CREEP RUPTURE OF STRUCTURES SUBJECTED TO VARIABLE LOADING AND TEMPERATURE

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SUMMARY

The service life of structures operating under the conditions of variable temperature and loading is limited by excessively large deflections or by a material deterioration referred to as creep rupture. Basing on the Kachanov concept of damage, Leckie and Hayhurst ("Creep rupture of structures", University of Leicester, Engineering Department, Report 73-21) suggested the constitutive equations which reasonably represent the macroscopic behaviour of creeping material:

$$\dot{v}_{ij} = \frac{K}{\psi^n}\,\Phi^n(\sigma_{ij})\,\partial\Phi/\partial\sigma_{ij}, \qquad \dot{\psi} = -\frac{A}{\psi^\nu}\,\Delta^\nu(\sigma_{ij}), \tag{1}$$

where $\dot{v}_{ij}$ is the creep strain rate tensor, σ_{ij} denotes the stress tensor, ψ is the damage function, Φ and Δ are the homogeneous functions of degree one is σ_{ij}, K, n, A and ν are material constants.

The aim of the present paper is to show on the basis of the equations (1) and the analysis of creep mechanisms the possibilities of a description of the creep behaviour of material under variable temperature and loading conditions. Also the influence of cyclic proportional loading and temperature gradient upon the rupture life and strains of a thick cylinder is investigated in detail. To account for the influence of temperature changes on the creep process the constants K, n, A and ν are assumed to be functions of temperature. The introduced functions are determined from the results of technically available experiments in the uniaxial stress state, i.e. K and n from the creep curve for the steady state conditions, A and ν from the rupture curve.

The obtained theoretical creep curves from eqs. (1) coincide with the experimental results for investigated steel in the temperature range from 500°C to 575°C. The constitutive equations (1) together with the functions determined previously are applied to solve the problem of thick cylinder subjected to cyclic proportional pressure and temperature gradient. Numerical results for the thick steel cylinder are presented both in diagrammatical and tabular form. The obtained new results clearly show the significant influence of temperature gradient, cyclic temperature gradient, and cyclic pressure upon the stress redistribution, the magnitue of deformation, the propagation of the front damage and the rupture life. It was found that small temperature fluctuations at elevated temperature can shorten the rupture life very considerably.

The introduced description of the creep rupture behaviour of material under variable temperature and loading conditions together with the results for the thick cylinder indicate the possibilities of solutions of practical problems encountered in structural mechanics of reactor technology.

1. Introduction

The service life of structures operating under the conditions of variable temperature and loading is limited by either excessively large deflections or a material deterioration referred to as creep rupture. Technically important problem of the prediction of creep deflections and the rupture life of structures subjected to variable thermal and mechanical loading remains amongst the most intractable problems of structural mechanics.

The phenomenon of creep in metals is found to be very complicated. In the following section the basic facts about the mechanisms of creep rupture and the influence of changes in temperature and loading upon the parameters of creep process will be briefly reviewed. It is known that two distinct modes of rupture can occur, depending on stress and temperature conditions. At high stress and low temperature fracture occurs accompanied by large elongations and pronounced necking. This is a ductile type of fracture. At low stress and high temperature a brittle type of fracture is encountered. These two distinct types of rupture are the result of different behaviour of grain boundaries at elevated temperatures, (Penny and Marriott [1]). If Θ_m is the absolute melting temperature, it was found that at higher temperatures of about 0,5 Θ_m and above, slip process is accompanied by temperature induced diffusion. Grains boundaries which formed barriers against continned slip become, in the presence of diffusion, a source of weakness. As a result of this process slip occurs on the grain boundaries. The studies having been made by metal physicists, (Oding et al [2], Kennedy [3], Mitra and McLean [4], Taira et al [5], Mullendore and Grant [6], McLean [7], Cottrell [8], Davies and Dutton [9], Williams [10], Bowring et al [11], Hull and Rimmer [12], Tilly and Harrison [13], and others) provide the following information: First, that sliding on the grain boundaries provides a small but important percentage to the total deformation. Secondly, the amount of sliding is controlled by slip within the grains. It means that any danger of excess deformation by sliding is remote. Thirdly, that voids open up as a result of slip at the grain boundary interface so that damage is related to slip generated by shear stress. Fourthly, the growth of the voids can also be a result of the diffusion of vacancies along the grain boundaries. The voids tend to concentrate on grain boundaries normal to the applied tensile stress. The growth of the voids is dictated by the value of maximum tensile stress. Fifthly, that the precipitated particles diffuse from the grain boundaries leaving behind a denuded and softer grain boundary region. This phenomenon has been especially observed in the regions of the highest deformation. The above mentioned processes deteriorating the structure of material lead to brittle rupture.

