RULES OF FRACTURE DEVELOPMENT IN THE CREEP OF HEAT-RESISTANT STEELS

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The life of a metal under load at increased temperatures is determined to a significant degree by the rate of accumulation of discontinuities in it. To describe this process, the mechanical equation of state, the constants of which are determined by the rules of accumulation of damage in a metal in creep, is normally used. Knowledge of the rules of development of the processes of creep and fracture make it possible to improve calculation methods and increase their accuracy. In addition, on the basis of a study of the rules of the development of damage it is possible to develop methods of determination of the residual life of long operating equipment.

In connection with this the purpose of this work is an investigation of the basic rules of the origin and development of discontinuities in heat-resistant steels under creep conditions. The materials of the investigation were steam-line pipe and specimens of 12MKh, 12Kh1MF, and 15Kh1M1F steels tested in a broad range of temperatures (500-650°C) and stresses (40-180 MPa). The study of the process of accumulation of discontinuities was made with the use of scanning and transmission electron microscopy, optical metallography, and density measurement.

For the metal of elements of modern thermal power equipment operating under creep conditions, such as steam pipes, the basic type of failure is pore formation. Therefore the temperature and force area in which failure occurs by the origin and growth of pores was considered. Below are presented the basic results of the investigation.

1. Features of the origin of pores. Until recently there has been a point of view that pores are formed only at grain boundaries under the action of normal stresses. The results of investigation of the fine structure of the metal show that in creep, pores originate not only at the grain boundaries, but also in the bodies of the grains at imperfections of the fine structure, including at points of intersection of the subboundaries with the grain boundaries and at carbide particles, that is, preferentially at points of retarded slip. The most probable size of embryonic micropores is $0.8\text{-}1.2\cdot10^5$ cm^{-2}, which agrees with the dislocation model of origin of pores [1]. The ratio of the overall dimensions of the embryonic micropores is described by a probability curve with a clear maximum in the region of $h_{\parallel}/h_{\perp} = 2$. This experimental data shows that under conditions close to service for steam lines the origin of pores occurs not by diffusion but by dislocation means. The diffusion mechanism of origin of pores is relatively improbable under the investigated conditions but it must be expected at high premelting temperatures.

2. The growth of pores. Investigations of the sizes and shapes of pores provide much information on the mechanisms of growth of individual pores. According to existing concepts of the diffusion nature of the growth of pores, the latter must have an elliptical shape with the long axis located parallel to the boundary. The experiments conducted did not confirm this assumption. An analysis of the shape of the most frequently encountered forms of micropores shows that they have the form, not of ovals, but of irregular polygons, with tips at the point of intersection with subboundaries or accumulations of dislocations. The growth of the pores depends upon their location.

Figure 1 presents the probability curve of the distribution of pores by size (d) in relation to the point of their origin. It may be seen that the micropores originating at the carbide—matrix interphase boundary in the overwhelming majority (85%) of cases have a size of up to 0.1 μm, that is, close to embryonic. At the subboundaries, pores with a size of 0.1 μm are half as many (45%) but the position of the maximum on the curve of distribution of the micropores by size does not change. A somewhat different distribution of the micropores by size is observed at grain boundaries. The maximum on the distribution curve is

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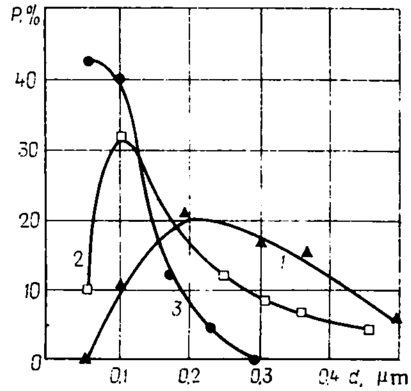

Fig. 1. Probability curves of the distribution of pores by size in relation to their location: 1) at grain boundaries; 2) at subboundaries; 3) at carbide particles in the matrix.

