Peculiarities of Cyclic Deformation and Fracture of Heat-Resistant Steel 10GN2MFA under Conditions Typical for the Steam Generator PGV-1000 Collector Material

F.F.Giginyak

ABSTRACT

In the present paper, the results are discussed concerning investigations into the regularities of deformation and fracture of steel, 10GN2MFA under conditions close to those of actual operation when used in collectors of PGV-1000-type steam generators, which are in service with WWER-1000-type reactors of nuclear power plants (NPP).

Institute for Problems of Strength,
National Academy of Sciences of Ukraine
2 Timiryazevskaya Str., Kyiv, 252014, Ukraine

Peculiarities of Cyclic Deformation and Fracture of Heat-Resistant Steel 10GN2MFA under Conditions Typical for the Steam Generator PGV-1000 Collector Material

F.F.Giginyak

1. INTRODUCTION

In recent years the guaranteed reliability of steam generators in NPPs is one of the most urgent problems. Collectors ("cold" collectors) made of steel, 10GN2MFA are the most critical components of those products [11, 12]. Therefore, a comprehensive investigation of the deformation under a single load application, from creep and low-cycle fatigue processes in the above steel, is of great importance for further development and validation of the methods for assessing their serviceability in structures during the calculated service lifetime, taking into account the specific nature of the thermomechanical loading. The present paper is devoted to the analysis of the peculiarities of the deformation and fracture processes occurring in heat-resistant steel 10GN2MFA at different ratios of principal stresses in the operating temperature range of PGV-1000 steam generators, as well as an extension of some versions of the methods for assessing life from a quasi-static fracture under a low-cycle repeating loading at a complex stress state.

The test method used in this work involves a comprehensive investigation of deformation, fracture kinetics and life of metallic materials under static and low-cycle loadings using the same equipment and thin-walled tubular specimens of the same geometry, which are loaded by an axial force and internal pressure. Heat-resistant steel 10GN2MFA in the as-received state, which is in common use in the reactor industry, has been chosen as the test material. As indicated above, the tests were carried out on thin-walled tubular specimens ($D/\delta = 50$ where D is the specimen inner diameter, δ is the thickness of the specimen wall) under static, stepwise and repeating loading.

Under conditions of static loading, the rate of loading or strain rate was kept constant; the cyclic loading was realized with a trapezoidal cycle developed through an axial force and internal pressure which were pulsating both in different combinations, at a frequency of 2 cycles / min and holding at a maximum load for 2s. For all the loading regimes, the ratios of principal stresses $K = \sigma_z / \sigma_\theta = \infty$; 2; 1 and 0.5 were achieved where σ_z and σ_θ are the axial and tangential stresses, respectively. The tests were carried out using the unique bench-type testing machine SNT-8U (Fig. 1) [1, 2, 3] which includes arrangements for loading by combinations of axial force and torque, axial force and pressure in the specimen internal cavity, with an automatic control over (a) static and cyclic loading, (b) the cooling and heating systems, and (c) the systems for measuring and recording forces and strains. The test bench enables one to obtain a biaxial loading of tubular specimens at various ratios of principal stresses σ_z / σ_θ in a range of $-\infty \le \sigma_z / \sigma_\theta \le \infty$ with a stress ratio of $0.06 \le r \le 1$.

Axial force (maximum): 10,000 kgf

Maximum internal pressure: 1500 atm

Maximum torque: 50 kg · cm

Temperature range: 400°C down to - 150°C

Proportional static and cyclic biaxial loading with a various shape of a cycle under both strain-controlled and stress-controlled modes at a frequency of 0.001 to $1 s^{-1}$ is implemented by a simultaneous supply of fluid from a pressure generator assembly to an actuating cylinder of a reverser and to the inside cavity of the specimen. The pressure generator assembly has beenbuilt around a thyristor drive-controlled hydraulic actuating piston mechanism. The advantage of this arrangement is in the static equilibrium of the loading system. This last circumstance enables one to change from the strain-controlled to the stress-controlled mode of loading and vice versa in the course of the experiment, the fact which extends considerably the potentialities of the test bench.

Electromechanical strain gages mounted on the specimen working sections are employed for measuring and recording axial and circumferential strains under static and cyclic loading. The novelty and practical usefulness of those strain gages were protected by the author's certificates. The strain gages were used together with the "TIS-DELTA-16" strain gaging system developed at the Institute for Problems of Strength of the National Academy of Sciences of Ukraine. The test procedure was described in more detail in [2, 3] for a single static loading and in [3, 4] for conditions of stepwise and cyclic loading.

