Journal of Applied Mechanics and Technical Physics, Vol. 51, No. 3, pp. 393–397, 2010

ON DETERMINATION OF ELASTIC LIMITS BY DISSIPATIVE HEATING OF MATERIALS

V. I. Kapustin,[1] V. P. Gileta,[1] and E. A. Tereshin[2]

UDC 539.4:629.7.015.4:669

This paper considers a method for determining the conventional elastic limit by dissipative heating of materials and the results of experimental investigation of these characteristics during periodic asymmetric loading of steel and alloy.

Key words: *stress, strain, elasticity, dissipative heating, fatigue.*

Introduction. During investigation of fatigue-induced deformation, fracture, and damage accumulation, it is important to know the laws of variation of the elastic stress during cyclic asymmetric loading of real metals. The stress at which transition from perfect elastic deformation to inelastic one occurs is characterized by a conventional elastic limit. As a rule, conventional elastic limits are determined with the use of methods based on deformation measurement. The accuracy of such methods is limited by the resolution of the equipment used to determine the difference between the total strains during loading and unloading (10^{-5}), which depends on the inelastic strain and the hysteresis loop width [1]. In experiments [1], the elastic limit was determined as the nominal stress amplitude of a symmetric cycle in which the inelastic strain of the cycle was equal to the resolution of the method.

The limiting values of individual stress tensor components and the relations between their limiting values above which the work in a strain cycle is not equal to zero are determined using the results of indirect measurements.

In the present work, the conventional elastic limit was determined by dissipative heating of material during cyclic loading. The conventional elastic limit was taken to be the cyclic stress amplitude at which, for instance, in the case of stepped increase in the cycle stress amplitude, the deforming material of the working section of the sample was heated to a prescribed temperature. In this method, the temperature variation of the working section of the sample obviously depends on the increment of the cycle stress amplitude and should be specified before the experiment taking into account the accuracy and sensitivity of the equipment used for temperature measurements.

The purpose of this work was to investigate the influence of a stress-cycle characteristic σ_m (mean stress) on the conventional elastic limit σ_a (stress amplitude) of steel and alloy in a uniaxial stress state.

During determination of conventional elastic limits by dissipative heating of material, the following condition should be satisfied: the frequency of periodic loading is such that at stresses below the elastic limit, adiabatic elastic deformation takes place, so that the following relations are valid [2]:

$$\Delta T = \frac{E\alpha_L T}{\rho c_\varepsilon (1-2\nu)} \sum_{i=1,2,3} \varepsilon_{ii}, \qquad \Delta T = -\frac{\alpha_L T}{\rho c_p} \sum_{i=1,2,3} \sigma_{ii}.$$

Here E is the elastic modulus, ν is Poisson ratio, α_L is the thermal coefficient of linear expansion of the material, ρ is the density of the material, T is the absolute temperature at the measurement point, and c_ε and c_p are the specific heats of the material at constant strain and stress, respectively. In this case, the temperature change ΔT of the elementary volume of the material depends linearly on the sum of change of the principal main strains $\sum\limits_{i=1,2,3} \varepsilon_{ii}$ or stresses $\sum\limits_{i=1,2,3} \sigma_{ii}$ and equals zero during the period of cyclic loading. If, during loading, the elastic limit is exceeded,

[1]Novosibirsk State Technical University, Novosibirsk 630092. [2]Construction and Design Institute of Applied Microelectronics, Institute of Semiconductor Physics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; macler06@mail.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 51, No. 3, pp. 112–117, May–June, 2010. Original article submitted March 19, 2009; revision submitted June 5, 2009.

the mean temperature of the sample in the cycle will increase. Thus, by measuring the stress which changes the mean temperature of the sample by a specified value in the experiment, it is possible to determine the conventional elastic limit. The surfaces separating the region of elastic deformation of a real material from the region of inelastic deformation can be constructed in the space of principal stresses without direct strain measurements by determining the conventional elastic limits for various relations between the amplitudes and mean values of each component of the stress tensor.

1. Samples and Equipment Used in the Experiment. In this work, the conventional elastic limits during cyclic asymmetric uniaxial loading of samples of various steels and alloys were determined. Samples of various shapes and sizes were used in the experiment. The shape of the working section and the accuracy of sample making were exactly the same as those in the samples used in the determination of the fatigue limit of the material.

