In this paper we present the results of the series of experiments for study of spall strength of the samples of natural uranium by laser interferometer method. Under the values of loading amplitude \( \approx 17 \) GPa and the rate of deformation \( 3 \times 10^5 \) sec\(^{-1} \) in the range of release wave interaction the average value of the spall strength was found to be \( 3,52 \pm 0,37 \) GPa. We found experimental curve of spall strength vs free surface velocity \( \sigma_s(W) \). The curve relatively quickly grows up to the value \( \sigma_s \approx 3,2 \) GPa (\( W \approx 370 \) m/sec, what corresponds to the loading amplitude \( \approx 10 \) GPa), and then in the range of growing \( W = 370 \ldots 660 \) m/sec the value \( \sigma_s \) weakly grows up to the value \( 3,52 \) GPa.

INTRODUCTION

It is considered that spall strength is objective enough characteristic for dynamic strength of the material under stretching at microsecond range of loading duration (Glushak et al. 1992). Spall destruction is multistage, evolutive in time process with formation of destruction region inside inner layers of the material.

For understanding the process of spall destruction under high intensive loads and for constructing models, permissive to calculate the results of explosion effects, high velocity impact and other pulse effects, it is necessary to have certain totality of experimental results that characterized different aspects of spall effect. Most informative way to determine destruction tensions at spall is based on measuring free surface velocity measuring of the sample under investigation. In this case laser interferometer methods not influencing on investigated process are preferred.

EXPERIMENTAL METHOD

To investigate spall strength we used the scheme of loading (fig.1) an experimental uranium sample by shock wave, coming from HE charge through an air gap and layer of plexiglass (Fedorov 2002, p.67). The amplitude of the shock wave was \( 17 \pm 1 \) GPa. The velocity of plastic wave was \( D = 2,98 \pm 0,03 \) mm/msec. The obtained values of spall strength correspond to the rate of deformation in the range of interaction of release wave \( 3 \times 10^5 \) sec\(^{-1} \).

The experiments were carried out with the help of as single channel, and as double channel scheme of registration. Probe laser irradiation (\( \lambda = 694,3 \) nm, \( P = 150 \) W) from pulse ruby laser was focused by a short focusing converging lens on a reflecting surface of simple under consideration into a spot \( \approx 150 \) \( \mu \)m. Using interferometer Fabry-Perot with the base length 140 mm (distance between mirrors) we fixed the Doppler shifted probe irradiation, reflected from the moving surface, by high speed streak camera. The mistake in velocity measuring was estimated \( \pm 12 \) m/sec, and temporal resolution was 7 nsec.
FIGURE 1. Scheme of experimental device

We investigated samples of natural uranium with Ø20…50 mm, thickness 3,8…10 mm and density $\rho=18.9 g/cm^3$. The values for longitude and volumetric sound velocity were taken from Glushak et al. (1992) and Grady (1986, p.710): $c_l=3.45 \text{ km/sec}$, $c_o=2.49 \text{ km/sec}$.

EXPERIMENTAL RESULTS

Typical free surface velocity profile when spall occurs in elastic-plastic solid obtained in the experiments is depicted in fig.2

![FIGURE 2. Typical curve $W(t)$, obtained in experiment.](image)

We carried out 10 experiments for investigation spall strength in the samples of natural uranium. The results are presented in Table 1.

In present work amplitude of critical tensile load $\sigma_s$ was calculated from Romanchenko-Stepanov formula (Romanchenko V.I., Stepanov G.V., 1980, p.142) as:

$$
\sigma_s = \frac{\rho c_l c_o}{c_l + c_o} \Delta W \left[ 1 + \frac{h}{\tau} \left( \frac{1}{c_o} - \frac{1}{c_l} \right) \right]
$$

(1)

The following symbols were taken in the Table: $\Delta$ - thickness of natural uranium sample; $W$ - maximum of velocity on the curve $W(t)$ on plastic wave; $\Delta W$ - difference between first maximum and minimum free surface velocity on the curve $W(t)$; $U$ - particle velocity behind shock wave front in the sample; $D$ - shock wave velocity in the sample; $P$ - shock wave pressure inside the sample; $\tau$ - time interval for action of tensile strains in spall section until destruction; $h$ - thickness of spall plate; $\sigma_s$ - spall strength (amplitude of critical tensile strains).
Table 1

<table>
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<tr>
<th>№ exp-nt</th>
<th>Δ, mm</th>
<th>( W, ) m/sec</th>
<th>( \Delta W, ) m/sec</th>
<th>( U, ) m/sec</th>
<th>( D, ) km/sec</th>
<th>( P, ) GPa</th>
<th>( \tau, ) nsec</th>
<th>( h, ) mm</th>
<th>( \sigma_s, ) GPa</th>
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</table>