Under cyclic loading, the maximum cyclic stresses used were determined by their capability to produce fracture of a specimen at service lifetimes not exceeding $2 \cdot 10^4$ cycles, which corresponds to $\sigma_{i\max} \geq 0.8\sigma_{ib}$ where σ_{ib} is the stress intensity at a given stress state corresponding to the specimen fracture under conditions of a single loading.

The test equipment built made it possible to perform a wide scope of experimental investigations and to obtain a large number of experimental results sufficient for generalizations.

As has been already pointed out above, the development of the method for assessing the service life of structural materials implies the availability of the required initial information on their mechanical properties under conditions of a single load application taking into account the main operational factors and, most importantly, the stress state type and temperature.

The findings of the investigations have shown the isotropic character of the metal studied, enabled one to establish the peculiarities of the stress state type and temperature effect on its strength and plasticity characteristics as demonstrated by some initial stress-strain diagrams for different principal stress ratios and temperatures given as an example in Fig. 2.

The anisotropy of strength properties of the steel under study is evidenced by the testing results for uniaxial and biaxial tension. Under conditions of uniaxial tension in longitudinal and transverse directions the stress-strain curves almost coincide (maximum discrepancy between the stresses does not exceed 3 %) and differ only in strains. In biaxial nonuniform tension, there is practically a total absence of plastic strain in the direction of lesser stress (K = 0.5 and 2) and the identical resistance to plastic deformation in longitudinal and transverse directions in uniform biaxial tension have been observed. Moduli of elasticity, E_z and E_θ, and Poisson's ratios have been found to be practically equal as well.

Based on the above data for the steel investigated, the generalized stress-strain diagrams were substantiated in the stress intensity, σ_i, - strain intensity, ε_i, coordinates over the whole temperature range studied, as evidenced by the results presented in Fig. 3. The above circumstance gives grounds for the further use of the stress intensity, σ_i, and strain intensity, ε_i, as representative characteristics of strength and deformation properties of this material.

It follows from the results obtained that the stress state type influences considerably the plastic properties of heat-resistant steel 10GN2MFA. In particular, the minimum plasticity as in the case of other materials [5] is observed at the principal stress ratios $K = \sigma_z / \sigma_\theta = 0.5$ and 2 over the whole temperature range.

The increase in temperature to 320°C somewhat deteriorates the strength and plasticity characteristics of the steel at all the principal stress ratios realized. In this case, the intensity of strength loss with the increase in temperature depends on the stress state type.

Establishing the criteria for the material ultimate state is of great importance when assessing the load-carrying capacity of structures. At the same time, it is known that the exhaustion of the load-carrying capacity of structures under a single loading or in long-term operation, can be caused not only by their discontinuity and inadmissibly wide deviations from the initial shape, but also by the loss of stability of the deformation process. Consequently, load carrying capacity is determined by both the mode of loading of the deformable object and its shape.
In this connection, for purposes of assessing the ultimate state at the Institute for Problems of Strength of the Nat. Ac. Sci of Ukraine it was proposed to use the condition of the loss of stability in the process of plastic deformation of the object (specimen) under study taking into account the effect of its size and mode of loading. This made it possible to develop a system of relationships which enables one to calculate the above characteristics for any ratio of principal stresses in the region of biaxial tension using a special procedure with a limited scope of simple experiments.
A detailed description of those developments is given in [6] together with the theoretical relationships used to describe the experimental results.
In order to validate the approaches developed, the limiting fatigue crack growth and yield curves were plotted. The 0.17% offset yield stress was determined from the generalized diagram, $\sigma_i(\varepsilon_i)$, as a stress corresponding to 0.17 % of the residual deformation. The calculation was made both using the known criteria of equivalence of isotropic media (those of Coulomb-Mohr, Mises and Pisarenko-Lebedev [7]) and basing on the above-mentioned criterion of the loss of stability in the process of plastic deformation.
It is seen from the results given in Fig. 4 that the best agreement between the calculation and experimental data is observed when the von Mises criterion is used for the yielding onset and the condition proposed in [6] for fracture.
To describe the kinetics of attaining the ultimate state of the metal in a structure under various loading conditions, the elastoviscoplastic model developed earlier [8] can be used which makes it possible to describe, from the unified standpoint, the processes of plastic deformation in the material under single and repeating loading under a complex stress state. The above model enables one to describe actual properties of the steel under study to a higher degree of validity than the other known models.
According to this model, metal creep is considered to be a result of relaxation of local stresses in a crystal lattice which occur by a process of active deformation. It is supposed that the material relaxation properties are amply reflected in the diagram of equilibrium state (quasistatic diagram) which is physically equivalent to the stress-strain diagram at a strain rate tending to zero. A comparatively simple method has been proposed and implemented for obtaining those diagrams by way of stepwise loading which will be discussed below. The experimental results have shown that for the heat-resistant steel studied, the strain curve in the stress intensity σ_i - strain intensity ε_i, coordinates is invariant to the stress state type.
At a final strain rate, a stress-strain curve always passes above an equilibrium (quasistatic) one. Here, the stress intensity, σ_i, corresponding to the specified strain, ε_i, can be presented as a sum of equilibrium stresses $\sigma_{eq}(\varepsilon_i)$ and some excessive stress σ_i^* (nonequilibrium) which determines the creep rate of the material under stress σ_i.
The investigation of the viscoplastic characteristics of steel 10GN2MFA has been carried out in accordance with the procedure of stepwise loading mentioned above. At each step of its loading, the specimen is subjected to an active deformation to a certain specified level of

