Each structure changes its dynamic and material characteristics in the course of time. In most cases, its properties, including the effort, can only be assessed on the basis of repeated strength calculations, taking into account such changes. For that purpose, computer-aided methods for analysing mechanical states are applied, which are particularly useful in evaluating strength in the possible extreme conditions.

The values of stress, displacement and strain are determined by building models of the structures [56, 57] (Fig. 7).

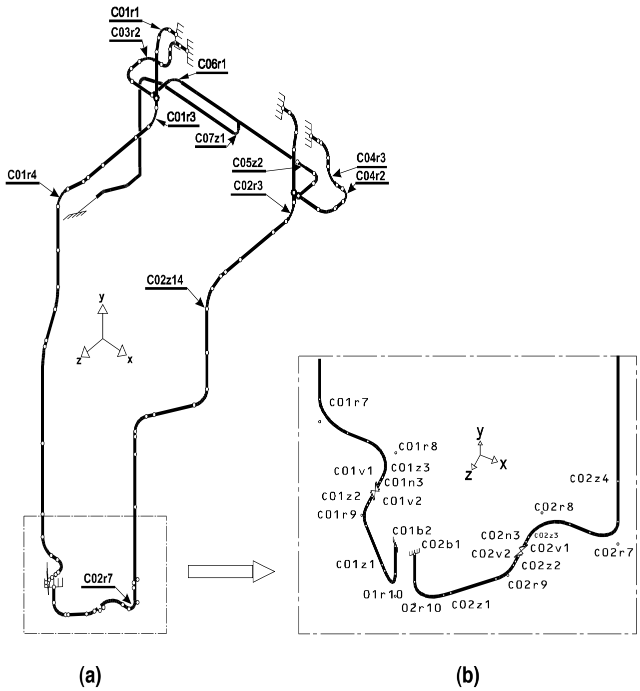


Fig. 7. An example of a pipeline subjected to tests, with marked selected fastening points; (a) - the entire pipeline; (b) -pipeline part for which stress distributions have been presented in the following drawings

Due to the complexity of the problem, currently, it is usually not possible to precisely determine those values at all points of the structure. In the analysis of strength in this case, the approximate solution to the problem can be used, and the solution divided into two stages. The first one is a "global analysis", in which the simplified models of the pipelines are adopted, and the elastic material model is assumed. The second stage is to analyse the state of stresses and strain in selected components or parts of the pipeline, subjected to predetermined internal factors. The formation of local permanent strain is allowed in that case. Such approach can be considered correct, assuming that the local areas of permanent strain are small, comparing to the dimensions of the components, in which they occur, and that the permanent strains only marginally affect the stress state in the rest of the structure. Such approach was based on previously accepted assumptions (for example in the work of Manson [22]) that in the case of minor local cyclic plastic deformations, their values can be estimated on the basis of the solution of the problem of the elastic deformations. In the case of the pipeline, the broadly understood model is a spatial frame secured by means of suspension, supports and fasteners, restricting its freedom of movements in different directions. The frame constructed of straight and curved sections of pipe, as shown in the example of a specific structure is assumed, operating in one of the national power plants (Fig. 7). The "secondary superheat steam" pipelines were analysed. The pipelines are suspended and supported at the points marked in the Figure 7.

The load involved the pipeline is the internal pressure, dead weight and temperature distribution along its axis. The calculations also take into account the pipeline load due to the movement of connectors as a result of thermal deformation of the boiler.

In the analysis of strength, fittings of complex shape: tees, reducers, dampers, valves, etc. are treated as objects characterized by suitable rigidity, weight and shape coefficient, describing the effect of stress accumulation. In this case, the stress distributions in those components is not analysed. The rigidity is taken from the relevant standards or regulations [1]. The global approach allows to identify areas along the pipeline axes, in which the effort will have the greatest values. In this way, also the time-varying internal quantity distributions can be determined: bending moments, twisting moments, shear forces and axial forces. A model of secondary superheat steam pipeline was built on the basis of technical documentation. The details include: pipe dimensions - lengths, diameters, wall thickness, bend radius, fitting characteristics - size, weight, characteristics of materials - steel grade, physical and mechanical properties, thermal insulation characteristics - thickness, specific gravity.

The model so adopted is then validated. On the basis of available information on the actual structure, the extent to which it is possible to represent the actual characteristics of the device by using the model approach, is checked. In many cases, users have the results of measurements of displacements of selected points along the pipeline axis. One method of validating the correctness of the model may consist in checking whether the results of the calculated displacements are consistent with the measurements and calculated values in the project. Figure 8 shows the results of this type of model verification approach.

The calculations are performed by finite element method for the state of the pipeline under normal operating conditions – "hot state", and the pipeline which is shut down - "cold state". In various sections of the pipeline, based on Huber hypothesis, the distributions of equivalent stresses along the axis of the pipeline are determined [56, 57]. The equivalent stress, at a specified point the pipeline axis, is defined as the greatest stress in a section of the pipe or fittings in a given element.

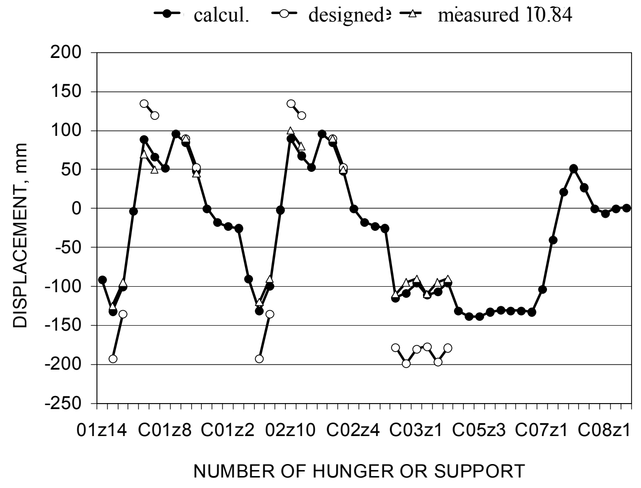


Fig. 8. Displacements of selected points along the pipeline axis – comparison of measured, designed and calculated values based on the model approach.

The nominal values of forces in the fasteners are predefined. The pipeline, over time, however, changes its material and geometric characteristics, and also its fastener characteristics change. One of the most common ways to secure power pipelines is the "constant-force suspension", in which a constant value of reaction at the support point is assumed, while allowing freedom of pipeline displacement in the horizontal plane. Such assumption, in the initial state, already involves some uncertainty arising from the possible mounting inaccuracy. The inaccuracy in estimating forces in the suspensions increases with time, due to changes in their characteristics (Fig. 9).

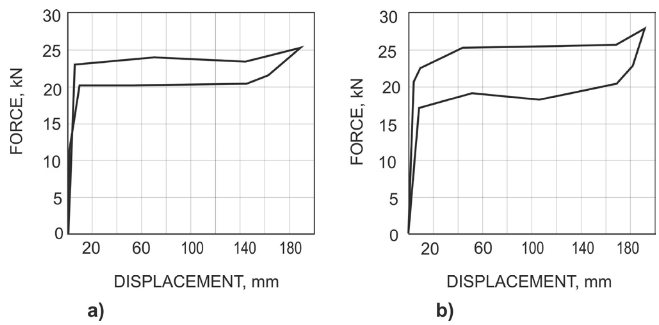


Fig. 9. Examples of the characteristics of supports of power pipeline: (a) - pipeline after 8 years of service, (b) - pipeline after 18 years of service

Forces in various hangers and supports may change over time and take on different values in the range specified by the size of the hysteresis loop (Fig. 9). The values of forces in the fasteners will be crucial for the local effort, as well as for the distribution of displacements along the pipeline.

In the present paper, the problem of the impact of force distribution on the effort of the fasteners and the displacement of the pipeline is resolved by considering the forces at the fasteners as random values. Two states characterizing the pipeline suspension have been assumed:

- initial state - characterized by a dispersion of the actual forces in relation to the nominal values within ± 5% of the nominal value;
- state conditioned by long-term services – which also takes into account the wear of moving parts of suspensions, and this scenario assumes the dispersion forces in the range of ± 10% of the nominal value.

