Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Deformation and fracture mechanisms of heat-resistant steels due to their thermal aging under cyclic loading in condition of complex stress state

Lebedev, A.[1], Giginyak, F.F.[1], Timofeev, B.T.[2], Titov, V.[3]
1) Institute for Problems of Strengib, Nat. Ac.Scl. of Ukraine, Kiev, Ukraine
2) Central Research Institute of Structural Materials "Prometey", St. Petersburg, Russia
3) EDO "Gidropress", Podolsk, Russia

ABSTRACT: The paper presents the results of low cycle fatigue for low-alloyed 10GH2MFA steel in condition after thermal ageing at complex stress state.

1 INTRODUCTION

The urgency of investigations aimed at the comprehensive study into mechanical properties of heat-resistant steels under complex stress state at elevated temperatures is due to steady improvements in performance of power equipment and requirement for the guaranteed reliability of its service to be kept. Therefore, a comprehensive study into deformation at single load application, creep processes and low cycle fatigue of materials being used in power engineering for the purpose of further development and substantiation of estimation methods for their serviceability in structures during the rated service life with allowance made for a specific nature of thermomechanical loading and characteristic properties of steels investigated, is of essential importance for science and application.

This communication is devoted to the analysis of evolutionary peculiarities of deformation and fracture processes in heat-resistant steels of different structures with different ratios of principal stresses in an operating range of NPP equipment and to the development of some alternative methods for life estimation as applied to the quasistatic fracture under repeating low cycle loading at complex stress state as well.

2 PROCEDURE, RESULTS AND THEIR DISCUSSION

The testing method employed in this work involves a combined study of deformation, fracture kinetics and lifetime of metallic materials under static and low cycle loading with the use of the same equipment and similar geometry of thin-walled tubular specimens loaded by the axial force and internal pressure.

The investigation is concerned with widely used in reactor engineering heat-resistant steels 15X2MFA and 15X2HMFA in the initial state and after heat treatment which simulates irradiation embrittlement of those steels toward the end of the NPP equipment service life [15X2MFA (KP-100) and 15X3HMFA (KP-100), respectively], as well as steel 10GN2MFA in the initial state. As mentioned above, tests were carried out on thin-walled tubular specimens ($D/\delta = 50$, where D is the specimen inner diameter, δ is the specimen wall thickness) under static, stepwise and repeating loadings. Under static loading, a rate of loading or deformation was kept constant. Cyclic loading was performed according to the trapezoidal cycle by pulsating axial force and pulsed internal pressure in different combinations with a frequency of 2 cycles/min and a hold at a maximum load during 2 s. Under all loading regimes, the principal stress ratios $k = \sigma_z / \sigma_\theta = 0$, 2, 1 and 0.5 were realized (here σ_z and σ_θ are the axial and tangential pressures, respectively).

Tests were carried out with the use of a unique testing bench SNT-80 described in detail in Refs

(Giginyak 1991b, Shkodzinsky 1987). The experiments were conducted at temperatures of 20, 270 and 350°C (steels 15X2MFA, 15X2HMFA in the initial and heat-treated states) and at temperatures of 20, 285 and 320°C (steel 10GN2MFA). A test procedure for conditions of single static loading is described in detail in Ref (Giginyak 1987) and for otepwise and cyclic loadings - in (Shkodzinsky 1989).

In case of cyclic loading, the maximum stresses of a cycle were specified by their intensity such that the specimen fracture could be realized with lifetimes not exceeding $2x10^4$ cycles which corresponds to $\sigma_{imax} > 0.8\ \sigma_{i6}$, where σ_{i6} is the intensity of stresses breaking down the specimen under conditions of single loading at the given type of stress state. The testing facilities created have made it possible to carry out a large scope of experimental investigations and to obtain such an amount of experimental results that are sufficient for the generalizations to be made. As already noted above, the development of a method for structural material lifetime assessment supposes the availability of the needed initial information on their mechanical properties under conditions of single loading with due regard for main operational factors, such as, primarily, the type of stress state and temperature.

