- Отмечена тенденция к снижению откольной прочности мелкозернистого высокочистого урана при его микролегировании углеродом и кремнием. При реализованных условиях ударно-волнового нагружения отличия в величине спада скорости, характеризующей способность материала сопротивляться действию растягивающих напряжений, при микролегировании образцов углеродом и кремнием находятся на уровне 2σ-интервала измерений ΔW.
- Будет продолжено исследование влияния чистоты, размера зерна и микролегирования урана на прочностные характеристики при разных режимах взрывного и ударно-волнового нагружения, а также проведение взрывных экспериментов с использованием, оконных материалов для получения новых данных по откольной прочности урана.

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EFFECT OF PURITY, GRAIN SIZE, AND CARBON-OR-SILICON MICROALLOYING OF URANIUM ON ITS STRENGTH CHARACTERISTICS UNDER QUASI-STATIC AND SHOCK-WAVE LOADING

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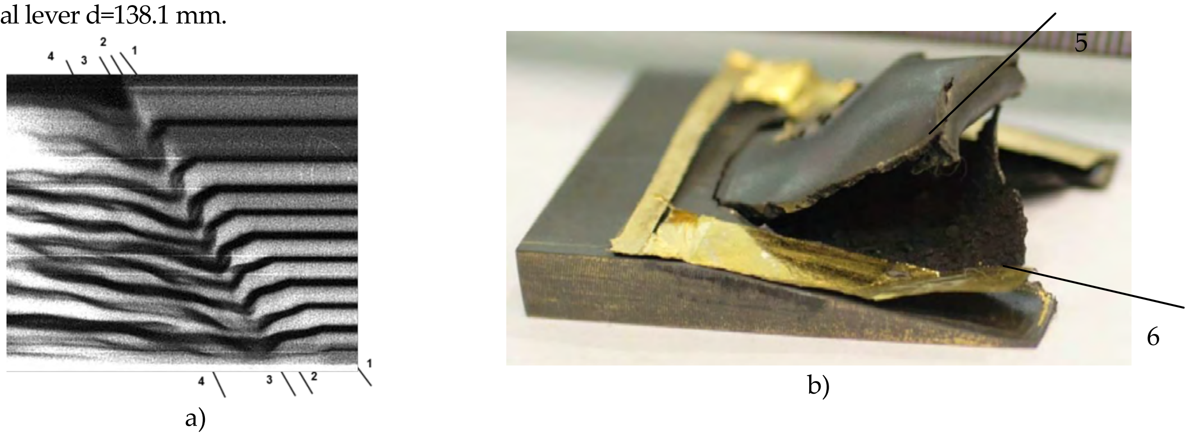
In addition to earlier published results how quasi-static extrusion of unalloyed technical-purity uranium and its lean molybdenum alloy influences strength characteristics under the quasi-static and explosive loading [1-4], this paper presents experimental setups and results of explosive and shock-wave experiments to study strength characteristics of the high-purity fine-grained uranium samples, as well as the C-or-Si microalloyed uranium samples under low-intensity loading by adjacent AMTs aluminum alloy impactors having 0.5 and 1 mm thicknesses. The multi-channel PDV diagnostics in the seven-channel configuration was used to record profiles of time-dependent velocity W(x,t) and time-dependent displacements S(x,t) of examined free-surface portions on the samples. This approach allows that few comparative explosive experiments can give statistically representative results. Just as in the technical-purity metal and its lean molybdenum alloy, quasi-static extrusion, accompanied by grain refinement and strength characteristics improvement under low-rate deformation, was not observed to seriously manifest itself under explosive and high-intensity shock-wave loading.

Studies how quasi-static extruded unalloyed uranium and its lean U-0.3%Mo alloy influences changes in the average grain size and associated changes in strength characteristics $\sigma_{0.2}$, σ_{HE} under quasi-static and Y, σ_{spall} explosive loading were performed and then results of this study were published in [1, 3].

It was shown that despite 2-times increase of strength characteristics, σ_{02} and σ_{HE}, due to decrease in the average grain size from 200-250 to 1-3 μm under quasi-static loading, no significant changes in the structure, shape, and parameters of the elastic precursor, as well as in the kinetics of stress relaxation thereon were observed in the fine-grained uranium and the U-0.3%Mo alloy under explosive loading .

