A THERMODYNAMIC BACKGROUND OF EMPIRICAL DEPENDENCE OF MATERIAL'S STRENGTH AND FRACTURE ON TIME

A.J.KRASOWSKY *) and L.TOTH**)

A correlations are established between two empirical parameters describing power law of steady state creep, creep rupture time, rate sensitivity of flow stress, high-cycle fatigue, etc. Formale and physical sources of this correlations are analysed. Analytical relationships are suggested to explain this correlation assuming that the activation energy depends on the logarithm of the reciprocal of stress. This approach relates the cohesive energy of material to the steady state creep and rupture time data. A simple formula is presented to estimate a priori the slope of the logarithm of rupture time versus the logarithm of rupture stress at given temperature.

INTRODUCTION

Two-parametric power relationships are often used in the material science in order to approximate the experimental data of the time-dependent characteristics of strength and fracture. The form of the power relationship is usually given as follows

$$y = C_i x^{n_i}, \quad i=1,2,3... \tag{1}$$

Equation (1) is used by Krasowsky and Toth (1), Frost and Ashby (2), Li (3) for isothermal steady state creep rate, $\dot{\varepsilon}$, with $y = \dot{\varepsilon}$; $x = \sigma$; $C_i = C_1$; $n_i = n_1 > 0$, or in reference (1) for creep rupture time, t_t, with $y = t_t$; $x = \sigma$; $C_i = C'_1$; $n_i = n' < 0$. It is possible to approximate the Woehler curve by the Eq.(1) with $y = N_t$ (cycles to failure); $x = \sigma_a$ (stress amplitude); $C_i = C_2$; $n_i = n_2 < 0$. Eq.(1) can be used for tensile testing at moderate strain rates with $y = \dot{\varepsilon}$; $x = \sigma$; $C_i = C_5$; $n_i = n_5 > 0$. The majority of cited here references use a linearisation of Eq.(1) in order to estimate the empirical parameters C_i and n_i. In this case Eq.(1) is transformed into a straight line of the form,

*) Institute for Problems of Strength, National Academy of Science of Ukraine.
**)University of Miskolc, Department of Mechanical Engineering.

$$lgy=n_i\ lgx + lg\ C_i \tag{2}$$

The main goal of our work is to establish the general relationships between above mentioned sets of experimental data and to explain why they have similar power law approximations [Eq.(1) -type] .

RESULTS

It is common within each of mentioned sets of the experimental data the established in reference (1) strong correlations between the C_i and n_i parameters. For each set of experimental data we plot n_1 versus lgC_1, n_1' versus lgC_1', etc. Fig.1 demonstrate these plots as an example corresponding to the Eq. (1). The following features are usually observed: a similar linear relationship exists between n_1 and lgC_1; for all materials the values n_1 and n_1' increase when the values lgC_1 and lgC_1' decrease; the absolute values $|n_1|$ and $|n_1'|$ decrease when the test temperature increases; the linear relations between n_1 and lgC_1 and between n_1' and lgC_1' are dependent only on the material; the absolute values $|n_1|$ and $|n_1'|$ are not very different for the same material when tested at the same loading conditions. Fig.2 demonstrates the n_2 vs. lgC_2 correlation for high cycle fatigue of high-alloyed steels. We will consider separately the formal and physical sources of the mentioned correlations.

Formal source of n_i vs. lgC_i correlation. It is possible to normalize the Eq.(1):

$$y = C_i x^{n_i} = B_i\left(x/x_0\right)^{n_i}, \qquad C_i = B_i / x_0^{n_i} \tag{3}$$

$$\lg C_i = \lg B_i - n_i \lg x_0. \tag{4}$$

Equation (4) represents the formal linear correlation between lgC_i and n_i depending on the normalized factor x_0. We can get or a direct ($x_0<1$), or inverse ($x_0>1$), or no ($x_0=1$) correlation. Evidently, only the case $x_0=1$ can not introduce a formal (artificial) correlation between n_i and lgC_i. Had we choosen the case $x_0=1$ no correlation is observed with the Eq.(4). However, the correlation between n_1 and lgC_1 is observed in Fig.1 and we have to find physical explanation for it.

