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EFFECTS OF SPALL FRACTURE AND STRUCTURAL-TIME APPROACH

A.A. Utkin[1,2]

[1]Institute of Problems of Mechanical Engineering, RAS, Bolshoj 61, V.O., Saint Petersburg, 199178, Russia

[2]Saint Petersburg State University, Universitetsky prospekt, 28, Peterhof, Saint Petersburg, 198504, Russia

e-mail: a.utkin51@gmail.com

Abstract. Using structural-time approach spall strength is studied in a wide range of loading rates. The effects detected in experiments on the spallation in the nanosecond range of loading durations are considered. The possibility of describing these effects using structural-time approach is shown.

1. Introduction

Spall fracture under short pulses impact of high intensity is an important object of study of the laws of materials dynamic fracture. Usually, dynamic strength associated with a strain rate in spallation cross-section, i.e. it is determined the velocity dependence of strength. Wherein, the increase in speed leads to the strength increasing. This pattern was observed in the range of microsecond loading duration. Lately it has become possible to increase the intensity of the load to such an extent that failure occurs on the nanosecond load durations. Under testing on spall fracture of aluminum alloy in the nanosecond duration loading range several effects were found that do not fit into existing concepts [1, 2]. Firstly, the stabilization strength effect was detected. The strength of the material increases with increasing strain rate, but when it reaches a velocity 10^7 s^{-1}, the strength ceases to grow. The authors of experiments explain this phenomenon by achievement of the material the limiting dynamic strength. Further, these authors have studied the duration of load action in the spalling cross-section depending on the strain rate. It has been found that the above relationship is nonmonotonic. The authors of experiments attributed the load duration increase at high loading rates with material hardening under intense compressive load when compressive wave passes. It was also found that, in the spall cross-section to the fracture moment stress can grow or a time interval at which the stress does not change or even decreases may be preceded by fracture. In this case, the authors of the experiments introduced in consideration two mechanisms of destruction - the dynamic and quasi-stationary (quasi-dynamic). The destruction is the result of competition between two mechanisms. In the second case the fracture can not be related to the velocity Quasi-stationary failure mechanism requires the study of the time dependence of strength. Thus, each of the three new detected effects require a separate explanation.

2. Incubation time criterion

As a rule, dynamic strength is associated with the speed of the load, not taking into account the duration of the load. Whereas fracture critical characteristics equally determine loading duration, shape and amplitude of the applied pulse including speed and load application. Application of the criterion of the incubation time for the analysis of destruction allows you to receive the effects observed under experiments in the framework of a unified approach. Incubation time criterion has the form [3, 4]:

$$\int_{t-\tau}^{t} \sigma(s,x)ds < \sigma_c \tau , \tag{1}$$

where $\sigma(s,x)$ – the stress at the point with coordinate x at time s, τ –structural (incubation) time - independent characteristic of the material in time dimension, σ_c – static strength of the material.

Spall cross-section coordinate and fracture moment are determined by the criterion of the incubation time. It is assumed that the moment of destruction is the shortest time in which the criterion condition is violated (1). Accordingly, the spatial coordinate in which this condition violated will be a place of destruction.

3. Analysis of Spall Fracture

We studied the fracture by triangular shape pulses. Analysis of failure with the help of the incubation time criterion indicates that the destruction is possible not at the moment of the maximum load achievement, but some time later, when the value of stresses in the spalling cross-section begins to decrease. In this case to tie the strength with the loading rate is no longer possible. In this case, you can only talk about the time dependence of strength. This situation in [1,2] is called quasi-steady mechanism of destruction. Fig. 1 shows dependence of stress on the time in spall cross-section. In both pulses the speed of the load and duration of the area of the load growth are the same. The duration of the load recession area vary. Time in Figure is normalized so that failure occurs in a point whose abscissa is 1. The stress is normalized with respect to the amplitude of the minimum required to break pulse. Points are the incident wave, dotted are reflected waves, solid line is the total wave. So what will be the mechanism of destruction - quasi-stationary or dynamic is primarily determined not by the rate of strain and the competition of two mechanisms, but by the amplitude of the applied pulse and by the rate of load drop.

It is accepted in all calculations: σ_c=335 MPa, c=5100 m/sec ρ=2690 kg/m^3, τ=30 nsec. Fig. 2 shows on the abscissa is strain rate, and on the ordinate is the dimensionless destruction time, which is the ratio of the time during which the stress at the spall cross-section is positive to the duration of the loading area. If this value does not exceed unity, the fracture occurs at the load growth phase. Otherwise, the more the dimensionless time is different from the unit the larger "degree of quasi-stationary". Here, the solid line shows the dependence of the destruction time on the rate of deformation by pulse, which amplitude at the area of the load increase exceeds the minimum one of 1.2 times, and the load growth phase 5 times longer than section of its recession. Points mark the same pulse in the growth area, but the section of load recession 5 times longer than growth phase. Finally, the dotted line marks the destruction by load at which the downturn rate of the load ($36 * 10^6$ sec^{-1}) and the magnitude of the applied pulse (72 Pa · s) are constant. In this case, by increasing the loading rate the duration of growth section of the load decreases and the recession portion increases.

