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RESEARCH INTO THE PROCESSES CAUSING THE CONSTRUCTIONAL MATERIALS DEGRADATION

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Abstract: The paper deals with the tasks solved in the framework of the research plan "Research into Service Degradation of Advanced Constructional Materials", which has been solved in ŠKODA VÝZKUM s.r.o. since the year 2004 and will be finished in 2010. The objective of the research plan is the development of both existing and new methodologies describing in a complex way degradation of new types of materials applied at production of engineering equipment, constructions and their parts, used in the power and the transport industry.

1. Introduction

The objective of the research plan MSM 4771868401 "Research into Service Degradation of Advanced Constructional Materials" is the development of both existing and new methodologies describing in a complex way degradation of new types of materials applied at production of engineering equipment, constructions and their parts, used in the power and the transport industry [1]. The plan has been solved in ŠKODA VÝZKUM s.r.o. since the year 2004 and will be finished in 2010. It is supported by the Ministry of Education, Youth and Sports of the Czech Republic.

The modern experimental and computational base in ŠKODA VÝZKUM s.r.o., focused on the applied research, enables to monitor and evaluate the impact of the whole range of potential factors causing the degradation of the constructional materials properties. The laboratory and service measurements and calculations of both construction joints and the whole constructions are supported by the analyses of the basic material properties (chemical composition, microstructure, mechanical and physical properties).

Regarding the ŠKODA VÝZKUM s.r.o. activities especially in the power and the transport industry the research plan is mostly focused on the problems as follows:

- Evaluation of the grade of degradation of the selected constructional materials' mechanical properties after the application of mechanical and mechanical-heat stress under laboratory conditions and comparison of the laboratory results with the really degraded materials.
- Correlation of the state and development of the substructure and of refractory properties of welded joints of new 9-12% Cr steels and low-alloy steels developed for thermal power plants with supercritical parameters of input steam.
- Assessment of residual lifetime of advanced materials used in thermal power plants on the basis of the analysis of materials' microstructure and sub-microstructure, measurement of electrochemical parameters and magnetostriction properties.
- Evaluation of the influence of the application of thermally sprayed coatings resistant to wear, corrosion and thermal degradation on the changes in the functional properties of the coated parts.

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- Experimental and calculation assessment of the constructional parts' residual lifetime on the basis of the low-cycle and the high-cycle fatigue properties of materials and the service stress spectra.
- Elaboration of the procedure for the assessment of the degradation of mechanical properties of materials of the turbines' moving blades due to the acting of dynamic forces.
- Assessment of the impact of high frequencies on the failure of construction parts' joints.

The solving of the research plan is divided into partial tasks [2], which have been defined on the basis of the background research of the research plan in the beginning of its solving. The partial tasks are not considered unchangeable (in the years 2006 and 2007 the existing partial tasks were supplemented with three other ones – see [3] and [4]) but it is supposed that during solving the research plan they will be modified to fulfil the main objectives of the plan [1], which is the elaboration and the application of the following methodologies:

- Evaluation of the grade of degradation of constructional materials' mechanical properties, especially the correlation of the results of destructive and non-destructive experimental procedures.
- Evaluation of the grade of constructions' and constructional elements' damage due to various service conditions.
- Prediction of negative manifestations of degradation processes occurring in the material, which the construction or the construction element is made of.
- Evaluation of residual lifetime of the constructions and the constructional elements.

In the following chapters the definition of the subject of all the partial tasks of the research plan is mentioned in brief [5]. The partial tasks are included into more general units (corresponding with the titles of the chapters) according to the organizational structure of the ŠKODA VÝZKUM s.r.o. company in the research departments or testing laboratories (despite the fact that the partial tasks are not aimed at the activities of only one research department or laboratory, but they are multidisciplinary). Persons responsible for solving the partial tasks given in Chapter 2 are the employees of the Laboratory of Metallography, in Chapter 3 of the Mechanical Testing Laboratory, in Chapter 4 of the Dynamic Testing Laboratory, in Chapter 5 of the Laboratory of Noise and Vibration, in Chapter 6 of the Thermal Spraying Department, in Chapter 7 of the Laboratory of Analytical Chemistry and in Chapters 8 and 9 of the Computer Modelling Department.