The fatigue characteristics and inelastic features of the material were investigated on an MTS servohydraulic testing machine (maximum stress equals 100 kN), which allows one to perform experiments in a frequency range from 0.1 to 20 Hz and deform samples in a soft mode and a harmonic cycle of periodic loading without kinematic restrictions. Strains were determined using an MTS extensometer with a 25 mm base.

A thermal imaging camera with an Indigo matrix bolometric detector (USA) was used to measure the temperature of the samples. The temperature resolution, characterized by the minimum difference of the measured blackbody radiation temperatures at room temperature, was 80 mK.

The use of the thermal imager was due to its advantages over other instruments and by the possibility of noncontact constant observation and registration of temperature processes on relatively large areas.

During the determination of the temperature increment of the working section using the thermal imager, measures were undertaken to provide the necessary linear resolution, exclude random errors due to the influence of the beforehand unknown reflective and refractive powers of the sample material, and took into account and suppress the influence of the nonuniformity of the thermal field on the determination accuracy of the sample temperature.

The temperature was determined in the center of the working part of the sample — the site of its greatest change.

2. Method of Determining the Conventional Elastic Limit. Conventional elastic limits during asymmetric periodic loading were determined using the method proposed in [3]. The conventional elastic limit was taken to be the nominal-stress amplitude determined at the moment when the temperature increment of the working section of the sample was 0.2 K at a specified mean stress of the cycle and a stepped increase in the stress amplitude.

The conventional temperature increment (0.2 K) was 2.5 times higher than the resolution of the thermal imager and remained unchanged throughout the series of tests. The dependence of the conventional elastic limit on the cycle stress characteristic in the experiment was determined in the following sequence:

1. The mean stress in the sample was produced by quasistatic loading.

2. The sample was subjected to periodic loading. The loading amplitude was increased stepwise from 0 to the value at which the working section of the sample began heating.

3. Maximum and minimum sample loads and nominal stress in the sample (conventional elastic limit) were determined after the working section of the sample had been heated to the specified temperature.

4. The stress amplitude reduced to zero.

5. In the sample, a higher mean cycle stress (belonging to the range of values) was produced by static loading. Then, the sample was subjected to periodic loading according to item 2, and the elasticity level of the material was determined according to item. 3. Thus, the whole specified interval of mean stresses of asymmetric cycles was investigated.

3. Test Results. A diagram of conventional elastic limits obtained for D16AT alloy by the procedure described above is shown in Fig. 1 in the Smith coordinates commonly used for constructing diagrams of fatigue stress limits. The abscissa shows the mean stresses σ_m, and the ordinate shows the maximum ($\sigma_{\max}$) and minimum ($\sigma_{\min}$) cycle stresses that correspond to the amplitude of the conventional elastic limit σ_a and the mean stress σ_m in the sample. The stresses $\sigma_{\max}$ and $\sigma_{\min}$ were calculated by the formulas $\sigma_{\max} = \sigma_m + \sigma_a$ and $\sigma_{\min} = \sigma_m - \sigma_a$. In Fig. 1, the conventional elastic limits are shown by points. The experimental dependences are approximated by regression lines. In addition, Fig. 1 gives a diagram of the strain $\sigma(\Delta l)$ for uniaxial tension of a sample of the same alloy (σ is the nominal stress, and Δl is the increment in the sample length).