The results of the investigations have revealed an isotropy of structure materials studied and have made it possible to establish peculiar effects of the stress state type and temperature on their strength and plasticity characteristics as demonstrated by initial stress-strain diagrams for some materials studied at different ratios of principal stresses and temperatures given in Fig.1 as an example.

The isotropy of strength properties of steels studied is evidenced by test results for uniaxial and biaxial tension: under uniaxial tension in longitudinal and transverse directions, stress-strain curves nearly coincide (maximum discrepancy in stresses does not exceed 3%) and differ solely in strains; under biaxial nonuniform tension this is, essentially, an entire absence of plastic deformation toward the lower stress (k = 0.5 and 2) as well as a similar resistance to plastic deformation in longitudinal and transverse directions in uniform biaxial tension. Moduli of elasticity E_z and E_θ, and Poisson ratios, μ_z and μ_θ were found to be practically the same as well.

For the steels investigated, starting from the data above as the base, the existence of generalized stress-strain curves invariant to the stress intensity, σ_i versus strain intensity ε_i coordinates over the entire temperature range studied is substantiated, as evidenced by the results presented in Fig.2 as an example for one of the steels investigated. The above circumstance gives grounds to futher use stress intensity σ_i and strain intensity ε_i as representative characteristics of strength and strain properties of those materials under cyclic loading. From the results obtained it follows that the type of stress state has a marked effect on plastic properties of heat-resistant steels. In particular, a minimal plasticity, as for other materials (Lebedev 1983), is observed with principal stress ratios $k = \sigma_z/\sigma_\theta = 0.5$ and 2 over the entire temperature range studied.

An elevation of temperature to 350°C somewhat degrades strength and plasticity characteristics of the steels with all the principal stress ratio realized. In this case, the rate of strength degradation as the temperature of heat-resistant steels of an initial structure increases, depends weakly on the stress state type. And for steels simulating a radiation-embrittled metal, especially, for steel 15X3HMFA (KP-100) the most intense reduce in strength was observed under conditions of nonuniform biaxial tension.

When assessing the load carrying capacity of the structure, to determine criteria for the material utmost state is of considerable importance. At the same time, it is known that the exhaustion of a load carrying capacity of structures in the process of single loading or during their long-term service can be not only the result of their discontinuity appearance and inadmissibly large departures from the initial form but also it can occur with the loss in stability of the deformation process and therefore is determined both by a manner of loading of a deformable object and by its form.

In this connection, to assess the limiting state it was proposed by scientists of the Institute for Problems of Strength of the National Academy of Sciences of Ukraine to use a condition of the loss of stability of plastic deformation process in the objet studied with allowance made for its form and a manner of loading which made it possible to formulate a system of relations enabling, using a simple procedure, the calculation of the above characteristics to be made for any ratio of principal stresses in biaxial tension with a limited scope of simple experiments. A detailed description of those developments is presented in (Giginyak 1991a). In the same work given are the theoretical dependences used to describe the experimental results.

To check the validity of approaches being developed, the limiting yield stress and fracture curves

are plotted. Conventional proof stress was determined from the generalized curve $\sigma_i(\varepsilon_i)$ as stress which corresponds to 0.17% of residual strain. The calculation was carried out both by the known criteria of isotropic media equivalence (Coulomb-Mohr, von Mises, Pisarenko-Lebedev (Pisarenko 1976) and on the basis of the stability loss criterion for the above mentioned plastic deformation process. It is seen from the results given in Fig.3 that for the onset of yielding better agreement between the calculated and experimental data is observed when using von Mises criterion whereas for fracture - a condition proposed in Ref (Giginyak 1991a).

To describe a kinetics of the limiting state attained for the metal in a structure under one or other regimes of loading, a viscoelastoplastic model developed earlier (Giginyak 1986) can be used which allows the description of the material plastic deformation processes under single and repeating loadings at complex stress state to be made from the unified positions. The investigation into viscoplastic characteristics of steel grades selected was performed in accordance with the procedure of stepwise loading (Giginyak 1991c). The results of the study into viscoplastic characteristics of the materials investigated with the use of the model proposed are presented in sufficient detail in works (Giginyak 1989).