A random number generator was used to generate, for each of the fastener states, 21 different states of the pipeline suspension. Figure 10a shows the equivelent stress distribution along a selected section of pipeline, determined for the nominal values of forces in the fasteners.

a)

b)

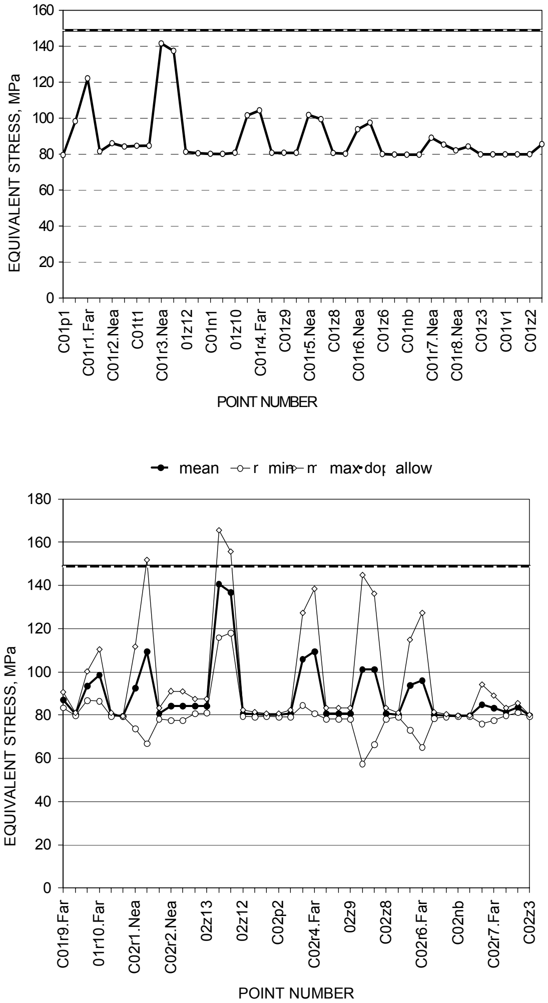


Fig. 10. The stress distribution along the axis of a chosen pipeline section: (a)stress distribution for the nominal values of forces in fasteners; (b) distribution of the maximum, minimum and mean equivalent stress, for the range of forces variation in fasteners equal to ± 10% of the nominal value

Figure 10b shows the distribution of the maximum, minimum and medium stress for the dispersion of forces in the fastener points, in the range of ± 10% of the nominal value and probability of 0.95.

That way, the confidence intervals were marked for the probability of 0.95, assuming a range of ± 10% of forces variation with respect to the nominal value, set for 21 random fasteners. In Figures 10a and 10b, also the allowable stress value determined in accordance with European Union standards is presented.

Based on the tests carried out, it can be concluded that the estimation of stresses around arcs is burdened with the greatest uncertainty. In those areas, the width of the confidence interval significantly increases. It may also be noted that, assuming the random values forces in the fasteners, it is possible to exceed the limit of allowable stresses in some parts of complex shape.

During the analysis on a global scale, the most tensed points were determined, which should be very carefully verified during the operation process. Determination of effort in those areas makes it possible to define the local conditions of the performance degradation of the material.

The difference in equivalent stress between the “hot” (σ_u) and “cold” (σ_o) states was also determined. Figure 11 shows the distribution of the equivalent stress differences σ_u-σ_o, determined for a selected section of the pipeline.

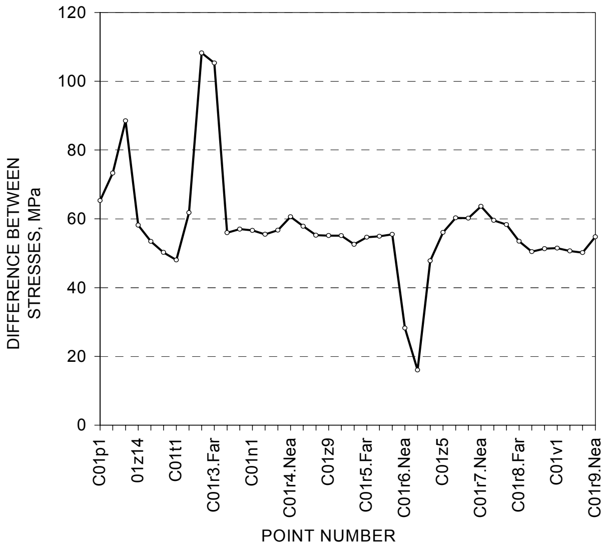


Fig. 11. Example distribution of equivalent stress difference between the steady state and the shut down state

Position of the pipeline axis is very important for the operator of the facility, due to a number of adverse consequences from deviating the axis from the state described in the project. These include, among others, blocking the suspension and "negative downgrades" of the pipeline sections.

The distribution of forces in the fasteners has a significant impact on the pipeline axial shift. Figures 12 A-C illustrate the effect of the suspension type on the shape of the pipeline at full load in the “hot state”. Figure 12 presents three cases, selected out of the analysed 21 pipeline suspension types - the cases A, B, C. The other figures show the results of calculations, assuming that the forces in the fasteners are in the range of variation of ± 10% of the nominal value. The thicker line, in each of the cases, presents the theoretical axis of the pipelines, while the thinner one characterizes the course of the axis provided on the basis of calculations. Compilation of the drawings A, B, C shows that, depending on the possible implementation of the suspension, qualitatively different arrangement of the pipeline axis is observed. In the case of A and C, the left and right branches of the pipeline have similar courses. Figure B shows the courses of pipeline axis, showing large variations of the left and right branch axes, much different from their theoretical position. For each of the structures studies, the presence of so-called "negative slope" in the pipeline can be observed. The "negative slope" is a term used by pipeline operators, and corresponds to the situation where the axis of the pipeline section is tilted in such a way that, in the cold state, the flow of water to the boiler becomes possible, and so, opposite to the direction of steam flow. In those sections, in the "cold" state, water can flow up, which is important for the behaviour of the pipeline during the start-up. The occurrence of the so called "negative slope" may be the cause of interference during the start up, sometimes resulting in excessive pipeline vibration, caused by the presence of so-called "water plug".

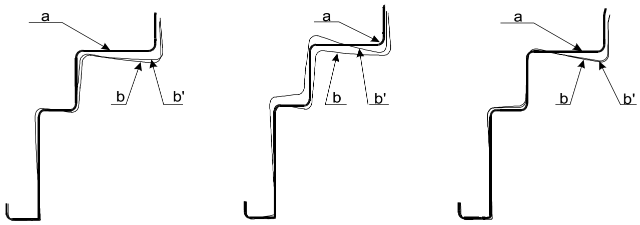


Fig. 12. View of the pipeline from Fig. 7, in the zy plane, presenting the nature of its axial shift, depending on force distribution in the fasteners. The figure presents the axial arrangements for 3 variants of force distributions, in the fasteners (ABC) selected from a set of 21 possible implementations. Letters a and b denote: (a) – the entire pipeline in a perfect condition, (b) – part C01, (b') – part C02

The models developed allow testing of their behaviour in various states of load, taking into account the diversification of suspension characteristics. Based on that, it has been found that it is possible to have multiple states of the same pipeline, depending on the fastener characteristics. Therefore, both the effort state and the pipeline axis should be considered as characteristics of random nature, determined, among others, by the random distribution of fastener properties and the material characteristics.

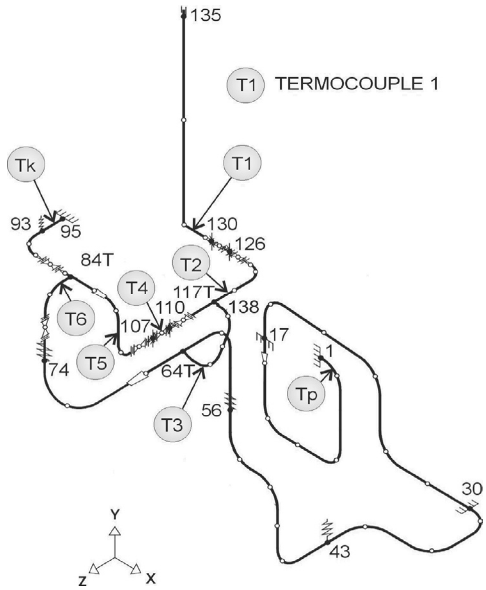
Figure 13 shows an example of another structure - a chemical pipeline.

The example is a pipeline for the first stage conversion of methane, connecting heater to the reactor in the plant producing ammonia. The so-called "gas reactor" is transported by the pipeline, which is a mixture of water vapour and methane at the pressure of 3.2 MPa at the calculation temperature of 550 ° C. The pipeline is made of austenitic steel with chemical composition as follows: C = 0,04 ÷ 0,1 % , Cr = 15 ÷17 % , Ni = 12 ÷ 14 % , Nb ≅ 10 × C (but at least 1,2%), Mn < 1,5 %.

The structure is supported in 13 points. The pipeline, in the part subjected to internal pressure (points 1 - 125), is made of seamless tube dimensions: 323,9 × 14,2 , 273 × 12,5 , 219,1 × 10. The entire length of the object is insulated with mineral wool layer, with a thickness of 160 mm, shielded with an aluminum casing thickness 1 mm.

