STAT

FATIGUE OF METALS

authors: Ya I. Feldshtein
N. S. Akulov
I. P. Mazin

STAT

FATIGUE ~~IN~~ OF METALS

Active Members of the
AN BSSR, N.S.Akulov,
I. P. Mazin and Ya. I.
Feldshtein

The phenomenon of fatigue, leading to the destruction of a metal under the action of alternating load, has an exceptionally important significance both in practice and in the solution of certain theoretical questions in the field of metallophysics. A large number of works have been dedicated to the study of the phenomenon of fatigue. Nevertheless, the physical mechanism of this phenomenon is still insuficiently clarified. It is known that after a definite number of cycles N at a given amplitutde of the vibration tension A, the metal is destroyed. The destruction is directly provoked by the appearance of fatigue cracks which, once formed and having reached a certain critical size, swiftly begin to grow at the expense of the redistribution and concentration of the tensions at the edge of the cracks themselves. Thus the problem of discovery of the nature of fatigue is reduced to the clarification of the formation and development mechanism of the cracks (lamination), the further growth of which leads to destruction.

The existing empirical ratios establishing the connection between A and N are extremely varied. Thus Iden, Rose and Cunningham (2) give us the formula $A = cN^{a}$, where c and a are the constants depending upon the material and the experimental system. Stomeyer (2) on the basis of his experiments arrives at the ratio $A = \sigma_D + c\left(\frac{10^6}{N}\right)^{1/4}$, where σ_D is the cycle amplitude in the presence of an infinite number of cycles. These norms however, can be applied only to a very narrow variation area of A and N. Orovan and N. N. Afanas'ev (5,6), examining fatigue as a special kind of plastic deformation, arrive at a ratio of the type

$$Bn = \ln \frac{\sigma_m - \sigma_y}{\sigma_m - \sigma_f}, \qquad (1)$$

where B is the coefficient depending upon the shape of the hardening curve, σ_y and σ_f are the tensions corresponding to the limit of elasticity and the limit of the plastic flow determined by the hardening curve, σ_m is the maximum tension in the so called "plastic" region depending upon external tension, and n is the number of cycles up to the appearance of lamination in the plastic region. This formula is qualitatively in agreement with experimental results. Difficulties arise, however, in the quantitative comparison with experimental results, for this theory does not give a quantitative connection between n and σ_m on one side and the directly determined values N and A on the other.

We can therefore accept the opinion that the "phenomenon of metal fatigue is such a complicated question that up to this time it is far from being developed to a degree corresponding to the contemporary condition of machine building" (1). In the present work, on the basis of a simple physical model of the formation of initial fatigue cracks, we establish a ratio between A and N which is in good agreement with the experimental data of various authors.

As we know, homogeneous, well-annealed, fine metals with a well expressed lattice have a very low elasticity limit. Under the action of very small forces there appear shears, more often than not along the planes most thickly populated with atoms, and there appear twinnings which lead to plastic deformation in the metal. In the course of plastic deformation there takes place a hardening of the metal with the consequent appearance of a very pronounced nonhomogeneity in the resistence to shearing on the part of the various parts of the metal. At the same time there appears a concentration of tensions near to those blocks or regions of the crystal which most resist the shearing. Let us call these regions "meshings". Near to such meshings the internal tensions are much stronger than their average intensity.

Let us note that with these essentially "static" fluctuations of the tensions which under the given condition of the metal have no relation to time there can take place uninterrupted tension fluctuations regulated by the heat motion of atoms (Debye's waves). These tensions fluctuate and are added to the "static" tensions. However, these "dynamic" tension fluctuations are generally much smaller than the static ones and we will not take them into consideration here.

Let now a sign-changing load with an amplitude A act on the metal in the absence of a constant load (meaning that the average tension of the cycle is equal to zero). There also is a certain number of meshings with such a large concentration of tensions near them that if the amplitude surpasses a certain critical value A_o, there occur breaks in the meshings leading to the lamination of the metal in those places. If the amplitude is smaller than A_o, then the meshings do not break, or so few of them break that the metal, under a regular load during a very large number of cycles is not destroyed.

It is easy to see that near each center where a lamination takes place, there occurs a redistribution of tensions as a result of which, near to a given destroyed meshing, new localizations of tensions can be created next to other meshings. We thus obtain a chain mechanism of destruction of existing centers of localization and the formation of new ones to replace them after each period of the sign-changing loading. The very breaks in the meshings which lead to the formation of laminations, also lead to the formation of tension concentrations next to new meshings. The following cycles destroy the newly formed centers with the subsequent generation of still new ones. With such a mechanism of destruction the time of one sign-changing cycle will have no effect on the general lamination area for one cycle.

