Influence of loading speed on tensile strength characteristics of high tensile steel

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ABSTRACT

The purpose of this paper is presented a rational method of predicting dynamic/impact tensile strength of high tensile steel materials widely used for structural material of automobiles. It is known that the ultimate strength is related with the loading speed and the Lethargy Coefficient from the tensile test. The Lethargy Coefficient is proportional to the disorientation of the molecular structure and indicates the magnitude of defects resulting from the probability of breaking the bonds responsible for its strength. The coefficient is obtained from the simple tensile test such as failure time and stresses at fracture. These factors not only affect the static strength but also have a great influence on the dynamic/impact characteristics of the joint and the adjacent structures. This strength is used to analyze the failure life prediction of mechanical system by virtue of its material fracture. The impact tensile test is performed to evaluate the life parameters due to loading speed with the proposed method. Also the evaluation of the dynamic/impact effect on the material tensile strength characteristics is compared with the result of Campbell-Cooper equation to verify the proposed method.

NOMENCLATURE

τ : Life ($\sec$)
τ_0 : Life Coefficient ($\sec$)
U_0 : Bonding Energy ($KJ/mole$)
k : Boltzmann Constant ($KJ/mole \cdot K$)
T : Temperature (K)
m : Lethargy Coefficient ($KJ/mole \cdot mm^2/N$)
τ_u : Failure Time ($\sec$)
σ_u : Ultimate Strength (MPa)
$\dot{\omega}$: Strain Rate ($\sec^{-1}$)
$\dot{\sigma}$: Loading Speed ($mm/\sec$)
m' : Dynamic Lethargy Coefficients ($KJ/mole \cdot mm^2/N$)
Subscripts
F : High speed tensile
S : Low speed Tensile

INTRODUCTION

If the repeated impacts or high speed tension between two surfaces produce local elastic cyclic deformations, the impact-induced cyclic deformations result in a field of sub-surfaces micro cracks that grow and coalesce in accordance with the surface fatigue behavior. Especially, the automobile structures must have shock-absorbing capacity preserve from accidents. Thin high tensile steel materials are widely used for structural of automobiles for weight reduction and high shock-absorbing capacity, simultaneously.

Theoretical as well as practical importance has simulated much interest in the mathematical modeling of the mechanical response of vehicle structural materials under-going severe impact or fast tension. Campbell and Cooper[1] tested for mild steel at medium strain rates, Shi and Meuleman[2] analyzed for the strain rate sensitivity of automotive steels, Cower and Symonds[3] discovered the strain effects in the impact loading of cantilever beams, and Paik et al.[4] presented the benchmark test results of high tensile steel.

To estimate the ultimate tensile strength characteristics of high tensile steel for influence of loading speed, Lethargy Coefficient concept and Campbell-Cooper equation with Paik's experimental results are used. Lethargy Coefficient concept[5,6] is proper to predict the fatigue life of complicated automotive structural materials with fast and even more easy.

LETHARGY COEFFICIENTS, ULTIMATE STRESS AND LOADING SPEED

Lethargy Coefficients

Zhurkov[7] expressed the fatigue life of materials as follows

$$\tau = \tau_0 \exp\left(\frac{U_0 - m\sigma}{kT}\right) \tag{1}$$

From Eqn. 1 and statistical molecular dynamics, the thermal oscillations of atoms or molecular in material lattices is written as dt/τ_0 during the time dt, the probability of dislocation becomes

$$e^{\left(-\frac{U_0 - m\sigma}{kT}\right)} \frac{dt}{\tau_0} \tag{2}$$

In the Eqn. 2, mechanical failures are occurred when the probability of dislocation is 100%, that is, one atom is fully dislocated from unstable zone to stable zone on the lattice. It is fully broken into two parts within this period so called the fatigue life of materials

$$\int_0^{\tau} \frac{dt}{e^{\left(\frac{U_0 - m\sigma(t)}{kT(t)}\right)}} = 1 \tag{3}$$