In the case of the analysed chemical pipeline, the start-up and shut down time is short enough that the temperature changes in transient states are likely to materially affect its momentary effort. In order to synchronize the production process, at the start of the pipeline, in the short term, the subsequent sections are put into service. Until the reactor gas reaches the required temperature, it flows through a part of the pipeline called the "main branch" (A) from point 1 to the 64T tee, and then through a connector and an outlet section (sections 117T -135) (C), from where it is released into the atmosphere.

a)



b)

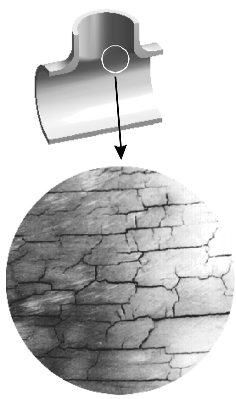


Fig. 13. Pipeline operating in the chemical industry with marked points, in which temperature measurements were performed – (a) and section of the 64T pipeline tee with an enlarged area of the inner surface, with visible effects of the cracking process – (b)

On reaching the required temperature, the 110 solenoid valve is opened, and the synchronized 130 valve is closed. The gas then flows through part of the main branch (points 1 ÷ 64T), and then, through a connector and the "starting branch" (B) (points 117T - 95), it enters the reactor chamber. In order to prevent overheating of the solenoid valves, mechanical valves are opened: the 75 valve is opened in the main branch and the 130 valve is closed in the outlet branch. After stabilization of the gas flow in the main branch, the solenoid valves are closed. During the stabilized manufacturing process, the gas flows through the main branch (A) (points 1 ÷ 64T - 84T -95).

The calculations take into account the impact of the uneven temperature distribution along the pipeline on the structure effort. The distribution has been determined during operation. For that purpose, in the selected points along the pipeline, thermocouples have been installed (Fig. 13). Continuous recording of temperature during the start-up, steady state and during shut-down operations was conducted. The temperature recorded at the individual measuring points versus time is shown in Figure 14a.

a)

b)

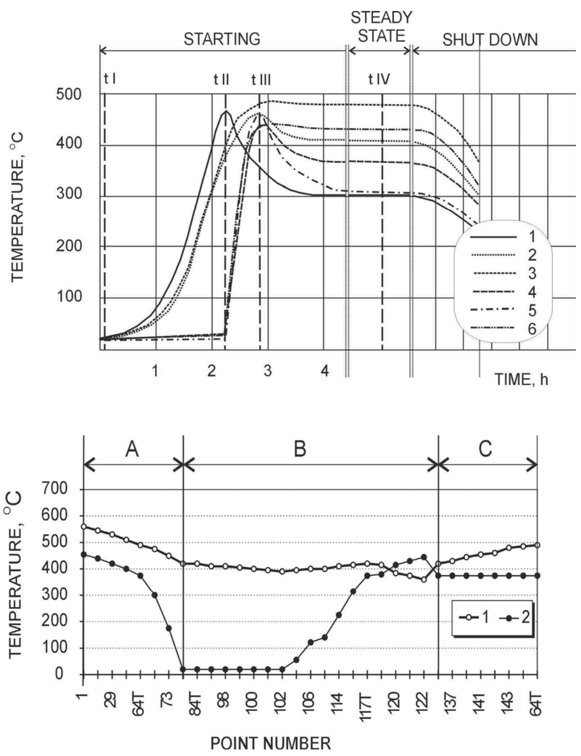


Fig. 14. Temperature changes in time determined by thermocouples 1-6 - a) and distributions of temperature on the along the pipeline in the tIV time (steady state -1) and tII (during start-up - 2) - b)

The characteristics obtained that way allowed to determine the time-varying temperature distributions along the pipeline, which were determined for selected time moments: tI, tII, tIII, tIV. Between the measuring points, the temperature distributions were approximated with straight line equations. Examples of temperature distributions for time tII and tIV are shown in Figure 14b.

The pipeline is fixed by means of supports and elastic and rigid suspensions, which prevent the free movement of some of its points in certain directions. The characteristics of the fasteners are changing over time. Tables 1 and 2 summarize the properties of pipeline fasteners in accordance with the design, and after many years of service. In the table include the ways to reduce the displacement and constant elasticity of fasteners.

In the case of elastic supports, which are present in chemical pipelines, the operation process affects mainly the probability of blocking freedom of their movements over time, and the occurrence of additional friction, related to the use of rolling elements, ensuring the free movements in a plane perpendicular to the axis of the spring deflection. In this case, the assessment of the current effort of the pipeline requires to determine the degree of wear of individual fasteners, and their current characteristics. In order to define the actual service conditions of the pipeline, the supports have been inspected ("reviewed").

Table 1.
Characteristics of the fasteners in accordance with the design

No	Suspension type	Lack of free movement
1	Rigid restrain - flange	X,Y,Z
17p	Rigid support	X,Y,Z
30p	Elastic roller support k = 58.2 N/mm	Y
43p	Elastic support k = 58.2 N/mm	Y
56p	Elastic support k = 415 N/mm	Y
74p	Elastic support k = 415 N/mm	Y
94p	Elastic support k = 415 N/mm	Y
95	Rigid restrain	X,Y,Z
107rp	Elastic support k = 415 N/mm	X,Y
110rp	Elastic support k = 415 N/mm	X,Y
126rp	Elastic support k = 415 N/mm	X,Y
130rp	Elastic support k = 415 N/mm	X,Y
135	Vertical guide	X,Z

Table 2.
Characteristics of the fasteners after many years of service

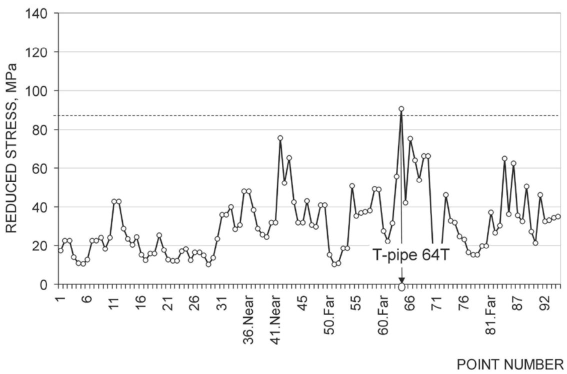
No	Suspension type	Lack of free movement
1	Rigid restrain - flange	X,Y,Z
17p	Rigid support	X,Y,Z
30p	Rigid support	X^*, Y, Z^*
43p	Elastic support k = 415 N/mm	Y
56p	Elastic support k = 415 N/mm	Y
74p	Elastic support k = 415 N/mm	Y
94p	Rigid support	X^*, Y, Z^*
95	Rigid restrain - flange	X,Y,Z
107rp	Rigid support	X^*, Y, Z^*
110rp	Elastic support k = 415 N/mm	X^*,Y
126rp	Rigid support	X^*, Y, Z^*
130rp	Rigid support	X^*, Y, Z^*
135	Vertical guide	X, Z

As a result of the measurements and tests, significant discrepancies between their current characteristics and those provided by the design were found. A summary of current characteristics of the supports was created. Such summary is provided in Table 2.

In Table 2, the symbol (*) at the letters X, Y, Z, denoting the direction of possible movement, indicates the presence of additional friction.

With data on the fastener characteristics, equivelent stress distributions were determined in the pipeline of features consistent with the pipeline design, and in the pipeline with fastener characteristics changed as a result of long-term operation. Figures 15a and 15b show the results of the calculations of stresses in the main branch of the pipeline, for selected moments of time in the production cycle. The tII was selected as the representative moment of time – the moment in which the greatest temperature variability was observed in the tIV branches of the pipeline - the moment corresponding to the steady process.

a)



b)

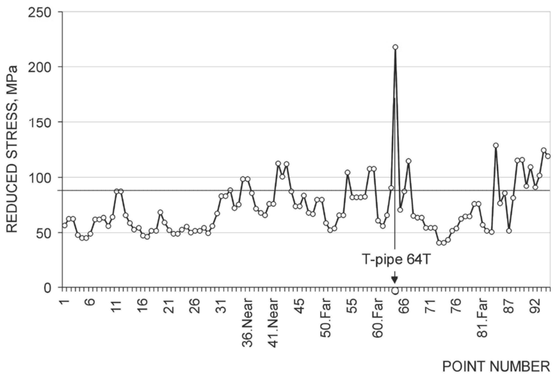
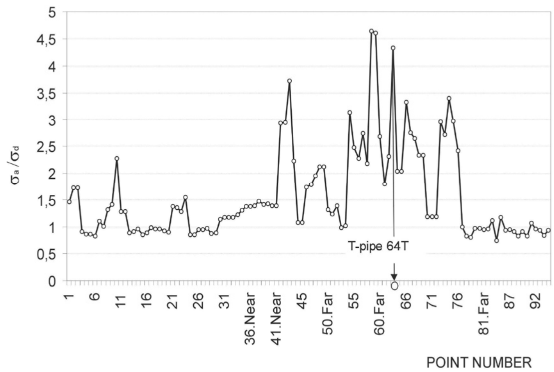


Fig. 15. Examples of determined distributions of equivalent stress along a selected section of pipeline, at the tII –(a) and tIV –(b) moments

Figure 16 shows the impact of changes in the fastener characteristics on the pipeline effort. The measure adopted for determining the significance of changes in characteristics of the fasteners for the pipeline strength, the ratio of equivalent stress as provided in the design and the equivalent stress after many years of operation.