The increases in temperature during the test, under constant stress, accelerate the creep, while the decreases in temperature delay this process due to the thermal recovery. Cyclic temperature fluctuations, in addition to temperature level, may lead not only to an increase in the creep rate, but also lower the rupture strength. The influence of cyclic temperature variation on creep depends on a number of conditions: material, temperature gradient, the rates of heating and cooling, the length of the cycle, the level of temperature and stress. The coefficient of linear expansion is a function of the crystallographic orientation of the crystal. As a consequence additional stresses arise in adjacent grains when the temperature varies which tend to move dislocations away from positions achieved during the lower temperature conditions. Moreover, a temperature variation unavoidably causes temperature gradients which promote the development of diffusion processes including the diffusion of vacancies. The varying conditions of temperature accelerate intergranular oxidation or corrosion and the ageing processes.

Cycling loading may accelerate creep. Similarly as in the case of cyclic temperature creep process depends on material, temperature level and the parameters of cycle. Immediately subsequent to unloading anelastic recovery occurs. During reloading this amount of recovery is rapidly eliminated in a period of enhanced creep rate. The anelastic effects are attributed to intergranular stresses arising from elastic anisotropy. Thus, at each change in load there are additional forces to move dislocations away from the attained positions during constant load. The result is the acceleration of creep after reloading, (Toft and Broon [14], Tilly [15]). During cyclic loading such processes as overageing, relaxation, recrystallization, oxidation or corrosion and loss of ductility are intensified (Guarnieri [16]). It has been observed that load cycling accelerates the process with precipitate particles that diffuse from the grain boundaries, leaving behind a denuded and softer grain boundaries. This is especially so in these regions where intergranular strains are a maximum. In consequence all these processes deteriorate the structure of material.

Review now creep under repeated stress reversals. Only a few creep data have been produced in which the stress is reversed periodically during the test. The experiments referred to torsion and bending. In the case of torsion of tubular specimens the effect of stress reversal has been shown to accelerate the creep process. Also the recrystallization process was observed in the highest strain regions, (Namestnikov [17], Morrow and Halford [18]). In the case of bending the experiments were made on aluminium and copper alloys beams. The test results have shown that for copper the material deterioration occurs only in tension and for aluminium the material damage occurs equally under tension and compression, (Hayhurst [19]).

This brief review of physical aspects of creep has been concerned with strain accumulation under uniaxial states of stress. The investigation of creep under variable loading and temperature conditions in the tri-axial states of stress is a technically difficult problem and the available results have so far been unsufficient.

The existing constitutive equations are based on the phenomenological approach. Nevertheless an understanding of the microscopic material behaviour is very helpful in ensuring that simplifications and methods are used in the correct context. The majority of the existing theories accounting for the variable loadings concern the primary and the secodary stage of creep and may be used in the special cases, (Oding et al [2], Rabotnov [20], Ponter [21]). Long-term creep leading to rupture and accouting for the tertiary portion of the creep curves may be considered from the standpoint of accumulation of damage. This is Kachanov's theory [22] extended somewhat by Odqvist [23] and Rabotnov [20], which reflects the material softening introduced by the damage occuring in the material. Basing on the Kachanov concept of damage Leckie and Hayhurst [24] suggested constitutive equations which represent in reasonable fashion the macroscopic behaviour of creeping material.

The aim of the present paper is to show on the basis of these equations and the analysis of creep mechanisms the possibilities of a description of the creep rupture behaviour of material under variable temperature and loading conditions. Also the influence of cyclic proportional loading and temperature gradient upon the rupture life and strains of a thick cylinder is investigated in detail.

2. The constitutive equations

The strain rate $\dot{\varepsilon}_{ij}$ is assumed to be the sum of the elastic $\dot{e}_{ij}$ and creep $\dot{v}_{ij}$ strain rate components, so that $\dot{\varepsilon}_{ij} = \dot{e}_{ij} + \dot{v}_{ij}$. The elastic strains e_{ij} are related to the stresses σ_{ij} by the relation $e_{ij} = C_{ijkl}\sigma_{kl} + \alpha\theta\delta_{ij}$, where C_{ijkl} is the tensor of elastic constans, α denotes the linear coefficient of thermal expansion and δ_{ij} is the Kronecker delta. The creep strain rate $\dot{v}_{ij}$ and the damage rate $\dot{\psi}$ can be described by the equations (Leckie and Hayhurst [24])

$$\dot{v}_{ij} = \frac{K}{\psi^n}\phi^n(\sigma_{ij})\,\partial\phi/\partial\sigma_{ij} \quad , \qquad (2.1)$$

$$\dot{\psi} = -\frac{A}{\psi^\nu}\Delta^\nu(\sigma_{ij}) \qquad (2.2)$$

where ϕ and Δ are the homogeneous and convex functions of degree one in σ_{ij}. The function ϕ is equal to unity when the applied stress is uniaxial. K, n, A and ν are material constants determined from uniaxial tension test. The equations (2.1) and (2.2) are a generalisation of the Kachanov equations [22] suitably modified to fit the results of tri-axial stress experiments. By introducing an internal state variable ψ Kachanov was able to modify the Norton Creep Law so that the tertiary portion of the creep curve could be represented. On the basis of the studies reported by metal physicists Leckie and Hayhurst [24] suggested that the ψ parameter can be used to measure the physical processes of deterioration. When the material is undamaged $\psi = 1$ and the equation (2.1) reduces to that suggested by Calladine and Drucker [25]. The surfaces of constant energy dissipation rate are given by $\phi(\sigma_{ij}) =$ constant. As damage occurs ψ decreases so that the strain rates increase, but the form of (2.1) implies that the ratio of strain rate components remains constant, which is apparently in accord with experimental observations [24].

