SCIENTIFIC AND TECHNICAL SECTION

ASSESSMENT OF DAMAGE LEVEL IN MATERIALS BY THE SCATTER OF ELASTIC CHARACTERISTICS AND STATIC STRENGTH

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The parameters of scatter of elastic characteristics and strength of an aluminum alloy and carbon steel are determined from the results of large-batch tests under identical static deformation conditions. The material degradation is demonstrated to occur in a stagewise manner associated with peculiarities and nature of structural damages accumulated during various deformation stages, which is responsible for nonlinearity of the damage accumulation law. A good correlation has been found between the Weibull homogeneity coefficient and the maximum probability density on lognormal distribution and Weibull distribution curves. Emphasis is put on the advantages of the LM hardness method in terms of information it provides about the integral pattern of material degradation over its lifetime.

Keywords: hardness, static strength, scatter of properties, damage level, distribution law.

Introduction. The kinetic fracture process in a material subjected to short- or long-term loading shows up in profound structural alterations on various scales and thus in physicomechanical properties as well. The breaking of atomic, molecular and other bonds, which occurs during various deformation stages, results in a given damage level in the material, i.e., degradation thereof.

The damage level associated with the formation of defects in a material should be considered as one of its representative quality indicators to be monitored during the structure operation. It stands to reason that some standards and codes for the in-service life assessment of structural members requires that in addition to determination of a structure's current safety factors based on the material yield stress and strength the safety factor must be also assessed by the damage level in the material [1]. Therefore, the research efforts aimed at improving the methods of nondestructive examination of kinetics of a material's state during its service life are of great practical importance.

At present, attempts are made to monitor the damage kinetics in service by various methods including assessment by the physical parameters that characterize any changes in internal friction, resistivity, elastic modulus, hardness and other properties of a material. The main criteria for choosing an appropriate method are (i) the sensitivity of the involved parameter to a change in the damage level and (ii) whether simple nondestructive techniques are available for the determination of this parameter.

In this respect, the LM hardness method was shown [2, 3] to offer definite advantages over the other methods because instead of hardness proper it involves, for the purpose of correlation with the damage level, the statistic parameters of scatter of hardness characteristics obtained by multitude measurements [4]. The method has been tested

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mainly on structural steels and gray cast iron [5] upon various stages of static tensile deformation as well as on pipe steels after various time periods of operation in main pipeline systems [6].

Since the method has been proved efficient, it is advisable to continue research in order to have a thorough physical substantiation of this method, improve its reliability and make it easy to use for practical applications. First of all, it is necessary to get a deeper insight into the nature of scatter of values of hardness characteristics and other mechanical properties of a material, explain the observed pattern of the in-service damage accumulation kinetics as assessed by the scatter parameters and by other methods in relation to the influence of loading conditions and type of stress.

Experimental. For further development of the method, it would be of great interest to study the possibility of the damage level determination by the scatter of characteristics of elasticity, plasticity, and static strength as obtained by large-batch testing of identical specimens under identical deformation conditions. It is along this important line that the present investigation has been carried out.

Considering the peculiarity of the problem to be tackled, special emphasis was placed on ensuring the repeatability of test conditions and modes in order to minimize any effects of human factor as well as tooling and instrumental errors on the test results.

The statistic nature of a material's mechanical properties, which is associated with structural inhomogeneity and defects in the material, requires that the results of large-batch tests should be thoroughly analyzed using the techniques of mathematical statistics and the theory of random processes, which are based on the law of large numbers (more than 200). However, when solving some practical problems one may encounter certain restrictions. In particular, Serensen et al. [7] reported the results of fatigue testing of V95 alloy under rather high stresses ($\sigma_{\max}/\sigma_{-1} \geq 1.5$). The analysis showed that for 10- and 26-specimen batches the difference in mean life did not exceed 0.2% while the difference in variance was about 15%. These results as well as those obtained earlier [2, 3, 5, 6, etc.] suggest that for the purpose of the present investigation the test data obtained for 26- to 28-specimen batches should suffice.

