PERIODS OF THE FATIGUE FAILURE PROCESS

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Results of investigations aimed at establishing connections between the changes in the microstructure of cyclically loaded metal (grade 08 KP steel) and changes in the shape of the temperature curve are reported. It was found that the characteristic intervals of this curve provide an indirect description of completely determinate stages (periods) in fatigue failure. Attention is directed to the role played by the stage of active formation of slip bands. It is demonstrated that correct treatment of the effect exerted by this factor makes it possible to provide a more complete explanation of some of the phenomenon brought into play by cyclic loading of the metal. It is proposed that the fatigue failure process be approached as consisting of five distinct periods. On the basis of the principal tenets of the structural energy theory, the argument is put forward that the periods of the fatigue failure process are constants, for any specific metal, in terms of percentages of the total service life.

The critical nature of the superficial layers of the metal for fatigue failure is a generally acknowledged fact, so that the availability of extensive material on investigations of the response of the surface substructure and surface microstructure to cyclic loads is hardly surprising.

On the other hand, many investigators are utilizing kinetic curves characterizing the variation of several mechanical or physical properties, such as curves of the variation in the level of internal friction or variation in the elastic modulus [1], variation in the deflection of a specimen [2], in the width of a hysteresis loop [3, 4], etc.

In our study of the variation of the microstructure of a cyclically loaded specimen in relation to the variation of the shape of the temperature curve of that specimen, specimens similar to those described in [5] were subjected to cyclic loading in symmetric flexure on a facility where a force of constant amplitude was applied at a frequency of 2800 cycles/min.

The curve of temperature variations (Δ-difference of the thermal emf) was recorded automatically with the aid of a Kurnakov photorecording pyrometer. The heat measurements were taken by the differential method, using the specimen as a component in the measurement system. The exceptionally high sensitivity of a differential thermocouple [6] combined with the high sensitivity of the mirror galvanometers in the Kurnakov pyrometer, as well as the location of the junctions of the differential thermocouple on the specimen at a slight distance apart, made it possible to obtain exact and reliable results which are practically independent of fluctuations in the temperature of the surroundings.

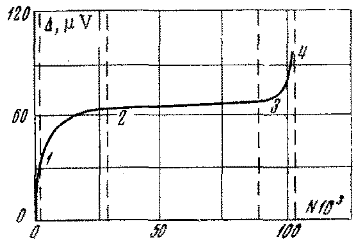

Fig. 1

The temperature curve obtained by automatic recording when the temperature difference is monitored in the process of cyclic loading of 08 KP steel at $\sigma = 1.3\sigma_{-1}$ is shown in Fig. 1. The numerals on the curve indicate the observation points tracking the change in the microstructure of the portion of the specimen recorded (the vertical broken lines mark the breakdown by periods).

Photographs of the microstructure (× 500) corresponding to the observation sites 1, 2, and 3 in Fig. 1 are shown in Fig. 2.1, 2.2, and 2.3.

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Analysis of the variation in the microstructure corresponding to the change in the shape of the temperature curve reveals that the process of formation of slip bands, which has its beginning in the early stage (point 1, Fig. 1 and Fig 2.1), terminates as the curve reaches the linear-slope region (point 1, Fig. 1 and Fig. 2.2). Later on there are changes characterized by the linear relationship on the temperature curve. No new bands are observed until the mainline crack develops (point 3).

Fig. 2

The resumption in the steep rise of the curve corresponds to the onset of active growth of the mainline crack (point 3). At lower cycle stresses, these regular patterns of variation in structure are retained, shifting toward the direction of deeper cycles.

The characteristic intervals of the temperature curve thereby correspond to completely determined stages of fatigue failure. The interval of the curve extending to point 1 defines the incubation period, the interval extending from point 1 to point 2 defines the stage of active formation of slip bands, the interval from point 2 to point 3 characterizes the stage of local buildup of changes and damage occurring in the first two stages, and interval 3-4 defines the stage of active growth of the mainline crack, which leads to the failure of the specimen.

The stage of active formation of slip bands, which features fairly clearcut boundaries marking the onset and termination of the process, is deserving of special attention. N. N. Afanas'ev [7] has drawn attention to the cessation of the formation of slip bands after a certain degree of saturation has been attained. This phenomenon has been pointed out subsequently by others [8, 9].

However, insufficient attention has been accorded this important period in the fatigue failure process, and it has not been duly accepted either in terms of its influence on fatigue failure or in terms of the time of the onset and termination of the process to date. The principal role played by this period in fatigue can be boiled down to the following:

1) after the formation of the bulk of the slip bands, the process of plastic deformation becomes localized;

2) the conversion to the stage of localized plastic deformation must necessarily be connected with the redistribution of stresses, the pattern of which also determines the direction of the development front of the fatigue crack leading to failure of the specimen.