Integrating the equation (2.2) and using the rupture condition $\psi = 0$ gives the expression for rupture time t_r as $t_r = 1/[(1+\nu)A\Delta^{\nu}(\sigma_{ij})]$. For uniaxial stress states this relationship gives the stress-time to rupture curve shown in Fig. 1 Isochronous surfaces are given by $\Delta(\sigma_{ij})$ = constant. The function $\Delta(\sigma_{ij})$ can take various forms. Tri-axial rupture experiments show the isochronous rupture surface of some important materials, such as stainless steel and aluminium, satisfy a Huber-Mises shear criterion. Other metals such as copper satisfy a maximum stress criterion, Fig. 2. The rupture criterion for most metals lies between these two extremes (Hayhurst [26]).

In some important materials such as stainless steel and certain aluminium alloys appears that the isochronous surface $\Delta(\sigma_{ij})$ has the some shape as the constant energy dissipation rate surface $\phi(\sigma_{ij})$. The constitutive equations of such materials are then given by

$$\dot{v}_{ij} = \frac{K}{\psi^n}\phi^n(\sigma_{ij})\partial\phi/\partial\sigma_{ij} \quad , \qquad (2.3)$$

$$\dot{\psi} = -\frac{A}{\psi^{\nu}}\phi^{\nu}(\sigma_{ij}) \ . \qquad (2.4)$$

For convenience, materials whose behaviour is described by the above equations are referred to as ϕ/ϕ materials, while other materials whose behaviour is described by equations (2.1), (2.2) are referred to as ϕ/Δ materials, [24].

The integration of equation (2.2) for variable uniaxial stresses gives the rupture condition $\sum t/t_r = 1$ where t_r is the rupture time associated with the constant uniaxial stress σ_r . The existing experimental results support the view that above equation is satisfactory for stepped cyclic loading of the form shown in Fig. 7, (see [1]). For more complex forms of stress history it has been shown that the equation $\sum t/t_r = 1$ can be substantially in error (Storåkers [27]), and consequently only proportional cyclic loading is considered.

To account for the influence of temperature changes on the creep process the constants n, K, ν , A and C_{ijkl} are assumed to be functions of temperature θ . Two functions K and A are introduced because the temperature dependences of creep and failure may be different, these processes being characterised by different energies of activation. The creep strain rate and the damage rate at any instant are determined by the actual stress state, temperature and depend on the structural state of the material which is characterised by ψ .

In this work the effects fatigue of the material are ignored. This can be justified since the maximum operating stress levels are low fractions of the yield stress at the test temperature and the frequency of temperature and load cycles is small. In these conditions the creep process is predominant.

The determination of the function n, K, ν, A and the comparision with the experimental results are presented in the next section.

3. Determination of the function n, K, ν and A

The introduced functions will be determined from the results of technically available experiments in the uniaxial stress state. These experiments were carried out on steel specimens at loads from 28 to 2 T/in^2 and temperatures from 450°C to 575°C (Glen and Hasra [28]). Details of these steels are given in [28]. Some results of these tests are presented in Fig. 1, 3 and 4.

In the uniaxial stress state Eqs. (2.1, 2,2) have the from

$$\dot{v} = K\left(\frac{\sigma}{\psi}\right)^n , \qquad \dot{\psi} = -A\left(\frac{\sigma}{\psi}\right)^\nu . \tag{3.1}$$

Integration of Eqs. (3.1) for σ = const. and θ = const. yields

$$v = K\sigma^n \frac{t_r}{1-n/(1+\nu)}\left[1-\left(1-\frac{t}{t_r}\right)^{1-n/(1+\nu)}\right] , \tag{3.2}$$

$$\psi = \left(1-\frac{t}{t_r}\right)^{1/(1+\nu)} , \tag{3.3}$$

$$t_r = 1/\left[(1+\nu)A\sigma^\nu\right] . \tag{3.4}$$

For $t = t_r$ we have $v = (K/A)\sigma^{n-\nu}/(1+\nu-n)$ where $1+\nu > n \geqslant \nu$. If this restriction cannot be satisfied for some material it is possible to introduce more parameters into Eqs. (3.1) (see [20]). The expression (3.4) gives a linear relationship between $\log\sigma$ and $\log t_r$ observed experimentally over a considerable stress range, Fig. 1. The values of ν and A can therefore be obtained from the rupture curve. Similarly, in the steady state creep conditions ($\psi = 1$), from a linear relation between $\log\dot{v}$ and $\log\sigma$ the values of n and K can be calculated, Fig.5. The determined functions n, K, ν and A in the temperature range 500°C – 575°C and for lower stress level have the following form:

$$n = -1{,}333\cdot 10^{-5}\theta^2 - 3\cdot 10^{-3}\theta + 8{,}033 , \tag{3.5}$$

$$K = \exp\left[-37{,}9561032 + 47{,}003878\cdot 10^3\left(\frac{1}{500}-\frac{1}{\theta}\right) + 17{,}5180052\cdot 10^6\left(\frac{1}{500}-\frac{1}{\theta}\right)^2\right] , \tag{3.6}$$

$$\nu = 12{,}267\cdot 10^{-5}\theta^2 - 143{,}200\cdot 10^{-3}\theta + 43{,}6133 , \tag{3.7}$$

$$A = \exp\left[-31{,}4431988 + 57{,}478940\cdot 10^3\left(\frac{1}{500}-\frac{1}{\theta}\right) - 80{,}2612757\cdot 10^6\left(\frac{1}{500}-\frac{1}{\theta}\right)^2\right] . \tag{3.8}$$

The calculated values of n, K, ν, A, the rupture strains and the rupture times for the investigated specimens are presented in Tables I, II. The obtained theoretical creep curves from the Eq.(3.2) are shown in Figs. 3, 4 by solid lines. The broken lines represent the steady state creep. The Eg.(3.2) takes no account of primary creep. Fairly good agreement with experiment can be noted in the investigated range of stress and temperature.

4. Thick cylinder

We shall cousider the axisymmetric problem of an infinitly long thick cylinder subjected to internal constant or proportional cyclic pressure and constant or cyclic temperature gradient Figs.6, 7. In this situation we have the following relationships:

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\varphi}{r} = 0 \quad , \tag{4.1}$$

$$\dot{v}_r = \frac{\partial \dot{u}}{\partial r} \quad , \quad \dot{v}_\varphi = \frac{\dot{u}}{r} \; . \tag{4.2}$$

From the equation $\dot{v}_r + \dot{v}_\varphi = 0$, ($\dot{v}_z = 0$, the plane strain conditions) we get a radially outward velocity

$$\dot{u} = C^n(t)/r \; . \tag{4.3}$$

Assuming $\phi = \sigma_\varphi - \sigma_r$ and using the equations (2.3), (2.4), (4.1) and (4.3) we obtain the basic set of equations:

$$\frac{1}{\psi}\frac{\partial \sigma_r}{\partial r} = \frac{C(t)^{1/n}}{K^{1/n}\, r^{2/n+1}} \quad , \tag{4.4}$$

$$\sigma_\varphi = \frac{\partial (r\sigma_r)}{\partial r} \quad , \tag{4.5}$$

$$\sigma_z = \frac{1}{2}(\sigma_r + \sigma_\varphi) \quad , \tag{4.6}$$

$$\dot{\psi} = -A\left(\frac{C(t)}{Kr^2}\right)^{\vartheta/n} . \tag{4.7}$$

We will consider the steady heat flow described by the equation

$$\theta(r) = \theta(a) + \frac{\theta(b) - \theta(a)}{\ln(b/a)}\ln(r/a) \; , \tag{4.8}$$

where θ(a), θ(b) are the temperatures of the internal and external surfaces of the tube respectively. The values of n, K, ϑ, and A at any radius r are given by (3.5), (3.6), (3.7) and (3.8). This set of equations can be only integrated numerically with the help of the computer. Two constants are determined by two boundary conditions.

The strains and radial displacement are given by

$$v_r = -v_\varphi \quad , \quad v_\varphi = \int_0^t \frac{C(t)}{r^2}\,dt \quad , \quad u = \int_0^t \frac{C(t)}{r}\,dt \; . \tag{4.9}$$

It may be seen from the Eg.(4.7) for constant temperature ($\Delta\theta = 0$) that ψ will become zero first at the inner boundary, r= a. Let us introduce a new floating boundary at r= s, so that $\psi = 0$ for $r \leqslant s$. In the general case where the temperature gradient exists ψ may become zero first for arbitrary value of $a < r < b$. It depends for a given geometry of tube on the value of pressure, temperature gradient and its direction. In such cases the integration will be terminated at the instant when $\psi = 0$, while for the situation when ψ becomes zero first at r= a, the integration will be carried out in full.

For convenience we introduce the following quantities:

$$\xi = r/a \quad , \quad \varsigma = s/a \quad , \quad h = b/a \quad , \quad c(t) = C(t)/a^2 \; . \tag{4.10}$$

The basic equations (4.4 - 4.9) then become

$$\frac{1}{\psi}\frac{\partial \sigma_r}{\partial \xi} = \left(\frac{c}{K}\right)^{1/n} \frac{1}{\xi^{2/n+1}} , \qquad (4.11)$$

$$\sigma_\varphi = \frac{\partial(\xi\sigma_r)}{\partial \xi} , \qquad (4.12)$$

$$\sigma_z = \frac{1}{2}(\sigma_r + \sigma_\varphi) , \qquad (4.13)$$

$$\dot{\psi} = -A\left(\frac{c}{K\xi^2}\right)^{\vartheta/n} , \qquad (4.14)$$

$$\theta(\xi) = \theta(1) + \frac{\theta(h)-\theta(1)}{\ln h} \ln\xi \qquad \text{when } \psi > 0 \text{ everywhere}, \qquad (4.15)$$

$$\theta(\xi) = \theta(1) + \frac{\theta(h)-\theta(1)}{\ln(h/\zeta)} \ln(\xi/\zeta) \qquad \text{when } \psi = 0 \text{ for } \xi \leq \zeta , \qquad (4.16)$$

$$v_r = -v_\varphi , \quad v_\varphi = \int_0^t \frac{c}{\xi^2} dt , \quad u = a\int_0^t \frac{c}{\xi} dt . \qquad (4.17)$$