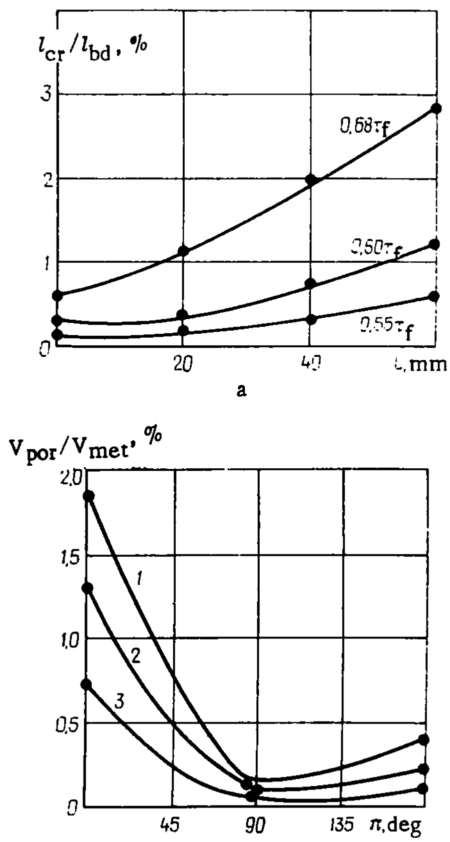

Fig. 2. The change in damage by pores along the length of a specimen (a) and on the perimeter of a pipe (b): 1) zone of failure; 2, 3) 65 and 300 mm from the crack, respectively.

shifted in the direction of larger dimensions (0.15-0.20 μm) and the embryonic pores are only 14% of the total quantity.

Therefore the micropores formed within the grains at carbide particles without a link with the boundaries and subboundaries possess the minimum tendency toward growth and primarily remain embryonic. The decrease in the relative quantity of embryonic micropores at the grain and subgrain boundaries indicates that here, growth of the pores occurs simultaneously with origin. Pores formed at the grain boundaries possess the maximum capacity

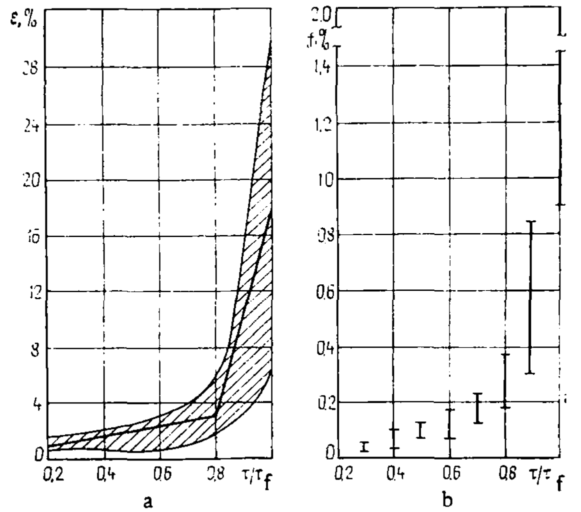

Fig. 3. Generalized creep curves (a) and the damage by pores (b) of specimens of 12Kh1MF steel.

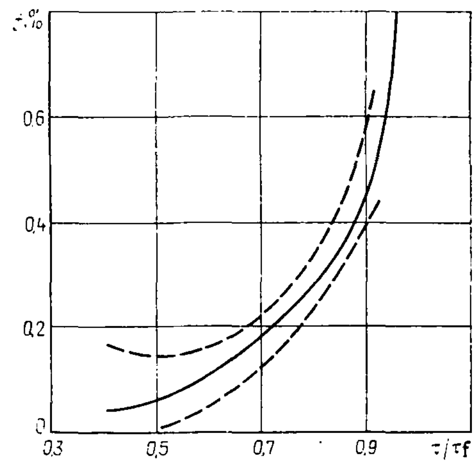

Fig. 4. The regression line (solid line) and the boundaries of the confidence interval (broken lines) of accumulation of damage by pores with time.

for growth. They are the first to reach the critical size. All the way to failure, pores with a size of more than 1 μm are located primarily at the grain boundaries.

An analysis of the shape and features of growth of the micropores shows that the growth of pores occurs according to several microscopic mechanisms. The round shape, elongation along the boundaries, and preferential growth of the pores near the boundaries are indications of the significant role of the processes of diffusion inflow of vacancies in the volume and the boundaries. The irregular form of the micropores and the presence of flat faces are the result of the dislocation mechanism of pore growth. A significant role in the growth of pores is played by the opening of them by boundary slip.

Therefore, in the growth of pores the role of diffusion processes is great, but together with this the growth of pores also occurs by plastic means as the result of discharging into the pore of volume and boundary dislocations. Such a dual character of the origin and growth of pores explains the unsuccessful attempts to describe the process of failure development on the basis of some single physical model.

3. The kinetics of the accumulation of pores. At the start of the accelerated stage of creep the individual pores reach 1 μm and are readily observed in metallographic investigation. This makes it possible to observe the kinetics and morphology of accumulation of discontinuities during creep. The morphological stages of pore formation may be divided into groups: individual pores, chains of pores, microcracks, and the main crack.

