4 The reciprocal rate of volume loss during the second steady-state period ($R_\sim$) is proportional to R_c. The value of the proportionality constant depends upon the structure of the steel.

5 The duration of the incubation and accumulation periods, which precede the first steady-state period, is primarily determined by the finishing condition of the surface.

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APPENDIX 1

Definition of Material Properties in Terms of Stress-Strain Characteristics

Strain Energy

The strain energy is defined as the energy per unit volume, supplied to a tensile bar during a tensile test performed until fracture occurs. It is mathematically expressed as follows:

$$U_s = \frac{\int_0^{\Delta l_f} F dl}{A_0 l_0} = \int_0^{\epsilon_f} \sigma d\epsilon$$

where

l = measuring length of tensile bar

l_0 = initial value of l

F = tensile force

A_0 = initial value of area of cross section of tensile bar

$\epsilon = \frac{\Delta l}{l_0}$, elongation

$\sigma = \frac{F}{A_0}$, tensile stress

f = fracture point

If a tensile test is continued after reaching the point at which the tensile force has its maximum value, subsequent deformation proceeds inhomogeneously [cf 10]. Thus, it seems more relevant to calculate the strain energy on the basis of the deformation energy per unit volume in the direct vicinity of the fracture, i.e., at the smallest diameter of the tensile bar. This true strain energy is formulated as follows:

$$U_s^* = \int_0^{\delta_f} \sigma^* d\delta$$

where

$\delta = \ln\left(\frac{l}{l_0}\right)$, logarithmic strain

$\sigma^* = \frac{F}{A}$, A being true area of cross section of tensile bar

In this case l and A denote the length and the cross-sectional area of a very small quantity of material in the direct vicinity of the point where fracture occurs at the end of the tensile test. In the region of homogeneous strain the formula $\delta = \ln(1 + \epsilon)$ holds. At fracture, σ^* and δ may be calculated from the tensile force at fracture and the smallest diameter of the fractured bar, making use of the assumption that the volume remains constant at plastic deformation.

Ultimate Resilience

The ultimate resilience is the maximum elastic energy per unit volume at the point of maximum tensile force in the stress-strain diagram. It may be defined as either $\frac{1}{2}\mathrm{UTS}^2/E$ or $\frac{1}{2}\mathrm{UTS}^{*2}/E$ where

$$\mathrm{UTS} = \frac{F_{\max}}{A_0}$$

and

$$\mathrm{UTS}^* = \frac{F_{\max}}{A} = \mathrm{UTS} \times \frac{A_0}{A}$$

Work-Hardening Exponent

The definition equation of the work-hardening exponent (n) is

$$\sigma^* = b\delta^n$$

in which b is a constant. It should be emphasized, that this is an empirical formula [cf 10].

APPENDIX 2

The Bravais-Pearson correlation coefficients were computed, using the following formula:

$$\gamma = \frac{N\Sigma xy - (\Sigma x)(\Sigma y)}{\sqrt{[N\Sigma x^2 - (\Sigma x)^2][N\Sigma y^2 - (\Sigma y)^2]}}$$

In this formula N denotes the number of measurements (14 in this case).

DISCUSSION

F. G. Hammitt[2]

Mr. Tichler and his coauthors are to be commended upon this comprehensive cavitation damage study upon a large variety of chromium steels. In connection with this work I would like to make the following more detailed comments.

[2] Professor-in-Charge, Cavitation and Multiphase Flow Laboratory, Mechanical Engineering Department, University of Michigan, Ann Arbor, Mich. Mem. ASME.

The authors obtain a very good correlation between the reciprocal volume loss rate for these materials and true ultimate tensile strength. However, I believe that a more general, and equally good, correlation would be obtained for the same data in terms of ultimate resiliance, since for the steels used the parameters are proportional (the elastic modulus of the steels is presumably approximately constant). Ultimate resiliance was originally suggested by Hobbs (Ref. 6 of paper). In very comprehensive tests on a wide variety of materials, we have found the linear correlation with this parameter to be superior to that with any other single parameter (reference [7] of paper, and also references [11 and 12][3] of this discussion). This conclusion has also been verified in recent tests at the Indian Institute of Technology [13].

We agree, as does the recent Indian work, that a good correlation is not obtained with strain energy (reference [5] of paper), and in fact with hardened steels the correlation is actually inverse with this latter parameter.

In the considerable controversy which has existed in the literature in this country regarding the proper portion of the volume loss rate curve to be used for measurement purposes, we disagree with Mr. Tichler in his statement that Dr. Thiruvengadam advocates the use of the peak rate of volume loss, since he has in fact been the principal exponent of the use of the later "steady-state" portion. In company with Dr. Hobbs (reference [6] of paper), we have consistently advocated the use of the peak loss rate (reference [7] of paper and references [11 and 12] of discussion), since we feel that this portion of the curve, which occurs earlier in the test before the generally prohibitive damage existing in the latter portion is obtained, is of primary practical interest. In addition, I have never seen data which leads me to the conclusion that a later "steady-state" rate actually exists, which could be used for accurate measurement. Either the rate continuously decreases, or considerable oscillations occur leading to secondary and tertiary maxima, depending upon the material characteristics and the mode in which the material actually damages.

Additional References

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[3] Numbers 11–13 in brackets designate Additional References at end of discussion.

Authors' Closure

The authors are indebted to Professor Hammitt for his kind and well-taken remarks.

The authors confirm, that the elastic modulus of the steels is approximately constant. Thus, it is agreed, that a good correlation is found between the reciprocal volume loss rate and the ultimate resilience as suggested by Hobbs. The data, given in the first and third entry of Table 4, do not really discriminate between the ultimate tensile strength criterion and the ultimate resilience criterion. The authors feel that further research on this subject is necessary.

The authors agree that Thiruvengadam has been the principal exponent of the use of the later "steady state" portion. However, Thiruvengadam seems to withdraw from this point of view, as in reference [1] he presented a theory, in which he attached special importance to the peak rate of volume loss. According to this theory, no later steady state rate in volume loss exists, the wear rate shading off asymptotically to 0. This is in contradiction with the authors' observations. The volume loss versus time curves of the 14 chromium steels were measured on to 10,000 minutes, with time intervals of 1,000 minutes in the later portion of the curves. The values of $R\sim$ were calculated by simple linear regression from the last 4 to 6 points. Also, correlation coefficients were calculated for these straight lines. The calculated values of these correlation coefficients were in the range of 0.997 to 1.000, nine of them being higher than 0.999.

In order to check the strain energy criterion the authors calculated the correlations of R_c with U_s and $U_s{}^*$ (cf Table 4). The correlations of $R\sim$ with U_s and $U_s{}^*$ are not better (correlation coefficients of 0.58 and 0.32, respectively).