Figure 1 shows the streak-camera record (a) and the recovered sample (b) of the fine-grained uranium, which were obtained in the experiment wherein loading was performed through the 2-mm thick uranium baseplate by the sliding detonation of the plastic-bonded explosive layer with the thickness of h_{HE}=1.9 mm and the optical lever d=138.1 mm.



a)

b)

Figure 1. Lines: 1-1 – arrival of the first C_+-characteristics of the elastic precursor at the free surface of the sample; 2-2 – arrival of the last C_+-characteristics of the extended elastic precursor at the sample surface; 3-3 – trajectory of the maximum free-surface velocities; 4-4 – trajectory of spall signals. 5 – separated spall, 6 – fracture surface

Figure 2 shows results on stress relaxation on the elastic precursor in the cast course-grained and quasi-statically extruded fine-grained uranium (a) and in the cast alloy of U with Mo (b) [3].

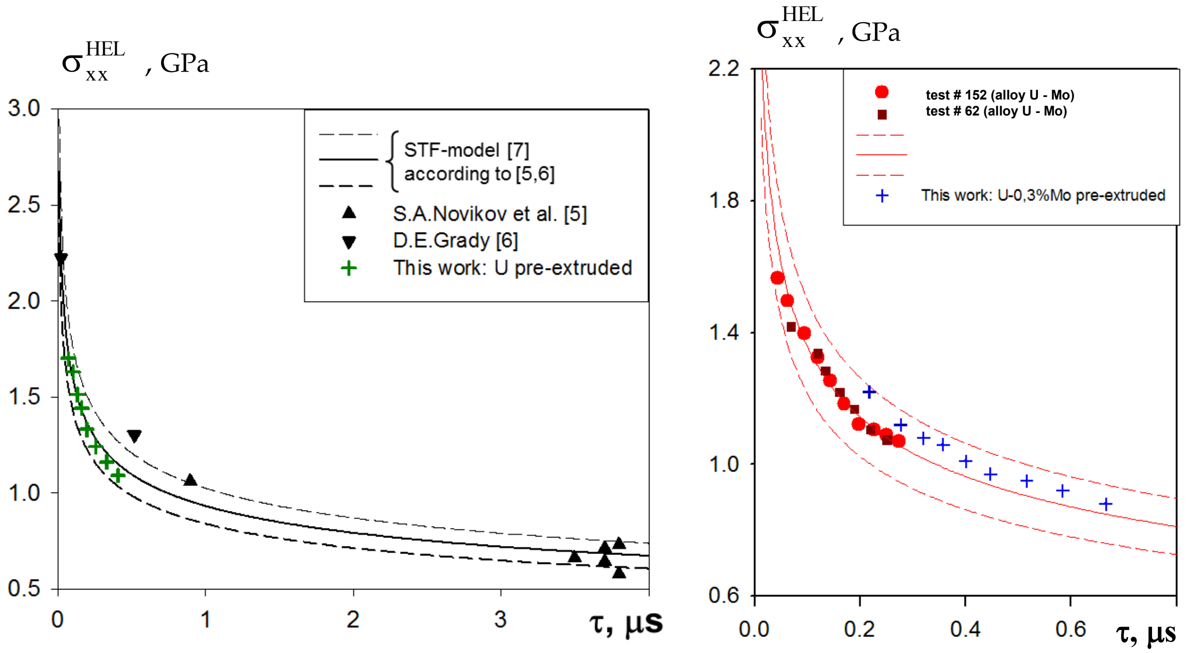


Figure 2. Stress relaxation on the elastic precursor

Below you will find (figure 3) comparative data on the spall strength of the extruded uranium and the U-0.3%Mo alloy, as well as the cast alloy of U with Mo under low-, and high-intensity explosive loading [3].