Thermodynamic sources of the correlation between n_i and lgC_i.. The plastic deformation rate can be described by the rate theory according to the following

$$\dot{\varepsilon} = \dot{\varepsilon}_{0i} \exp\left[-U_i(\sigma^*)/kT\right] \tag{5}$$

The activation energy, U_i, has been given by Yaroshevich and Rivkina (4), Pisarenko, Krasowsky and Yokobory (5) as the logarithmic function of the stress

$$U_i(\sigma^*) = U_{0i} \ln \frac{\sigma^*_i(0)}{\sigma^*} \tag{6}$$

Relation (6) have been demonstrated repeatedly for tensile tests in references (4,5) and for creep in references (1,3). In the case of steady state creep rate Eqs.(1),(5) and. (6) gives:

$$\lg C_1 = \lg \dot{\varepsilon}_{01} - \frac{U_{01}}{kT} \lg \sigma *_1 (0); ... n_1 = U_{01}/kT \tag{7}$$

which reflect a linear correlation, Eq.(4), between n_1 and $\lg C_1$, so far as for the material of given structure and at given a temperature the values of preexponential factors, $\dot{\varepsilon}_{01}$,t_{0i}, and effective stresses at absolute zero, $\sigma *_1 (0)$,$\sigma_i^{*'}(0)$, can be considered as constants. It follows from Eqs.(7) that $n_1 \sim 1/T$ which demonstrated by Fig.3. Would the n'_1-values be plotted with a negative sign against 1/T so as to be comparable with Fig.3, they are similar in character as in reference (1). For the materials tested at the same temperatures in both the steady state creep and the creep ruture regimes, the values n_1 and $-n_1'$ are similar. The values U_{01} and U'_{01} should also not be quite different although they characterize different processes (steady state creep and creep rupture respectively). This fact is a reflection of the Monkman-Grant (7) empirical rule. Therefore, from the Monkman-Grant rule it follows $n_1 \approx -n'_1$ and $U_{01} \approx U'_{01}$.It should be mentioned here for all the materials the good correlation have been established between the value U_{01} estimated by Eq.(7) and the value $3RT_m$. This correlation is demonstrated by Fig.4. The good correlation between U_{01} and T_m is apparently evidence of the direct relation of U_{01} to the interatomic potential of material. From Fig.4 the simple formula for the a priori evaluation of the values n_1 and n'_1 is as follows:

$$n_1 \approx -n_1^{'} \approx 3\frac{T_m}{T} \tag{8}$$

This formula is verified for the pure metals. It predicts minimum value of n_1= 3 which does not contradict to the experimental observations, reference (2). From Eq.(8) the values n_1 and n'_1 are sensitive to structural parameters which affect the melting point of the material (e.g. crystallographic structure) and are insensitive to other parameters (e.g. dislocation structure, grain size, etc.). The most obvious practical significance of Eq. (8) is in its possibility to predict for given temperature both the steady state creep rate dependence on stress and creep rupture time dependence on stress by using the creep curve for only one specimen tested at given temperature.

CONCLUSIONS

A strong linear correlation exists between the parameters n_1 and $\lg C_1$; n'_1 and $\lg C'_1$. The reason for such correlation is the thermally activated processes of the plastic flow and of the creep damage of material. The slopes n_1 and $-n'_1$ are inversely proportional to temperature. The constants U_{01} and U'_{01} are directly related to the material's cohesive energy. This is the main reason for existance of the Monkman–Grant rule.The slopes n_1 and n'_1 can be simply estimated [Eq.(8)] from knowlege only of the melting and test temperatures.

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SYMBOLS USED

C_i, n_i = material parameters

k = Boltsman constant (J/K)

T, T_m = absolute temperature and melting temperature, respectively (^{0}K)

U_i, U_{0i} = activation energy and constant with unit of energy (kJ/mol)

R = universal gas constant (J/mol.K)

σ, σ^*, σ_μ = applied, effective and athermal stress, respectively (MPA)