Since Lethargy Coefficient m is the material dependent property, a lot of tensile test are needed to determine m. In this paper, simple tensile test results performed by Yang et al.[8,9] are used for computed the Lethargy Coefficients :

$$m = \frac{U_0}{\sigma_0}(1-\eta) \tag{4}$$

and

$$\eta = \frac{\ln\left(\frac{\tau_u}{\tau_0}\right)}{\frac{U_0}{kT}}\left(1 - \frac{\ln\left[\frac{U_0}{kT} - \ln\left(\frac{\tau_u}{\tau_0}\right)\right]}{\ln\left(\frac{\tau_u}{\tau_0}\right)\left[1 - \frac{U_0}{kT} - \ln\left(\frac{\tau_u}{\tau_0}\right)\right]}\right)$$

where fatigue life with ultimate stress σ_u and failure time τ_u in a constant loading speed.

Ultimate Stress and Loading Speed

If a stress is constant with variable loading speeds, Eqn. 3 becomes

$$\int_0^{\tau_u} \frac{dt}{\tau_0 e^{\left(\frac{U_0 - m\sigma(t)}{kT(t)}\right)}} = 1 \tag{5}$$

From $\sigma_u = \dot{\sigma}\tau_u$, ultimate stress σ_u is expressed

$$e^{\frac{m\sigma_u}{kT}} = 1 + \frac{m\sigma_u}{kT}\left(\frac{\tau_0}{\tau_u}\right)e^{\frac{U_0}{kT}}$$

$$\sigma_u = 1 + \frac{m\sigma_u}{kT}\left(\frac{\tau_0}{\tau_u}\right)e^{\frac{U_0}{kT}}$$

$$= \frac{U_0}{m} + \frac{kT}{m}\ln\left(\frac{m\tau_0\dot{\sigma}}{kT}\right)$$

or

$$\sigma_u = \frac{kT}{m}\left(\frac{U_0}{kT} + \ln\left(\frac{m\tau_0}{kT}\right) + \ln(\dot{\sigma})\right) \tag{6}$$

Let the ultimate stresses be σ_{UF} at high-speed tensile test and σ_{US} at low speed tensile test. Also Lethargy Coefficient are m_F and m_S at corresponding test, respectively. The ratio of σ_{UF} and σ_{US} can be written as

$$\frac{\sigma_{UF}}{\sigma_{US}} = \frac{\left\{\frac{U_0}{kT} + \ln\left(\frac{m_F\tau_0}{kT}\right) + \ln(\dot{\sigma}_F)\right\}}{\left\{\frac{U_0}{kT} + \ln\left(\frac{m_S\tau_0}{kT}\right) + \ln(\dot{\sigma}_S)\right\}} \tag{7}$$

ULTIMATE STRESS CHARACTERISTIC EQUATION WITH LETHARGY COEFFICIENTS

In automobile structures, the influence of loading speed of the high tensile steel material should be examined. To estimate the dynamic final tensile stress of material, the Cambel-Cooper equation has been widely used, namely

$$\frac{\sigma_{TD}}{\sigma_T} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{q}} \tag{8}$$

where σ_T is the final tensile stress, σ_{TD} is the dynamic final tensile stress, and $\dot{\varepsilon}$ is the strain rate. D and q are material coefficients determined on the basis of test data. For the high tensile steel $D = 6844\,(\sec^{-1})$ and $q = 3.91$ [1].

The Dynamic Lethargy Coefficient, m' is introduced in terms of the Lethargy Coefficient and loading speed from Eqn. 4 and Eqn. 6 :

$$m' = (m,\ \dot{\sigma}) \tag{9}$$

Ultimate stress characteristic equation with the Dynamic Lethargy Coefficient becomes

$$\frac{\sigma_{UF}}{\sigma_{US}} = \frac{\left\{\frac{U_0}{kT} + \ln\left(\frac{m'_F\ \tau_0}{kT}\right) + \ln\left(\dot{\sigma}_F\right)\right\}}{\left\{\frac{U_0}{kT} + \ln\left(\frac{m'_S\ \tau_0}{kT}\right) + \ln\left(\dot{\sigma}_S\right)\right\}} \tag{10}$$

EXAMPLE

To verify the proposed equation of Eqn. 10 with Dynamic Lethargy Coefficients, the comparing by using the data of dynamic/impact with the Cambel-Cooper equation is presented. Paik's experimental data[4] are used as shown in Table 1. These data were measuring ultimate tensile stress with varying loading speed from $100\,mm/\sec$ to $950\,mm/\sec$ of which strain rate are in $10^0 \sim 10^4\ (\sec^{-1})$ for specimen thickness $0.71\,mm$, width $25\,mm$ and shoulder radius $15\,mm$.