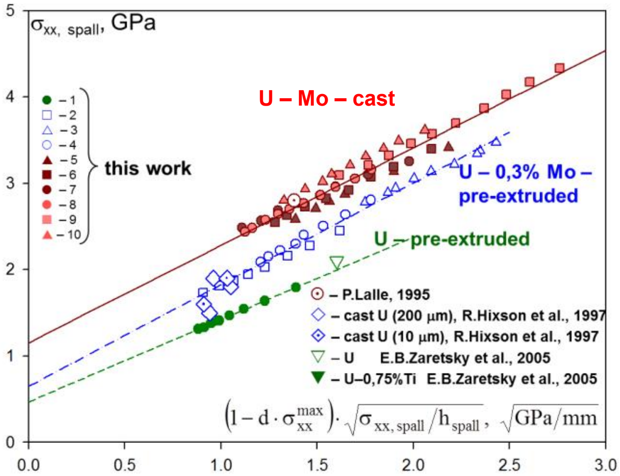


Figure 3. Tensile stress in the spall plane, $\sigma_{xx,spall}$, versus stress gradient in the tensile pulse, $(\sigma_{xx,spall}/h_{spall})^{1/2}$, and versus amplitude of shock-wave compression that precedes tension, σ_{xx}^{max}

The scanning electron microscopy of recovered samples after explosive loading [4] revealed incipience and development of the spall and shear fractures on non-metallic inclusions, i.e. oxicarbonitrides, the content thereof in the tested blank was estimated to be 1.5±0.2 vol.%. As a rule, inclusions (figure 5a) or a trace of the precipitated inclusion (figure 5b) are observed to present in the origin of all observed cracks.

Previous investigations into spallation fracture of the course-grained cast uranium at the normal temperature and under the low-intensity shock-wave loading with the characteristic loading-pulse duration of 1.5 μs also noted the incipience of spallation cracks to take place mainly near carbonitride inclusions. To a lesser extent, incipience of microcracks and also intercrystalline cracking were observed along twins.

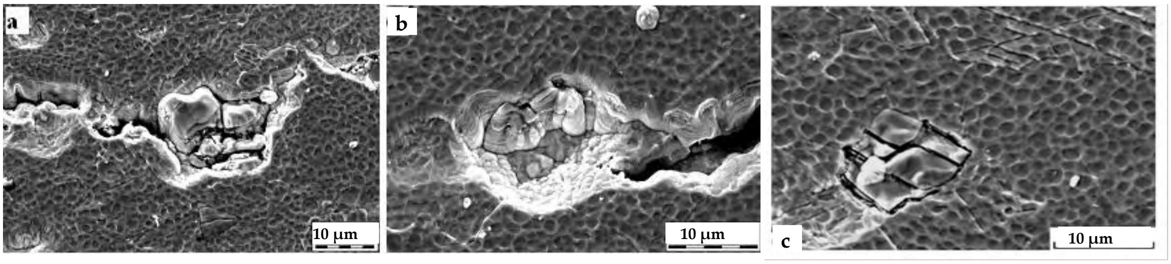


Figure 5. Effect of inclusions on the material strength; scanning electron microscopy.
a – inclusion in the crack origin, **b** – inclusion trace in the crack origin,
c – fractured inclusion

Based on investigations into the role of the quasi-static extrusion of uranium and the U-0.3%Mo alloy with the purpose to further refine the average grain size and to further improve their strength characteristics, the conclusion was made that:

– finer purification of the material is necessary prior to its quasi-static extrusion in order to further refine its average grain size and to improve its strength characteristics not only under quasi-static, but also under explosive loading;

– further improvement of diagnostic methods is expedient: improvement of their time, spatial, and amplitude resolution as for the sample's free-surface velocity.

It was interesting to obtain data on the shear and spall strength of the material of three blanks under their low-, and high-intensity shock-wave loading in order to compare them with the available data on:

– quasi-statically extruded fine-grained unalloyed uranium and the U-0.3%Mo alloy [1, 3],

– quasi-statically extruded uranium [4].

Goal of investigation

The goal of investigation was to obtain (with the help of the multi-channel PDV-technique) new comparative data on the shear and spall strength of samples made from the high-purity fine-grained uranium, as well as from the uranium microalloyed either by carbon, or silicon when these samples are loaded in the low range of longitudinal stresses, i.e. in the region with the existing two-wave elastic-viscous-plastic configuration and the realized spallation.