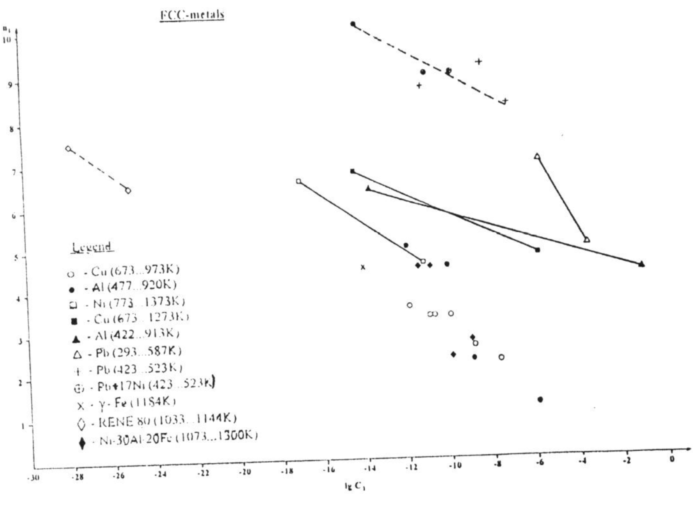
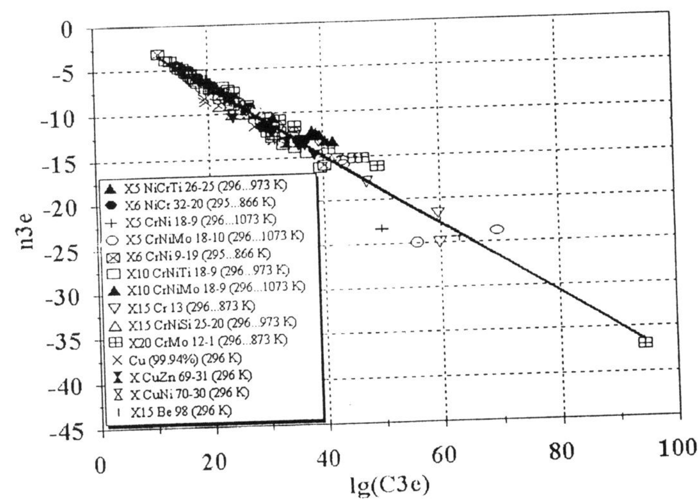


Fig. 1. Relation between the parameters n_1 and lgC_1 [Eq.(1)] for the minimum creep rate of face centered cubic metals. The units are: stress [MPa], creep rate [sec^{-1}].



`Fig. 2. Relation between the parameters $n_2 = n_{3e}$ and $lgC_2 = lgC_{3e}$ of Eq.(1) for high-cycle fatigue of high-alloyed steels.

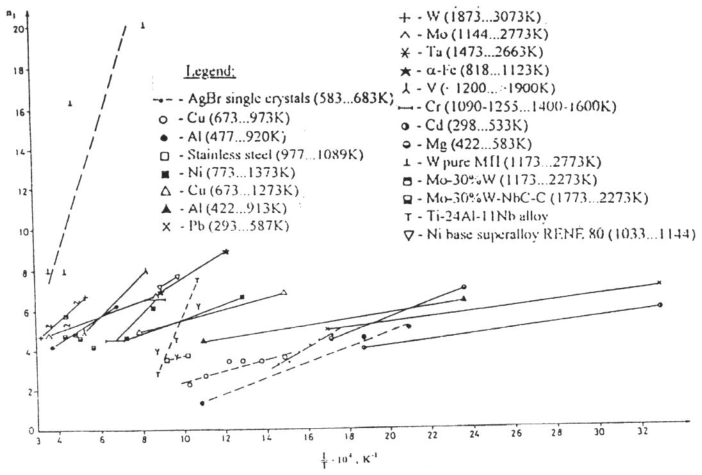


Fig.3. Dependence of the exponent n_1 for power law of creep [Eq.(1)] on the reciprocal of the testing temperature.

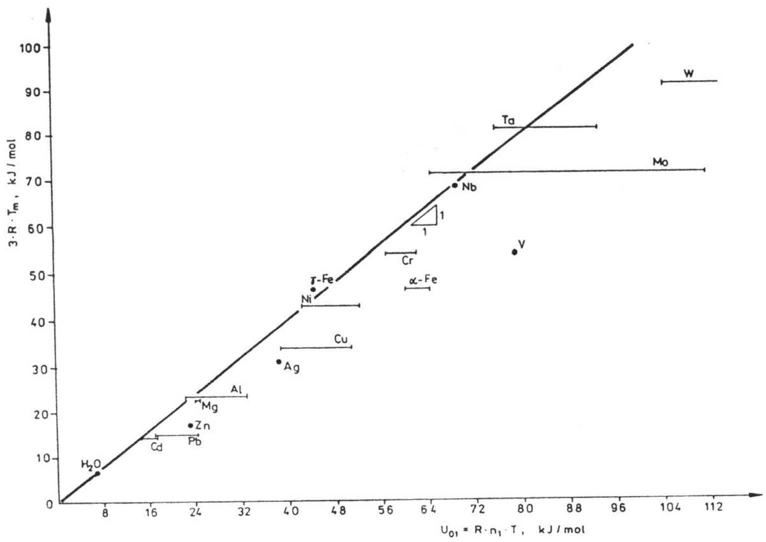


Fig.4. Dependence of the constant U_{01} [Eq.(8)] on T_m at steady state creep.