When the dynamic/impact loads are applied, these responses are mainly affected by material loading speed. Figure 1 shows the ultimate stresses of high tensile steel under the different loading speed.

Lethargy Coefficient must be modified as follows from Eqn. 9, and then substituted into Eqn. 10.

$$m' = m - n\ \dot{\sigma} \quad , \qquad m = 2.13,\ n = 0.00055$$

As shown in Eqn. 10 and Figure 1, the ultimate stresses of material increases with enlarge the loading speed like other existing equations. On the basis of experimental data[4], the proposed equation of Eqn. 10 is more approximate than the Cambel-Cooper equation.

TABLE 1
Test results of high tensile steel under uniaxial tension

Specimen	Cross-head speed($mm/\sec$)	Strain rate ($\sec^{-1}$)	Yield stress (MPa)	Ultimate tensile stress(MPa)
HT-100	100	2	342.0	410.6
HT-300	300	6	350.0	429.4
HT-600	600	12	390.0	467.9

HT-950	950	19	425.0	537.6

CONCLUSION

To estimate the dynamic/impact properties in the automobile crushing and dynamic situation, this paper presents the dynamic final strength of thin high tensile steel material with loading speed varying. Thin high tensile steel is widely used for automobile structural material to endure dynamic/impact severeness and to reduce the total weight of automobile, simultaneously.
Ultimate stress characteristic Equation for thin high tensile steel is formulated with the Dynamic Lethargy Coefficients. Lethargy Coefficients concept is proper to predict material properties with easy and fast. To investigate the accuracy and applicability of the ultimate stress characteristic

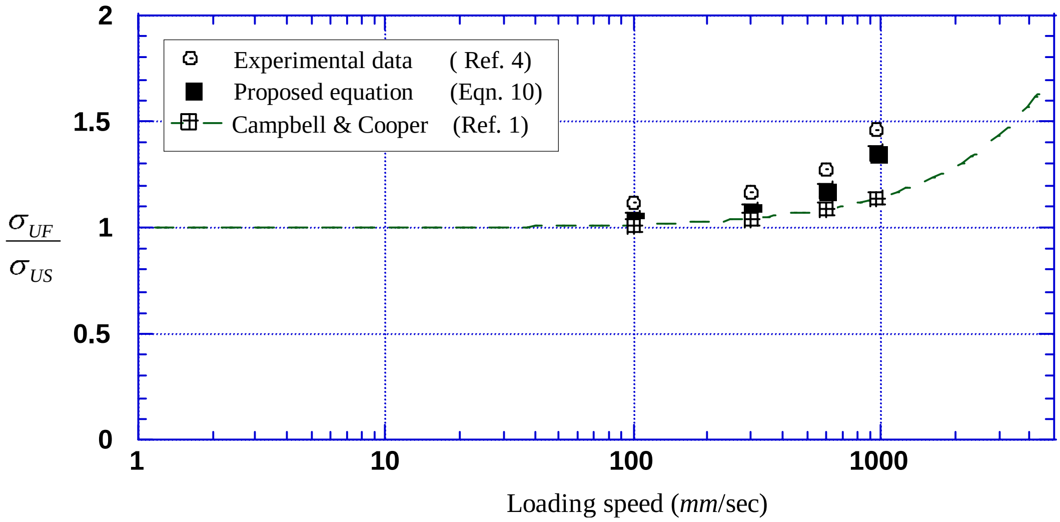

Figure 1: Ultimate stress of high tensile steel with increase loading speed

equation, the comparing with the Cambel-Cooper equation is carried out. Based on the experimental data, Ultimate Stress Characteristic Equation is more accurate and applicable to conventional iterative experimental method.

In beginning of design of vehicle, for the situation of impact and dynamic, presented method would be very helpful for prediction of ultimate stress varying resulted from the structural modification. This method will reduce the coast and the time consuming for design of vehicle and making a prototype.

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