The study was performed using the following test materials: a low-alloy carbon steel 40Kh and a high-strength aluminum alloy V95. From these we prepared quintuple-ratio cylindrical specimens of type IV with a test portion diameter of 8 mm and initial length of 40 mm in strict conformity with the State Standard (GOST 1497-84 [8]), ensuring the identical manufacturing conditions, dimensions and surface roughness of the test portion. Twenty eight specimens of each material were made from two identical 20-mm-diameter rods on a lathe under a conventional cooling conditions. The surface roughness of the test portion of the turned (with a minimum depth of cut) and ground specimens did not exceed 1.25 μm . Prior to testing the test portion was accurately measured. The specimens which did not meet the standard requirements [8] were rejected.

The tests were performed on a machine equipped with a mechanical and manual drive providing rigid loading which is especially required for the determination of elastic modulus and yield strength.

U-shaped strain gauges were used to measure axial and transverse strains. The presence of two gauges attached to diametrically opposite sides of a specimen and the appropriate connection of gauge bridge channels to the measuring device enabled us to detect eccentric tension which could be eliminated by re-installing the specimen between grippers. For more accurate force measurements the standard strain gauges were backed up by a resistive strain sensor device whose signals, like the signals from the strain gauge resistors, were recorded by digital voltmeters and $X-Y$ recorders.

The strain recording scale at the starting segments was about 1500:1 and 3000:1 for the longitudinal and transverse strains, respectively. As the plastic strains grow the recording was scaled down in a stepwise manner.

Results and Discussion. Mechanical characteristics of the steel and alloy under study were determined by processing the stress-strain curves following the standard procedure [8]. Typical stress-strain curves for 40Kh steel and V95 alloy are shown in Fig. 1 and their mechanical characteristics determined from the test results for 28 identical specimens are summarized in Table 1. Unfortunately, for the technical reasons we have not managed to record the test portion strains corresponding to the specimen fracture. Also, the adequacy of the yield stress data is in doubt because of their considerable scatter. It may be due to a very slight hardening of the aluminum alloy in the zone of small elastoplastic strains.

TABLE 1. Characteristics of Mechanical Properties of the Materials under Study

Specimen No.	Steel 40Kh				Alloy V95			
	$E \times 10^{-1}$, MPa	μ	$\sigma_{0.2}$, MPa	σ_u , MPa	$E \times 10^{-1}$, MPa	μ	$\sigma_{0.2}$, MPa	σ_u , MPa
1	21,039	0.295	607	920	7450	0.323	438	562
2	21,233	0.296	610	934	7495	0.333	438	562
3	21,473	0.298	621	397	7511	0.333	439	565
4	21,583	0.299	628	939	7514	0.333	440	568
5	21,637	0.303	634	940	7530	0.339	440	568
6	21,697	0.304	638	942	7556	0.340	441	571
7	21,710	0.309	638	945	7561	0.342	442	571
8	21,864	0.310	638	948	7565	0.346	443	572
9	21,900	0.311	642	949	7573	0.347	443	574
10	21,958	0.311	647	950	7574	0.352	443	574
11	21,968	0.321	653	951	7607	0.354	443	575
12	21,969	0.321	656	953	7625	0.356	444	575
13	22,041	0.322	658	955	7625	0.358	444	575
14	22,055	0.326	660	956	7625	0.359	444	576
15	22,060	0.327	666	957	7626	0.359	444	577
16	22,080	0.327	667	969	7641	0.360	444	577
17	22,104	0.330	678	977	7647	0.363	444	577
18	22,142	0.331	684	981	7685	0.367	445	578
19	22,175	0.334	699	983	7698	0.369	445	578
20	22,214	0.336	699	985	7732	0.370	445	578
21	22,274	0.337	704	991	7736	0.372	445	578
22	22,348	0.340	708	991	7743	0.373	446	579
23	22,359	0.343	732	1001	7746	0.376	446	579
24	22,588	0.344	734	1003	7825	0.379	447	581
25	22,632	0.345	738	1004	7837	0.379	447	581
26	22,637	0.346	746	1016	7841	0.383	447	581
27	22,680	0.360	751	1023	7844	0.388	449	582
28	23,179	0.367	782	1065	7870		451	583
<i>m</i>	53.21	18.57	16.17	32.98	71.76	22.46	158.55	110.73
HV_{av} , MPa (initial material)			2708.96				1406.45	
<i>m</i>			91.63				99.83	

It is evident from the tabulated data that for each mechanical property the values of the respective characteristics (E_i , μ_i , $\sigma_{0.2i}$, and σ_{ui}) exhibit some scatter which is attributable to the natural microstructural heterogeneity of a material, the presence of various intrinsic or accumulated during the deformation defects (damage) as well as to other factors that are independent of structural features and minimized during the test preparation and execution as shown above. This is demonstrated in particular by the absence of any systematic (recurrent) spikes in various samplings.