strain. Then the tests for relaxation are performed at the strain level attained until the equilibrium stress-strain state is reached, following by a change-over to creep tests without the unloading of the specimen at a maximum - for this loading step - load, preceded by relaxation and a hold time until the equilibrium stress-strain state is reached.
When the testing machine is switched to the strain-controlled regime of loading, the tests for relaxation are performed with a hold as before, followed by unloading. The experiment is repeated once again at a higher level of stress and so on until the stability of the deformation process is lost.
The results of the studies on viscoplastic characteristics of a number of materials based on the proposed model are amply presented in [9, 10].
We use the coefficient of ductility, K_i, as a parameter characterizing the ductility of the steel under study. Here, the interrelation between the above coefficient, minimal rate of creep $\varepsilon_{i\min}$ and value of intensity of nonequilibrium stresses in accordance with the Newton non-linear model takes the form

$$\varepsilon_i = K_i \sigma_i$$

The invariance of the K_i-parameter to the stress state type and the value of the irreversible strain attained has been established experimentally. This coefficient depends on the level of nonequilibrium stresses only, and this dependence is satisfactorily described by the power function $K_i\left(\sigma_i^*\right) = a\left(\sigma_i^*\right)^b$ where a and b are the material constants for the specified temperature conditions which are determined from the results of two experiments in uniaxial tension. Some results in support of the above for static and cyclic loading are presented as an example.
The cycle of investigations carried out made it possible to offer and substantiate experimentally the method for assessing the viscoplastic characteristics of heat-resistant steels based on the equilibrium diagrams and the procedure for their obtaining which enables a significant reduction in time necessary for conducting the corresponding experiments as protected by the author's certificate.
Based on the results of a series of investigations on viscoplastic characteristics of steel 10GN2MFA, the estimation of the stress state type effect on the material behaviour has been made. It has been found that the value of the irreversible plastic strain preceding the loss of stability of the plastic deformation process depends essentially on the stress state type. It is minimal at the ratio of principal stresses $K = \sigma_z / \sigma_\theta = 0.5$ (loading by internal pressure).
The experiments have shown that in the region of the quasistatic fracture the instant of the transition from the first stage of creep to the second, already steady-state, one is conditioned by the equilibrium between the material strain hardening and the process of softening due to the change in the effective cross-sections of the specimen and its associated change of true stresses.
We note that under conditions of stepwise loading, considerable creep caused by the rate effects of the preceding active deformation, is observed at 20°C, much lower at 320°C and it is absent at 285°C.
The absence or significant retardation of the creep processes at elevated temperatures is likely to be explained, primarily, by thermal or strain aging of the heat-resistant steel studied which manifests itself best when the process of deformation ceases under conditions of stepwise loading. Note that under repeated loading (stepwise static and stepwise cyclic loading),

the yield stress of the steel under investigation at 285°C increased by 20 to 50 MPa compared to the value of the stress preceding unloading at which the experiment on creep (stepwise static loading) or cyclic creep (stepwise cyclic loading) was carried out.

After the stresses of the previous stage of loading have been exceeded, the deformations are accumulated in a jump-like manner in one or two cycles, which is evidenced by the data presented as an example in Fig. 5b, as compared to the diagram of Fig.5a, obtained at room temperature. Under conditions of stepwise loading at 285°C no quasistatic fracture in creep was attainable: the specimen either fractured under loading or transited into the equilibrium stress-strain state.

The peculiarities of the behaviour of heat-resistant steel 10GN2MFA make it possible to apply certain considerations, together with the known ones [11], to possible causes for crack nucleation in some highly loaded elements of nuclear power facilities, in particular, "cold" collectors of PGV-1000- type steam generators made of steel 10GN2MFA.

The defects in "cold" collectors are likely to be attributable to an unfavourable combination of a number of causes including those associated with manufacturing (a process of pressing of heat-exchange pipes into a collector by the explosion method) and service factors (stress state type, mode of loading, i.e., a cyclic loading, temperature and corrosive attack on a collector metal).

