SPALLING OF ALUMINUM ALLOY 7020-T6, EXPERIMENTAL AND THEORITICAL ANALYSES

P.F.Chevrier and J.R.Klepaczko*

Dynamic tensile fracture of metals and alloys is generally strongly affected by rate of loading (or strain rate), stress state, temperature and also by loading history. One representative of tensile fracture at short time loading is spallation. A short discussion of existing spalling criteria, a new simple cumulative criterion, experimental setup and test results for aluminum alloy 7020-T6, are presented in this paper. The results for this material are also compared with similar data obtained for different aluminum alloys.

INTRODUCTION

A special case of dynamic fracture is spallation of materials exposed to high-rate tensile loading. This type of damage is a result of tensile stress created by reflection of compression waves at the interfaces adjacent to low impedance media. More specifically, in the case of plate loaded by a plane impact the initial compressive stress wave traveling across the plate reflects back at the free surface as a tensile wave. The superposition of the propagating compressive and tensile wave fronts, when of sufficient intensity (amplitude) and time duration, can cause partial or complete separation inside of the target material along a plane perpendicular to the propagation direction of the wave fronts. The process of spallation has been studied in a number of laboratories with a view to obtain acceptable criteria for dynamic fracture at high loading rates. Post- fracture photomicrographic observations have shown that spallation in the form of free surfaces represents the end result of an accumulation of micro damage that takes place during the tensile phase of the stress wave loading. In

* Laboratory of Physics and Mechanics of Materials, Metz University.

ductile materials the micro-damage consists of microvoids that nucleate, grow and finally coalesce to the form of separation plane inside of the material.

In this paper, the most common criteria are discussed which are representative for the present state of the art and a more detailed discussion is focused on a relatively new time-dependent cumulative criterion proposed in ref.(1). In order to verify the validity of this criterion, a series of test have been performed with the plate/plate impact technique on aluminum alloy 7020-T6.

SPALL FRACTURE CRITERIA

Generalities

It is generally accepted that fracture process in a ductile material is due to microvoid nucleation, growth and coalescence, whereas in brittle materials fracture is due to the process of microcrack creation and propagation.

However, different approaches can be spotted in literature how to formulate the spall criteria. The first one, is analogous to the approach by micromechanics in the process zone represented in fracture mechanics. The second is a microstatistical approach, which takes into account an analysis of consecutive steps of damage in a material by counting and measuring the traces of the microfractures. After such analysis one can formulate statistical law which gives an empirical differential equations of damage evolution. In general, the spall fracture must be time-dependent in order to reproduce experimental observations and to be able to predict the results obtained at different conditions. The following three stages of ductile spall are commonly observed : the incipient, intermediate and complete. Each stage can be classified according to the severity of surface separation. The incipient spall can be found only by metallographic examination at high magnification. The intermediate spall can be visible without magnification and microcracks or microvoids are larger and sometimes connected. The complete spall is defined as a free surface (complete separation). The combination of the normal stress history $\sigma(t)$ and pulse duration t_c at which the complete spall occurs defines the threshold spall values needed to define a spall criterion. Such criterion must be based on wave dynamics and delay time in material separation. Experiments do show that the process of spallation, from the incipient stage to the final separation, must be time dependent. Simply, ductile materials require more time to create a free surface than brittle materials. Those differences are amplified by relaxation of the normal stress due to the local plasticity in the process zone. It is clear that spallation is a process with its specific kinetics. Thus, the physically plausible criteria of spalling found in the literature are based on two independent approaches. The first one proposed in ref.(2) is based on time evolution of microvoid population and size. Explicit form for the cumulative damage criterion is given in ref.(2).

$$\dot{N} = g(\sigma) \quad \text{and} \quad \dot{R} = h(\sigma, R_0) \tag{1}$$

where $\dot{N}(t)$ and $\dot{R}(t)$ are respectively time-dependent evolution of the number of microvoids or cracks and its size. Both rates are increasing functions of the overstress σ - σ_0, where σ_0 is the threshold stress below which no damage occurs, R_0 is the initial dimension of microvoid and σ is the instantaneous value of the tensile stress. The formulation in ref.(2) is logic but the problem of specifying the complete material evolution, including the range of microscopic voids, is clearly a formidable task. In addition, this treatment is empirical and cannot be extrapolated with confidence to other materials and loading conditions than applied. Recent progress made in quantitative fractography, ref.(3), may push forward our understanding of dynamic fracture phenomenology. Application of statistic models in numerical schemes are difficult and sometimes even impossible, mostly because lack of data.