2. Structural aspects of degradation of materials of power plant equipment

The partial tasks in this area are especially aimed at materials the power plant equipment parts are made of. Their subject is monitoring and evaluating the degradation processes and the verification of new materials of better resistance to the individual degradation processes. Attention is especially paid to the creep loading but the influence of corrosion, fatigue damage and embrittlement is monitored as well.

2.1. Database of superficial defects indicated with an endoscope

The aim of the partial task is creating the database of defect indications determined by means of endoscope inspections of the parts of the power plant equipment and to correlate them with the data acquired using other non-destructive methods (supersonic testing, replica technology of microstructure monitoring etc.) and possibly even using destructive tests (determination of mechanical parameters, chemical, microstructural and fractographic analysis etc.). The currently supplemented file of data will be the source of information and the basis for further videoendoscope monitoring on the power plant equipment in service.

2.2. Study of materials degradation using the electrochemical methods

In the framework of the partial task the advanced portable electrochemical apparatus (suitable for measurements out of the laboratory) was set up (see Fig. 1) and verified to evaluate the degradation of material properties of power plants equipment caused by a long-time service. The aim of the partial task is the determination of electrochemical characteristics of the used materials and the correlation of those values with other data that characterize the material degradation (i.e. with the changes in mechanic properties, with the development of microstructure and submicrostructure etc.). The files of data classified in this way will enable, on the basis of electrochemical measurements performed "in-situ", the qualified estimates of both the changes in the properties of the constructional materials and the residual life of the constructional parts.

Figure 1: *Portable electrochemical apparatus GAMRY Reference 600.*

2.3. Development of the microstructure of the advanced steels' weld joints under creep loading

The aim of the partial task is to determine the principle of the creep strength and the microstructure stability of welded joints of the advanced materials which are used for producing the steam turbines parts [6], [7]. The study results will serve for the selection of the most suitable combinations of materials and technological processes at turbines production, which ensure the required parameters for the selected parts and nods.

2.4. Standard scale for the evaluation of microstructure degradation of the materials the power plant equipment is made of

The aim of the partial task is to work up the standard scale for the evaluation of degradation changes in the microstructure of the selected steam turbine materials during a long-time service. The microstructure is evaluated using the replica-technique. The scales will be used for the assessment of material degradation or residual life.

3. Assessment of degradation processes of constructional materials for the purposes of residual lifetime determination of components and structures

Degradation of mechanical properties of constructional materials can be defined as a deterioration of their original mechanical properties considered at designing and dimensioning constructions, at calculating their lifetime, reliability and safety.

The basic engineering problem of degradation of mechanical properties due to external factors is the deterioration of materials' and constructions' resistance to the brittle fracture failure. In some cases, an inevitable deterioration of mechanical properties of constructional parts owing to their utilization in the particular construction is concerned (multiaxial stress, constructionally inevitable notches, welding etc.). Other cases of "classical" degradation are caused by a long-time acting of external influences or service conditions (high temperature, cyclic loading, corrosion and their combinations). The influence of the degradation factors shall be respected as early as the stage of the construction design.

The understanding of degradation processes and their research are especially important due to the following reasons:

- It is a general interest to utilize the constructions as effectively as possible and also as long as possible without the danger of their failures, which might result in economic or human lives losses.
- Due to the development of more resistant constructional materials it is both in the manufacturer's and user's interests to be able to evaluate the range and rate of degradation processes of materials under various service influences and to guarantee a desirable lifetime of designed parts and equipments.

3.1. Development of the methodology of measuring the mechanical properties of metals using classical and miniature test specimens

The aim of the partial task is to get acquainted with the methods of measuring the basic mechanical properties of constructional materials exposed to fatigue and creep loading and to determine their resistance to the brittle fracture failure on small test specimens (the tip of the instrumented impact hammer striker for dynamic compression testing is given in Fig. 2). The methodology of the mechanical properties testing of materials my means of small test specimens has not been sufficiently worked out and is not standardized yet.

Figure 2: *Tip of the instrumented impact hammer striker for dynamic compression testing.*

The testing of mechanical properties of constructional materials by means of tests on small test specimens is important in many practical cases, in which it is not possible to take sufficient amount of representative sample of the material from the constructional element for the manufacturing of the classical test specimens [8]. In the framework of this partial task the methodologies of the measurement of mechanical properties by means of small test specimens are elaborated and the results are compared with the results obtained on the classical test specimens.