The following scheme can be assumed for the damage development in the most critical collector zone (close to a wedge). The analysis of the results of the investigations carried out at the "Hydropress" Experimental Design Office using the models of an optically active material has shown that the area of the perforated section (close to the wedge tip) of a collector under actual operating conditions is subjected to a force action in nonuniform biaxial tension with $K = \sigma_z / \sigma_\theta = 2$, i.e., the plasticity characteristics prior to fracture, which are commonly used for calculated estimations, are essentially lower in this case than in the uniaxial tension. We note that at the temperature of the "cold" collector (285°C), the mechanism of accumulation of residual deformation in the process of cyclic loading changes considerably as compared to that under conditions of room temperature (Fig. 5,a and b). Here the situation is complicated by the availability of considerable local plastic strains in the danger zone of the collector perforation caused by the procedure for pressing heat-exchange pipes into the collector as well as the availability of mounting stresses in the collector.

It we imagine that in the danger zone of perforation of the collector, preloaded by mounting stresses whose metal is, in a way, perforated in the process of pressing the pipes into the collector, a cyclic loading is realized under conditions of biaxial tension ($K = \sigma_z / \sigma_\theta = 2$) at 285°C, and what is more, in the process of operation, overloads in stresses can occur, then as a result of the jump-like exhaustion of the deformability of the collector metal (under the action of one or several overloads) a site of origin for fracture in the above mentioned collector zone occurs well before the calculated time of the occurrence of the collector damage, which has been obtained by calculation on the basis on the initial data on the metal properties determined by the standard procedures for conditions of uniaxial tension. It is necessary to emphasize that the situation with crack initiation is accelerated considerably due to the action of the corrosive environment on the collector metal.

The analysis of the above considerations on possible reasons for the development of damage in "cold" collectors of the PGV-1000-type steam generators based on the experimental data obtained for the mechanical properties of the heat-resistant steels, their viscoplastic characteristics, the governing laws for cyclic creep and low-cycle fatigue taking into account the stress state type and temperature, has made it possible to outline the ways of improving the methods for assessing the service life of highly loaded elements of nuclear power facilities which operate under complex conditions of thermomechanical loading.

It is proposed to accept the condition of the loss of stability of plastic deformation as that of the ultimate state (up to the instant of the crack occurrence) and to use the approaches based on the viscoplastic characteristics of the steel investigated for the description of the kinetics of attaining the above ultimate state.

Let us concentrate on this point using a diagram involving a generalized equivalent stress, σ_{eq}, - strain intensity, ε_i, diagram $\sigma_i(\varepsilon_i)$ and lines corresponding to the condition of the loss of the load-carrying capacity of the structure studied (specimen) at different stress state types in view of its size and shape variation at the points intersecting the generalized diagram and corresponding to the material strength at a prescribed ratio of principal stresses.

If the material fracture under cyclic loading is developed by the quasi-static mechanism, then, by analogy with the fracture kinetics under a single loading, as considered at the beginning of the paper where the approaches have been used based on the evolution of the process of the loss of the plastic deformation stability in relation to the proposed criterion for the ultimate state, it can be suggested that, on the one hand, with the service life, the increase in the strength of the material will occur at the expense of its strain hardening and, on the other hand, the reduction in the load-carrying capacity of the object under study will occur as a result of changes in its sizes and geometry, e.g., the decrease in the cross-section of the cylindrical specimen subjected to cyclic tension. At the first stage of creep, the reduction in the load-carrying capacity of the specimen, by decreasing its interior cross-section is compensated in abundance by the strain hardening of the material. Therefore, creep proceeds at a decelerating rate. The second (steady-state) stage is an equilibrium one; its duration can be different depending on the capacity of the material for hardening, structural peculiarities of the specimen and stress state type. The process of creep is further activized and proceeds at an increasing rate (the third stage).

Thus, taking into account the above-proposed analogy between the process of deformation under single loading and the development of creep due to the rate effects of the preceding active deformation, we arrive at the conclusion that the second (equilibrium) stage of creep corresponds to the development of the loss of stability of plastic flow, whose condition for biaxial tension in the range of relations $K = \sigma_z / \sigma_\theta = \infty ... 0$ can be written in the same way as it has been shown at the beginning of the paper for the case of a single loading and the diagram presented here (Fig. 6) can be used, as earlier, for the geometrical interpretation.

Based on this diagram, it is possible to determine the magnitudes of stresses and strains which correspond to the loss of the load-carrying capacity of the element as well as to calculate some parameters entering in the equation for assessing the lifetime under cyclic loading at a complex stress state.