Using the results of the investigations into viscoplastic characteristics of steels performed, the assessment of the stress state type effect on the material viscoplastic behaviour was made. The magnitude of accumulated irreversible deformation preceding the loss of stability by the plastic deformation process is shown to depend appreciably on the type of stress state, and it is minimal with the principal stress ratio $k = \sigma_z / \sigma_\theta = 0.5$ (loading by internal pressure). It was noted that substantial creep under stepwise loading, caused by prestraining rate effects, is observed at a temperature of 20°C, much smaller at 320 and 350°C, and it is absent at 270 and 285°C.

The absence or essential deceleration of the creep processes at elevated temperatures should, probably, be explained primarily by thermal aging of heat-resistant steels studied, which manifests itself particularly efficiently when the deformation process ceases under stepwise loading. It should be noted that during repeated loading (stepwise static and stepwise cyclic loading) at T = 270°C and T = 285°C all the steels studied exhibited an increase in the yield stress by 20...50 MPa as compared to the stress value preceeding the unloading, at which the creep test (stepwise static loading) or cyclic loading test (stepwise cyclic loading) were performed.

When the stresses of the preceding loading step were exceeded, the strains were accumulated in jumps within 1...2 cycles, which is evidenced by the data presented in Fig.4,b as an example for one of the steels studied in comparison with the diagram in Fig,4,a obtained at ambient temperature. It was impossible to get quasistatic fracture in creep regime under conditions of stepwise loading at 270 and 285°C: the specimen either fractured during loading or transformed into equilibrium stress-strain state. The above features of heat-resistant steels behaviour allow certain assumptions to be made along with the known ones (Karzov 1993) concerning possible causes of fracture initiation in some highly-stressed elements of nuclear power equipment e.g. «cold» collectors of steam generators PGV-1000 manufactured of steel 10GN2MFA.

It is suggested that damages of cold collectors are the result of unfavourable combination of a number of factors, including those which are associated with technological (the technology of heat exchange pipes pressing in into the collector by explosion) and service factors (the type of stress state, the loading technique, cyclic loading, temperature and the effect of corrosion medium on the collector's metal). One can infer the following (one of possible) scheme of damage inittiation in the most dangerous zone of the collection (in the wedge region). The analysis of the test results obtained at the Experimental Design Bureau «Gidropress» on models of optically - active material revealed that the perforated area (near the wedge tip) of the collector under actual service conditions is exposed to mechanical loads in nonuniform biaxial tension with $k = \sigma_z / \sigma_\theta = 2$, i.e. in this case plasticity characteristics before fracture are essentially lower than those at uniaxial tension, which are generally used for calculations. Recall that at a temperature of «cold» collector (285°C) the deformation accumulation mechanism changes essentially during cyclic loading as compared to that at ambient temperature (see Fig.4). In this case the situation is aggrevated by appreciable local plastic deformations in the dangerous zone of the collection's perforation due to the used method of pressing in of heat exchange tubes into the collector and also by the presence of mounting-induced stresses in the collector.

If we assume that in the collector's perforation dangerous zone preloaded by mounting-induced stresses (the collector's metal being deformed a certain way during pressing in of pipes into the collector) cyclic loading is realized under conditions of nonuniform biaxial tension ($k = \sigma_z / \sigma_\theta = 2$)

at T = 285°C, and overstressing may occur during operation, then as a result of jump-like exhaustion of the collector's metal deformation capacity (under the action of one or several overloads) a site of failure appears in the collector's zone mentioned much earlier than the time of demage initiation calculated on the basis of initial data on the material properties determined by standard procedures in uniaxial tension. It should be mentioned specifically that the situation with crack initiation is much accelerated due to the corrosive medium effect on the collector's metal.