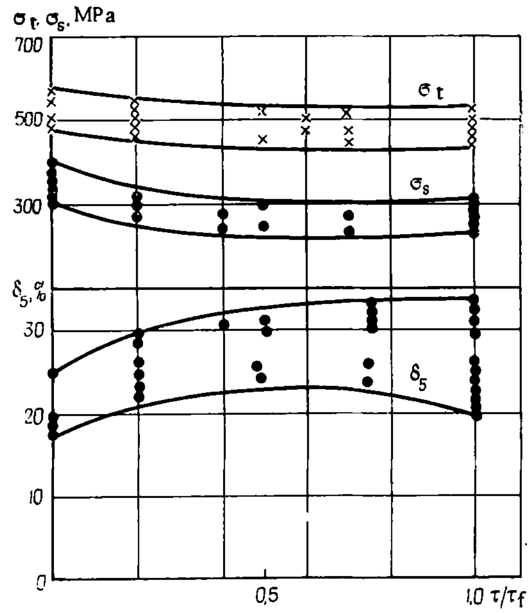

Fig. 5. The change in mechanical properties during creep.

The third stage of creep is conditionally divided into two phases [2]: the transition and the critical. In the transition phase of the accelerated stage of creep the accumulation of individual pores is observed. The appearance of chains of pores and the first microcracks coincides with transition of creep into the critical phase. The formation of microcracks and growth of the main crack occur in the critical phase of the third stage of creep. The accumulation of pores by stages is comparable to the kinetics of the increase in deformation. In the transition phase of the third stage the number of pores in a unit of volume and the intensity of their accumulation are significantly less than the limiting values. The share of boundaries damaged by pores l_{cr}/l_{bd} changes during the transition stage from 0.2 to 3.0%. At the moment of failure, the value of the l_{cr}/l_{bd} ratio above which failure itself starts reaches 15-20%.

With development of the third stage of creep there is an increase in the nonuniformity of deformation and accumulation of damage along the length of the specimen L and on the length and perimeter of the pipe (Fig. 2).

To compare the parameters characterizing the kinetics of accumulation of deformation and discontinuities in creep a series of specimens were tested at temperatures of 550-625°C and stresses of 60-160 MPa. The volume share of discontinuities was measured by the metallographic method on the surface of the specimens during periodic stoppages of the tests.

Figure 3 shows curves of generalized ε—τ/τ_n creep and f—τ/τ_n accumulation of damage by pores in specimens. The volume of share of discontinuities in %, equal to the ratio of the volume occupied by pores to the volume of the investigated metal $f = \frac{V_{por}}{V_{met}}$, %, was taken as the characteristic of damage by pores. The shaded area on the ε—τ/τ_f relationship is the zone of spread of the creep curves. As may be seen, upon reaching a life of 0.76-0.8 τ_f, an intense increase in deformation starts. Similarly, after this life an intense increase in damage starts. The regression equation describing the relationship of the accumulated damage by pores to life has the form

$$f = \frac{f_f}{\exp \sqrt{a - (1 - \tau/\tau_f)}}, \quad (1)$$

where f is the current damage by pores in %, f_f and a are constants (f_f is taken as equal to 2% and coincides with the volume share of pores in the metal in the fracture zone, a is a structurally sensitive parameter), and τ_f is the time until failure of the specimen.

Figure 4 represents the calculated relationship of the damage by pores to life for specimens of 12Kh1MF steel with a ferritic—carbide structure. With lives of up to 0.6 τ_f, the accumulation of pores occurs slowly. In the 0.7-0.9 τ_f range, the rate of accumulation of pores increases, which makes it possible to evaluate the relative life from the amount of damage. The error in determination of the relative life from the degree of damage, determined from the width of the probability interval with a significance level of 0.9, is 10%. With lives lower than 0.7 τ_f, the error in determination of the relative life from the damage increases sharply.

The results obtained indicate that, with the use of the structure method by determination of the degree of pore formation, it is possible to calculate the relative life. From the viewpoint of the service reliability of power-equipment parts it is desirable to determine the residual life until the moment of transition of creep into the critical phase τ_{cr}. The structural method of determination of residual life makes it possible, from the amount of damage f and from the accrued operating time at the moment of establishment of the damage τ, to calculate the residual life of the part τ_{res} based on Eq. (1) from the equation

$$\tau_{res} = \tau \cdot K_\tau,$$

where $K_\tau = \frac{\tau_{cr}/\tau_f - \tau/\tau_f}{\tau/\tau_f}$.