The boundary conditions are then

$$\sigma_r(1) = \begin{cases} -p & \text{for } 0 \leq t \leq \mu T , \\ -\lambda p & \text{for } \mu T \leq t \leq T , \end{cases} \quad \sigma_r(h) = 0 \qquad \text{when } \psi > 0 \text{ everywhere}, \qquad (4.18)$$

$$\sigma_r(\zeta) = \begin{cases} -p & \text{for } 0 \leq t \leq \mu T , \\ -\lambda p & \text{for } \mu T \leq t \leq T , \end{cases} \quad \sigma_r(h) = 0 \qquad \text{when } \psi > 0 \text{ for } \xi \leq \zeta . \qquad (4.19)$$

5. The numerical results and discussion

The aim of this paper was to shown the possibilities of a description of the creep behaviour of material under proportional cyclic loading and temperature. The introduced functions are determined from the results of technically available experiments in the uniaxial stress state, i.e. n and K from the creep curve for the steady state conditions, A and ϑ from the rupture curve. The obtained theoretical creep curves from the Eq.(3.2) coincide with the experimental results for investigated steel in the temperature range from 500°C to 575°C, Figs.3, 4. The problem of the thick steel cylinder was solved numerically by means of CDC computer for the following values: p= 310 kG/cm^2, λ = 0,4, μ = 2/3, T= 24 hours, h= 1,5 and for the temperature range 5oo°C - 575°C. The step of time was taken equal to 2 hours and the thickness of wall was devided into 100 parts. Numerical results are shown in Table III and in Figs. 8 - 13. The significant influence of nonisothermal conditions upon the stress distribution for steady state creep is shown in Fig.8. In Fig.9 are shown the stress distribution and the propagation of the front damage for the case of constant pressure and constant temperature while in Figs.11, 12, 13 the stress redistribution is presented for constant pressure and constant temperature gradient or cyclic temperature gradient. It can be seen that the stress redistribution is growing as compared with the steady state distribution, ($t = 0$) when time is approaching the time to final rupture. Also in Fig.10, where the circumferential strain and the radial displacement are shown, the acceleration of creep process can be observed. It is a result of material softening in the tertiary portion of the creep curve.

Depending on the temperature gradient, the value of pressure and the dimensions of cylinder the first rupture can appear at $r > a$. In some cases the values $r = 1{,}05\ a \div 1{,}085\ a$, were obtained for the first rupture, Table III.

Numerical results show the significant influence of temperature gradient and its fluctuations upon the rupture life, Table III. In the case of constant pressure the following results are obtained, for example: for constant temperature $\theta(a) = \theta(b) = 575^{o}C$ the time to first rupture is about 5 times less than for $\theta(a) = 575^{o}C$, $\theta(b) = 500^{o}C$. For constant gradient $\Delta\theta = 75^{o}C$, ($\theta(a) = 575^{o}C$, $\theta(b) = 500^{o}C$) the time to first rupture is 1,6 times shorter in comparison with the result for $\Delta\theta = 50^{o}C$, ($\theta(a) = 550^{o}C$, $\theta(b) = 500^{o}C$) and about 1,4 times shorter than for the case of cyclic temperature gradient $\Delta\theta = 75^{o}C$, ($\theta(a) = 575^{o}C$, $\theta(b) = 500^{o}C$). In the case of constant temperature gradient $\Delta\theta = 75^{o}C$, ($\theta(a) = 575^{o}C$, $\theta(b) = 500^{o}C$) the time to first rupture for the proportional cyclic pressure is about 1,4 times longer as compared with the time for constant pressure.

The obtained results for the thick cylinder clearly show the significant influence of temperature gradient and its cyclic fluctuations at elevated temperature and proportional cyclic pressure upon the stress redistribution, the magnitude of deformation, the propagation of the front damage and the rupture life.

The introduced discription of the creep rupture behaviour of material together with the results for the thick cylinder indicate the possibilities of solutions to the practical problems encountered in structural mechanics of reactor technology.