Test materials

The test samples were made from the high-purity, fine-grained uranium wherein the total amount of mass fractions of admixtures was $22*10^{-3}\%$ and from uranium microalloyed either by carbon ($84*10^{-3}\%$), or silicon ($130*10^{-3}\%$). In the second and third blanks, increase in mass fractions of admixtures has led to the reduction in the material density approximately by 1%.

Static testing of physical and chemical characteristics of blanks at the manufacturer's indicates that:

- average values of elastic limits under quasi-static tension equaled in the relative form 1, 1,29, and 1,43;

- average value $\sigma_{0.2}$ for the high-purity fine-grained uranium was approximately 3 times(!) greater than the similar characteristic of the unalloyed uranium;

- average values of the ultimate strength under static tension for the high-purity uranium samples and the carbon-alloyed uranium samples coincided though for silicon-alloyed samples, they were 1.25 times greater;

- average value of tensile strength, σ_B, for the high-purity fine-grained uranium was approximately 3 times(!) greater than the similar characteristic of the unalloyed uranium.

Samples and conditions of their shock-wave loading

The manufactured samples had Ø30×3 mm and Ø30×5 mm. All samples were subjected to grinding and polishing. Prior to explosive experiments, samples were kept in a sealed container in the dry-argon atmosphere.

The samples were shock-loaded by the high-speed impact (W=2.55 km/s) of a thin adjacent impactor made from the AMTs aluminum alloy. By the HMX-based primary charge (Ø60×20 mm), the impactors were accelerated in the air through the 12Kh18N10T steel baseplate with the thickness of 5 mm. The Ø60 mm explosive lens with a foam spacer served as the plane-wave generator.

Measurement results given by the multi-channel PDV technique

The experiment used two four-channel PDV units. The fiber-optic laser that generates radiation with the 1550-nm wavelength and the <1 kHz spectral linewidth was used as the radiation source. Heterodyne signals were recorded with the help of fast photodetectors and their output signals were recorded by the 4-channel oscilloscope.

The free-surface velocity and displacement profiles are given in table 1. Table 2 shows estimated levels of spall stresses in the Zababakhin approximation.

Table 1. Free-surface velocity and displacement profiles for samples under realized conditions of their shock-wave loading

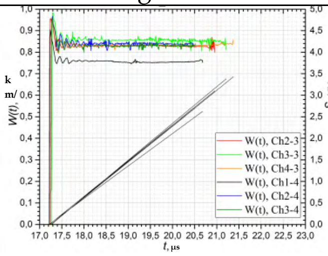
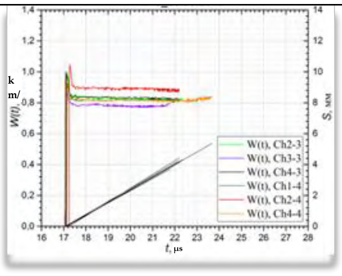
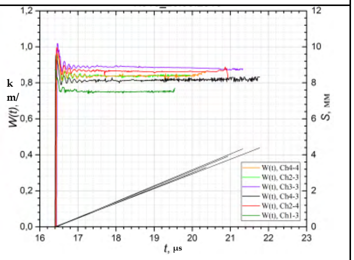
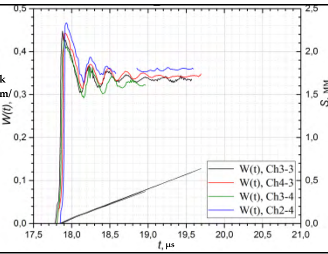
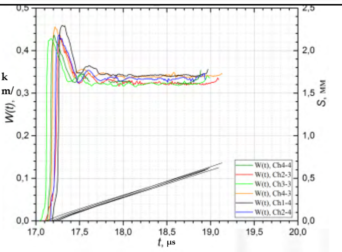
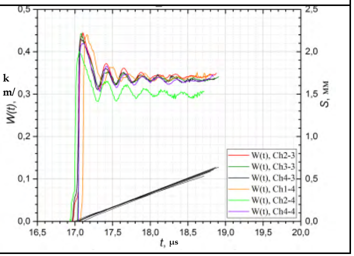
	Fine-grained U	U-0.084%C	U-0.130%Si
Sample with Ø60×3 mm AMTs impactor h=1 mm			
Sample with Ø60×5 mm AMTs impactor h=0.5 mm			