3.2. Evaluation of constructional materials degradation and of residual life of the selected degraded elements

The aim of the partial task is to elaborate the methodologies of the evaluation of degradation of mechanical properties of the constructional materials used in power and transport engineering. The properties of materials degraded in service after creep and fatigue loading are investigated.

4. Degradation of materials and structural nods under the operational dynamic loading

Partial tasks in this area are aimed at engineering constructions during service loading with time variable forces. Attention is focused on the impact of the material degradation on the constructions and constructional parts, especially welded joints, and the effect on the service life.

Residual life of the constructions exposed to a cyclic loading is evaluated on the basis of the changes in materials properties due to degradation processes and on the basis of the grade of constructions and constructional parts damage due to various service conditions. Both experimental (fatigue tests, record of service loading spectra) and theoretical (modelling of investigated impacts by means of computational methods) approaches are applied to solve the mentioned problems.

To evaluate the grade of degradation of constructional parts' materials non-destructive methods are important. The method based on the analysis of changes in magnetostriction properties of materials seems to be one of the suitable ones.

4.1. Prediction of the service reliability of constructional parts exposed to the cyclic loading

The partial task is focused on the development of the methods of cyclic laboratory tests of machine parts and on the laboratory tests of constructional nods. Both the methods of low-cycle and high-cycle fatigue tests of materials under the low and the high temperature and the software for their evaluation are developed. The processes for two-parametric decomposition of stress time history using the rain-flow method and for the damage calculation are proposed.

Various strategies of fatigue life tests are realized: laboratory simulations of service loading by means of random processes, equivalent blocks of harmonic cycles, equivalent accelerated tests etc.

The methods for the determination of residual fatigue life of parts exposed to cyclic loading are studied and applied. Software for the estimation of constructional parts and units on the basis of the service stress spectra and on the basis of estimated S-N curves (nominal approach) according to Eurocode No. 3 is being introduced.

Fatigue tests of selected welded joints (tubular joints) are evaluated together with calculations on their detailed FEM models in order to classify the constructional nod according to Eurocode No. 3 (those nod types are not included in the standard) and to compare S-N curves of those nods with S-N curves of the nods not included in the standard.

Besides the methods of service fatigue life prediction of dynamically loaded constructions and their parts the methods of the evaluation of their service reliability on the basis of a stochastic approach are applied, too.

4.2. Development and verification of a portable measuring system

In order to estimate the residual life of the constructional part based on fatigue damage it is necessary to know the history of the part's stress in the course of the substantial part of its service. The stress in the constructional elements can be monitored by a portable unmanned measuring system, which samples continuously mechanical stresses (and possibly even other quantities), performs the necessary on-line data processing and stores the measured values in memory for further processing, e.g. using the rain-flow method.

The portable measuring system and software for multi-channel long-time monitoring of service stress and other quantities (e.g. acceleration) is being developed. The portable measuring system in a compact version is concerned, composed of the processor core, the multi-channel measuring part with independent A/D converters for the dynamic measuring of the resistance strain gauges (maximum sample frequency 3 200 Hz for each channel, maximum number of connected strain gauges 32), the storage of the Compact Flash type for data storing and the ethernet interface for data transmission and the system control. This interface is also wireless using WiFi and thus it is possible e.g. to control the signal and to record data outside the equipment, constructional element of which is monitored. In-house application software for data storing and in-house software for data displaying and their further processing in attending computer are the parts of the measuring system. The GSM communication interface, enabling remote control of the measurement, is developed and the off-line application of GPS unit for the system position detection is realized (see Fig. 3).

The measuring system has been verified during a long-time both laboratory and service measurement on the chosen means of transport [9] and will be verified at a long-time service measurement on a representative constructional unit in the field of power engineering.

Figure 3: *Components of the portable measuring system and its application in the trolleybus roof unit.*

4.3. Development of the database for evaluating the fatigue tests

In the framework of the partial task the records of all the registered fatigue tests performed in ŠKODA VÝZKUM s.r.o. during the last years were collected. Most registered records are of a tabular form and contain data concerning the test material (material designation, composition, heat treatment and the specimen shape; some records contain graphic representation – S-N curves and diagrams including the influence of the mean stress).

A standard process for the evaluation of the high-cycle fatigue tests of materials including the graphic outputs (S-N curves and Smith diagram) was tuned up.

