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THE INFLUENCE OF GRAIN SIZE ON THE SPALL FRACTURE OF COPPER

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Résumé : L'influence de la taille des grains sur la fracture par écaillage du cuivre soumis à une charge explosive est étudiée. On trouve que la contrainte d'écaillage dépend de la taille des grains. La transition fracture intergranulaire - fracture transgranulaire est étudiée en détail. La simulation numérique des expériences est réalisée.

The influence of grain size on the spall fracture of copper under explosive loading was studied. It was found that samples with different grain sizes exhibited different spall strength. The fracture mode transition from intergranular to transgranular fracture was studied in details. The numerical simulation of explosive experiments were performed.

INTRODUCTION

The spall is a specific kind of fracture which is generally caused by development of tensile stresses during the interaction of opposing release waves /1,2/. Its occurrence is connected e.g. with the explosive loading, used extensively in a number of practical applications /3/.

The process of spallation has been studied in a number of laboratories with a view to obtain criteria for dynamic fracture at high strain rates. Much of these experimental works, see /4,5/, for a review, has been based on the examination of recovered samples from which attempt has been made to correlate the degree of material damage with various features of the stress-time history.

Table 1 Spall strength of Copper

σ_c /GPa/	Reference	Remark (kind of loading)
1.8-2.5	given in /1/	OHFC (different impact velocities)
0.8-1.64	/9/	99.5% Cu (different impact velocities)
1.62	/10/	99.6% Cu - explosive loading (independent of p_m)
1.9-2.1	/11/	single crystals-explosive loading <111>
1.2-1.5	/12/	OHFC - laser irradiation
0.85-1.4	/13/	OHFC (200 μ m grains) - expanding ring

The study of the metallurgical aspects of spalling revealed that the stress at which material failure occurred was generally dependent on its preconditioning, which determined its microstructure, and its purity /5-8/. This phenomena can explain the usually wide variety of the spall strength as it may be well documented e.g. for polycrystalline copper. The spall strength of copper may vary between 0.8 to 2.5 GPa as it is documented in Table 1.

The given paper deals with the study of main metallurgical aspects of copper spalling with the emphasis on the grain size influence.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used was polycrystalline copper (0.097Ag, less than 0.003 Fe and Al, 99.96 Cu - in wt %), annealed at 850°C for different time. This annealing led to the different values of average grain size (94, 104, 112, 130, 154 and 185 μm).

Sample discs 100 mm in diameter were machined to thickness 20 mm. The samples were subjected to shock loading produced by the detonation of the explosive charge. The used experimental arrangement enables to obtain the loading pressure pulse $p(t)$ and the free surface velocities $v(t)$ /10/. In order to obtain different loading conditions five different explosives were used. By this way the values of $p_m = 7.4; 12.8; 17.5; 25.3$ and 54 GPa were achieved.

The spall strength σ_c was inferred from the record of free surface velocity - time history using "pull-back" signal /14/. The corresponding strain rates in the spall plane were evaluated using the formula developed in /15/:

$$(1) \quad \dot{\epsilon} = \frac{1}{\rho U^2} \frac{dp}{dt}$$

where ρ is the material density, $\frac{dp}{dt}$ is the mean rate of pressure change in the spall plane and U is the shock velocity which may be determined using data given in /16/.

For numerical simulations of spall fracture the thermo-mechanical calculations were made by using PR2D finite difference code /17/ with explicit time integration. The behaviour of copper was described by the state equation

$$(2) \quad p = a_1 (V_0/V - 1)^n$$

relating the pressure to the initial volume V_0 and volume V . The equation (2) was obtained by the fitting of data given in /16/, $a_1 = 278.2$ GPa and $n = 1.2$. The next material parameters used for numerical simulations were: Initial density $\rho = 1/V_0 = 8.93 \text{ g cm}^{-3}$, Poisson ratio $\nu = 0.33$, Young's modulus $E = 1.19 \times 10^5 \text{ MPa}$, thermal expansion coefficient $\alpha = 49.5 \times 10^{-6} \text{ K}^{-1}$, thermal conductivity $k = 394 \text{ W m}^{-1} \text{ K}^{-1}$, specific heat $c_p = 0.092 \text{ cal g}^{-1}$ and Grüneisen parameter $\gamma = 1.89$. The influence of grain size was expressed by the value of the yield stress σ_y . The values of σ_y were determined in /19/.

The loading was simulated by the pressure - time history which was recorded by the manganin foil gauges /18/. The example of this record is given in Fig. 1.

The loaded samples were cross-sectioned and examined by the light microscopy. The spall fracture surfaces were examined using scanning electron microscopy. All experiments were performed at room temperature.