Using the data given in Table 1 we determined the parameters of scatter of characteristics of main mechanical properties of the materials (elastic characteristics E and μ and strength characteristics $\sigma_{0.2}$ and σ_u) as assessed by a homogeneity coefficient which for each property was found by the Gumbel formula

$$m_k = \frac{d(n)}{2.30259} \left[\frac{1}{n-1} \sum_{i=1}^n (\log k_i - \overline{\log k}) \right]^{1/2}, \quad (1)$$

Fig. 1. Stress–strain curves for steel 40Kh (1) and aluminum alloy V95 (2).

where $\log k = \frac{1}{n} \sum_{i=1}^n \log k_i$ is the mean value of the logarithms, which were obtained in n experiments for the characteristics of the k th property.

Analyzing the data obtained and comparing them with each other and with the test results of the initial material by the LM hardness method (Table 1) we have found neither quantitative not qualitative correlation between the values of the damage parameters as determined from the scatter of characteristics of various mechanical properties. Furthermore, the damage level does not grow monotonically with the deformation development, namely: during the elastic-to-plastic transition and then to the pre-fracture state whereby the damage level in both materials is lower than that at the beginning of the plastic yielding. This may be attributed to the fact that a change in individual properties of the materials with lifetime is not governed by all of the damages to the same extent, i.e., each group of damages controls mainly one or, at best, a few properties. For instance, the scatter of yield strength values is associated mostly with damages of shear nature, while the ultimate strength values are related to the damages resulting from cleavage and loosening of the material.

It should be mentioned that the revealed stagewise pattern of the process may be one of the reasons why the damage summation laws, which are widely used for the development of kinetic fracture theories, are nonlinear.

A separate class of damages is responsible for the scatter of values of elastic characteristics. This fact explains why the known damage accumulation models, including those based on the LM hardness method and using current values of elastic moduli and transverse strain coefficients as criteria, give correlating values of the damage level. The above-mentioned criteria are as follows:

the elastic modulus deviation in the form [5]

$$\varepsilon_p = \Delta E / E',$$

where E' is the current value of the elastic modulus;

the deformation criterion given by [9]

$$\varepsilon_p = (1 - 2\mu)\varepsilon,$$

where μ is the transverse strain coefficient for a strain ε ;

the criterion in the form of the Gumbel homogeneity coefficient (1) calculated by elastic characteristics, namely, the transverse strain coefficient and elastic modulus,

$$\overline{\log k} = \frac{1}{n} \sum_{i=1}^n \log \mu_i, \quad \overline{\log k} = \frac{1}{n} \sum_{i=1}^n \log E_i.$$

Fig. 2. A relationship between the damage parameters determined by the elastic modulus deviation and the transverse strain coefficient (1) and by the scatter of elastic modulus and Poisson ratio (2).

The results of calculations by the above criteria for cast iron with different strain values (Fig. 2, line 1, light points), for steel 40Kh and aluminum alloy (line 2, dark points) render sufficient experimental proof of reliability of the above-mentioned correlation.

The data given in Table 1 can be analyzed by the parameters of the distribution functions plotted from the available experimental data on 28 tests.

In the case of a limited number of tests, a more generic in terms of loading conditions and material properties (plastic, low-plastic materials) parameter is the lognormal distribution whereby the distribution function $f(y)$ and the probability density $\varphi(y)$ are determined not from values of the variates x (normal distribution) but from the logarithms $y = \log x$,

$$\varphi(y) = \frac{1}{\sqrt{2\pi} \sigma_y^2} e^{-(y-a_y)^2/2\sigma_y^2}, \quad (2)$$

where σ_y^2 and a_y are the variance and expectancy of the variate $y = \log x$.

The frequency curves corresponding to the lognormal law and adequate to the event (probability) density curves were plotted from the measurements of elastic characteristics, yield stress and strength of the alloy and steel under study (Fig. 3). It is evident that the parameters of the curves pertaining to the scatter of characteristics of various mechanical properties of the same material differ considerably. Their expected quite logical ordered variation in the process of deformation is not confirmed either.

