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Strain Rate Dependence of the Spall Strength of Steels

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Abstract : The data on the dynamic (spall) strength for more than 30 steels are reported. These data were interpreted in terms of the fracture mechanics. The experimental data are interpreted in terms of the energy-based spall theory which predicts the dependence of the spall strength on the strain rate in the spall plane. Even if most of the tested steels exhibit the agreement with this theory there are some exceptions. In order to explain this disagreement a modification of the theory mentioned above has been suggested. The obtained model predicts the observed steel behaviour.

Résumé. L'étude mentionne les valeurs de la résistance dynamique (d'écaillage) pour plus que 30 aciers. Ces valeurs ont été interprétées sur les bases de la mécanique de la rupture. Les résultats des expériences sont interprétés par la théorie énergétique d'écaillage prédisant la dépendance de la résistance d'écaillage et de la vitesse de déformation sur le plan d'écaillage. Malgré que la plupart des aciers examinés montrent l'accord avec cette théorie, il y a aussi des exceptions. Dans l'intention d'expliquer ces désaccords, une modification de la théorie mentionnée est proposée dans cet ouvrage. Le modèle obtenu prédit avec succès le comportement des aciers examinés pendant l'écaillage.

1.INTRODUCTION.

Spalling is a consequence of the nucleation, growth and coalescence of voids or cracks [1]. The fundamental mechanisms of these processes have been developed [2-5]. The spall models which involve these mechanisms generally need a large number of material parameters. Some of these parameters are difficult to obtain. Owing to this fact the simple and physically based models are required. One of them is the energy based spall theory [6]. This theory predicts the dependence of the spall strength on the strain rate, $\dot{\epsilon}$. At relatively gentle strain rates it was suggested that the spall process involves the activation and growth of mature ductile cracks before coalescence and spall fracture occurs. Ductile crack growth is assumed to be a K_{IC} (fracture toughness) controlled phenomenon and, consequently, the spall process is also K_{IC} controlled. As a result this model predicts that the spall strength, σ_c , should be proportional to $\dot{\epsilon}^{1/3}$. At higher strain rates it was suggested that spall in the same metal is a process of hole growth and coalescence without formation of mature cracks. In this event K_{IC} is not a violable material property. Hole growth and, consequently, the spall process is $\dot{\epsilon}$ (flow stress) controlled and spall strength is predicted not to depend on strain rate. Both kinds of behaviour have been actually observed e.g. in our study on the spall behaviour of steels [7].

However, with some steels, exhibiting ductile mode of crack growth, the model mentioned above doesn't predict the observed strain rate dependence of the spall strength. The modification of the energy - based spall theory is suggested in order to explain this discrepancy. The dependence $\sigma_c(\dot{\epsilon})$ is used in a computer code. The numerical results are compared with experimental ones. This comparison suggests that the theory gives a reasonable prediction of the fracture (spall) behaviour. The model requires only few parameters in addition to those required by the chosen equation of state and constitutive model. From this point of view this model seems to be useful for the solution of the practical engineering problems like explosive cladding etc.

2.EXPERIMENTS.

For the experiments the following materials were tested :

a) Structural steels which differ in chemical composition and mechanical and fracture properties. (Yield strengths $Y \in <300 - 1100> \text{MPa}$, Fracture toughness $K_{IC} \in <100 - 210> \text{MPa} \sqrt{\text{m}}$).

b) Cast austenitic steel (steel 18/8) (0.09 C, 18.64 Cr, 7.51 Ni, 0.16 Mn, 0.47 Si, 0.13 Mo - in wt.%). Yield strength = 197 MPa, Tensile strength = 476 MPa.

c) High strength steel (steel-2P) (0.28 C, 1.43 Mn, 0.014 P, 0.004 S, 0.06 Cu, 0.32 Ni, 0.14 Cr, 0.002V, 0.002 Al- in wt.%). Yield strength = 1590 MPa, Tensile strength = 1930 MPa.

The fracture behaviour of these steels has been studied with experimental method described in [8]. Specimens discs 100 mm in diameter were machined to thickness 20 mm. The specimen were subjected to shock loading produced by the detonation charge. This method enables to determine the loading pressure, $p(t)$, as well as the history of the free surface velocity, $v(t)$. The knowledge of $p(t)$ and $v(t)$ is sufficient to determine the spall strength, σ_c , and the strain rate, ε in the spall plane.

3.RESULTS.

In Fig.1 the values of σ_c and ε for structural steels are plotted.

Fig.1. The dependence of the spall strength on the strain rate for the structural steels.

These data can be fitted by the relation following from the energy - based spall theory :

$$\sigma_c = 3^{1/3} \left(\rho c_o \varepsilon K_c^2 \right)^{1/3}$$

where ρ is the material density, $c_o = (B/\rho)^{1/2}$ and B is the elastic bulk modulus.

The observation of the fracture surfaces approved that the fracture is the consequence of the ductile cracks growth. It means the fracture behaviour of these steels is in agreement with the prediction of the theory mentioned above. The experimental data for the remaining two steels are plotted in Fig.2.

Fig.2. Strain rate dependence of the spall strength (in GPa) for the steel -2P (boxes) and for the 18/8 steel (circles).

Their analysis leads to the conclusions that for the cast austenitic steel is $\sigma_C \sim \varepsilon^{0.54}$ and for the steel 2P is $\sigma_C \sim \varepsilon^{0.40}$. The appearance of the fracture surfaces is very similar to that for the structural steels - see Fig.3. In Fig.3 we can also observe some evidence of the fracture caused by the linkup holes without mature formation. It means that the fractures of these steels may correspond to the transition area between the K_C controlled and the Y controlled spall.

Fig.3. Fracture surface of the 18/8 steel .(503 x).