4. Features of the accumulation of damage by pores in power equipment parts. At present, the most damaged parts of power equipment are the bends of steam lines, and to a significant degree, their damage by pores is a structurally dependent value. Inspection of the damage of bends reveals a significant spread in this characteristic and with an increase in service life the spread increases. In studying the character of distribution of pores in bends which failed during service, the following were established:

a) in all cases, failure occurs under the combined action of such factors as the maximum stresses and temperature and the minimum high-temperature strength of the material. In the majority of studied cases, failure of bends occurred in the fibers under tension in pipes with the minimum high-temperature strength properties;

b) the character of distribution of pores around the perimeter is the same in the failure zone and at a distance from it (Fig. 2b);

c) the damage of bends measured in the zone directly adjoining a through crack of different bends is 0.8-2.0%;

d) agreement is observed between the amount of damage by pores f and the morphological features of failure in bends and in specimens, which makes it possible to extend the investigation results obtained on specimens to production bends.

For the purpose of determination of the possibility of use of indirect integral methods of determination of the damage of metal by pores, the influence of the damage on the short-term properties of the metal of steam lines was investigated. In long service, in addition to the accumulation of discontinuities, there occur in the metal structural and phase changes which lead both to loss of strength and to strengthening of the metal. Since the mechanical properties are an integral characteristic, the question of the influence of damage by pores was studied with the exclusion of such factors as structural changes during service. For this, the mechanical properties were determined on steam-line bends with the same structure. In all cases, the specimens were cut from the zones of bends in tension, including those which had failed in service. The test results are presented in Fig. 5. Except for the original condition and the condition after failure ($\tau/\tau_f = 0$ and $\tau/\tau_f = 1$), the coordinates of the points on the time axis were obtained by calculation based on the degree of damage of the investigated metal on the basis of Eq. (1).

For all relative lives the values of the strength (σ_t, σ_s) and plastic (δ_5) properties of the zones of the pipe bends under tension lie on a band of spread which is ±10% for the strength properties and ±15% for the elongation. From Fig. 5 it may be seen that a reduction in strength and an increase in plastic properties occurs at the start of the second stage of creep as the result of redistribution of dislocations, lining up of them at subboundaries, and securing by carbides. Further development of the creep processes does not influence the change in the strength and plastic properties all the way to the critical phase of the third stage. In this phase, there is an increase in the spread in the values of elongation related to nonuniformity of the degree of damage of the metal adjoining the point of failure. The metal with significant damages has a low elongation. The strength properties do not reveal a sensitivity to the degree of damage of the metal.

Consequently, the mechanical characteristics of the condition of the metal may not serve as an indicator of its damage by pores.

CONCLUSIONS

1. The process of development of sources of failure in heterogeneous heat-resistant steels is a complex one and may not be described within the limits of any single physical model. More promising is a phenomenological approach to describing the kinetics of this process.

2. The relationship of the damage of the metal by pores to the time of creep is presented and, on the basis of it, a structural method is proposed for determination of the residual life based on the degree of damage by pores.

3. The short-term mechanical properties may not serve as an indicator of the degree of damage of the metal by pores.

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RESISTANCE TO DEFORMATION AND FRACTURE OF 35Kh3NM STEEL UNDER CONDITIONS OF SHOCK LOADING

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1. Formulation of the experiments. Investigations of the strength properties of materials under conditions of shock-wave loading have been stimulated by the necessity of prediction of the action of intense pulsed loads on various structures. Measurements of mechanical properties under these conditions which have been described in the literature have been made primarily on low-strength materials (mild steels, aluminum alloys). In this work the strength properties and features of the $\alpha \rightleftarrows \varepsilon$ structural transformation of high-strength (σ_t = 1.6-1.8 GPa) 35Kh3NM steel were investigated by recording of the wave profiles of the longitudinal stress $\sigma_x(t)$ and the velocity of the free rear surface of the specimens w(t).

The 120-mm-diam. 10-15-mm-thick specimens were cut from a round blank and heat-treated to a hardness of 46-49 HRC. The unidimensional compressive stresses were generated in the specimens by detonation of a 100-mm-diam. shaped explosive charge in direct contact with the specimen or with 2-7-mm-thick aluminum strikers with a diameter of the flat portion at the moment of impact of not less than 60 mm. Impact of the strikers with rates of 0.45-2.0 km/sec was provided with the use of explosive devices.

To record the w(t) profiles capacitive sensors [1] with a measuring electrode diameter of 20 mm and an initial distance between the electrode and the specimen surface of 4-6 mm were used. The $\sigma_x(t)$ profiles of the stresses were recorded with double-wound manganin pressure sensors [2, 3], the dimensions of the sensitive foil elements of which were ∼4.2 × 4.2 mm. The pressure sensors were located between the plates of the composite specimens and insulated with layers of Dacron, fluoroplastic, or mica. The total thickness of the sensors together with the insulation was 0.1-0.2 mm, depending upon the intensity of the shock wave to be recorded.

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