System solution of the database was proposed and realized: structure, type and number of the stored data. All the collected data are transferred into the created forms, which contain the text, tabular and graphic data including the graphic evaluation and tolerance limits. An interactive procedure for filling in the individual records and a pattern of sheets put in the database are parts of the database. The IBM Lotus Notes software was chosen to administrate the created database.

A tool for sharing the data included in the database through the Intranet, which will enable the designers and test engineers an immediate access to the data concerning all the performed fatigue tests, is being created. Results of all the future fatigue tests shall be included in the created database.

4.4. Prediction of fatigue damage applying the magnetostriction principle

The research and development study of the possibility of using the phenomenon of magnetostriction and Barkhausen noise for the material fatigue damage prediction was performed. Up to now those phenomena have been used especially for the estimates of residual or real stress of constructional parts. But in some references the sensitivity of those induced magnetic phenomena to the change in the material texture is mentioned and correlations between the fatigue damage and the level of detected Barkhausen noise are pointed out.

The tests are performed by means of the ION-C apparatus, originally meant for the residual stress measurement. The possibility of the apparatus utilization was verified on flat specimens made of the selected constructional material, which were subjected to a fatigue bending test. The system calibration was performed on the control specimen in the course of the tension and compression test under an uniaxial stress (see Fig. 4). On the scratch patterns of the outer surfaces of the specimens a metallographic analysis was performed.

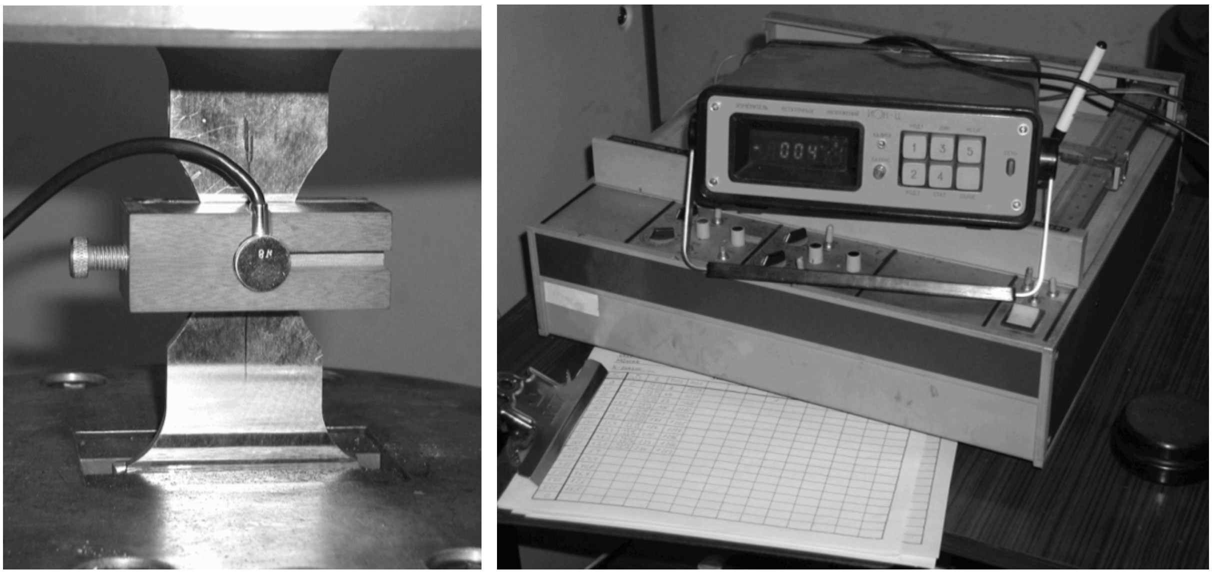

Figure 4: *Fatigue test monitored by means of the ION-C device.*

During the fatigue test on various levels of the rated stress the influence of the level of the ION-C output signal in correlation with the data measured by a strain gauge was monitored. When the signal level was changed the test was interrupted and the change in the material microstructure was monitored. The study results were correlated with the number of oscillations up to the specimen failure. The influence of the level and change in the signal on the specimen residual life was assessed.

The fatigue damage evaluation will also be performed at the laboratory test on the real constructional element (the rail vehicle bogie frame).

5. Development of the fatigue tests methods with the application to moving blades of rotating machines

Dynamic behaviour of moving blades under service conditions, which is especially given by their geometric shape and by the material which they are made of (its resistance to mechanical properties' degradation) influences decisively the lifetime and reliability of turbines, compressors and other bladed rotating machines. Under the service conditions the blades are exposed to higher temperature, humidity, centrifugal force, excitation caused by the multiples of the speed frequency etc. Before putting into operation the blades must undergo fatigue tests and on the basis of their results the original blades' design must be modified in case of need.