In the case of quasi-static fracture as shown in [4, 10], extremely encouraging results can be obtained with the use of the relationships of a strain-kinetic nature wherein the intensity of deformation processes and service life are the correlated parameters. The condition for the loss of stability of the plastic deformation and the elastoviscoplastic model developed has formed the basis of the strain-kinetic criterion proposed by the present author et al. in [9] which has been used in the extension of the computational-experimental method for assessing the life of steels in the case of quasi-static fracture under repeating low-cycle loading at a complex stress state [4].

The calculated relation has the form

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

where N_b is the number of cycles to fracture; C_i is the parameter which in the general case characterises the deformation properties of the material and, being independent of the level of stresses in a cycle at a specified ratio of principal stresses, is determined from the condition of the loss of stability of the plastic deformation; a and b are the constants determined by the characteristics of the viscoplastic properties of materials at specified temperatures; σ_{itr} is the stress intensity corresponding to the fatigue-to-quasistatic fracture transition which is calculated for various ratios of principal stresses from the condition of the plastic deformation stability. The proposed computational-experimental method for assessing the lifetime is described in detail in [4].

A sufficiently large scope of investigations carried out on various steels has lent support to the high validity of this method which is evidenced by the results presented in Fig. 7 for the steel under study.

As is shown, a satisfactory agreement between the calculated values of lifetimes and the experimental ones is observed for all the realized ratios of principal stresses and temperatures, when the fracture proceeds by the quasi-static mechanism.

CONCLUSIONS

To assess the service life of a compared with highly-loaded structural elements in nuclear power plant equipment and for the steam generator collectors in particular, which in their operation are subjected to the action of cyclic thermomechanical loading when the quasi-static fracture is realized, it is proposed to use a computational-experimental method developed using the experimentally justified strain-kinetic criterion which enables one to take into account the viscoplasticity behaviour of the material and the loss of stability of the plastic deformation process for the particular stress state.

REFERENCES

1. O.K. Shkodzinskiy, F.F. Giginyak, V.V. Bashta et al. "A unit for cyclic creep and low-cycle fatigue tests at a complex stress state over a wide temperature range." *Probl.Prochn.*, **2**, 114-117 (1987).
2. F.F. Giginyak, O.K. Shkodzinsky, R.K. Fedorov et al. "An automated bench for tests of structural materials under conditions of a complex stress state." *Probl. Prochn.*, **10**, 70-74 (1991).
3. F.F. Giginyak, Yu.I. Zvezdin, A.A. Lebedev, and B.T. Timofeev "Low-cycle fatigue and cyclic creep of high-pressure at a multiaxial stress state." *Res. Mechanica*, **21**, 35-53 (1987).
4. O.K. Shkodzinsky, A.A. Lebedev, and F.F. Giginyak "On the assessment of the life of heat-resistant steels under a pulsating stress-controlled loading at a complex stress state." *Probl. Prochn.* **5**, 32-37 (1989).
5. A.A. Lebedev, B.I. Kovalchuk, F.F. Giginyak, and V.P. Lamashevsky "*Mechanical Properties of Structural Materials at a Complex Stress State.*" Naukova Dumka, Kiev (1983).

6. F.F. Giginyak, O.K. Shkodzinsky, A.A. Lebedev, and B.T. Timofeev "On the loss of stability of the plastic deformation process at a complex stress state." *Probl. Prochn.* **10**, 3-8 (1991).
7. G.S. Pisarenko and A.A. Lebedev, *"Deformation and Strength of Materials at a Complex Stress State."* Naukova Dumka, Kiev (1976).
8. F.F. Giginyak, A.A. Lebedev, and O.K. Shkodzinsky, "Elastoviscoplastic model for describing the properties of a pearlitic steel," XXI All-Union Meeting on the Problems of Strength of Engines. Abstracts of papers. TsIAM, Moscow (1986).
9. F.F. Giginyak, O.K. Shkodzinsky, A.A. Lebedev, and V.T. Timofeev, "Viscoplastic behaviour of heat-resistant steels under conditions of a complex stress state," *Probl. Prochn.* **11**, 52-57 (1991).
10. F.F. Giginyak, G.P. Karzov, A.A. Lebedev, and B.T. Timofeev, "Life of high-stressed pressure vessel components under cyclic loading at a complex stress state," 10th Int. Conf. Structural Mechanics in Reactor Technology, Anaheim, 171-176 (1989).
11. G.P. Karzov, B.Z. Margolin, and V.A. Shvetsova, "Physico-mechanical simulation of fracture processes" [in Russian]. Polytekhnika, St. Petersburg, 1993.
12. V.F. Titov. "Status of steam generators for NPPs with WWER-1000." IAEA Specialists Meeting on Steam Generator Problems and Replacement, Madrid, Spain, 199-233 (1993).