The calculations performed enabled the identification of the places with the greatest effort and comparison of the effects of suspension changes on the effort of the structure. In the design methods used, including the methods for strength calculations of components of complex shape, covered in the standards, such components are treated in a simplified manner, with respect to their geometry and loads. The assessment of a pipeline, from the point of view of its stability under time-varying loads, requires a more precise description of the stress and strain in those components. An analysis carried out on a global basis makes it possible to formulate boundary conditions for such approach, which refers to the areas of the greatest effort. Only the local approach ensures the possibility of determining the characteristics of deformation, which are the relations between the stress and strain tensor components, temperature and time, which are necessary in predicting the service life. One important element of the local approach is to define the load conditions on the edges of determined areas of the pipelines. This is because the transition from the global to local approach involves the adoption of a different object model.

a)



b)

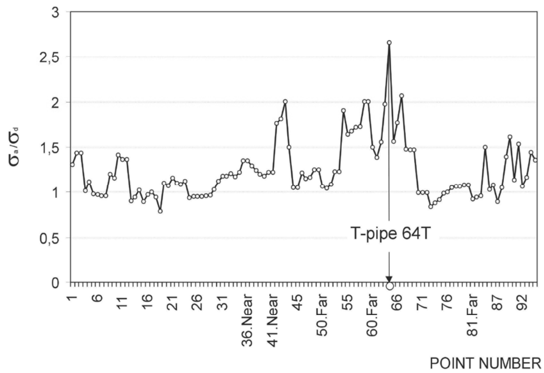


Fig. 16. Examples of determined distributions of the ratio of equivalent stress as provided in the design and the substitute stress of the current state, along a selected section of the pipeline, at the tII -a) and tIV -b) moments

The model of the analyzed fragment which, in a global approach, is a spatial frame loaded at the edge with the internal forces, is replaced with a solid (Fig. 17).

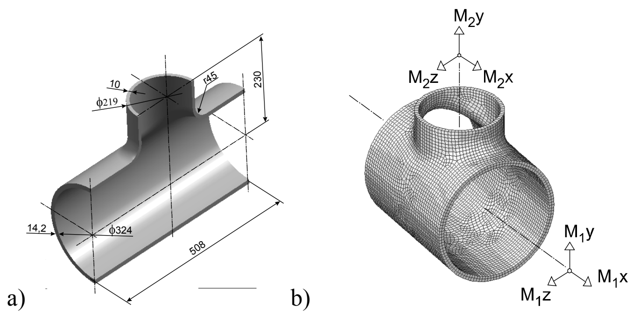
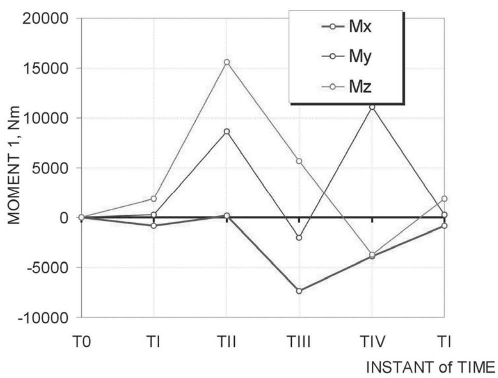


Fig. 17. Geometric features of a tee-pipe – (a) and its model with marked division into finite elements and vectors of moments applied at the planes of division – (b)

a)



b)

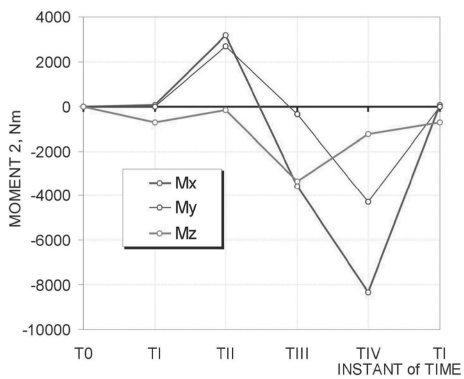
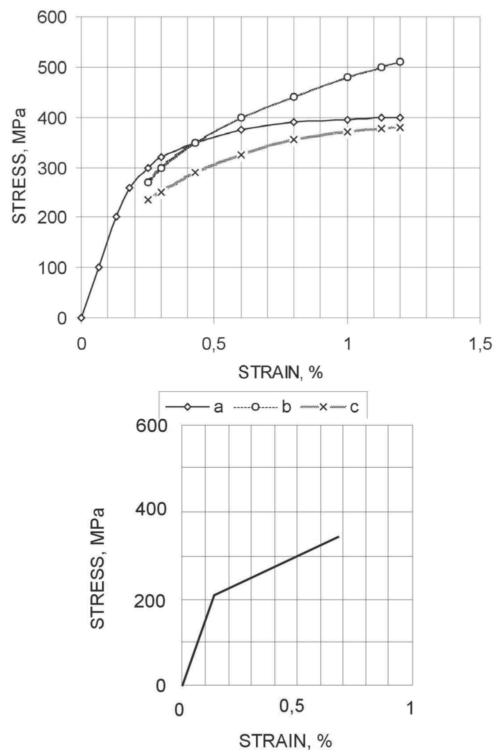


Fig. 18. Courses of changes in time of moments marked in Figure 17: a) - the moment M1, b) - the moment M2

The bending and torsion moment at the plane of the implied division was replaced by the system of concentrated forces applied in the grid nodes, defined in a given plane of the implied division.

In the operating conditions, the presence of cracks in welded joints within the tee and on its inner surfaces were often found. The type of cracks and their place of occurrence indicated the fatigue character of the impacts as the cause of material decohesion. Such type of load is present in the structure start-up and shutdown conditions. For those reasons, the transient states mentioned have been analysed in detail. An elastic-plastic material model was then assumed, the characteristic of which was built on the basis of the stress-strain curve of austenitic steel (Fig. 19a). Using the finite element program, equivalent stress distributions were determined in successive moments of time, typical for operation of the pipeline. Figure 19b shows the distributions of stresses on the inner surface at the time tIV. The areas in which, the greatest equivalent stress values were found, coincide with the locations where cracks were observed on the 64T tee surface (Fig. 13).

a)



b)

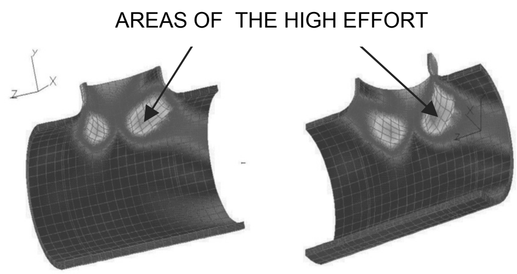


Fig. 19. The curve of cyclic deformation of the tee material -a) and equivalent stress distributions on the tee surface at the moment tIV –b)

Such approach can be applied for forecasting the tee-pipe life. The characteristics should then be determined for the cyclic deformation, in the form of the relationships between the components of stress and strain tensor and the time, in order to compare their performance with the material properties provided by the life criteria. The problem of the approach to the local deformation process is separate comprehensive issue which should be considered in terms of the phenomenon of creep, fatigue and crack formation.

Assuming of the possibility of force distribution across individual supports has led to exceeding the allowable stresses by the calculated value of the maximum stress, in the confidence interval in the vicinity of certain points of the power pipelines studied.

The study showed that in the chemical and power pipelines, after long years service, the stresses may exceed the limit values, determined in accordance with Polish Standard PN-79/M-34033. This leads to the need for a particularly careful, ongoing monitoring of areas, in which the exceeded calculated limit values were found. This is because the low cycle fatigue process may occur in those areas. Due to the cyclical nature of impacts in the power pipelines, in some parts of steam lines, as shown in Figure 7a, there is a risk of the crack formation.

Evaluation of stresses in the thick wall elements, on a global basis, consisted of the adoption of appropriate ratios of stress concentration. Calculations made in such simplified method showed the importance of variation of load for the strength of the pipeline. The coefficients of stress concentration adopted in the calculations, not constitute a sufficient basis for a precise analysis of local deformation processes in the areas most vulnerable to cracking. Such areas are, for example, tees, elbows, reducers, and, particularly, their welded joints. The study of local deformation processes often requires the application of computer-aided calculation methods to determine the characteristics of cyclic deformation. On the basis of a local analysis, also the risk of uncontrolled development of cracks can be assessed, if they are found by the diagnostic tests in the pipeline. The basic characteristics of the material in this case is the diagram FAD [2,49], which allows determining the dimensions of crack, which would cause damage to the pipeline.

Creep characteristics, which were and still are a major source of data in the process of construction and selection of geometrical and dynamic features of pipelines, may no longer be deemed sufficient for a thorough evaluation of strength of the analysed structures. The loads of the system are variable in time, due to fluctuations in operating parameters and the start-ups and shut-downs required by the process. The materials are subjected, in such conditions, to loading processes, in which the periods of creep, relaxation and fatigue occur alternately. Moreover, the issue is further complicated by the possibility of the formation and development of cracks, especially in welded joints.