On the basis of experimental verification of degradation of moving blades material due to acting the cyclic stress is studied. The influence of the exposure to higher temperatures is also investigated, viz. in combination with the simultaneous acting of the cyclic stress.

Further the impact of high frequencies on materials' degradation is investigated. This character of loading is caused e.g. by aerodynamic forces and produces a sudden rise of failures.

5.1. Test workplace for performing the fatigue tests of rotating machines blades

The aim of the partial task was to put into operation the workplace for fatigue testing of rotating machines blades, which consisted in reconstruction of electromagnetic vibrator and in putting together the system based on the modern computer technology for the experiment control, data recording and measuring records evaluation. The test workplace will be provided with the furnace for testing under higher temperatures (see Fig. 5).

Figure 5: *Workplace for fatigue testing of rotating machines blades under higher temperatures and the tested blade detail.*

5.2. Testing of the moving blades of rotating machines

The aim of the partial task is to carry out and evaluate the fatigue tests performed on the chosen sets of the moving blades of rotating machines and the assessment of the blades material degradation.

5.3. Assessment of the high frequencies impact on the failure of the construction parts' joints

The aim of the partial task is to make the specimens of the chosen constructional joints, perform their oscillation till the failure and monitor the frequency effect on the number of oscillations up to the failure.

6. The influence of the thermally sprayed coatings on the changes in the functional properties of the coated parts

Thermal spraying is an advanced technology providing functionally effective coatings used in many industrial branches. It enables to adapt optimally the surface properties of the elements to the service conditions, which prolongs its lifetime, improves its reliability and safety of the whole construction.

Conventional applications of the thermally sprayed coatings are focused particularly on the surfaces protection. At present applications utilizing the coatings as functional surfaces are used, which is an alternative between the application of thin films and volume materials. Practical impact of the thermally sprayed coatings on the quality of products consists in the technical and the economic improving in their utility properties both in primary production and in renovation. The thermally sprayed coatings are resistant to abrasive wear, erosion and cavitation, they have excellent tribologic properties (self-lubricating, sliding, sealing coatings), they are resistant to oxidation and corrosion, to aggressive chemical medium and to extremely high temperatures.

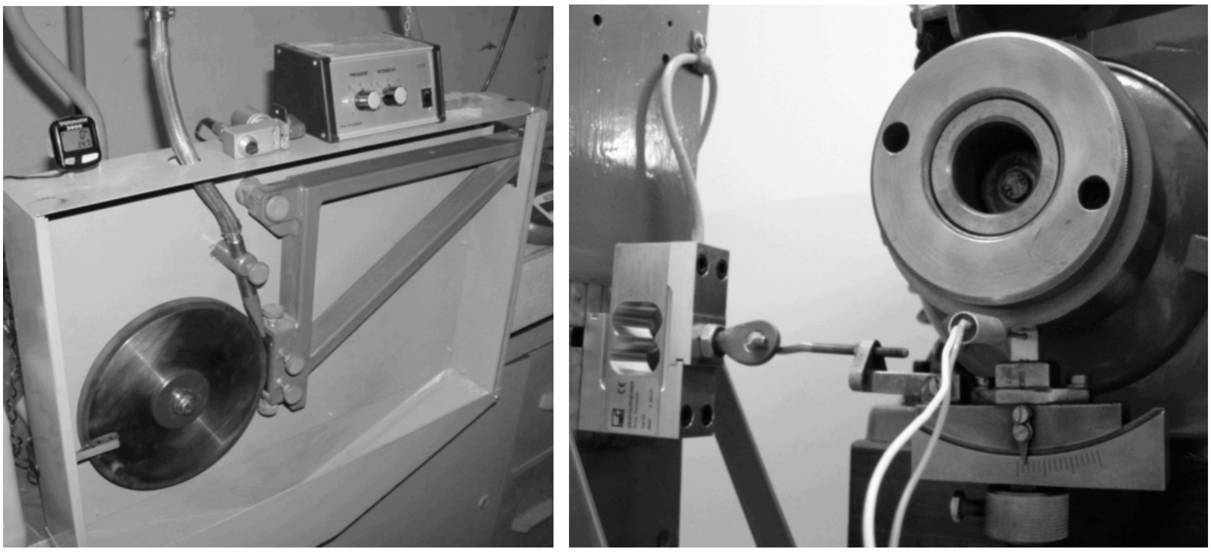

Figure 6: *Equipment for the evaluation of abrasive properties of coatings and detail of the equipment for the determination of sliding properties of material pairs.*

Suitable choice of material and preparation of the technology of thermal spraying for the individual applications is dependent on the coatings properties knowledge, on the basis of which it is also possible to predict the coatings lifetime under various modes of loading.