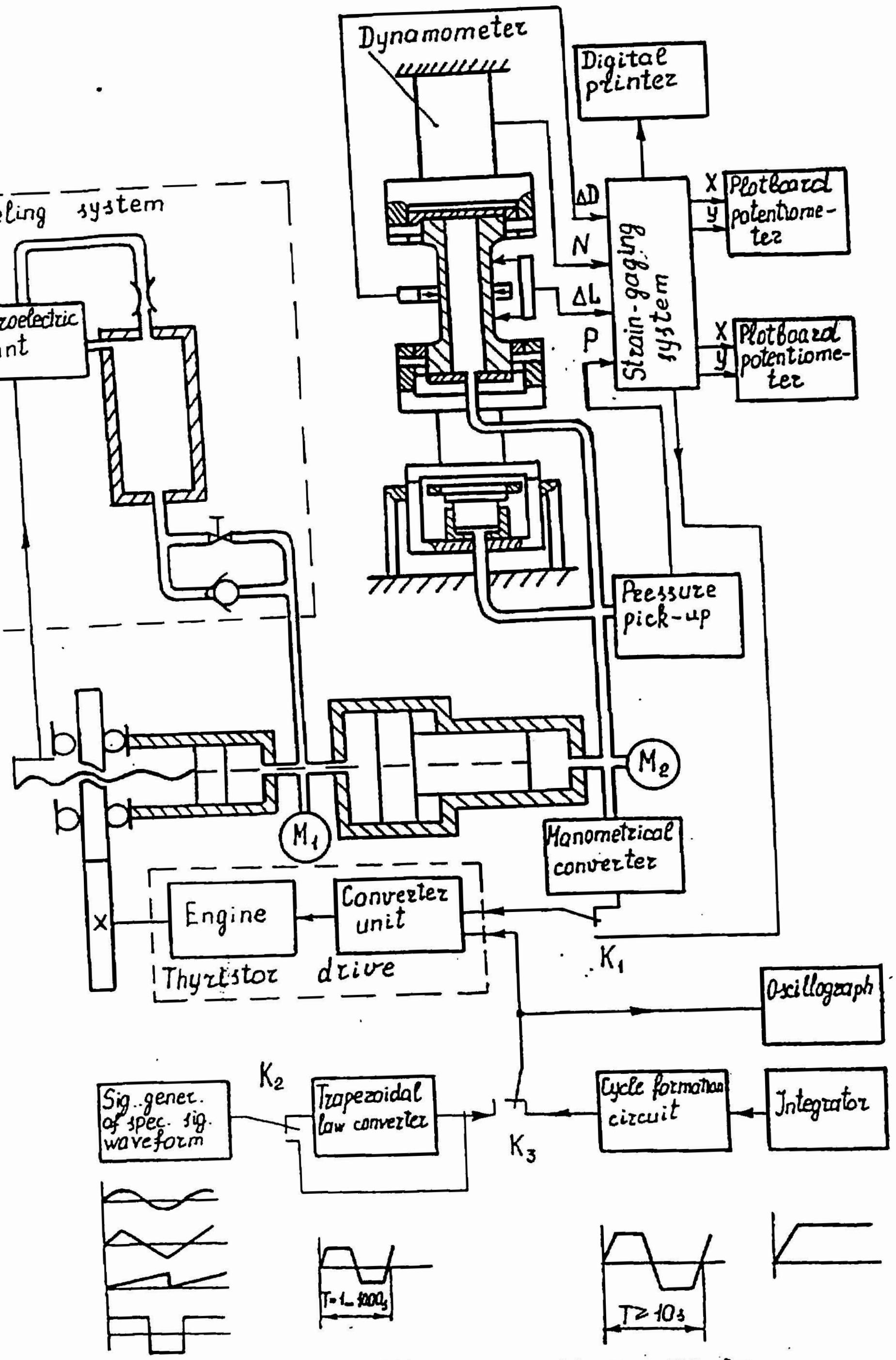

Fig. 1.Functional block diagram of the Type SNT-8U setup.