A more simple approach is based on only one evolution equation, like eq.(1), (the first one). In principle the time to fracture t_c is a function of the applied tensile stress $\sigma(t)$.

If N_c is the critical number of microvoids accumulated during t_c then the spall criterion can be written as follows, ref.(4),

$$K = \int_0^{t_c} (\sigma - \sigma_0)^\delta \, dt \quad \text{and} \quad K = (\sigma_F - \sigma_{F0})^\delta \, t_c \quad , \sigma_F = \text{const} \tag{2}$$

with the threshold stress σ_{F0}, K and δ are material constants. Some improvements of such criterion have been proposed by different authors, ref.(5), (6) and (7). All criteria of spalling based on the overstress concept with σ_0, the measure of fracture stress at the longest critical time, $t_{c0} = K\, \sigma_0^{\delta}$, are applicable without difficulties into numerical codes.

Every kinetic process, including spallation, must depend on temperature. The most straightforward approach to fracture and spallation is to use the theory of thermally activated processes, for example in dynamic plasticity, ref.(6). The common feature of this theory, based on statistics, is that the rate a of a system overcoming an energy barrier is given by

$$\dot{a} = \dot{a}_0 \exp\left(-\frac{\Delta G}{kT}\right) \quad \text{and} \quad \dot{a}_0 = \dot{a}(\sigma)\exp\left(-\frac{\Delta G(\sigma)}{kT}\right) \tag{3}$$

where $\dot{a}_0$ is the characteristic frequency (attempt frequency) of the system oscillating in an equilibrium position in front of the barrier, and ΔG is the difference in free energy between the equilibrium position and the maximum position (the saddle point) of the barrier.

The term exp $(-\Delta G/kT)$ is related to the probability that the system can be excited to a state of the free energy higher by ΔG. In practice an exact form of eq.(3) is difficult to obtain for any thermally activated process, for example creation of a free surface (fracture). In case of spalling eq.(3) can be applied under the hypothesis that both the rate $\dot{a}$ and the free energy ΔG are functions of the normal stress σ. Eq.(3) can be an ample source of fracture criteria. A reasonable assumption in deriving a spall criterion is the constancy of the frequency factor $\dot{a}$ combined with a very simple dependence of the free energy on stress, the so called Yokobori's expression for the free energy

$$\Delta G(\sigma) = \Delta G_0 \ln \left(\frac{\sigma}{\sigma_0}\right) \tag{4}$$

If eq.(3) is combined with eq.(4) the final form of the spall criterion is obtained

$$t_{co} = \int_0^{t_c} \left(\frac{\sigma_F(t)}{\sigma_{F_0}}\right)^{\alpha(T)} dt \qquad \text{where} \qquad \alpha(T) = \frac{\Delta G_0}{kT} \tag{5}$$

at constant temperature T, σ_{F0}, t_{c0} and α are the three material constants, t_{co} is the longest critical time when $\sigma_F(t_{co}) = \sigma_{F0}$, for $t_c > t_{c0}$, $\sigma_F = \sigma_{F0}$. The exponent $\alpha(T)$ is related to the activation energy of material separation ΔG_0. When the process is nonisothermal the exponent $\alpha(T)$ is time-dependent, $\alpha(T,t) = \Delta G_0/kT(t)$, and eq.(5) must be integrated accordingly. This cumulative criterion in the form of eq.(5) has been proposed by Klepaczko, ref.(1), and several forms of the $\sigma(t)$ histories were analyzed in this reference. For the case of square pulse $\sigma_F(t) = \sigma_F H(t)$, where H(t) is the Heaviside step function the criterion takes the form

$$\sigma_F(t_c) = \sigma_{F0} \left(\frac{t_{co}}{t_c}\right)^{1/\alpha} \qquad \text{or} \qquad t_c = t_{co} \left(\frac{\sigma_{F0}}{\sigma_F}\right)^{\alpha} \tag{6}$$

The cumulative criterion in the form of eq.(6), has been so far verified for some aluminum alloys, however here, the criterion will be directly applied to alloy 7020-T6.