EXPERIMENTAL RESULTS

Fig. 2 shows the cross-section of sample with fracture in form of the spall. This kind of fracture, which appears closer to back

free surface, was reported in all tested samples. The microfracture is observed to have a range of shapes from nearly spherical voids to grain - boundary separation. The extent of damage was observed to increase with an increase in the loading pressure, p_m , irrespective of grain size.

In large grained samples the following nucleation sites of the voids were found:

- grain boundaries (nearly spherical voids)
- grain boundary tripple point
- the junction of a grain boundary and an annealing twin

In these samples plastic deformation in the form of twinning was also observed. Similar results were reported in /20/. Small grain size samples do not exhibit such features. This feature is not unique to shock loading, and has been observed e.g. in conventionally loaded Fe - 3% Si /21/. In smaller grained samples numerous spherical voids were found to be nucleated inside the grains and not at the grain boundaries. Around these voids very high density of dislocation occurs. According to the results obtained in /22/, the high density of dislocations around the voids is thought to be produced by shear strains which are required for growth of the microvoid. The number of nucleation sites inside the grains is increasing function of pressure, p_m , and decreases with the increase of grain size.

The detail fractographic observation revealed that up to some values of p_m and d the fracture surfaces of shock loaded samples showed a characteristic dimpled appearance. The fracture of these samples was ductile intergranular.

The scanning electron microscopic examination of the fracture surfaces of the sample with lower grain sizes loaded at higher pressure revealed the transgranular ductile fracture mode. This kind of fracture was firstly reported in /23/ where it was termed as a "pseudo brittle" fracture.

This fracture was futher reported in /20/ where the spall experiments were performed. Its occurrence is also typical in specimens deformed at very high rates to very large strains such as of explosively formed projectiles /24/. Regardless to experimental evidence of transition from intergranular to transgranular fracture mode the quantitative evaluation of this phenomena have not been reported. In order to obtain a little more information on this fracture mode transition the experimental procedure was modified by the inserting of PMMA plate between explosive charge and sample. This arrangement enables to obtain continuenously varying loading pressure p_m /25/. In Fig. 3 the pressure p_m corresponding to the fracture mode transition is plotted as a function of grain size.

In the next step the strain rate $\dot{\epsilon}$ in the spall "plane" was evaluated using the Eq. (1). It was found that the points $(\sigma_c, \dot{\epsilon}_c)$ did not lie on the single curve. In order to examine this phenomena the next experiments on the samples with grain sizes $d = 94, 130$ and 185μ were performed. The results of these experiments are reported in Fig. 4. There are two regions of strain rate dependence of spall strength. The spall strength, σ_c , increases with strain rate, $\dot{\epsilon}$, up to some critical value, $\dot{\epsilon}_c$ and than it remains constant. Similar tendency in spall strength behaviour was reported for 6061-T6 aluminum /26/ and for some steels /27/. This behaviour was interpreted as a transition from brittle to ductile spall and the theory of this phenomena was developed /28,29/.

In copper this form of $\sigma_c(\dot{\epsilon})$ dependence corresponds to the transition from intergranular to transgranular spall fracture. The metalographic observation suggests that these fractures are a consequence of ductile voids growth and linkup. The influence of strain rate consists in different processes of voids linkup /23/.

In order to explain the observed influence of strain rate on the spall strength the theory of spall developed in /28,29/ was applied. One of the main proposition of this theory is an energy condition which requires that the elastic potential and kinetic energies associated with the tensile loading process exceed the fracture energy absorbed in the spall process. An expression for the fracture energy in ductile spall is based on an assumption of failure through plastic hole growth and linkup. Based on the theory described in /30/ a relation for the ductile spall strength may be obtained

$$(3) \quad \sigma_c \approx (2\rho c_0^2 \sigma_f \varepsilon_c)^{1/2},$$

where the flow stress, σ_f , is assumed to completely characterize local plasticity during spall damage. The stable hole growth proceeds to a critical void fraction, ε_c , after which void coalescence and rapid loss of tensile load carrying capacity ensues. The value of ε_c is assumed to be independent of the kind of material, $\varepsilon_c \approx 0.15$ /15/. In high strain rates region, i.e. $\dot{\varepsilon} > \dot{\varepsilon}_c$, the theory leading to the Eq. (3) fails. The model of voids growth is thus probably approved for voids at grain boundaries.

The independence of spall strength on the strain rates was also observed in /10/ where spall experiments performed on samples made from copper with significantly higher content of impurities than that used in the given research. This independence was not connected with transgranular fracture. The reason of these strain rate insensitivity is a consequence of the heterogeneous nucleation of voids at second phase particles /4/.

