TEMPERATURE EFFECTS IN SPALL MECHANICS

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It is well-known that spall fracture is the result of a cumulative process which includes nucleation, growth and coalescence of microvoids or microcracks. Dynamic fracture is generally dependent on strain rate, stress state, loading history, microstructure and also initial temperature. The objective of this contribution is to analyze and modelize the effect of initial temperature on the threshold stress of spalling. A new spall criterion, based on cleavage and plasticity, combined via probability relation with two simple cumulative criteria for low and high temperature, is proposed.

INTRODUCTION

Only limited number of experimental data exists concerning the effect of initial temperature on spall strength of metals. The initial temperature in the whole range, 0-T_m (K), where T_m is the melting temperature, changes the kinetics of nucleation and growth of failure. The final fracture is the result of a competition between the cleavage mechanisms for relatively low temperature and ductile mechanisms for higher temperatures. It is very important to understand the final effect of the initial temperature caused by different contributions of plasticity and cleavage to fracture. Moreover, during material separation, a local temperature increases due to localization of plastic deformation and formation of adiabatic micro-shear bands, have also an influence on the coalescence stage.

Departure point of the present study is a literature survey (1, 2, 3) where some experimental results have been reported on spall fracture at temperatures from 77K to 1073K. Several materials like aluminum alloys, steel, copper, titanium and nickel were tested.

In order to model all temperature contributions, a universal cumulative criterion has been formulated which is based on two simple fracture criteria of

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spall : one for quasi-cleavage separation and the second for fracture mechanisms associated with plasticity. A statistical partition of each micromechanism is assumed.

This approach has been applied for an aluminum alloy which had been studied in plate impact configuration at LPMM-Metz. This unified criterion allows to predict the spall fracture in a wide range of temperatures.

EXPERIMENTAL DATA

In order to analyze the temperature influence on the dynamic fracture of metals, some Russian authors (1, 2, 3) have performed spall experiments over a wide range of temperature from very low up to the melting point. The mean results are presented in Fig.1 and Fig.2, where spall strength versus homologous temperature is plotted. From these data, it is possible to formulate two important remarks :

- the two mechanisms, cleavage and plasticity, play a role with different proportion. For example, plasticity dominates for steel Z12CNT18-10, whereas, cleavage and plasticity, at higher temperatures, characterize behavior of pure iron, Fig.1 ;

- for some alloys, spall strength varies little in a wide interval of temperatures, but it sharply decreases when temperature approaches the melting point, Fig.2.

In fact, the temperature range can be separated into three parts. One range at low temperatures where the brittle fracture dominates (local stress state controls fracture), the second range at intermediate temperatures where a brittle to ductile transition is observed, and the last part concerning high temperature, where ductile fracture dominates (plasticity controls fracture). After those remarks new spall criteria for all ranges of temperature are proposed.

SPALL CRITERIA

A temperature-dependent cumulative spall criterion was proposed and proved to be useful in reference (4). This criterion can be applied for a low temperature range when cleavage dominates. The explicit form is given by eq.(1).

$$t_{c_0} = \int_0^{t_c} \left(\frac{\sigma_F(t)}{\sigma_{F_0}} \right)^{\alpha(T)} dt \qquad t_c \leq t_{c_0} \quad \text{and} \quad \sigma_F \geq \sigma_{F_0} \qquad (1)$$

σ_{F_0}, t_{c_0} and $\alpha(T)$ are three material constants at constant temperature, t_{c_0} is the longest critical time when $\sigma_F(t_{c_0}) = \sigma_{F_0}$. The exponent α is temperature dependent and is related to the activation energy of material separation by the following relation : $\alpha(T) = \Delta G_0 / kT$, where k is the Boltzmann constant. In the particular case of square pulse the criterion takes the form :

$$\sigma_F = \sigma_{F_0}\left(\frac{t_{c_0}}{t_c}\right)^{kT/\Delta G_0} \qquad t_c \le t_{c_0} \qquad \text{and} \qquad \sigma_F \ge \sigma_{F_0} \tag{2}$$

If we analyze eq.(2), it is observed that spall strength increases with temperature. In order to take into account plasticity, another spall criterion based on rate-dependent plasticity is proposed. Equation (3) summarize the physics behind this criterion. The frequency of microdefects apparition, $\dot{\delta}$, is both due to the applied stress amplitude, eq.(4), and the effect of stress on activation energy of material separation, eq.(5).