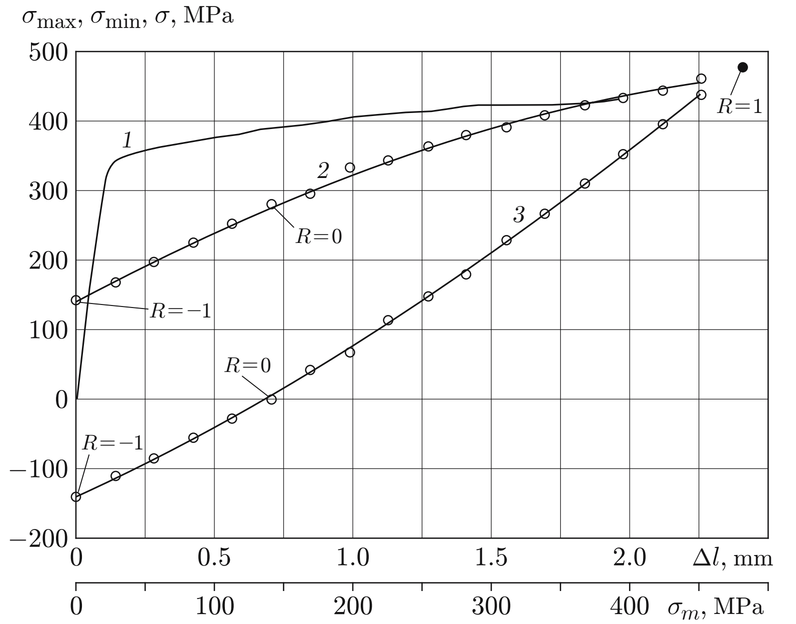

Fig. 1. Diagram of strain $\sigma(\Delta l)$ (1) and conventional elastic limits $\sigma_{\max}(\sigma_m)$ (2), and $\sigma_{\min}(\sigma_m)$ (3) for D16AT alloy samples: the dark point is the ultimate tensile stress.

A comparison of the strain diagrams and the diagram of conventional elastic limits in Fig. 1 shows that, as the stress ratio $R = \sigma_{\min}/\sigma_{\max}$ $[R \in [-1;1)]$ increases, the characteristics of the conventional limiting cycle of elasticity $\sigma_{\max}$ and $\sigma_{\min}$ tend to the ultimate tensile stress $\sigma_{\rm t} = 480$ MPa.

Moreover, two regions can be distinguished in the diagram of conventional limits of elasticity. The first region $R \in [-1;0]$ is characterized by a constant amplitude of the conventional elastic limit. In the second region $R \in (0;1)$, the amplitude decreases monotonically and residual strains are accumulated.

From the comparison of the diagrams of strain and conventional elastic limits in the case of a symmetric loading cycle (points $R = -1$ in Fig. 1), it follows that the conventional elastic limit is much lower than the yield point of the material. During cyclic loading in the case $R = 0$, the fracture of D16AT alloy samples occurs for an average number of cycles equal to $5.6 \cdot 10^4$.

Figure 2 shows diagrams of conventional elastic limits of an alloy based on copper, aluminum, and steel in Hay coordinates commonly used for constructing diagrams of the limiting amplitudes of fatigue stresses. It is clear that when $R > 0$ for all materials studied, the conventional elastic limits decrease, and as the mean cycle stress increases, they tend to zero. It follows from Fig. 2 that 40Kh2N4MA and 18KhN4MA steels, whose mechanical characteristics are similar in quasistatic loading, have different elastic limits under cyclic loading with different degrees of asymmetry. For instance, in a symmetric cycle, 40Kh2N4MA steel has a greater elastic limit, and in a zero-to-stress (pulsating) cycle, 18KhN4MA steel has a greater limit.

An analysis of dependences of the conventional elastic limits on the mean stress obtained over a wide range of the stress ratio) reveals regions in which the material resists periodic loading without a significant change in the elastic properties; for instance, for D16T alloy, this region is $R \in (0;1)$.

Figure 3 shows diagrams of the limiting stress amplitudes for various steels and aluminum alloys [4, p. 179]. Each of these diagrams corresponds to a certain basic number of cycles before material fracture. From Figs. 2 and 3, it follows that the diagrams of conventional elastic limits of metals are similar to the diagrams of the limiting cycle-stress amplitudes. To illustrate the similarity of the above-mentioned dependences in the case of 40Kh2N4MA alloyed steel, curves of those dependences (obtained with the use of the Goodman and Herber equations) are drawn through the points ($\sigma_m = 0$, $\sigma_a = 400$ MPa) and ($\sigma_m = 1080$ MPa, $\sigma_a = 0$) [4. p. 177]. In the case where experimental data are limited, these equations used to approximate diagrams of limiting amplitudes

$$\sigma_a = \sigma_{-1}(1 - \sigma_m/\sigma_{\rm t}), \qquad \sigma_a = \sigma_{-1}[1 - (\sigma_m/\sigma_{\rm t})^2]$$

do not describe the properties of each material.