However, even leaving aside the issue of crack growth and its role in the processes of failure, and focusing on the period of initiation of cracks and failure as a result of growth in the damage, the issue of development of material characteristics, needed to assess the life of the system, is a very complex task, due to the large number of possible relationships between the temperature, stress and strain. It seems justified, therefore, to search for specific characteristics for the specific equipment and conditions of service. Determination of the characteristics of this type requires a combination of strength analysis, taking into account the changing nature of the load of a particular structure or group of devices, with laboratory tests. Analysis of the conditions of use of components is, in this case, the source of data needed to define the grade of material, test parameters and the nature of their variability over time.

6. Thermo-mechanical fatigue

In the previously discussed examples the linear elastic or elastic-plastic material models have been taken into account. The models didn't take into consideration the influence of the temperature on the actual properties of the material. Such assumption is sometimes justified. For instance in situations in which the main load has mainly mechanical character or the temperature changes in time are not big and the temperature doesn't change the mechanical properties of the material during the operation period. It is not possible to assume such lack of temperature influences on the components in which the temperature changes in wide range and the temperature rate is high. In such situation the thermo-mechanical fatigue takes place. This is the phenomenon that is not included in procedures of a high temperature component life prediction in the adequate level. The reasons of such situation are diverse. Beside them are such as lack of the unified method of material testing and the complicated analysis of the component behaviour during influence of the temperature and mechanical load changing. It seems to be justified in such situation to perform investigations of the chosen components in operation conditions, which are focused on the problem of the stress-strain characteristic description methods. One of such components is superheater chamber in the classic steam boiler [58]. 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 20. Figure 20 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.

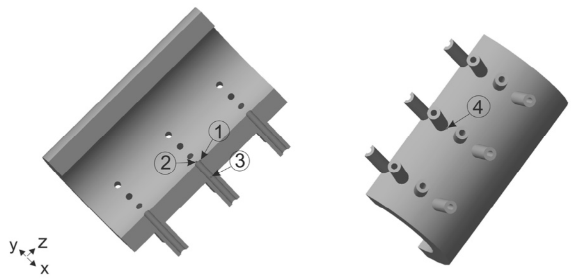
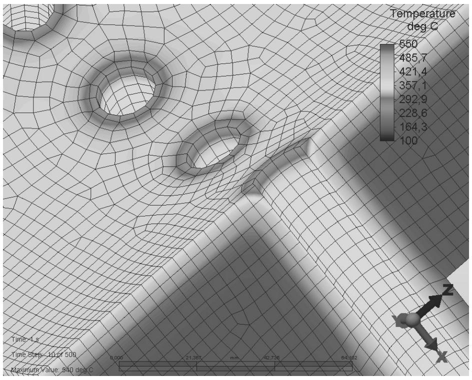


Fig. 20. Models for the analysis of heat flow and calculating the distribution of stresses and strains variable in time

The thermal influences have been taken into account. In the calculations the surface film conductance values were assumed. The boundary coefficients were adopted based on a handbook by Zbigniew Orłoś entitled "Thermal Stresses" [59], 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 during the periods of the cooling. 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.

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 thermo-elstic-plastic material model has been assumed. In the model the Young modulus and coefficient of hardening depend on the temperature. The isotropic material hardening model has been taken into account during calculations. The material characteristics shows the large variety of the material behaviour dependent on the relationships between mechanical strain and temperature changing. This has an influence on the local stress-strain bahaviour in thermo-mechanical processes of components, that operate under mechanical and thermal loading.

a)



b)

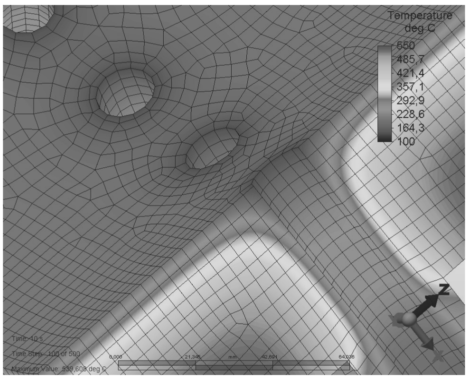


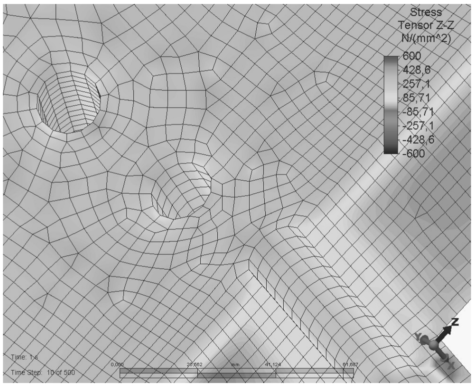
Fig. 21. Temperature distributions in the chamber, determined for its model under cooling and heating conditions determined for chosen instants of the time: a) - 1 s, b) -10 s

Calculations were carried out, based on which the distributions of temperature were calculated and the values of this variable changing in time in selected points of chamber were computed as well. The points were located near the holes through which water steam is supplied and carried away (Fig. 20), 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 21 and 22.

Values of total, mechanical and thermal strains variable in time, and the dependency between temperature and mechanical strains, computed for different points (Fig. 20) are shown in the Figures 23 and 24.

a)



b)

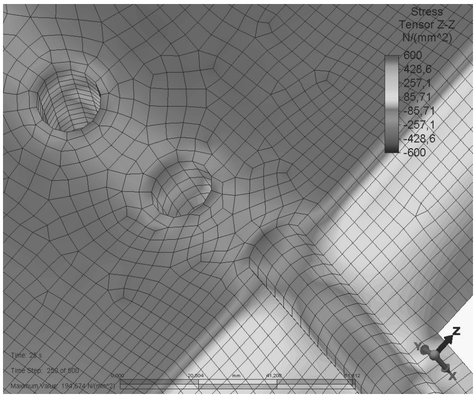
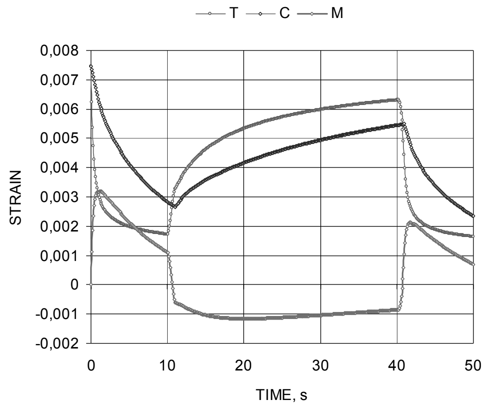


Fig. 22. Distributions of axial stresses caused by thermal loads determined for chosen instants of the time: a) – 1 s, b) -25 s

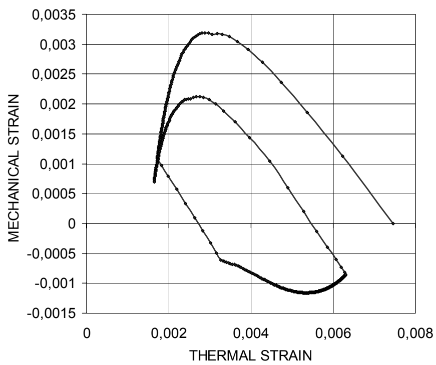
The temperature fields show the high temperature gradients particularly in the areas near the holes in the inside surface of the header during the cooling period of the cycle (Fig. 21). This influences on the high thermal stresses around the holes (Fig. 22). The areas of high stresses unite with themselves that gives the good circumstances for the initiation of the cracks and their growth between the holes perpendicularly to the header axis "z".