Though the relation of the structure, mechanical properties' quality and the lifetime of coatings is evident, sufficient attention has not been paid to this sphere yet.

6.1. Development of the methodologies for evaluating the properties of the wear resistant coatings

The aim of the partial task is to elaborate the methodologies for the evaluation of surface properties of the thermally sprayed parts considering their resistance to mechanical damage caused by various types of wear (equipments for the evaluation of the surface properties of coatings are given in Fig. 6). The solution can be found in the existing methods of surface properties evaluation (hardness, microhardness, resistance to abrasive, adhesive and erosion wear etc.), which are adapted to the requirements of thermal spraying following from their specific microstructure [10], [11].

6.2. Study of high temperature behaviour of thermally sprayed coatings

The aim of the partial task is to monitor the changes in the structure, properties and lifetime of thermally sprayed coatings exposed to high temperature [12]. The rate of the coating surface oxidation leading to the coating degradation and degradation of mechanical properties of thermally sprayed coatings due to high temperature are monitored, too.

6.3. The influence of the spraying at an angle on the deposition efficiency and coating's properties of the complicated-shape parts

Partial task is focused on the influence of the spraying at an angle on the deposition efficiency of the process, on the microstructure and on the properties of the deposited coating. The rate of porosity, the splat morphology quality, surface roughness and mechanical properties of thermally sprayed coatings deposited at an angle are investigated above all. On the basis of the acquired data the suitable conditions for spraying the complicated-shape parts by means of the programmable robot are determined.

7. The material ageing study applying the method of dilatometry and the preservative agents' degradation study

Dilatometric analysis is based on monitoring the changes in the specimens dimensions, which occur as a consequence of the atoms rearrangement in the crystal lattice after the temperature change. Dilatometric analysis is used to determine the course of phase changes in a solid state at heating or cooling. On the basis of the dilatometric curve it is possible to determine the coefficient of linear thermal expansion, or the dependence of the coefficient of linear thermal expansion on temperature. The method also enables to monitor the course of isothermal change under a higher temperature and it is used for the determination of the critical temperatures at heating and cooling metals and alloys. The dilatometric analysis results are, in combination with the metallographic analysis, the basis for drawing of the IRA and the ARA diagrams of steels.

Preservation oils and vaselines serve for the temporary protection of metal surfaces against the atmospheric corrosion. The atmosphere aggressivity, which is given by the climate, humidity, vicinity of the corrosive fumes sources, vicinity of sea and by surroundings, in which the protected object is stored, is the decisive factor for the suitable choice of the preservative agent. Further point of view of the choice of the suitable preservative agent is time, for which the object is to be protected against corrosion. As corrosion-preventive additives, agents on the basis of lanoline, surface-active oil-soluble substances, petroleum sulphonates and synthetic sulphonates of calcium, magnesium and zinc are applied. The majority of the mentioned components can be found using so called infrared spectrometry, which enables to identify substances on the basis of the infrared spectrum course. The relative intensity of the infrared spectrum bands also show the quantitative presence of the given component. Degradation of the preservative agent can show up in the form of the change in its chemical composition, i.e. by the occurrence of a new band in the infrared spectrum or on the contrary by the decrease in the intensity of the existing band.

7.1. Study of material ageing applying the method of dilatometry

The measurement of the changes in dilatometric behaviour of the chosen types of steels after and before creep in heat and after the applied mechanical and mechanical-thermal stress in the laboratory conditions are performed. The measurement results are compared with the metallographic and the mechanical properties of steels.

7.2. Study of the degradation of preservative agents on metal materials used in power engineering when storing for a long-time in maritime localities

The aim of the partial task is to evaluate the degradation of preservative agents used in power engineering in dependence on their exposure in a tropical chamber (20 °C, 23 °C and 40 °C). The tests are performed on the specimens of P92 steel with the application of eleven preservative agents.