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The calculated values of rupture time for the specimens and the corresponding strains

Table II

σ [kG/cm²]	500°C		550°C		575°C	
	$v(t_r)$ [%]	t_r [hr]	$v(t_r)$ [%]	t_r [hr]	$v(t_r)$ [%]	t_r [hr]
310 (2)*			8,47	81300	12,7	32000
465 (3)			9,84	37000	12,95	15600
620 (4)	9,001	415000	12,03	22180	13,1	9190
930 (6)	11,035	139000	13,52	10000	13,76	4340
1085 (7)			13,9	7022		
1240 (8)	12,198	61200	14,63	5404		
1395 (9)	13,35	45950				
1550 (10)	14,074	34574		3500		1680
1860 (12)	15,473	21210				
2170 (14)	16,8	14061				

* The numbers given in the parentheses denote stresses in [T/in²]

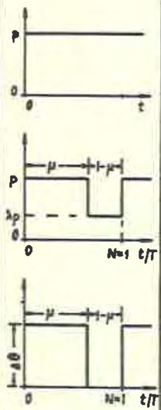
Values of the functions n, K, ν and A

Table I

θ [°C]	n	K $\left[\left(\frac{kG}{cm^2}\right)^{-n} \cdot hr^{-1}\right]$	ν	A $\left[\left(\frac{kG}{cm^2}\right)^{-\nu} \cdot hr^{-1}\right]$
500	3,2	$3,28.10^{-17}$	2,68	$2,21.10^{-14}$
510	3,0658	$2,12865.10^{-16}$	2,4878	$1,86088.10^{-13}$
525	2,784	$3,38085.10^{-15}$	2,2443	$2,5447.10^{-12}$
535	2,6126	$2,07513.10^{-14}$	2,1125	$1,03233.10^{-11}$
550	2,35	$3,0125.10^{-13}$	1,96	$5,38.10^{-11}$
560	2,1727	$1,73598.10^{-12}$	1,8906	$1,23875.10^{-10}$
575	1,90	$2,285.10^{-11}$	1,83	$3,05.10^{-10}$

Thick cylinder. Rupture time and the corresponding circumferential strain

Table III

Loading	p = const. Δθ = const.				p = cycl. Δθ = const.			
	θ(a) = 575°C θ(b) = 575°C	θ(a) = 575°C θ(b) = 500°C	θ(a) = 550°C θ(b) = 500°C	θ(a) = 500°C θ(b) = 575°C	θ(a) = 575°C θ(b) = 575°C	θ(a) = 575°C θ(b) = 500°C	θ(a) = 550°C θ(b) = 500°C	θ(a) = 500°C θ(b) = 575°C
	$t_r(a)$=5720 N = 329 $v_\varphi(a)$=12,4% t_r =5950 N = 248	$t_r(1,08a)$=29216 N = 1218 $v_\varphi(1,08a)$=10,08%	$t_r(a)$=46600 N = 1942 $v_\varphi(a)$=7,93% t_r =47092 N = 1963	$t_r(1,05a)$=29028 N = 1210 $v_\varphi(1,05a)$=8,71%	$t_r(a)$=7844 N = 327 $v_\varphi(a)$=12,25% t_r =8185 N = 340	$t_r(1,085a)$=41176 N = 1716 $v_\varphi(1,085a)$=9,96%	$t_r(a)$=65984 N = 2750 $v_\varphi(a)$=7,79% t_r =66664 N = 2778	$t_r(1,055a)$=40910 N = 1705 $v_\varphi(1,055a)$=8,51%
	p = const. Δθ = cycl.				p = cycl. Δθ = cycl.			
		θ(a) = 575°C θ(b) = 500°C	θ(a) = 550°C θ(b) = 500°C			θ(a) = 575°C θ(b) = 500°C	θ(a) = 550°C θ(b) = 500°C	
		$t_r(1,05a)$=41140 N = 1715 $v_\varphi(1,05a)$=10,42%	$t_r(a)$=63080 N = 2629 $v_\varphi(a)$=7,79% t_r =63708 N = 2655			$t_r(1,075a)$=43574 N = 1816 $v_\varphi(1,075a)$=10,02%	$t_r(a)$=69256 N = 2886 $v_\varphi(a)$=7,9% t_r =69976 N = 2916	
p = 310 kG/cm² λ = 0,4 μ = 2/3 T = 24 hr	$t_r(\ldots)$ - time to the first rupture t_r - failure time				N - Number of cycles t_r - hr			

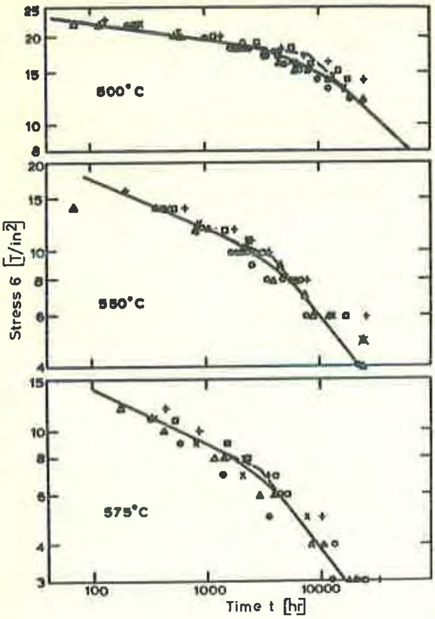


Fig. 1 Uni-axial stress times to rupture data for a BS 1501-271 steel at 500°C, 550°C and 575°C