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.

a)



b)



c)

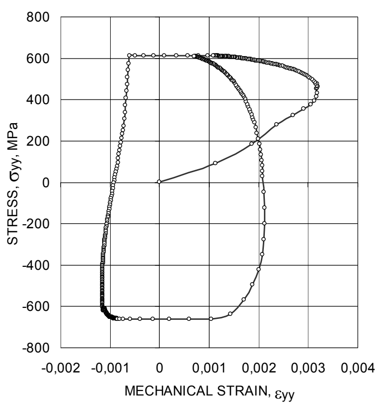
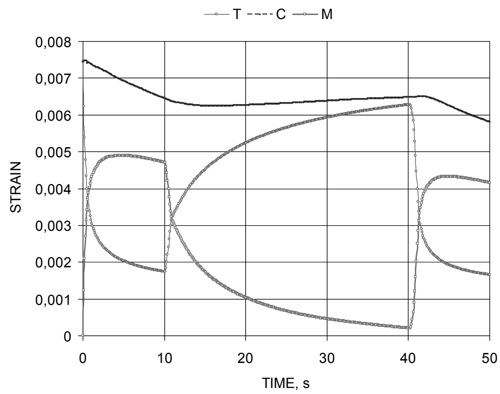


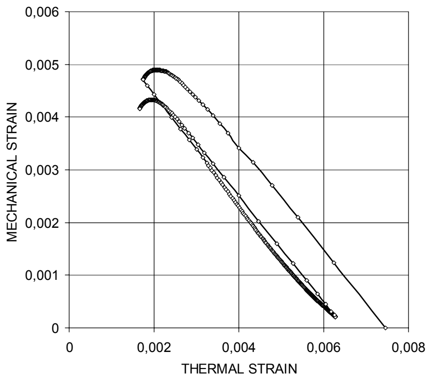
Fig. 23. Total - C, thermal -T and mechanical – M strains versus time characteristics – (a), mechanical strain versus thermal strain – (b) and interdependencies between mechanical strain and stress – (c); in the point 1; y direction

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.

a)



b)



c)

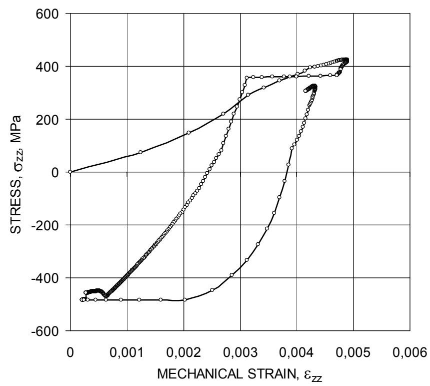


Fig. 24. Total - C, thermal -T and mechanical – M strains versus time characteristics – (a), mechanical strain versus thermal strain – (b) and interdependencies between mechanical strain and stress – (c); in the point 2; z direction

We can see that the local component characteristics differ from the typical used in the methods of material testing. 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 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 [60-68]. Particularly it concerns the problem of the fatigue life that is determined for the chosen types of the mechanical and temperature cycle characteristics only.

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.

7. Effects of the operation process on material properties

The system material in the conditions of use is largely subjected to a process of creep, which can lead to the formation of voids at grain boundaries. Over time, the degree of structure defects increases which, in turn, with the simultaneous influence of time-varying thermal stress field, leads to the formation of cracks [2, 57, 58, 60]. Over the time, cracks increase their length under the influence of constant load in creep conditions, or due to the impacts of cyclical nature. Inside the structure of the material, changes occur due to temperature effects. They are the processes remodelling the dislocation structure, the processes of aging caused by precipitation processes, coagulation of carbides, etc. Changes in the structure need not necessarily lead to deterioration of material properties. It can be observed, for example, that the low-cycle fatigue strength of steel alloys used for the power pipelines increases with the time of use [58, 60]. However, the strength properties are deteriorated, which is illustrated, for example, by the course of cyclic deformation curves. The life evaluation requires, therefore, a very cautious interpretation of the results of material tests, taking into account the aforementioned factors of mechanical nature.

8. Attempt to evaluate technical conditions of system components with concept based on the FAD method

In any case, allowing a structure, after many years of service, to continue its operation, requires estimation of its current strength and the forecast of the period of continued safe and efficient performance. One of the major problems one may face in this case is the presence of cracks in some of their elements. This applies especially to elements of the installations, where working conditions were not precisely defined by the designers and essentially depend on the increasing demands for availability of power units and process equipment in the chemical industry, while their general technical condition is continually deteriorating. Such components are the turbine intermediate pipelines.

Given the current conditions of the assessment of the life of intermediate turbine pipelines during long-term operation, as set by the standards and the availability of material characteristics, the evaluation of the technical condition and life of those components can be done in a simplified manner, based on the approximate computational models, creep and fatigue characteristics, using the TRD 508 standard. In the TRD 508 standard, stress in the evaluated structures is calculated as a function of internal pressure, having regard to the factors characterizing the shape of the elements in question. This is the most commonly applied approach. In many cases, the technical documentation obtained only allows an initial characterization of the life, in the absence of complete information regarding the magnitude of the remaining loads. In case of the intermediate pipelines, this relates to the impacts from other installation components. In most cases, there is also no data regarding the changes in the structure of the tube and fitting material, and this is also the case as the precise defectoscopic tests of cracks are concerned.

Pressure is one of the few important effects of effort. The stress condition in intermediate pipelines is affected by the following factors:

- internal pressure;
- turbine shift due to thermal expansion;
- effects of steam pipelines connecting the boiler with the turbine on the valve chambers;
- action of time-varying temperature.

Another, more accurate approximation can be taking into account some of those factors, and the adoption of the model which represents such geometric features of the intermediate pipelines as the radii of arch curvature and the shape of the elements that connect them with the turbine body.

Using, prepared in this way and still simplified, the calculation model enables the determination of stress distributions in the intermediate pipelines on the basis of conservative boundary conditions. While examining the external impacts of a selected pipeline, the Cartesian right reference system has been adopted in this paper. The turbine axis coincides, in this case, with the "x" axis turned at the generator. The "y" axis is vertical and oriented upwards. In such a system adopted constraints and loads were determined. In the absence of data on the size of impacts of the steam pipelines on the valve chambers at pipe connection points with the chambers, the following conditions were adopted:

- possibility of free movement in the direction of the "x" and "y" (horizontal plane);
- no possibility of movement in the "z" direction.

Rigid connection to the fixed valve chamber should cause greater stress in the intermediate pipelines, comparing to the impacts of a flexible pipeline located on the other side the same chamber. Hence, more unfavourable service conditions were assumed. For the adopted boundary conditions, the pipelines were subjected to the internal pressure. The following drawings show an example of an intermediate pipeline model and some results of calculations (Fig. 25).

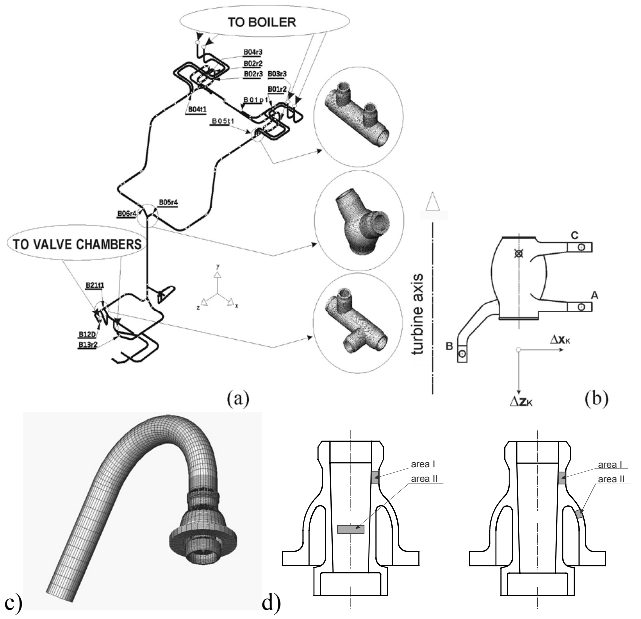


Fig. 25. Example of the re-superheated steam pipeline - (a); valve chamber draft with dislocation directions indicated - (b); Model of WP turbine intermediate pipeline – (c), its cross section with marked areas of higher effort – (d)

The degree of weakening due to creep under the 508 TRD procedure is determined on the basis of the creep resistance. Therefore, the test results are presented in the form of the graphs shown in Figure 26. On the basis of a specific experimentally described $R_{z/T}(T)$ characteristics, the $0{,}8\ R_{z/T}(T)$ curve parallel to is determined, where T is the time for failure. Points located on the $0{,}8\ R_{z/T}(T)$ curve correspond to the boundary states, according to the standard.

Intermediate pipeline cracks occur mostly close to the connection point with the turbine. This follows from the nature of the mechanical impacts in the area and, supposedly, it is due to the complex shape of this part of the pipeline and the presence of the weld.

In the present paper, the presence of crack has been assumed and an attempt has been made to assess the risk of spontaneous development in conditions of turbine operation.

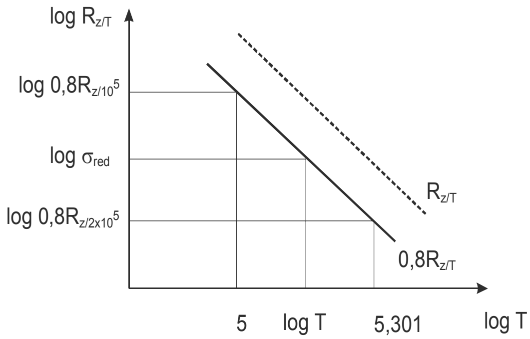


Fig. 26. Method of determining the time T to failure, for the assumed σ_{red} substitute stress value, in accordance with the TRD 508 procedure

The calculations were based on the FAD (Failure Assessment Diagrams.) It was assumed that the cracking toughness can be expressed as the K_Q value. On the y-axis of the graph, the values $\frac{K_I}{K_Q}$ were removed. On the x-axis, the values of equivalent stress and yield point $\frac{\sigma_{red}}{R_{0,2}}$ are given.