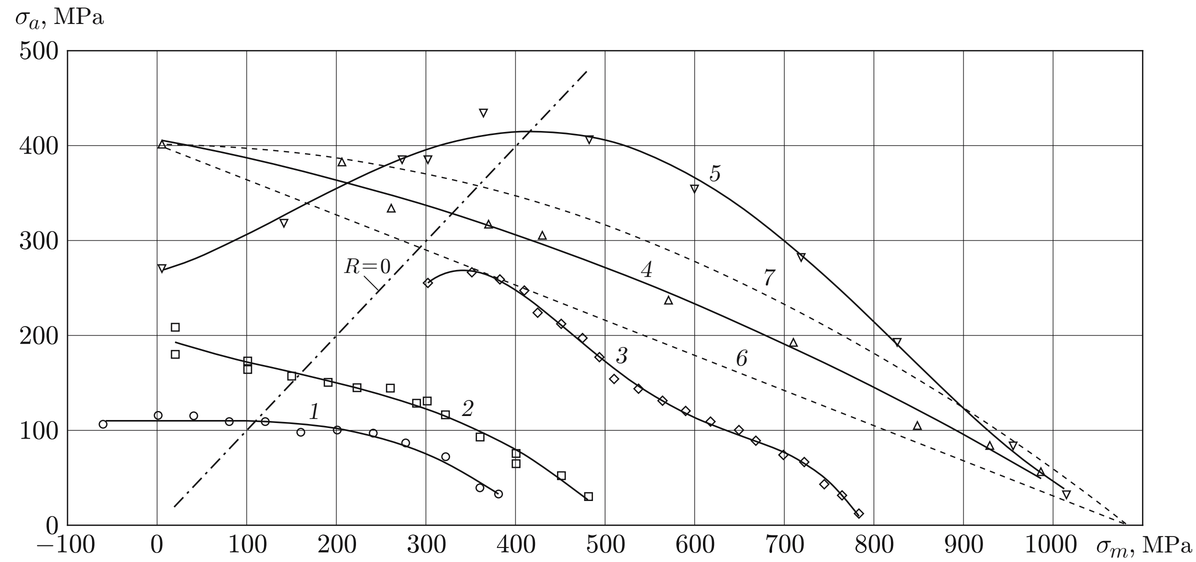

Fig. 2. Diagrams of conventional elastic limits for D16T aluminum alloy (1), LS59 copper alloy (2), 30KhGSA steel (3); 40Kh2N4MA steel (4), and 18KhN4MA steel (5), dashed curves are the curves of $\sigma_a(\sigma_m)$ obtained using the Goodman equation (curve 6) and Herber equation (curve 7); points are experimental data; solid curves are their approximations.

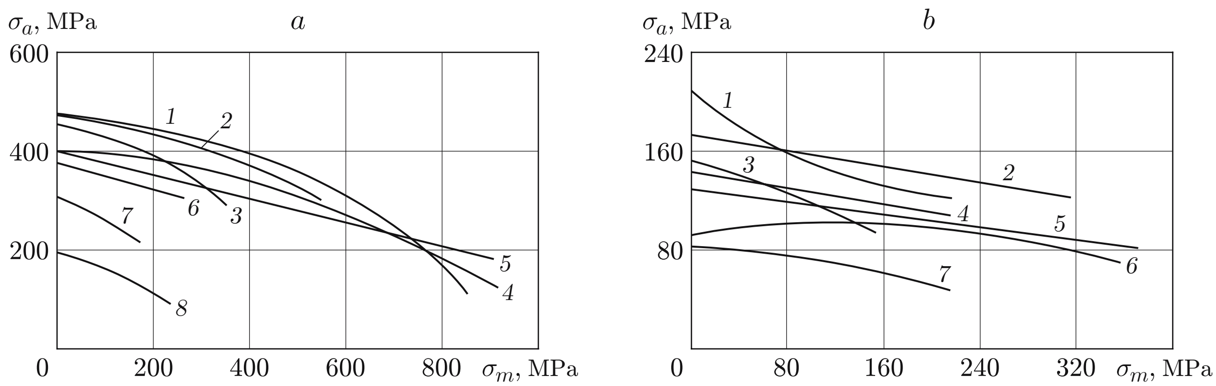

Fig. 3. Diagrams of limiting stress amplitudes for steels (a) and aluminum alloys (b): (a) curve 1 refers to SAE4340, 2 to chromium–nickel–molybdenum steel, 3 to steel (σ_e = 890 MPa), 4 to 18 KhMBA, 5 to 40KhMA; 6 to steel (σ_e = 800 MPa), 7 to steel ($\sigma_e = 650$ MPa), and 8 to soft steel; (b) curve 1 refers to 755-T6, 2 to BS1476, 3 to BD-17, 4 to 24S-T3, 5 to 7075-T6, 6 to 2014-T6, and 7 to 6061-T6.