There are at least two reasons of possible strain rate insensitivity of spall strength

- High impurities content when the spall strength does not depend on $\dot{\varepsilon}$ over broad spectrum of strain rates values. The resulting fracture is ductile intergranular.
- The transition from intergranular to transgranular fracture at higher strain rates or detonation pressure maxima, respectively. This transition is operating only for copper of relatively high purity. The influence of material purity should be further examined.

In the next step the numerical simulation of the given experiments were performed. The simple criterion, $\sigma \geq \sigma_c$, was adopted to characterise the damage development. This analysis was performed for the samples with grain sizes of 96 μm ($\sigma_c = 3.9$ GPa), 130 μm ($\sigma_c = 2.6$ GPa) and 185 μm ($\sigma_c = 1.5$ GPa) which were loaded by the pressure pulse given in Fig. 1. Numerical results are displayed in Fig. 5. The numerical results confirm the results of observed fracture extent. The numerical code mentioned in Chapter 2 enables to obtain further important information like the free surface velocity. The example of this function is given in Fig. 6. It may be seen some agreement with experimental record. It means that the stress development in the explosive loaded sample can be predicted numerically. Owing to the limited scope of this paper the more details will be presented in the forthcoming paper.

CONCLUSIONS

- (1) It is shown that the tensile stresses produced in copper by the reflection of a shock wave at a free surface induce spalling which occurs as a process of nucleation and coalescence of voids.
- (2) The grain size affects the kind of voids nucleation sites and their number, as well. The observed number of voids is in agreement with observed extent of spall damage.
- (3) Quantitative valuation of experimental records of shock wave propagation revealed that the spall strength of copper was strain

rate dependent up to some critical value of strain rate $\dot{\epsilon}_c$. This sensitivity is decreasing function of grain size and very probably depends on the material purity.

- (4) The critical strain rate, $\dot{\epsilon}_c$, corresponds to the transition from intergranular to transgranular fracture.
- (5) This fracture mode transition which is not evident in copper tested under conventional loading conditions (quasistatic etc.) is also dependent on the detonation pressure maximum. The obtained dependence of this pressure on grain size is in agreement with conclusions of previous research /23/, where the possible microphysical explanation of this phenomena was given.
- (6) The general features of spall fracture can be predicted numerically using of very simple criterion, $\sigma \geq \sigma_c$.

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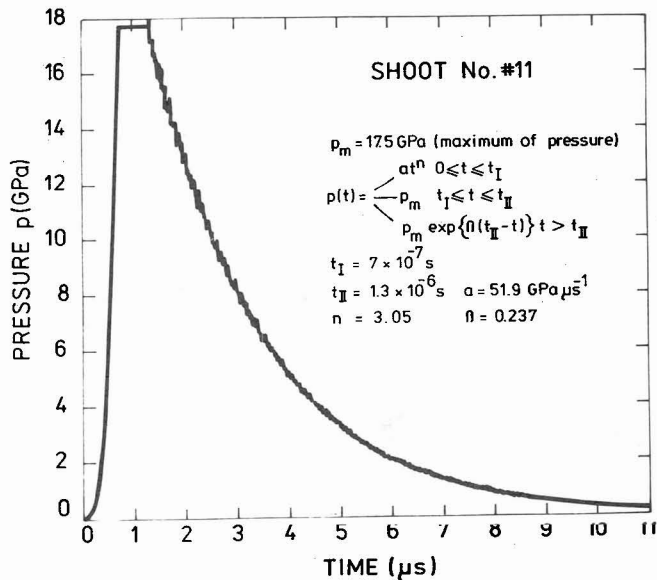


Fig. 1 Experimental record of the pressure - time history.

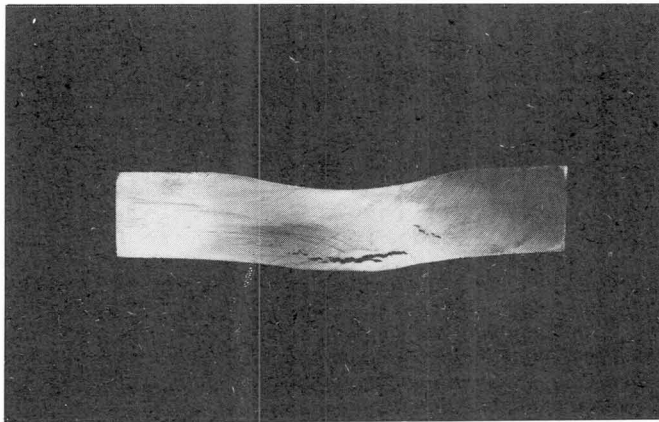


Fig. 2 Cross - sectional view of shock loaded copper specimen impacted at 12.8 GPa. 0.75x.