Shock wave parameters in the samples were defined using measured free surface velocity as \( W=2U, \) and the help of shock Hugoniot for natural uranium \( D=2,51+1,51U \) (LANL Shock Hugoniot Data, 1980). In the study of Kanel’ et al. (1996) an expression to determine the thickness of the spall plate in elastic-plastic solid is following:

\[
h = \frac{\tau}{\left(\frac{1}{c_0} + \frac{1}{c_i}\right)}
\]  

Estimation for the mistake of determining \( \sigma_s \) is \( \sim 10.5\% \). Average value of \( \sigma_s \) from ten experiments is \( 3,52 \pm 0,37 \) GPa. Values dispersion of experiment data can be explained by errors in loading device. It is necessary to mark, that in the experiments №№ 1636 and 1653, where thickness of the sample was the greatest, – 10 mm, we registered the least values of \( \Delta W=95 \) m/sec и \( \Delta W=93 \) m/sec. General rule was find in the studies of Ogorodnikov et al. (1993 pp.88-92, 1999 pp.108-114): when destruction takes place in condition of one dimension high rate deformation (\( \dot{e} =10^3 \cdot 10^5 \) sec\(^{-1}\)), there are strong scale effects of energy nature.

Experimental setup didn’t allow us to preserve all samples during the experiments. The samples, preserved in some of the experiments, let us speak about main crack formation in sample’s section with total separation of spall layer (fig.3) under shock wave loading with amplitude \( 17 \pm 1 \) GPa.

**FIGURE 3.** Samples of natural uranium preserved during the experiments
DISCUSSIONS AND CONCLUSIONS

The obtained experimental results are presented in fig. 4 as a dependence of amplitude of critical strain tension from sample free surface velocity. In the figure one can see data for uranium obtained by other authors (Cochran and Banner 1977 pp.2729-2737, Grady 1986 pp.703-804, Hixson et al. 1997 pp.479-482, Tonks et al. 1997 pp. 239-242, Zurek et al. 1997 pp. 423-426). Experimental points are described by one curve, that relatively quickly rises up to value $\sigma_s \approx 3.2$ GPa ($W \approx 370$ m/sec, what corresponds to loading amplitude $\approx 10$ GPa), and then in the range of $W=370…660$ m/sec the value $\sigma_s$ slowly rises up to value 3.52 GPa. It can be supposed, that for $W>660$ m/sec the value $\sigma_s$ becomes constant. Ogorodnikov V.A. et al. (1992, pp.88-92) assumed, that the growing of spall strength of constructional materials in the range of relatively low pressures caused by its hardening in shock wave. Influence of the hardening on the next destruction in spall appears apparently in the fact that due to formation of defects in the material there is a spectrum of potential centers of destruction, and the limit tensions for initiation of this centers becomes higher with decreasing of its dimensions, the last must depend on shock wave amplitude. Under certain pressures the material is in loading condition which approaching to the pressures of recrystallization, and a result of development of the two competitive processes (hardening and weakening) the spall strength becomes constant ($\sigma_s =$const).

Data from Robbins et al. (2001, pp. 499-502) with spallation strength of foil samples (thickness 100 µm) for two kinds of uranium (purified and with great quantity of admixtures) are also depicted on the dependence $\sigma_s(t)$ in fig.4. It is necessary to note, that values of $\sigma_s$ were estimated by another formula, but in this work this values were recalculated by formula (1) for correct comparison. The value of spallation strength for thin samples of highly purified uranium considerably exceeds the value of spallation strength for thin samples with admixtures and samples with thickness 2…10 mm on $\approx 1.5$ GPa and $\approx 2.0$ GPa accordingly.

![Figure 4](image-url)

**FIGURE 4.** Critical strain tension amplitude vs free surface velocity of natural U samples.
• We carried out investigations of dynamic strength in natural uranium samples with thickness 3.8...10 mm by laser interferometer method. When amplitude value of loading was $\approx 17$ GPa and deformation rate in the range of release wave interaction was $3 \cdot 10^5$ sec$^{-1}$ the average value of spallation strength came to be $3,52\pm0,37$ GPa.

• We compared the obtained experimental results with data of other authors. Our results are in agreement with data of other authors for samples with thickness 2...10 mm. Experimental points on the dependence $\sigma_s(W)$ are satisfactorily described by one curve, which relatively quickly rises up to value $\sigma_s=3,2$ GPa ($W=370$ m/sec, this corresponds to loading amplitude $\approx 10$ GPa), and then in the range $W=370...660$ m/sec the value $\sigma_s$ weakly growth up to 3,52 GPa. It can be supposed, that the value $\sigma_s$ becomes constant and practically doesn’t depend on loading amplitude.

REFERENCES