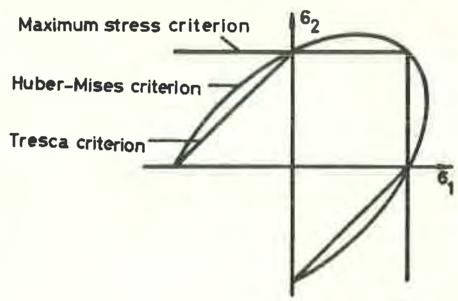


Fig. 2 Isochronous surfaces

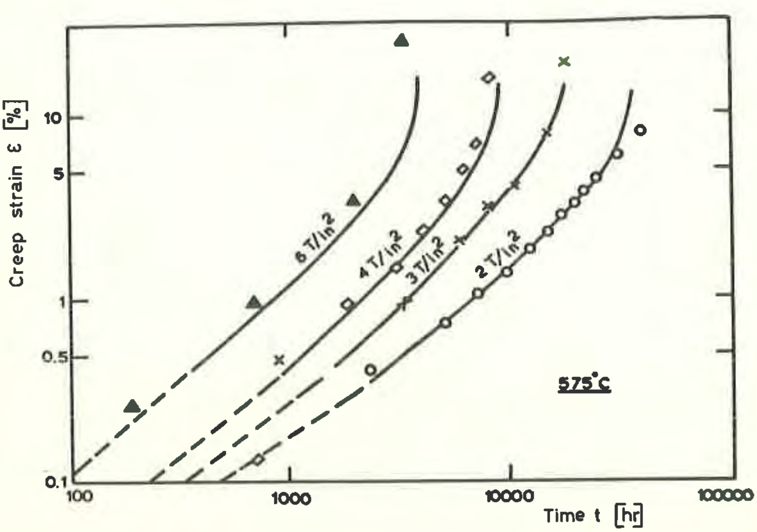


Fig. 3 Creep curves to rupture for a BS 1501-271 steel at 575°C

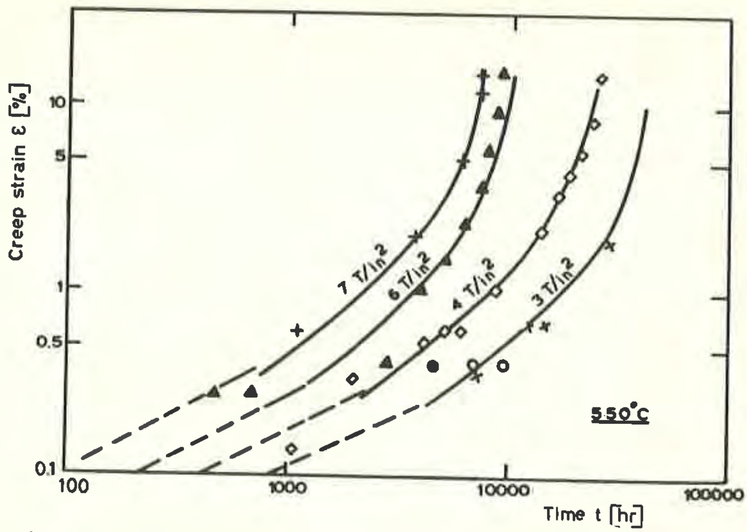


Fig. 4 Creep curves to rupture for a BS 1501-271 steel at 575°C

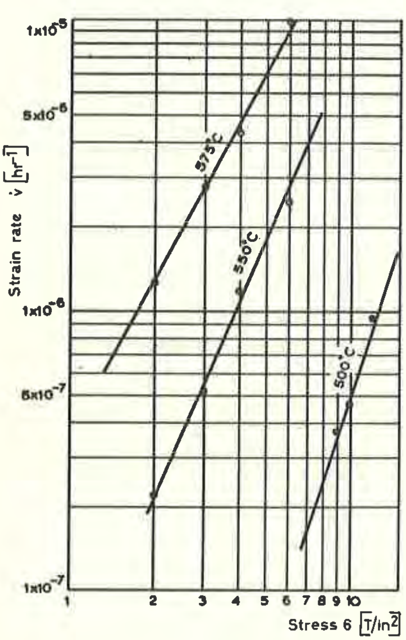


Fig. 5 Relationship between stress and creep rate in the steady state conditions for a BS 1501-271 steel at 500°C, 550°C and 575°C

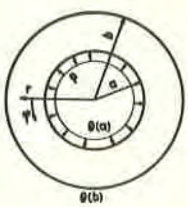


Fig. 6 Thick cylinder-coordinates, dimensions and loading

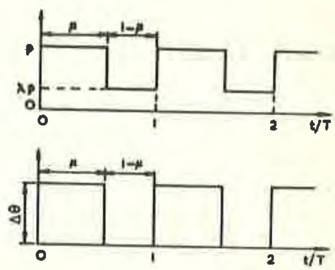


Fig. 7 Cyclic loading and cyclic temperature variations

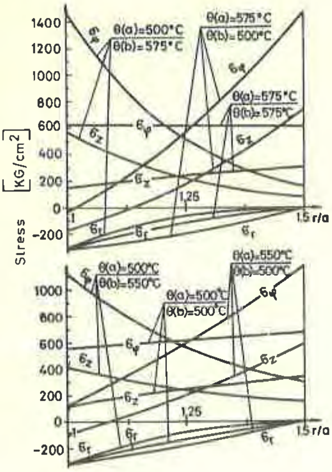


Fig. 8 Stresses distribution in the steady state creep conditions of thick cylinder for different temperature gradients