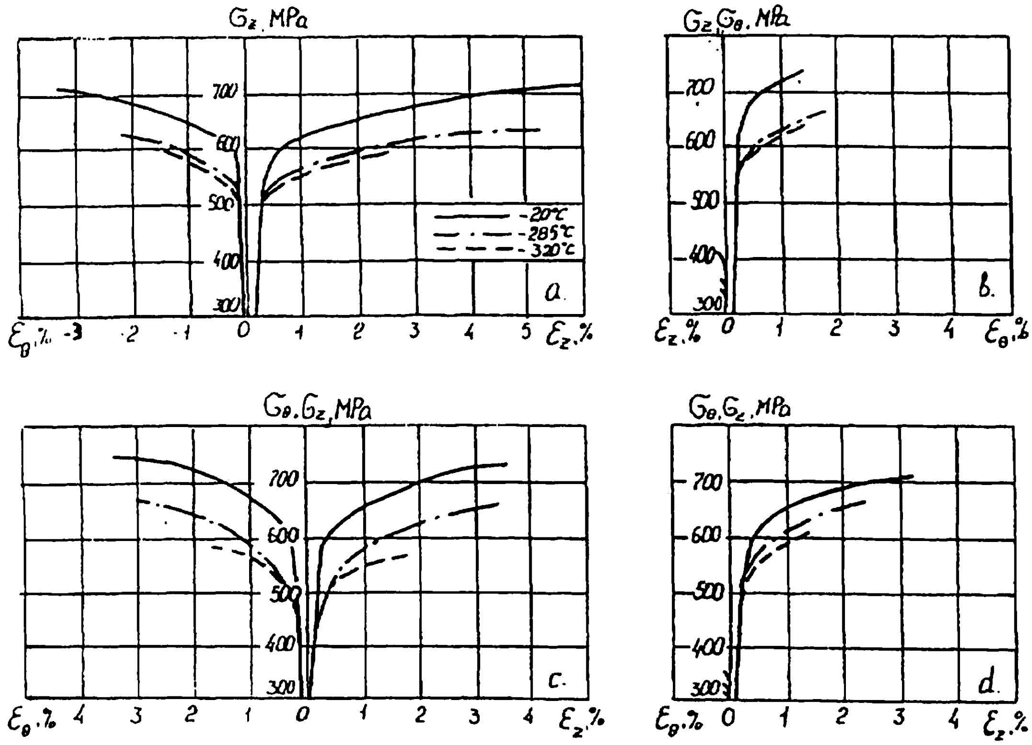

Fig. 2. Stress-strain curves for steel 10GN2MFA at various temperatures and ratios of principal stresses :

a) $K = \sigma_z / \sigma_\theta = \infty$; b) $K = 0.5$; c) $K = 1$; d) $K = 2$; solid lines for $T = 20$ °C; dashed lines for $T = 320$°C; dot-and-dash lines for $T = 285$°C.

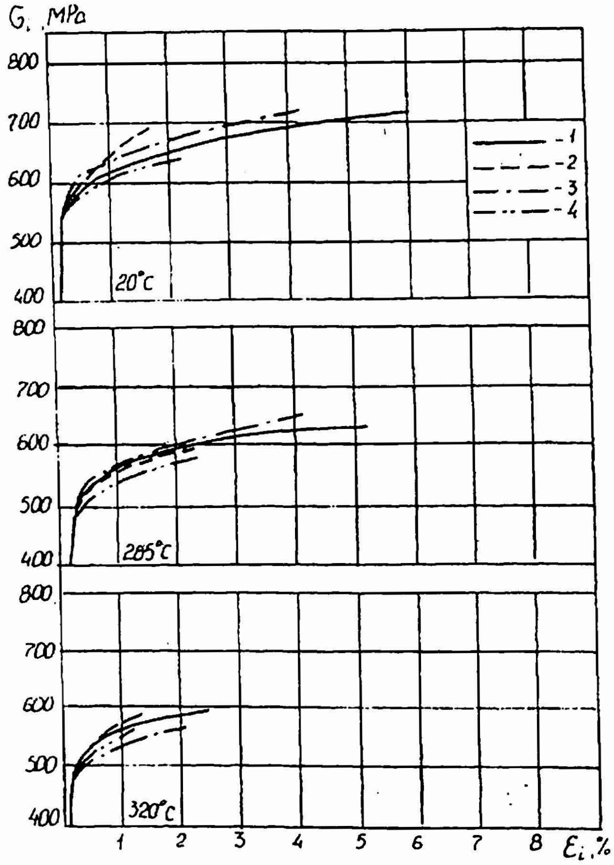

Fig. 3. Generalized stress-strain diagrams for steel 10GN2MFA at various temperatures and ratios of principal stresses: 1) $K = \sigma_z / \sigma_\theta = \infty$; 2) $K = 0.5$; 3) $K = 1$; 4) $K = 2$.