In order to explain the observed $\sigma_c(\varepsilon)$ dependencies we modified the present theory to the form described in the following session.

4. THEORY.

Our approach to the modelling of the spall process is based on the hypothesis that the transition from the K_c controlled to the Y controlled spall may go through the stage where the ductile crack exhibits some amount of the stable growth, commonly referred as to a R - curve. In order to develop an analytically amenable model several assumptions must be made. First, it is proposed that a theoretical R - curve originally developed for quasi - static crack extension [9] can be used also for the dynamic crack initiation. The validity of this assumption is supported by the results obtained in [10] where the interaction of stress wave with a semi - infinite Dugdale crack has been studied. It has been shown that the zone of yielding emanates from the tip of crack at the instant the tip is struck and for a step- stress wave it initially extends linearly with time. When the constant crack opening displacement is reached the crack tip also starts to propagate approximately linearly with time. It means that the time can be understood as a scaling parameter which cannot change the shape of a particular quasi - static R - curve at least at the very beginning of the interaction.

Secondly among various concepts of R - curve behaviour the concept introduced by Cherepanov [11] was chosen for its analytical simplicity. The basic equation of this concept is

$$\frac{\partial}{\partial l} R = \frac{3}{2} \frac{R_{\infty} - R}{R} \quad (1)$$

where R is an instantaneous yielding zone length, R_{∞} is the maximum value R just before the unstable fracture sets on and l is an instantaneous crack half - length. If we introduce the dimensionless variables

$$R_o = \frac{R}{R_{\infty}}, l_o = \frac{l}{R_{\infty}}$$

leads the integration of Eq.(1) to

$$l_o = -\frac{2}{3} R_o - \frac{2}{3} \ln(1 - R_o) + C \quad (2)$$

where the constant C determines the propagation threshold of yielding zone length for a given initial crack size.

In the next step we need to invert Eq.(2) to get an analytical formula for the function $R(l)$. Because the function (2) is not invertible analytically, Eq.(2) is fitted to the power function

$$l_o = a (1 - R_o)^b$$

The best fit we obtain for $a = 0.120893$ and $b = 0.7736$. Thus, an approximation of $R(l)$ may be assumed in the form

$$R = R_{\infty} \left(1 - .49 \left(\frac{R_{\infty}}{l} \right)^{1/3} \right)$$

Using the well - known relation for the length of plastic zone :

$$R = \frac{1}{8} \frac{\pi K^2}{\sigma^2}$$

and the relation for the stress intensity factor K of crack in infinite medium, the point of instability is defined by

$$\frac{1}{8} \frac{\pi \sigma^2}{\sigma^2} = \frac{\partial}{\partial l} R_{\infty} \left(1 - .54 \left(\frac{r_{\infty}}{l} \right)^{1/3} \right)$$

where σ is a remote loading. Using the relation

$$R_{\infty} = \frac{1}{8} \frac{\pi K_c^2}{\sigma^2}$$

we obtain

$$\sigma^2 = .0055 \frac{K_c^{4.6} \pi^3}{\sigma^{2.6} l^{2.3}}$$

Here, the following assumption is applied. Especially, under the stress wave loading and at early times after the crack tip was struck by the wave, the crack tip perceives only this part of crack, s , which was affected by the wave diffracted at the crack tip. Approximately, $s \cong c_0 t$. Thus, the initial crack length at the R - curve diagram, i.e the parameter C in Eq.(1) is identified with s . Because the velocity of stable crack extension is much more lower than the bulk velocity, c_0 , it is possible to write $l \cong c_0 t$. The instant of the crack instability could be determined as a function of strain rate

$$\rho^2 c_0^4 \epsilon^2 t^2 = .0055 \frac{K_c^{4.6} \pi^3}{\sigma^{2.6} (c_0 t)^{2.3}}$$

where the time dependence of the tension stress is given by $\sigma \cong \rho c_0^2 \epsilon$. After some manipulation we obtain

$$\sigma_c = .327 \left(\frac{K_c^{4.6}}{c_o^{6.3} y^{2.6} \rho^2} \right)^{.23} \epsilon^{.54}$$

The exact coincidence of the predicted spall strength dependence on strain rate with the experimental data for the cast austenitic steel is undoubtedly incidental. Owing to some uncertainties in the analytical representation of the Eq.(2), one can except the range of strain rate exponent to be about $0.45 \div 0.6$. It means that the given theory is able to explain the observed data for the steel 18/8 and 2P.

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References.

- [1] Meyers M.A., Dynamic Behaviour of Materials. John Wiley & Sons, New York, 1994.
- [2] Johnson J.N. and Addesio F.L., J. Appl. Phys. **64** (1988) 6699-6712.
- [3] Rajendran A.M., Dietenberger M.A. and Grove D.J., J. Appl. Phys. **65** (1989) 1521-1527.
- [4] Addesio F.L. and Johnson J.N., J. Appl. Phys. **74** (1993) 1640-1648.
- [5] Chen D., Al-Hassani S.T.S., Sarumi M. and Jin X., Int. J. Impact Engng **19** (1997) 107-116.
- [6] Grady D.E., J. Mech. Phys. Solids **36** (1988) 353 -384.
- [7] Buchar J. and Krejci J., Journal de Physique IV (1994) C8-713- C8-716.
- [8] Buchar J. and Hrebicek J., Czech. J. Phys. **43** (1993) 73-85.
- [9] Wnuk M.P., J. Appl. Mechanics **41** (1974) 234-241.
- [10] Achenbach J.D., Int. J. Engng Sci. **8** (1970) 974- 979.
- [11] Cherepanov G.P., J. Appl. Mathematics and Mechanics **32** (1968) 1050-1062.