$$\dot{\delta} = \dot{\delta}_0^{'}(\Delta\sigma)\dot{\delta}_0^{*}[\Delta G(\Delta\sigma)] \tag{3}$$

where $\dot{\delta}_0^{'} = \dot{\delta}_0\left(\frac{\Delta\sigma}{\Delta\sigma^0}\right)^{\beta}$ **(4)**

and $\dot{\delta}_0^{*} = \exp\left(-\frac{\Delta G(\Delta\sigma)}{kT}\right)$ **with** $\Delta G = \Delta G^0\left(1-\left(\frac{\Delta\sigma}{\Delta\sigma^0}\right)^{p}\right)^{q}$ **(5)**

with $\Delta\sigma = \sigma_F - \sigma_{F_0}$**, and** $\Delta\sigma^0 = \sigma_F^0 - \sigma_{F_0}^0$**, where** $\sigma_{F_0}, \sigma_{F_0}^0, \sigma_F^0, \beta, \Delta G^0, p, q$ **are material constants. It is also assumed that fracture occurs via a cumulative process. When the condition (6) is satisfied, the fracture is complete.**

$$\int_0^{t_c} \dot{\delta} dt = \delta_c \tag{6}$$

By putting : $\delta_c / \dot{\delta}_0 = t_c^0$**, one obtains the final expression :**

$$\int_0^{t_c}\left(\frac{\Delta\sigma}{\Delta\sigma^0}\right)^{\beta}\exp\left\{-\frac{\Delta G^0}{kT}\left(1-\left(\frac{\Delta\sigma}{\Delta\sigma^0}\right)^{p}\right)^{q}\right\}dt = t_c^0 \tag{7}$$

If a square pulse is considered, the criterion takes the following simplified form :

$$\frac{t_c^0}{t_c} = \left(\frac{\Delta\sigma}{\Delta\sigma^0}\right)^{\beta}\exp\left\{-\frac{\Delta G^0}{kT}\left(1-\left(\frac{\Delta\sigma}{\Delta\sigma^0}\right)^{p}\right)^{q}\right\} \tag{8}$$

By plotting the spall strength versus temperature according to eq.(6), a decreasing curve is obtained. This second criterion is true for relatively longer loading time and/or for elevated temperature. To calculate the spall strength in the total range of temperature, a probability relation, eq.(9), balancing contributions of eq.(2)

and eq.(8) have been used, (5). It is reasonable to suppose that the plasticity contribution increases with temperature from probability P_{pl} at 0K to 1 at melting point. The value of P_{pl}, (from 0 to 1), can be determined by microscopic observation of fracture surface. Finally, the threshold stress is found.

$$\sigma_F = \left(1 - P_{pl}\right)\left(\sigma_F^{cl}\right) + P_{pl}\left(\sigma_F^{pl}\right) \tag{9}$$

COMPARISON WITH EXPERIMENTAL DATA

A series of tests have been performed at room temperature with the plate/plate impact configuration on aluminum alloy 7020-T6 in order to determine the spall strength at different level of spall and different loading time. The constants of eq.(2) and eq.(8) have been determined by fitting the points of the incipient spall presented in Fig.3. In Fig.4 the two criteria are plotted for 7020-T6.

CONCLUSIONS

It is well-known that dynamic fracture includes cleavage and plasticity micro-mechanism with different proportion, which is temperature dependent. Spall fracture is also cumulative in nature. Derivation of the global spall criteria using the concept of thermally activated processes is not new. It is demonstrated however, that such concept can lead to more universal spall criteria applicable to a wide range of temperatures.

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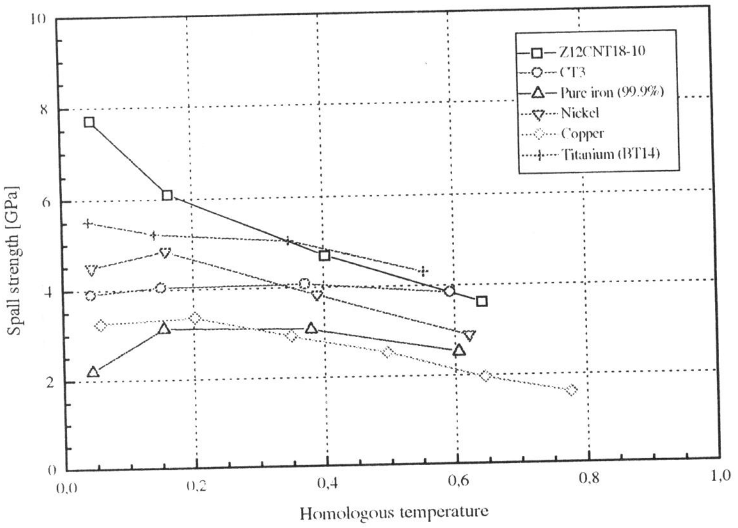

Fig.1 Spall strength vs. homologous temperature for several materials, re-analyzed after (1, 2, 3).