Analysis of the above considerations of the possible causes of damaging of «cold» collectors of PGV-1000 steam generators involving the obtained experimental data on mechanical properties of heat-resistant steels studied, their viscoplastic characteristics, regularities in cyclic creep and low cycle fatigue with the account taken of the type of stress state and temperature made it possible to direct the ways to improvements in the methods of life assessment for highly-stressed elements of nuclear power equipment operating under tough conditions of thermal and mechanical loading.

As it is shown in Refs (Giginyak 1989, Shkodzinsky 1989), quite primising results can be obtained for the case of quasistatic fracture with the use of relationships of deformation - kinetic nature where the intensity of deformation processes and lifetime are the parameters being correlated. The condition of the loss of plastic deformation stability and the elastoviscoplastic model developed were the basis of the deformation-kinetic criterion proposed at the Institute for Problems of Strength National Ac.Sci. of Ukraine (Giginyak 1989) which was used in the development of the calculation-experimental method for the assessment of service life of steels in the case of quasistatic fracture under repeating low cycle loading at complex stress state (Shkodzinsky 1989).

The calculation relationship has the following form:

$$N_b = \frac{C_i}{a\left(\sigma_{i\max} - \sigma_{itr}\right)^{b+1}},$$

where N_b is the number of cycles to fracture; C_i is the parameter which characterizes the material deformation properties in the general case and is independent of the stress level in a cycle at a specified principal stress ratio; it is determined from the condition of the loss of plastic deformation stability; a, b are constants defined by the characteristics of the material viscoplastic properties at specified temperatures (Giginyak 1991c); σ_{itr} is the stress intensity which corresponds to the fatigue-to-quasistatic fracture transition and is calculated for different principal stress ratios from the condition of the loss of plastic deformation stability. A detailed description of the proposed calculation-experimental method for the lifetime assessment is given elsewhere (Shkodzinsky 1989).

A quite large amount of investigations performed on different steels confirmed high reliability of this method which is proved by the results presented in Fig.5 for the steels investigated. As is seen, a fair agreement between the calculated and experimental lifetimes is observed for all principal stress ratios and temperatures realized when fracture is progressing according to quasistatic mechanism.

3 CONCLUSIONS

To assess the lifetime of highly-stressed elements of nuclear power equipment operating under severe conditions of cyclic thermomechanical loading during the realization of quasistatic fracture, it is proposed to use a calculation-experimental method based on the deformation kinetic criterion involving viscoplastic characteristics of the material and the condition of the loss of plastic deformation stability with the account takenof the type of stress state.

REFERENCES

Giginyak F.F., Lebedev A.A., Shkodzinsky O.K. Elastoviscoplastic model for describing the properties of pearlite steels. Abstracts of papers. XXI all-union meeting on the Problems of strength of enginers. Moscow.TsIAM, 1986, p.57.

Giginyak F.F., Zvezdin Yu.I., Lebedev A.A., Timofeev B.T. Low cycle fatigue and cyclic creep of high-pressure in multiaxial stress state . Res Mechanica, nr.21, 1987, p.35-53.

Giginyak F.F., Karzov G.P., Lebedev A.A., Timofeev B.T. Life of high-stressed pressure vessel

components under cyclic loading at complex stress state. 10th Int. Conf. Structural Mechanics in Reactor Technology, Anaheim, 1989, p.171-176.

Giginyak F.F., Shkodzinsky O.K., Lebedev A.A., Timofeev B.T. Loss of stability for the process of plastic deformation with a complex stressed state. Strength of Materials, vol.23, nr.10, 1991, p.1039-1047.

Giginyak F.F., Shkodzinsky O.K., Fedorov R.K., Storchak M.V., Bashta V.V. An automed stand for tests of constructional materials under conditions of the complex stressed state. Strength of Materials, Vol.23, nr.10, 1991, p.1135-1140.

Giginyak F.F., Shkodzinsky O.K., Lebedev A.A., Timofeev B.T. Viscoplasticity characteristics of heat resisting steels in multiaxial stress state. Strength of Materials, vol.23, nr.11, 1991, p.1203-1208.