EXPERIMENTAL PROCEDURES AND RESULTS

The plate/plate configuration was used to produce a short tensile pulses in one-dimensional strain in a flat, round specimens. A flyer plate mounted on a cylindrical sabot is accelerated in a barrel by release of pressurized gas. The flyer impacts the target plate at desired velocity. All plate impact experiments can be performed in vacuum at different impact velocities from 50 m/s to 400 m/s. This high pressure gas launcher is controlled entirely by a computer and an automaton. The impact velocity is the only one parameter necessary to find the three constants after analysis of the specimen cross section. A series of plate impact tests have been performed on aluminum alloy 7020-T6 at different impact velocities and different plate thicknesses. Fig. 1, shows the spall strength σ_F vs. loading time for aluminum alloy 7020-T6, ref.(9), the solid line represents the spall criterion, eq.(6). Fig.2 shows the spall strength σ_F vs. loading time for aluminum alloy 2011 and 6061-T6, the solid lines represent again eq.(6).

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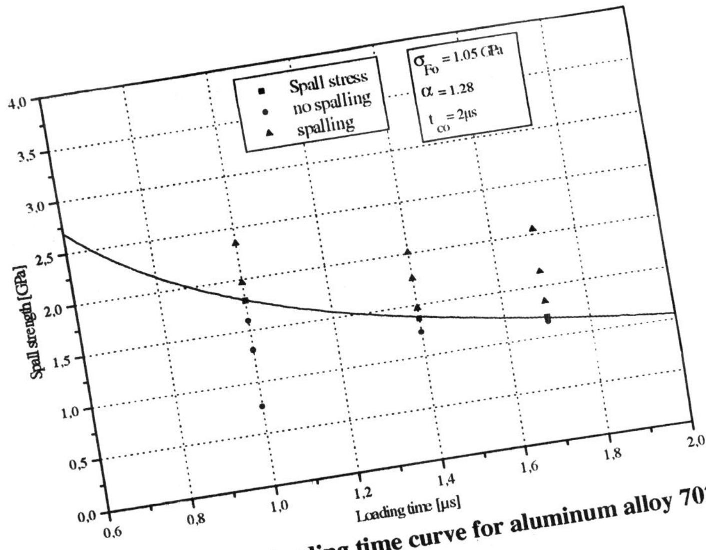

Fig. 1 Spall strength vs. loading time curve for aluminum alloy 7020-T6, the solid line represent eq.(6).

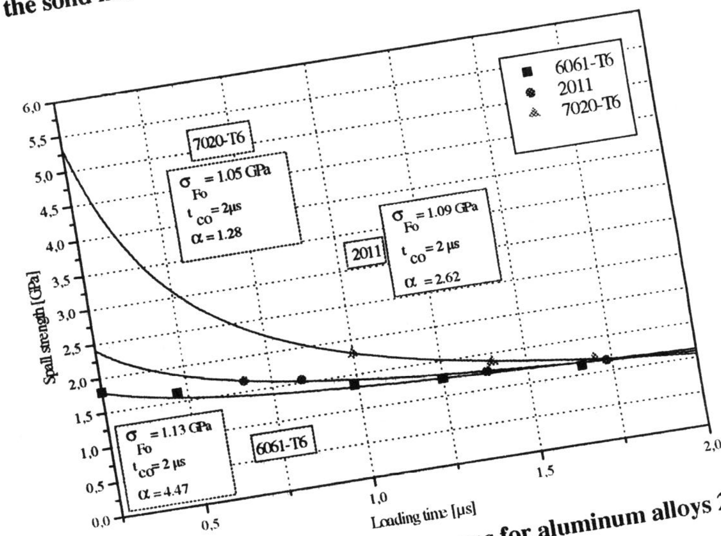

Fig.2 Spall strength vs. loading time curves for aluminum alloys 2011 and 6061-T6, the solid line represent eq.(6).