Due to the complex shape of the pipeline section in question, currently, there is no analytical solution available for the designation of stress intensity factor for cracks occurring in that element. In such cases, the crack of substitute shape and size is adopted [2,10,49]. The paper assumes that, in exceptional circumstances, circumferential cracks can occur across the pipe wall. Cracks of similar shape, but with slightly less depth, are found in parts of the installation. In the case of an overall crack, a gap would occur which indicative shape is shown in Figure 27a. For the crack in Figure 27a, the stress intensity factors are expressed by [69] the dependencies:

$$K_I = \sigma_m \sqrt{\pi R \Theta} F_m \quad \text{or} \quad K_I = \sigma_t \sqrt{\pi R \Theta}\, F_t \quad \text{or}$$
$$K_I = \sigma_b \sqrt{\pi R \Theta}\, F_b, \tag{15}$$

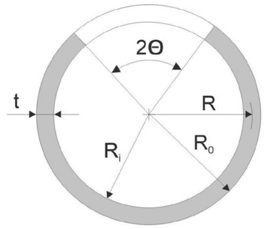
where σ_m, σ_t, σ_b denote stress resulting from the internal pressure, axial force or bending moment, F_m, F_t, F_b denote functions of tube dimensions and crack length, which depend on the load type [69]. For the internal pressure impact:

$$\sigma_m = \frac{pR}{2t}$$
$$F_m = 1 + 0{,}1501\gamma^{1,5} \quad \text{for} \quad \gamma \le 2 \tag{16}$$
$$F_m = 0{,}8875 + 0{,}2625\gamma \quad \text{for} \quad 2 \le \gamma \le 5 \tag{17}$$

where: $\gamma = \Theta \sqrt{\frac{R}{t}}$.

Figure 27b shows the dependency between the θ angle and K_I stress intensity factor for a thick-wall tube, of the same internal and external radius as in the tube with a cracks of the shape as shown in Figure 27a.

a)



b)

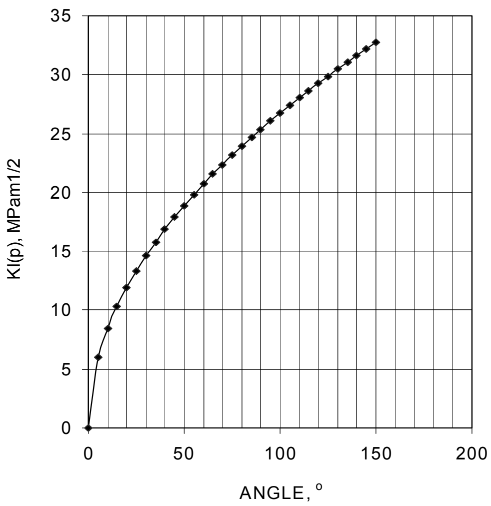


Fig. 27. Crack diagram -a) and values of stress intensity factor depending on the Θ angle which determines the crack dimensions -b)

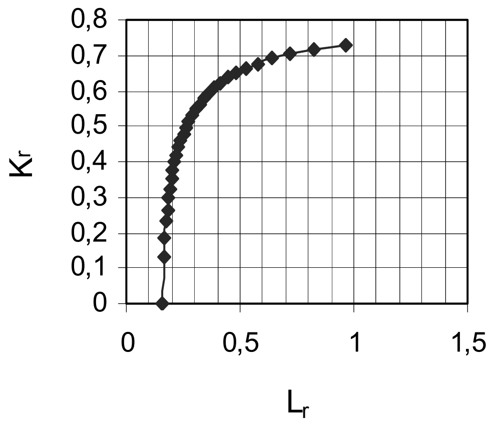
To assess the risk of spontaneous crack development, two criteria are assumed. It has been assumed that there are two limitations to the dimensions of the cracks. One of them is the value of the stress intensity factor, which may not exceed the critical value. The second is the value of axial stress in the section of the pipe weakened by the crack. It has been assumed that the stress should be lower than the conventional yield point or boundary creep strength. The failure graph is described as follows:

$$K_r = L_r \left[\frac{8}{\pi} ln\, sec\left(\frac{\pi}{2} L_r \right) \right]^{\frac{1}{2}}, \qquad (18)$$

where: $K_r = \frac{K_I}{K_Q}$, $L_r = \frac{\sigma_a}{R_{0,2}}$, $R_{0,2}$ denotes the conventional yield point and σ_a is an average axial stress in the section of the pipe weakened by the crack.

With the details regarding the internal pressure and material properties available, the relationship between the K_r, L_r values for cracks of various sizes were determined. Figure 28a shows a graph of that relationship, illustrating the so called “load path”. Figure 28b shows a set of curves illustrating the load path and FAD boundary curve. Their crossing point is determined by the boundary state.

a)



b)

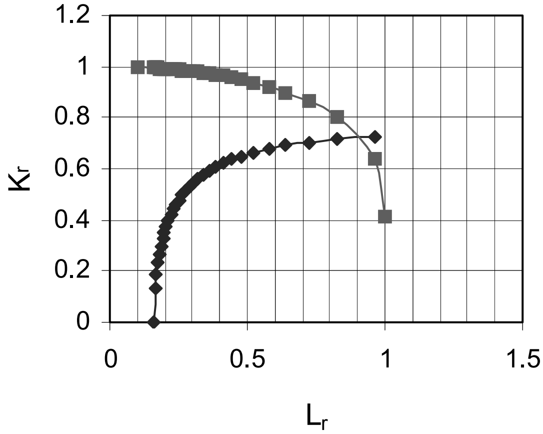


Fig. 28. Relationship between the K_r, L_r ($L_r = \frac{\sigma}{R_{0,2}}$) values for cracks of various sizes, determined for a tube with the substitute crack – (a) and the method for determining critical values K_r and L_r – (b)

The calculations were performed assuming the estimated value of cracking resistance, without taking into account the value of safety factor, the adoption of which would reduce the permissible value of the θ angle. The analysis estimated the length of the crack, which could pose a risk to the structure investigated. That length was many times greater than the length of the crack, whose presence was found in service. It should, however, be noted that this crack can grow, especially when under the influence of overloads and dynamic loads. Taking into account that possible effect, and the length of the periods between each tests, the release of the pipeline for continuous operation involves the risks resulting from inaccurate estimates of the dimensions and the actual values of the local loads. There is also no data on the characteristics of the growth rate of cracks in materials used in the Polish power generating sector, which is necessary for forecasting the development of cracks. Thus, the approach presented should be regarded as another approximation, based on the available material characteristics. Such approximation provides the ability to more fully evaluate the technical state of pipelines, determining, at the same time, the direction of activities that should be taken to develop a methodological basis and a material database, needed by designers and users of industrial installations to ensure the safety of operation.

9. Legal considerations of the assessment of the technical condition of equipment subjected to mechanical and thermal impacts

Parts of Polish power units, only several years ago, were designed taking into account mainly the creep strength. Their "computational lifetime" refers to the mechanical properties of material. For example, for structures for which the allowable stress was determined on the basis of $R_{z/T/10^5}$ creep strength, in accordance with the Polish standards, the "computational lifetime" is one hundred thousand hours. This does not mean, however, that power devices, which have exceeded such time, completely lost their technical efficiency. The technical condition of facilities after many years of service may vary depending on their type and usage history. Often, the release of the device for further use, after the expiry of the designed lifetime, is fully justified. In each case, however, it is necessary to assess the current technical condition of the equipment, as well as to forecast the period the date of the next technical inspection or decommissioning.

At present, in Poland, there is no unified procedure for such an assessment. Some companies operating in the energy sector have developed their own methods, based primarily on the principles of "good engineering practice". Such companies are the Institute of Power Engineering in Warsaw, the Institute of Ferrous Metallurgy and the company Pro Novum of Katowice. These companies, while making the technical assessment of the equipment, mostly apply the German TRD 301 and TRD 508 standards, and the requirements of the Polish Office of Technical Inspection. Until recently, the UDT (Polish Office of Technical Inspection) requirements did not take into account the life aspects, related to the possible presence of cracks in the elements of pressure equipment [6]. In the latest edition of the Conditions of the Technical Inspection Office, on the pressure equipment, failure caused by the presence of cracks is included in a form of general guidelines recommending the inclusion of methods of cracking and fatigue mechanics. There are, however, no detailed standardized procedures related to various devices and conditions of use. The procedures used by national companies are based primarily on studies of material structure. In this respect, they significantly differ from the rules and guidelines valid abroad, including the British R5 and R6 procedures.

The service time of the component at elevated temperatures, and without a defect, is usually limited by the formation of cracks due to the accumulation of damage caused by the creep phenomenon at constant load, the fatigue phenomenon, resulting from varying loads, or complex interaction of the two load cases. There is also a possibility of reverse impact of the mentioned phenomena, with the domination of fatigue with less impact on the process of creep on the crack initiation process. Important role in those processes plays the condition of material structure which, during prolonged exposure to temperature and load, degrades affecting the life of the material and structural components.