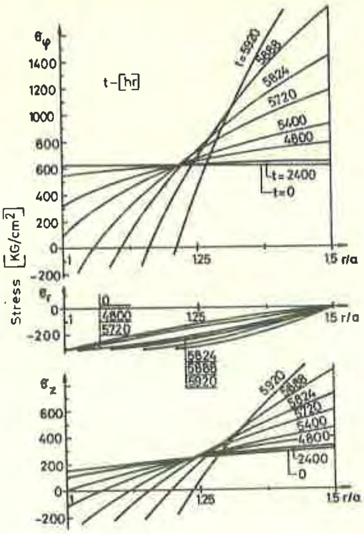


Fig. 9 Stresses redistribution and propagation of the front damage in thick cylinder for the case of constant pressure and temperature $\theta(a) = \theta(b) = 575^{\circ}C$

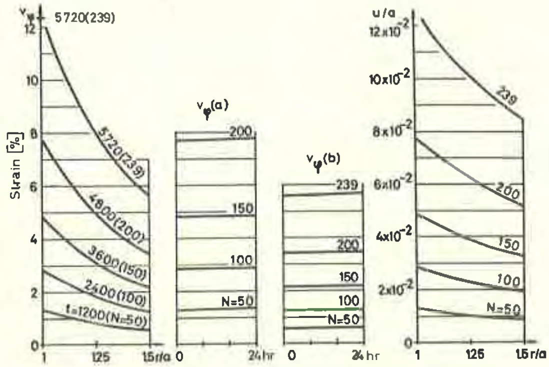


Fig. 10 Variation of the circumferential strain and the radial displacement with time in thick cylinder for the case of constant pressure and temperature $\theta(a) = \theta(b) = 575^{\circ}C$

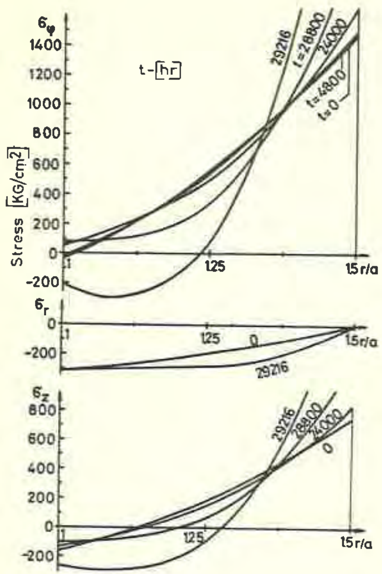


Fig. 11 Stresses redistribution in thick cylinder for the case of constant pressure and constant temperature gradient $\theta(a) = 575^{\circ}C$, $\theta(b) = 500^{\circ}C$

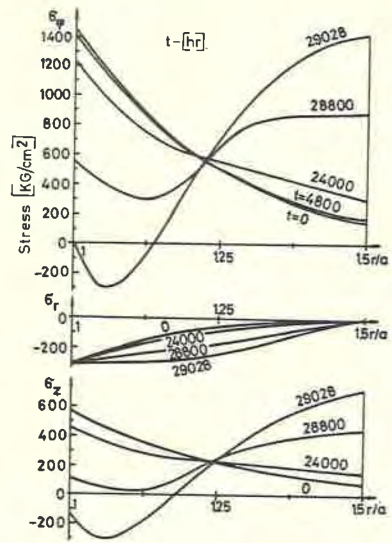


Fig. 12 Stresses redistribution in thick cylinder for the case of constant pressure and constant temperature gradient $\theta(a) = 500^{\circ}C$, $\theta(b) = 575^{\circ}C$

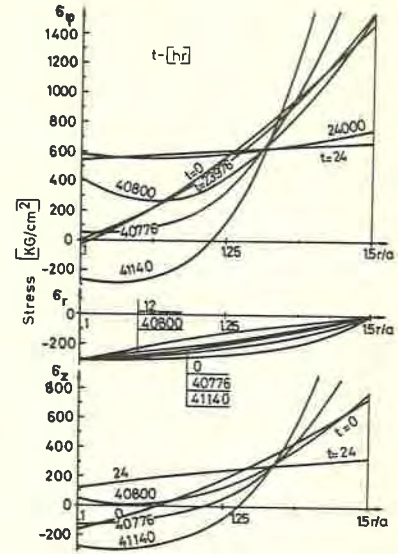


Fig. 13 Stresses redistribution in thick cylinder for the case of constant pressure and cyclic temperature gradient $\theta(a) = 575^{\circ}C$, $\theta(b) = 500^{\circ}C$