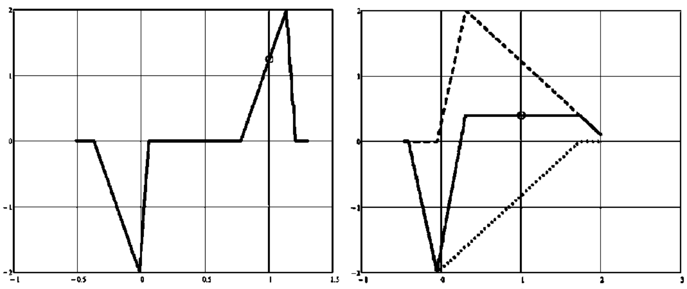

Fig. 1. Dependence of stress on time in the spall cross-section under different durations of load downturn area.

Calculations show that the strength at a given strain rate may vary within wide limits with changes in the applied pulse of the maximum amplitude and duration of load recession section. Assuming that the decay rate of load is close to the constant, if the loading rate is relatively small (less than 10^7 s^{-1}) fracture moment occurs at the area of the load increase. At higher speeds of deformation fracture occurs after reaching maximum load, at the decline of the stress values. Wherein, the section of the decline load is small. This phenomenon is associated with effect of "stabilization" of the strength. Fig. 3 shows the results of calculation of the velocity dependence of the strength on the assumption that the applied pulse value and the rate of load decrease are constant. Experimental points from [1, 2] are marked by circles.

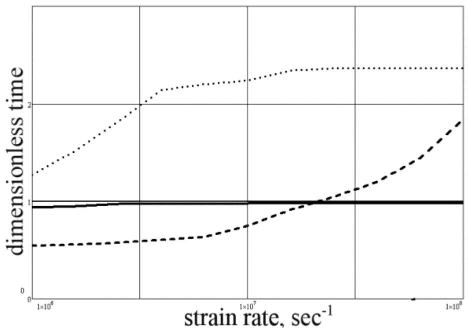

Fig. 2. Quasi-stationary and dynamic mechanisms of destruction, depending on the speed of the applied load.

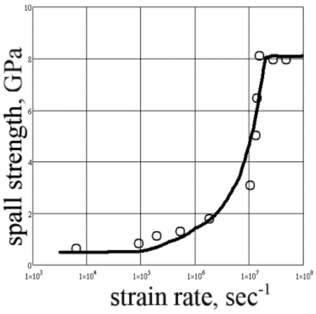

Fig. 3. Speed dependence of the strength.

If the form of the applied load is such that the area of load increase exceeds the load decay portion, it is possible the appearance of situation in which the condition of failure occurs in the two sections of the sample simultaneously. Here the duration of the load action will be different in the sections of spalling. If under the increasing of speed action this situation arises, the jump in the duration of the load action can take place. Figure 4 shows the dependence of applied pulse value on the coordinate. The calculation shows that the condition of the destruction in the second (more distant) coordinate occurs when the duration is quite small, so the speed is high (total duration of the pulse should be close to the value of incubation time). With further increase of the velocity points of maximum in Fig. 4 will converge.This phenomenon may be connected with the appearance of the jump found in [1,2].

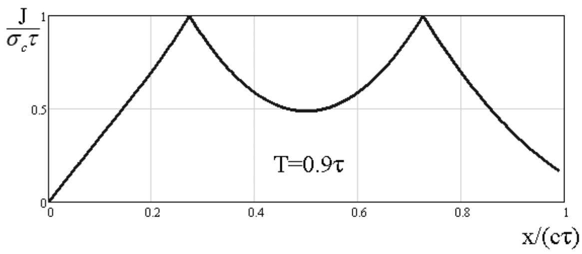

Fig. 4. The dependence of the applied pulse value on the coordinate.

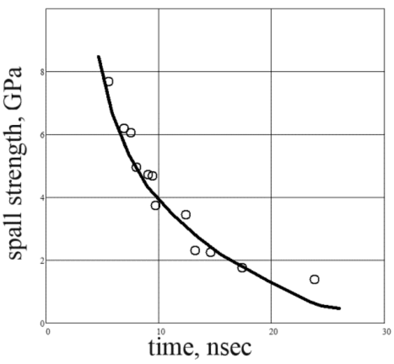

Fig. 5. Time dependence of strength.

Finally, Fig. 5 shows the results of calculation of the time dependence of the strength. The calculation was performed for the pulse, loading of which leads to a "quasi-stationary" fracture mechanism (curve of the points in Fig. 2). Experimental points from [1,2] are marked as circles.

4. Conclusions

- Application for the fracture analysis the criterion of the incubation time allows to receive effects, observed in experiments, without tying them with the achievement of material strength limit and without considering the two mechanisms of destruction;
- Incubation time criterion predicts well the experimental data on the spalling in the nanosecond range of action duration;
- "Dynamic" strength of the material, if taking as such the tensile stress at the time of destruction, is not a constant but depends on the pulse duration; Thus, the material may withstand any stresses if they are within a relatively short time.

Acknowledgments

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