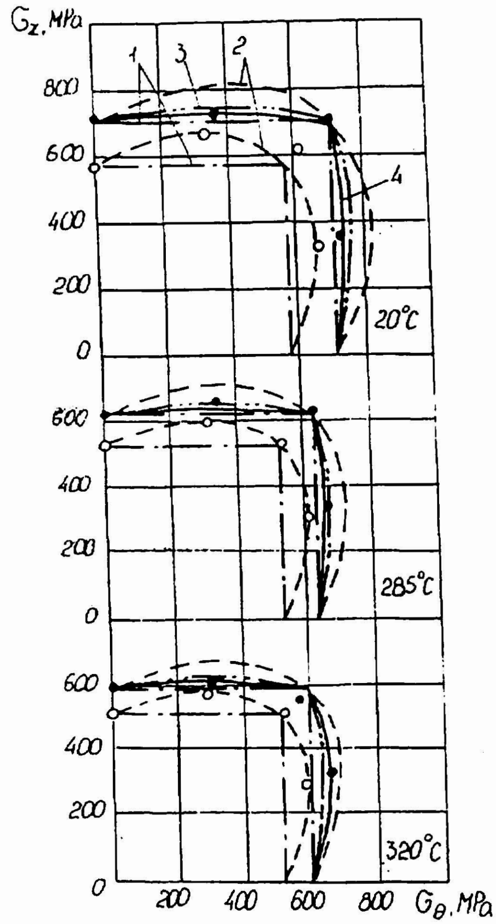

Fig. 4. Limiting curves of yielding (open points) and fracture (dark points) for steel 10GN2MFA at various temperatures; 1. Saint Venant's condition; 2. Von Mises condition; 3. The Pisarenko - Lebedev condition; 4. Based on the condition of the loss of stability of the plastic deformation.

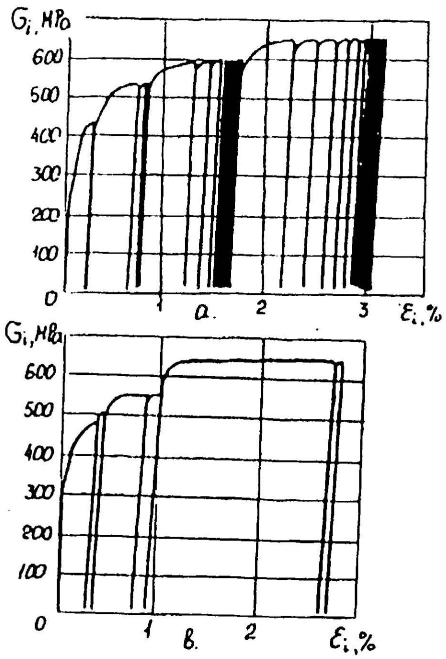

Fig. 5. Stepwise cyclic stress-strain diagram for steel 10GN2MFA at various temperatures: a) $T = 20°C$; b) $T = 285°C$.

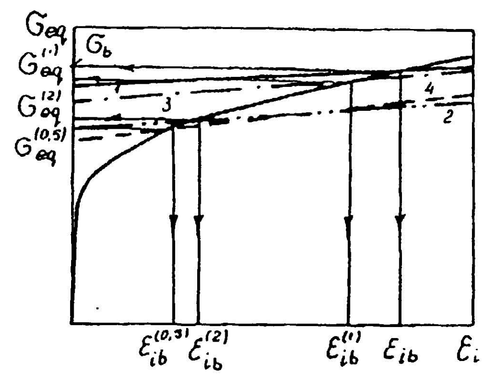

Fig. 6. Geometrical interpretation of the solution of the set of equations for assessing the material ultimate state based on the condition of the loss of stability of the plastic deformation process at various principal stress ratios: 1) $K = \sigma_z / \sigma_\theta = \infty$; 2) $K = 2$; 3) $K = 1$; 4) $K = 0.5$.

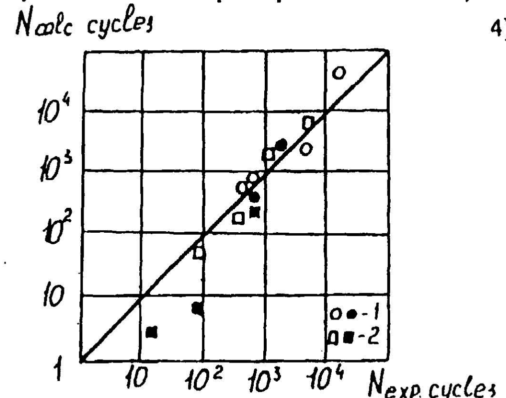

Fig. 7. Comparison between the calculated values of lifetimes according to the proposed criterion and the experimental ones for steel 10GN2MFA at 20°C (light symbols), 320°C (dark symbols) at the following principal stress ratios: 1) $K = \sigma_z / \sigma_\theta = \infty$, 2) $K = 2$