For the purpose of comparison, Fig. 3 shows experimental curves (dash lines) of the Weibull distribution which is usually applied to describe the test results for low-plastic materials under long-term static or cyclic loading. Nevertheless, for the plastic aluminum alloy V95 that exhibits a slight strain hardening the Weibull distribution curves and the lognormal curves are almost coincident (Fig. 3,e-h), while for steel 40Kh which is a less plastic material there is no such agreement (Fig. 3,a-d). A noteworthy finding is that for both materials the peak values of the curves of scatter of characteristics of each property are equal (within the unavoidable dispersion limits), although the Weibull distribution for steel 40Kh has a noticeable left-hand asymmetry with modes and medians differing from property to property.

Analysis of the results obtained has revealed a stable qualitative, as well as quantitative, correlation between the homogeneity coefficient m (1) and the maximum values of the probability density $\varphi_{\max}(y)$ (2) (see Table 2), the correlation coefficient α_{av} being almost the same for all characteristics of mechanical properties of both materials. This opens up new potentialities for the assessment of scatter of characteristics of the properties at hand by the parameters of the distribution density curve.

The correlation found can certainly be extended to the LM hardness method which is physically more substantiated and unbiased for the volume of material in the indentation zone which undergoes all the damage accumulation stages during the testing. This enables the LM hardness method to give the results which integrally represent the accumulated damages of various nature, i.e., the actual damage level in the material at a particular stage

Fig. 3. Distribution curves of Poisson ratios (a, e), elastic moduli (b, f), yield stress (c, g), and ultimate strength (d, h) for steel 40Kh (a–d) and aluminum alloy V95 (e–h).

TABLE 2. The Homogeneity Coefficient and Maximum Probability Density Calculated for the Characteristics of Various Mechanical Properties of Alloy V95 and Steel 40Kh

Mechanical property scatter parameters		Alloy V95				Steel 40Kh			
		E	μ	$\sigma_{0.2}$	σ_u	E	μ	$\sigma_{0.2}$	σ_u
m		71.46	22.46	158.55	110.73	53.21	18.57	16.17	33.00
$\Phi_{\max}(y)$	$\Phi_{\max}^{\lognorm}(y)$	25.70	8.16	48.94	41.47	19.14	6.70	5.82	11.91
	$\Phi_{\max}^{\text{Weibull}}(y)$	27.73	8.02	55.24	43.09	18.78	6.81	5.67	12.89
$\alpha = \frac{m}{\Phi_{\max}}$	$\alpha^{\lognorm}$	2.77	2.75	2.78	2.67	2.78	2.77	2.78	2.77
	α^{Weibull}	2.89	2.80	2.87	2.57	2.88	2.91	2.85	2.56
Mean value of the ratios	$\alpha_{av}^{\lognorm}$	2.743				2.775			
	$\alpha_{av}^{\text{Weibull}}$	2.782				2.800			

of its lifetime under study. One more factor that supports the great potential of the method is the theoretically and experimentally proven correlation between hardness and entropy [10], which is known to characterize a measure of disorder in any system, including a material in which an increase of the degree of dispersion is accompanied by a growth of entropy.

CONCLUSIONS

1. The characteristics of mechanical properties were found to have a larger scatter at early deformation stages than at further pre-fracture stages. This is indicative of a stagewise pattern of the damage accumulation process, where each stage can differ in the damage nature, nucleation mechanism, and rate of development.

2. More objective data on the actual damage level in a material can be obtained from tests by the LM hardness method which is sensitive to damages of various nature and thus integrally represents the degree of material degradation at a lifetime stage under consideration.

3. For the plastic aluminum alloy V95 the Weibull distribution curves are almost coincident with the lognormal curves, while for the less plastic material, steel 40Kh, they qualitatively differ from each other because of the left-hand asymmetry of the Weibull distribution.

4. There is a stable correlation between the homogeneity coefficient and the maximum values of the probability density, the correlation coefficient being almost the same for all properties studied of these two materials. This suggests that the parameters of the distribution density curves of characteristics of a property at hand can be used for the assessment of the damage level in the material.

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