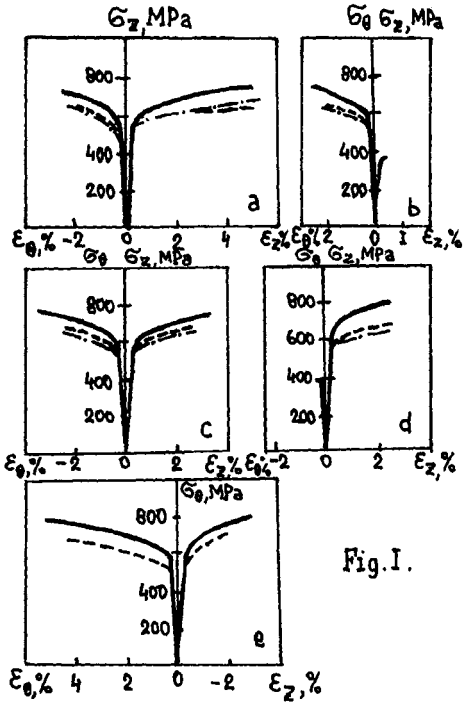
Karzov G.P., Margolin B.Z., Shvetsova V.A. Physicomechanical Modelling of Fracture Processes. Polytechnika, St.Petersburg, 1993.

Lebedev A.A., Kovalchuk B.I., Giginyak F.F., Lamashevsky V.P. Mechanical properties of engineering materials at complex stress state. Naukova Dumka, Kiev, 1983.

Pisarenko G.S., Lebedev A.A. Deformation and strength of materials at complex stress state. Naukova Dumka, Kiev, 1976.

Shkodzinsky O.K., Giginyak F.F., Bashta V.V., Storchak M.V., Stepanenko N.V. A machine for cyclic creep and low cycle fatigue tests in the complex stressed state of broad temperature range. Strength of Materials, Vol.19, nr.2, 1987, p.274-277.

Shkodzinsky O.K., Lebedev A.A., Giginyak F.F. Evaluation of endurance of heat-resistance steels in soft pulsed loading in multiaxial stress state. Strength of Materials, vol.21, nr.5, 1989, p.599-603.



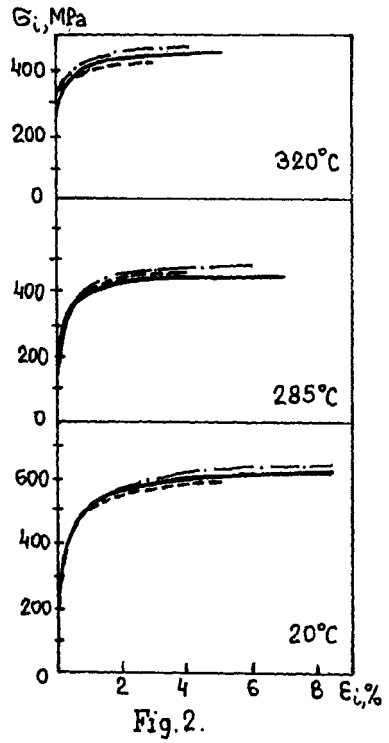


Fig.1. Stress-strain curves for 15X2HMFA steel at different temperatures and principal stress ratio: a) $K = \sigma_z/\sigma_\theta = \infty$; b) K = 0.5; c) K = 1; d) K = 2; e) K = 0; T = 20°C - solid lines; T = 270°C - dashed lines; T = 350°C - dot-and-dash lines.

Fig.2. Generalized stress-strain diagram for 15X2MFA (KP-100) steel at different temperatures and principal stress ratios: 1) $K = \sigma_z/\sigma_\theta = \infty$; 2) K = 1; 3) K = 0.5.