After the expiration of the exposure in the tropical chamber the state of the preservative agents was evaluated applying the method of the infrared spectrometry with the Fourier transformation. Attention was paid to degradation processes occurring in the course of the experiment. At the same time the possibility of the identification of the steel materials corrosive attack using the infrared reflection method will be verified. Corrosion intensity will also be evaluated by means of mass decreases.

8. Processes and methods of the evaluation of the material degradation impact on its fatigue properties

Computer simulations are an important and indispensable stage at developing new engineering equipments and constructions. Their applying enables to predict the critical points of constructions and to estimate their operational strength and fatigue life. Approximate estimate of the service strength can be determined when considering the mechanical properties of basic materials. But the qualified strength evaluation must be based on the knowledge of the principles and rate of changes in properties of the materials exposed to particular degradation processes. The aim of the partial tasks is to find the approaches to the fatigue life assessment of structures or materials exposed to degradation processes. The FEM stress analysis is used for the fatigue life assessment.

8.1. Determination of strength and lifetime of welded steel constructions, Theory of high-frequency fatigue and its application in the finite elements analysis and Creep loading calculations using the finite element method

Solving the partial tasks given in the headline usually includes the following steps:

- choice of the suitable postprocessor for processing the results of FEM calculations,
- getting know with the theory utilised in the appropriate postprocessor,
- assumption of the postprocessor from the practical point of view,
- knowledge verification on simple examples,

- knowledge application to the particular task from the technical practice.

8.2. Application possibilities of neural networks

Artificial neural networks are an important part of the scientific branch of artificial intelligence. They are especially utilised for solving the problems, for which it is difficult to create a mathematical model and acquire the solution in an explicit form. Artificial neural networks can be applied almost in all spheres of human activities.

The aim of the partial task is to create users' models of neural networks for various theories of fatigue (creep loading) assessment on the basis of FEM calculations and their applications for the evaluation of the example from the technical practice.

8.3. Study of the influence of the welded joints modelling on the deformation resistance of thin-walled steel constructions

The most common way of joining construction elements of thin-walled steel constructions besides a screw joint is a welded joint. During the welding of constructions degradation of the material properties occurs due to acting high temperatures in the joint area. In case the constructions are exposed to acting the extreme loadings (impacts and other breakdown states), during which their plastic deformation occurs, the thermally effected joint area can behave in a different way than the basic material. At mathematical modelling of processes at which plastic deformations occur and at which the deformation resistance of thin-walled constructions is investigated, it is reasonable to consider the welded joints areas in the computational model.

The aim of the partial task is to determine the optimum approach to modelling the welded joints in FEM software for short duration events and large deformations and the evaluation of the necessity of the welded joints modelling in the thin-walled constructions which are exposed to loading causing large deformations and the determination of the results deviation when neglecting the modelling of the welded joint.

9. Application of multibody simulations in the field of transport and power engineering

The multibody systems dynamics is the field that started to develop noticeably in the 70's of the last century in connection with the development of the computer technology and computer softwares. Multibody simulations serve for the investigation of kinematic quantities and dynamic behaviour of non-linear three-dimensional mechanical systems. The multibody simulations results are one of the possible source of the input data for virtual investigation of degradation of materials the engineering equipment and their parts are made of, due to the acting of dynamic loading.

9.1. Applying multibody simulations in the field of transport and power engineering

Attention is focused on the development of existing approaches to multibody models creation and to searching new possibilities of the simulations results' application to the evaluation of reliability, safety and lifetime of constructions and their parts (e.g. [13]). The multibody simulations' results are usually verified with the records of service measurements on the real constructions [14].

The example of the multibody model of the ŠKODA 21 Tr low-floor trolleybus is given in Fig. 7.

Figure 7: *The ŠKODA 21 Tr low-floor trolleybus – a real vehicle and a multibody model visualization in the SIMPACK simulation tool.*

10. Conclusion

The results of a five-year solving of the research plan are presented in 119 titles of ŠKODA VÝZKUM s.r.o. research reports. So far 10 papers have been published in scientific journals, 83 ones in conference proceedings, 9 chapters have been published in books and 38 other outputs have been realized (e.g. putting into operation, innovation and assembling new experimental equipment etc.). The overview of the process of solving the research plan and of the achieved results is given in the research reports [2], [3], [4], [15] and [16].

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