With the growth of the amplitude of the sign-changing load to dA the lamination area for one cycle will also grow. This is because the tension near every localization center gradually decreases. Therefore near each such center there exists an area of subcritical tensions in which at a given amplitude A there is no lamination. With the growth of the amplitude to dA the destruction partially begins to expand also to this subcritical area. As a result the lamination for one cycle increases by a certain value

The size of the additionally invaded subcritical area will be larger in proportion to the size of the critical area around which is disposed the area of subcritical tensions. Thus the value dS is proportional to S, where S is the total area of lamination in a unit of volume for one cycle, i. e.,

$$dS = aS\,dA, \qquad (2)$$

where a is the coefficient of proportionality. From (2) there follows

$$S = S_0 e^{a(A-A_0)}, \qquad (3)$$

where $A > A_0$, that is, given $A = A_0$ in the sample for one cycle there appear laminations with an area S_0 in one unit of volume. As a consequence of the nonhomogeneity of the sample the number of laminations referred to the unit of volume may be different. We will be interested in the future in those areas of the metal which correspond to the maximum of emerging laminations. Such a part of the metal we will call the region of fatigue danger.

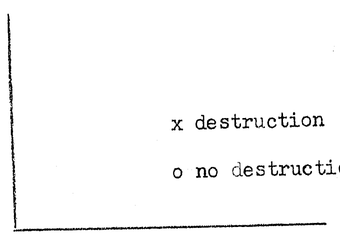

Figure 1. Fatigue curves for Carbon Steels. (a) -- 0.82 percent of C. (b) -- 0.55 percent of C.

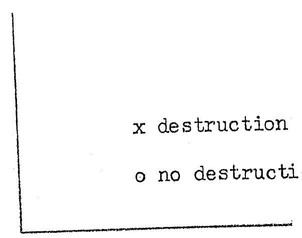

Figure 2. Fatigue curves for steels with additions of Mo, Cr, W. (a) -- 0.51 percent of Mo at

Figure 2 [continued]

300 degrees Centigrade. (b)-- 0.51 percent of Mo at 400 degrees Centigrade. (c) -- 0.51 percent of Mo at 20 degrees Centigrade. (d) -- 15.5 percent Cr, 13.3 percent Ni and 2.02 percent of W at 20 degrees Centigrade.

If the average lamination area for one cycle remains constant during a large number of cycles, then for n cycles the whole lamination area

$$S_n = Sn. \tag{4}$$

When S_n reaches a certain critical value S_k the change in the internal structure strongly begins to affect the general field of tensions. As a result of this a large crack appears. One may say that the value S_k is related only to the material of the sample and not totthe size of the amplitude, in other words is not related to how the critical size of lamination is reached. Correspondingly, the number of cycles N, which is indispensable for the reaching of the critical lamination area, is determined by the ratio

$$S_k = SN \tag{5}$$

From here we have

$$N dS + S dN = 0 \tag{6}$$

Substituting (2) in (6) we get

$$N = N_0 e^{-a(A-A_0)} \quad \text{for } A > A_0$$
$$N \to \infty \quad \text{for } A \leq A_0.$$

To check the obtained theoretical ratios we used the experimental data of various authors (2,7). From the curves we see that the theoretical relation of A to $\log N$ with $A > A_0$ is a straight line with a varying inclination in relation to the abscissa for different materials (see figures 1 and 2). The experimental points, although giving some divergence, fit well on this straight line.

Submitted on 8 February 1951

Bibliography

1. I. A. Oding, Allowable Stresses in Machine Building and the Cyclic Strength of the Metal, 1947
2. G. Dzh. Gaf, Fatigue of Metals, 1936
3. N. Akulov u. R. Raewsky, Ann. d. Phys., 20, 113 (1934)
4. N. S. Akulov and N. Z. Miryasov, ZhTF, 18, No 3, 389 (1948)
5. N. N. Afanas'yev, Zh.TF 14, 638 (1944)
6. E. Orowan, Proc. Roy. Soc., 171, 79 (1939)
7. M. Hempel u. G. Tillmann, Mitteil KWI, Eisenf. 18, 12 (1936)

- E N D -