Table 2. Absolute (±2σ) and relative data on spallation strength

		Fine-grained U	U-0.084%C	U-0.130%Si
Sample with Ø60×3 mm AMTs impactor, h=1 mm	$\sigma_{spall1}/\sigma_{spall1}^{max}$	1	0.95	0.97
Sample with Ø60×5 mm AMTs impactor, h=0.5 mm	$\sigma_{spall1}/\sigma_{spall1}^{max}$	1	0.82	0.91

Conclusions

- The paper presents experimental setups of the PDV-diagnostics and its first results on the spallation fracture of the Ø30×5 and Ø30×3-mm samples made from the high-purity fine-grained uranium and also from the carbon-and-silicon microalloyed uranium when these samples are loaded by the impact of the adjacent AMTs impactors with the thickness of 0.5 and 1 mm.
- Investigations demonstrated the tendency to the reduction of spallation strength of the high-purity fine-grained uranium when it is carbon-and-silicon microalloyed. Under realized conditions of shock-wave loading, discrepancies in the velocity drop value that characterizes the material capability to withstand tensile stresses are at the level of the 2σ-measurement interval, ΔW, when the samples are microalloyed by carbon and silicon.
- For obtaining new data on the spallation strength of uranium, further investigation into the effect of purity, grain size, and microalloying of uranium on its strength characteristics under different modes of explosive and shock-wave loading is required, as well as explosive experiments with the use of window materials.

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ОСОБЕННОСТИ ОТКОЛЬНОГО РАЗРУШЕНИЯ В МЕДИ ПРИ КВАЗИОСЕСИММЕТРИЧНОМ СХОЖДЕНИИ

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Введение

В классической редакции экспериментов, посвящённых изучению процесса откольного разрушения, импульсные растягивающие напряжения реализуются в плоских образцах из исследуемых материалов. Для создания одномерного напряженно-деформированного состояния используется метод торможения плоской пластины-ударника или взрыв слоя ВВ.

Новые перспективы открываются при переходе к экспериментам, в которых напряженно-деформированное состояние является неодномерным [1] или обладает цилиндрической [2] или сферической симметрией [3], [4]. Численное моделирование таких опытов позволяет тестировать модели разрушения в условиях неодномерных течений. В частности, одним из преимуществ экспериментов, в которых реализуется осесимметричное схождение, является возможность исследовать совокупность процессов (откольное разрушение, компактирование поврежденной среды, разрушение на сдвиговых деформациях), протекающих одновременно.

В настоящей работе представлены редакция и результаты эксперимента по исследованию особенностей процессов разрушения в толстостенном медном цилиндре при осесимметричном нагружении.

1. Постановка эксперимента

Для реализации в полой цилиндрической мишени сходящейся ударной волны применён метод соударения. Для разгона цилиндрического ударника до требуемой скорости использовано устройство, в котором за счет энергии взрыва тонкого слоя ВВ, инициируемого в режиме скользящей детонации, ускоряется тонкий ($\Delta_л$ = 0,5 мм) конический медный лайнер. Угол раствора конической оболочки и её толщина, а также толщина ВВ обеспечивали приемлемую степень синхронности подлёта лайнера к двухслойному цилиндрическому демпферу («трансформатору импульса»), внутри которого расположен медный цилиндрический ударник. Ударник разгонялся до скорости ~175 м/с и формировал импульс квазиосесимметричного сжатия (амплитудой ~3 ГПа) при торможении на толстостенной полой цилиндрической мишени. Таким образом, в рассматриваемом устройстве отсутствовала многоточечная система инициирования, вносящая (при инициировании относительно тонких слоев ВВ) разномасштабные возмущения в процесс разгона ударников. Габаритные размеры компонентов экспериментальной сборки определены в рамках численного моделирования с использованием 2D программного эйлерового комплекса ВНИИЭФ. В частности, толщины ударника и мишени выбраны достаточно большими, в том числе, чтобы снизить интенсивность нагружающего импульса за счет затухания волн и зарегистрировать