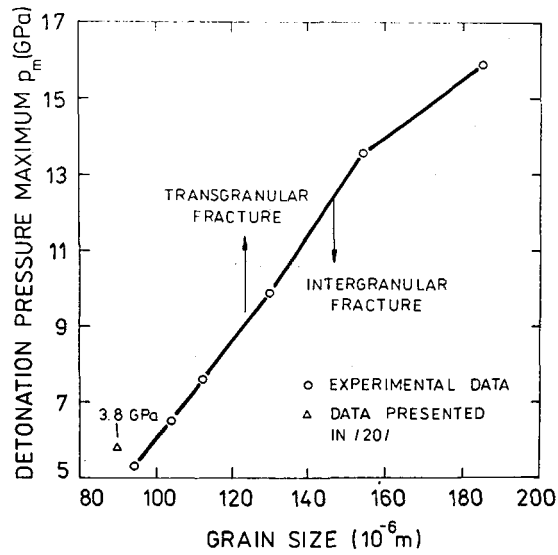


Fig. 3 The influence of grain size on the pressure corresponding to the fracture mode transition.

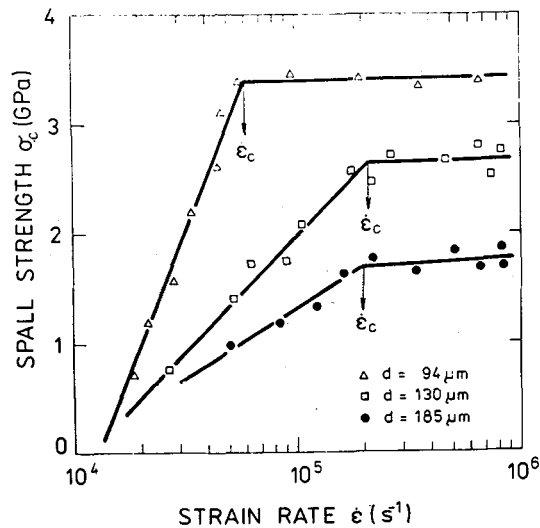


Fig. 4 The dependence of the spall strength on the strain rate in the spall "plane".

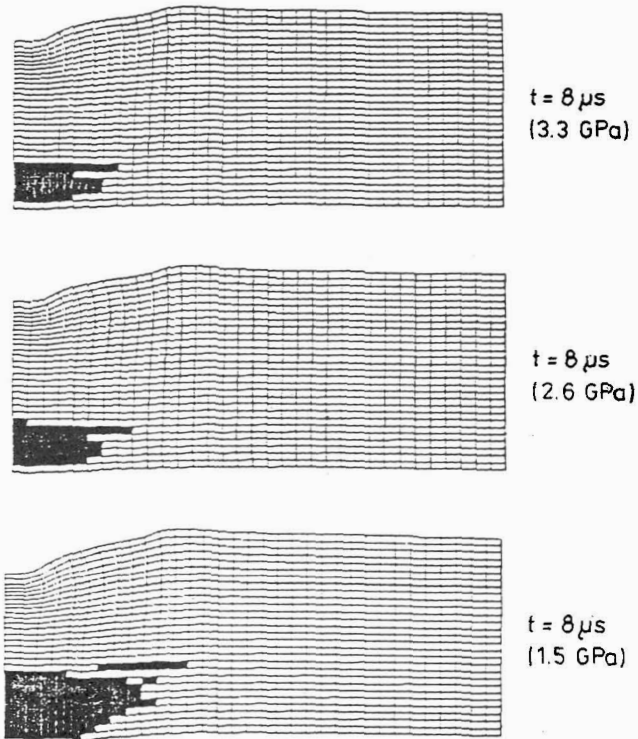


Fig. 5 The damage development.

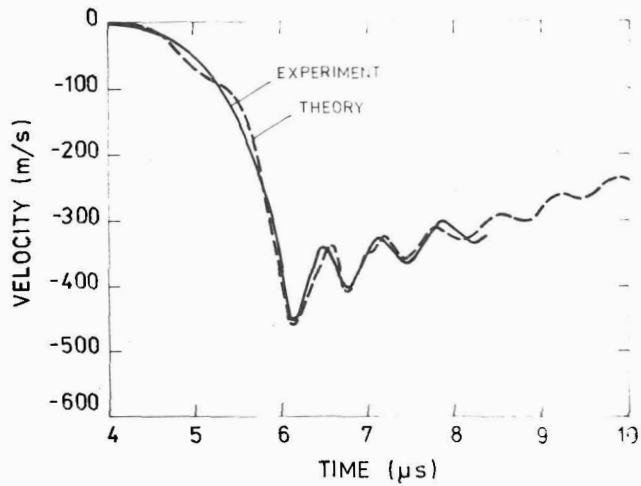


Fig. 6 A comparison of the experimentally determined free surface velocity with the result of the numerical computation.