It seems that the correct treatment of this factor may possibly open the way for some other approach to evaluating some of the processes and changes related to metal fatigue, as can be illustrated by the following example. Results of an investigation into the effect of prior cyclic loading and subsequent ageing on the cyclic fatigue strength of steel containing 0.22% carbon have been reported [10]. The curve of the variation in internal stress level (Fig. 3) was used [10] as the kinetic curve for evaluating the properties of the cyclically loaded specimen.

When the number of preloading cycles corresponding to the emergence of the internal friction curve onto the horizontal plateau region (80,000 cycles) is reached, the specimens are held at t = 180°C for 17 hours, as a result of which their service life is roughly doubled.

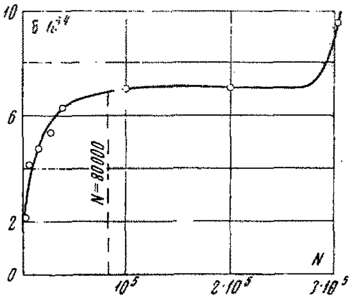

Fig. 3

The authors of [10] ascribe this effect primarily to the fact that the commencement of the emergence of the curve onto the horizontal plateau region corresponds to the maximum density of "fresh" dislocations.

Comparison of the temperature curve (Fig. 1) and the curve of the variation in internal friction (Fig. 3) clearly demonstrates their identical character, which is evidently accounted for by a direct relationship between temperature and internal friction. Despite the contrasting lengths of service life (102,000 versus 300,000 cycles), the curved intervals account for about 25-26% of the total length of service life. We may therefore state that the processes indirectly described by those curves are of the same nature. Accordingly, the emergence of the internal friction curve onto the horizontal plateau interval, just as in the case of the temperature curve, corresponds to the concluding phase of the stage formation of slip bands. Data on microstructure variations are not reported in the article in question [10]. To acknowledge complete agreement with those authors on the assertion that the emergence of the curve onto that interval corresponds solely to maximum density of fresh dislocations means to acknowledge that the process of slip band formation commences at that point where it actually comes to a halt.

Actually, after the maximum density of fresh dislocations has been attained, a critical density of fresh dislocations may be arrived at (in discrete volumes). When the critical dislocation density is attained, mass relaxation of dislocations occurs with the formation of coarse slip bands [11], so that the process commences only after 80,000 loading cycles, which stands in contradiction to the available data on the time at which the first slip bands appear [9, 12] in materials of the type, including the results arrived at in our work. At service lives in the range of $10^5 < N < 10^6$ cycles, for instance, the first slip bands are recorded as early as 10^3 loading cycles [12]. Once started, this process unfolds quite intensively [13]. The effect of strain hardening combined with aging [10] can be accounted for, consequently, not only from the standpoint of a dislocation mechanism, but also by invoking the effect of active plastic shear caused by and prepared by the movement of the dislocations. It might be precisely that consequently, of active plastic deformation and heat treatment that was responsible for that pronounced hardening effect.

The fatigue periods have been treated in different manners [14, 15]. Most reliable is the classification proposed by V. S. Ivanova [11], since this classification was arrived at through analysis of a multiplicity of data based on the theory of hardening and softening and from the standpoint of the structural energy theory. It seems that the acceptance of a period of active slip band formation within the framework of this theory will contribute to a fuller study and understanding of the nature of fatigue.

Subsequently, investigation of the nature of the change in the microstructure of the surface of the metal in relation to changes in the shape of the temperature curve, has made it possible to single out the following periods in the fatigue process.

1. Incubation period. The duration of this period depends on several factors, and principally on the cycling stress.

2. Period of active formation of slip bands.

3. Period of localized buildup of damage and changes brought about in the course of the first and second periods. This period sets up the conditions prerequisite to the formation and growth of the mainline crack.

4. Period of the development and growth of the mainline crack.

5. Period of the failure of the specimen. The duration of this period is negligible in the case of specimens of small cross section [11].

These periods stand out quite distinctly on the temperature curve (Fig. 1).

According to the structural energy theory of fatigue, processes in the different periods are constants of the specific metal, and are independent of the amplitude of the applied stress. We may expect, therefore that the fatigue failure periods will be constants in their percentage relation to the total service life, for any one material, and as such will be independent of the stress level. By analogy with the curves of equal energy capacity on the fatigue diagram [9, 11], the characteristic intervals on the temperature curve (just as in the case of other kinetic curves) can be treated as intervals of identical energy capacity.

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