Similarity between the diagrams of the conventional elastic limits and fatigue limits is confirmed by data obtained in experiments with alloys of various chemical compositions for various thermal treatment conditions and loading histories (24 grades of alloys and steels were tested).

As is known, the elasticity limit of a material can change after its deformation at a stress exceeding the yield point. Figure 4 gives experimental data showing that, after loading of a 30KhGSA steel sample by stresses exceeding the yield point, the conventional elastic limit can both increase or decrease as the mean cycle stress increases. Curve 2 was obtained after deformation of the sample at a maximum stress of 550 MPa. From Fig. 4, it follows that the conventional elastic limits change after the initial sample was loaded by a stress exceeding the fatigue limit. In the interval of the mean cycle stress from 100 to 320 MPa, the amplitude of the diagram of the conventional elastic limit decreases; in the interval from 320 to 630 MPa, it increases. This variation in the properties of the material, called softening and hardening, indicates a complex nature of material deformation in the elastoplastic region even under uniaxial loading.

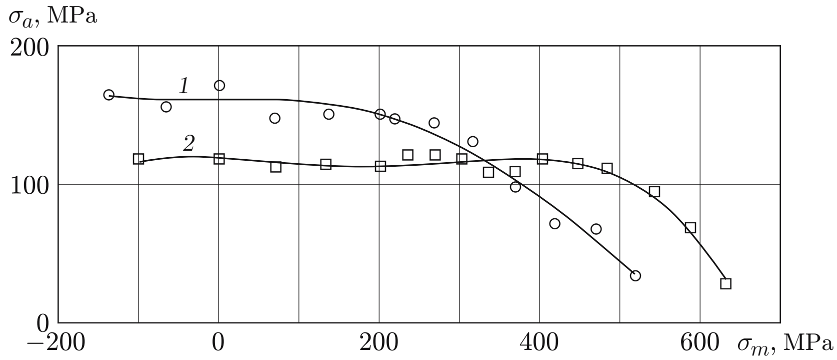

Fig. 4. Diagrams of conventional elastic limits for various loading histories: 1) loading at a stress not exceeding the fatigue limit; 2) loading at a stress exceeding the fatigue limit.

Conclusion. The results of fatigue tests of various materials at stresses equal to the conventional elastic limit were considered. The test results indicate that, in spite of the similarity between the diagrams of the conventional elastic limit and limiting stresses, these two characteristics are different. Conventional elastic limits cannot be identified not only with fatigue limits, but also with fatigue strength of metals because at stresses equal to the elastic limit, first, the number of cycles before fracture becomes dependent on the degree of asymmetry of the stress cycle; second, the conventional elastic limits (for instance, for 12Kh18N10T steel) can be significantly (20%) lower than the elastic limits obtained for a number of cycles equal to 10^8.

This discrepancy is likely due to the fact that the amplitude and mean stress of a cycle differently influence the material damage kinetics during cyclic loading.

Conventional elastic limits can be used to approximately estimate the region of applicability of elastic deformation models for periodic deformation of real materials.

REFERENCES

1. V. T. Troscshenko, *Deformation and Fracture of Metals under Multiple-Cycle Loading* [in Russian], Naukova Dumka, Kiev (1981).
2. A.S. Kobayashi (ed.), *Handbook on Experimental Mechanics*, Prentice Hall, Englewood Cliffs, New Jersey (1987).
3. V. I. Kapustin, “Method of determining the life of structural members,” Russian Federation Patent No. 1821674, M. Kl G 01 N3/32, Publ. 06.15.93, Byull. No. 22.
4. V. T. Troscshenko and L. A. Sosnovskii, *Fatigue Resistance of Metals and Alloys: Handbook* [in Russian], Part 1, Naukova Dumka, Kiev (1987).