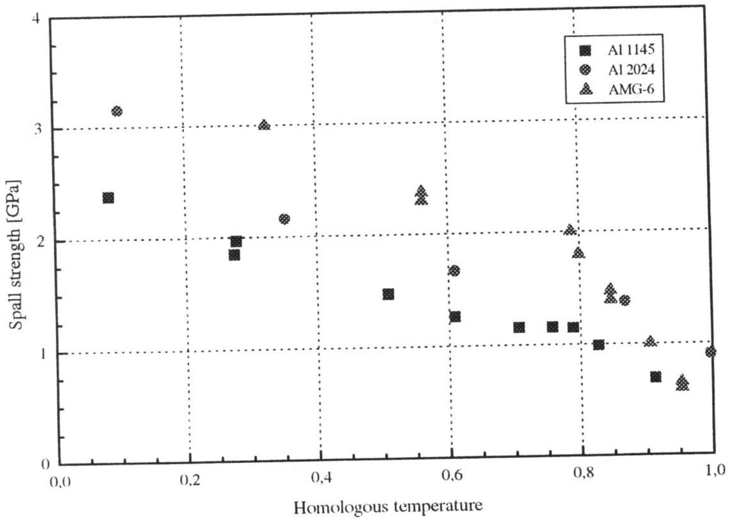

Fig. 2 Spall strength vs. homologous temperature for three aluminum alloys, re-analyzed after (1, 2, 3).

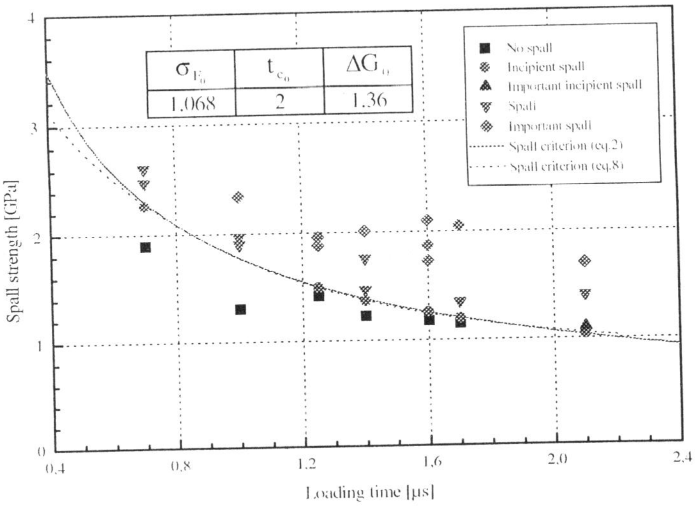

Fig.3 Spall strength vs. loading time for aluminum alloy 7020-T6 at room temperature, the doted line represents eq.(2) and the solid line represents eq.(8).

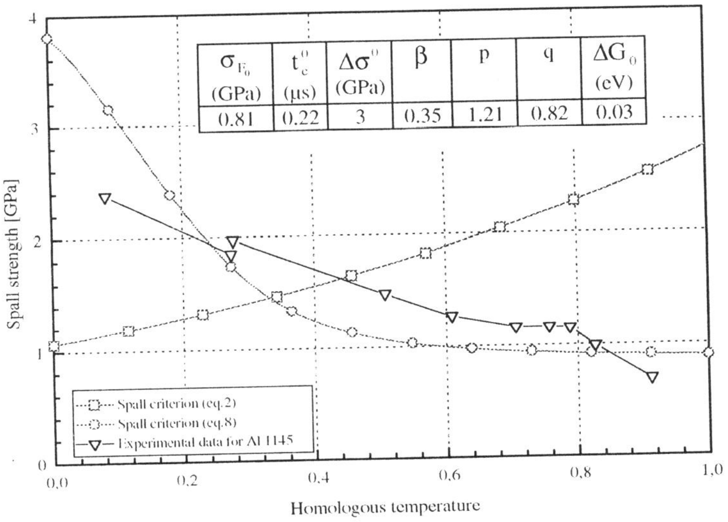

Fig. 4 Spall strength vs. homologous temperature for aluminum alloy 7020-T6.