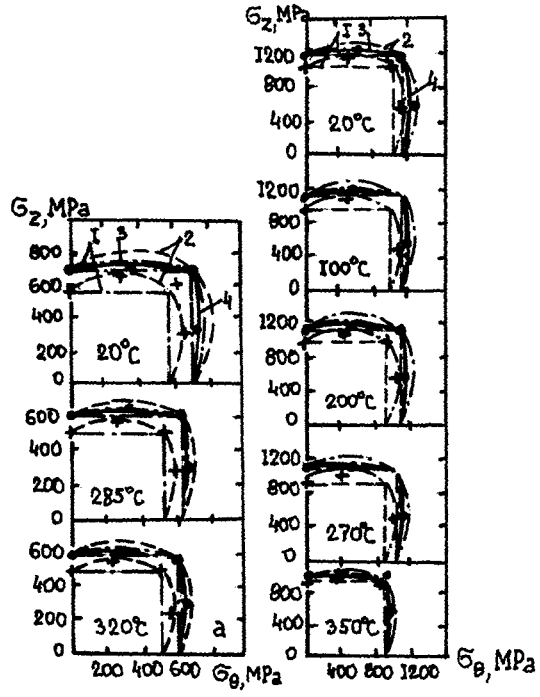


Fig.3.

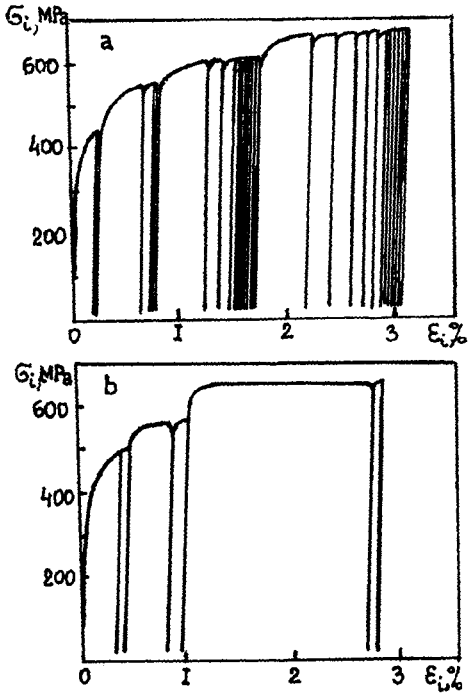


Fig.4.

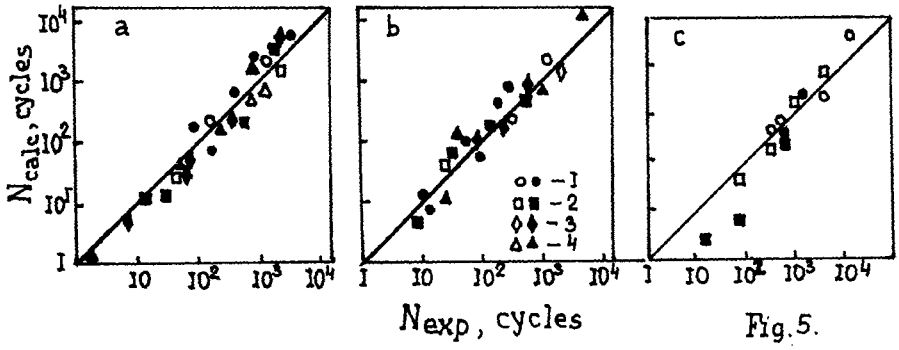


Fig.5.

Fig.3. Limiting yield curves (open symbols) and fracture (dark symbols) of steels 10GH2MFA (a) and 15X2MFA KP-100 (b) at different temperatures calculated from: 1 - Coulomb-Mohr's condition; 2 - von Mises's condition; 3 - Pisarenko-Lebedev's condition; 4 - Pisarenko-lebedev's condition of the loss of plastic deformation stability.

Fig.4. Diagrams of stepwise cyclic deformation of 10GH2MFA steel at different temperatures: a) T = 285°C; b) T = 20°C.

Fig.5. Comparison of lifetimes calculated by the proposed criterion with experimental ones for 15X2MFA (a), 15X3HMFA KP-100 (b), 10GH2MFA (c) at temperatures 20°C (open symbols), 350°C (a, b), 320°C (c) (dark symbols) at the principal stress ratios: 1) $K = \sigma_z/\sigma_\theta = \infty$; 2) K = 2; 3) K = 1; 4) K = 0.5.