The criteria for strength currently used in the selection of materials designed to operate at higher temperatures, based on the creep strength and/or creep limit, for the structures discussed are imprecise in variable load, lack objectiveness and are not very useful Moreover, they do not include the impact of stress concentration induced by mechanical grooves on the initiation and growth of cracks and changes in mechanical properties resulting from the operation, in particular the reduction of resistance to cracking. For this reason, among others, attempts are being made to apply additional criteria for assessing the life, such as the low-cycle life criteria at elevated temperature, the material failure criteria in the presence of a sharp notch under the static load, taking into account the accumulation of defects as a result of creep, and failure criteria in the presence of a sharp notch under variable loads. One of the more sophisticated approaches to strength calculations, combining the criteria of fracture mechanics and creep criterion, is the aforementioned FAD (Failure Assessment Diagram), used as Code R5 for the design of elements of power equipment by British Energy Generation Ltd, UK.

Among the European standards regarding the design of pipelines, the provisions of TRD are applied, many of which relate to thick-walled elements. They also cover the methods for design and verifying calculations of mouldings subjected to cyclically varying loads, which can be generated by the internal pressure or the temperature field varying in time, during the start-up and shut-down of the system.

Siemens has its own bicryteria approach to the process of crack formation. The procedure is based on the value of the nominal stress and stress intensity factor.

The French RCC-MR standard in Appendix 16, and the British BS 7910 relate to the initiation and growth of a single crack. Both standards differ in details about how to determine the criteria stress and the value of the integral C * [2], which is the basic value used in the description of stable crack growth in creep conditions. The BS 7910 standard, first published in 1994 as BS PD6539, is based on the R5 procedure, developed by Nuclear Electric.

The methodology of all these procedures based on the use of various types of samples. Only the ASTM-E-1457 standard, first published in 1992, contains the instruction based on the results of tests of one type of compact CT-type samples. Such samples have deep cracks. As the experience shows, the behaviour of the deep and shallow cracks may be different and the problem is not fully resolved yet. In the research programs implemented in the

European Union, addressing these issues, samples, fragments of system components and finished parts of machinery and equipment are examined. Often, geometric properties of samples depend on the actual industrial conditions, wall thickness and dimensions of objects - vessels, pipes, cylinders, valves, tees, etc. Studies have shown large variations of results obtained in different laboratories. For that reason, this problem still requires concepts in relation to the use of samples and test conditions.

At present, in the European Union work is underway to develop new common standards and design guidelines taking into account the methods of fracture mechanics. It is carried out, inter alia, in the framework of ESIS - European Structural Integrity Society [49]. There is now a need to integrate national centers dealing with fatigue and fracture mechanics and life with the work to accommodate the requirements of Polish regulations to those in force in Europe. It seems necessary to adapt the existing national procedures to the methods developed in European FITNET and SINTAP research programs, whose results are expected in the near future to become the subject of an Europe-wide document. It is necessitated by the specificity of Polish industrial plants, among others, due to the diversity of materials of which they were made, in comparison with the steels used in the UK, Germany or France, where the base materials are the basis of FITNET SINTAP procedures.

10. Research programs on fracture mechanics and „structural integrity”

Ended some years ago, the program HIDA (High Temperature Defect Assessment) [70] funded by the European Commission concerned the methods of determining the life of elements working under the influence of elevated temperature and mechanical stress in power industry. Continuation of this program is the "INTEGRITY" [71], which covers repairs to power equipment. Objectives of the program are as follows:

1. Developing scientific basis for understanding and prediction of formation and development of cracks in components repaired by welding methods.
2. Development of mathematic-based finite element models for mapping the microstructure and properties of the reconditioned welded parts, in order to examine the behaviour of the process of initiation and growth of cracks along the boundaries of the property gradient.
3. Determining the methodology for assessing the life of reconditioned items based on the conclusions of the project.
4. Reference of failure development to the issues of supervision over the structures being reconditioned by welding technologies.
5. Quantitative assessment of the impact of internal stresses, especially in the case of welding, without preheating, on the life of repaired parts.

Solving those problems should lead to a reduction of costs resulting from the downtime due to cracking of system components subjected to mechanical and thermal impacts. This complex issue should be studied in a methodical way. Reducing the downtime and increasing the availability of power units and chemical plants is conditioned by economic considerations that determine the need to improve the repair technology and skills forecasting periods between successive repairs. The repair of old and damaged structures, as the experience of developed countries shows, is an increasingly attractive method of "life management". That requires, however, appropriate scientifically based tools. In terms of the national conditions, the following actions are becoming urgently needed:

- Modification and implementation of new methods of assessing and properties of materials operated at elevated temperatures.
- Development characteristics of the materials subjected to mechanical and thermal impacts.
- Determining the relationship between the processes of failure of the material subjected to creep and fatigue at elevated temperature, taking into account the structure of the material at different times of thermal-mechanical impacts in the service conditions.
- Determining the impact of the load on the functional properties, structural changes and the initiation of cracks.
- Developing numerical models to simulate actual working conditions of the tested structural components.
- Formulation of criteria for selecting material for the tubular elements of retrofit or new-built power systems, with regard to the interaction of creep and fatigue.
- Developing procedures to assess the life of the material and facilities operating under the influence of fixed and variable force and temperature fields.
- Determining the criteria to enable users of power equipment forecast and evaluate the material condition after various periods of use.
- Developing guidelines for the continued operation of the diagnosed and repaired pipelines.

11. Forecasting the development of methods of evaluation of the „structural integrity”

In Poland, the problem of developing methods for life prediction and evaluation of the power and chemical facilities is particularly urgent because of the safety of the system characterized by a high degree of degradation in terms of material and changes of the dynamic characteristics. On the Polish accession to the European Union, legal conditions regarding the safety assessment of facilities have changed. It becomes necessary to develop procedures taking into account the specific conditions of use and individual components of the system, based on the existing standards and regulations. Currently, actions are taken to coordinate research programs in this field by various research units. Among others, the Centre for Diagnostics of Industrial Pipelines was established, with the goal of developing appropriate procedures in relation to the typical plant components, in cooperation with their designers and users. The Centre includes research teams from such centres as the Institute of Power Engineering in Warsaw, Kielce University of Technology, Wrocław University of Technology, Military University of

Technology in Warsaw and the Silesian University of Technology. The developed procedures and methodology for the assessment and forecasting of material for further safe operation will be applied in particular for the following structures:

- pipelines connecting the boiler with the turbine;
- turbine pipelines;
- process and transfer pipelines in the chemical and petrochemical industry.

Special attention will be paid to the life of components of complex shape, including the steel and cast steel splitters, dampers, valves, and reducers. The issue of the evaluation of fastening system after many years of use will be analysed separately.

The condition of pipelines is associated with the operating safety of a power unit and installations in the chemical and petrochemical industry, with the reliability and the amount of harmful substances released to the environment. The confirmation of the advisability of research issues discussed are the plans for the two largest power plants in Poland: the “Bełchatów” Power Plant and "Opole" Power Plant, as well as the plans to modernize the Pątnów Adamów Konin Power Plants, where the continuation of the supercritical boiler project is still valid.

In the case of the “Bełchatów” Power Plant, units 1 and 2 will operate until 2016, then the retrofit of the 3-12 boiler units will take place, including installation of the NOx burners. Construction of the unit no. 13 of power output 800 MW supercritical will be started. The unit is to be launched by end-2008. Projects are being planned in the field of organic waste incineration. Since 2016, the plant is expected to meet the EU standard for SO2, NOx and particulate matter. Between 2005 and 2016, the FGD (flue gas desulphurisation) system in units 3 and 4 is planned, and the retrofit of installations in units 8, 10, 11 and 12.

The “Opole” Power Plant meets the general emission standards according to the relevant provisions, except for NOx which has to be lowered, and this is planned to be achieved by catalytic methods. Other planned investment projects is the construction of units 5 and 6, or the gas unit with a capacity of about 1000 MW. The construction of NOx installation is planned. There are plans to upgrade the heating system.

All planned projects in the context of the new legal requirements require a new approach to the safety of their use. The most important argument for the need to approach the issues presented, is the safety and reliability of the use of industrial installations. The possibility to develop grounds for predicting the service life of those installations has also its serious environmental implications, because of the reduced likelihood of environmental pollution, which must be taken into account, particularly in the chemical and petrochemical industries. The possibility to prolong safe operation and retrofit of the existing installations is an important economic argument. It is also significant that such a solution, while ensuring the operational safety, should be less damaging to the environment as compared to the alternative possibility of building new power or chemical plants.

A stimulus for the coordination of distributed teams working for the energy and chemical industry, whose research topics are often redundant, could be the ordered project. The result of the project should be the adjustment of the Polish methodology of assessing the technical condition and life of industrial plants to the provisions of the European Union. Complementary scope of such a research project exceeds the capabilities of one research centre. The number and type of work necessary for the issues presented and the expected scope of their use exceed the framework set for individual and target projects.

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