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Estimating the Brittle Strength of Nuclear Fuel Material

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Abstract

The development of nuclear energy involves use of promising nitride nuclear fuel in reactors of the 4th generation. This will require improving the fuel production technology as well as its test methods. For estimation of the strength of the nuclear fuel material as well and for further refinement of nuclear fuel test technology we propose to use small discoid samples, similar in shape to the elements of nuclear fuel in the context of "Brazilian test" (compression applied to disk specimen in the median plane). We present here the results of testing small discoid specimens made of brittle materials such as cast iron and graphite (both being considered as possible model materials for the nuclear fuel). We compared these materials to nuclear fuel itself (as represented by uranium dioxide). In addition the effect of the specimen size on resistance to destruction was investigated. The type of deformation and fracture found in samples made from cast iron suggests that this material cannot be used as a model for the nuclear fuel. At the same time the results obtained in tests on samples composed of graphite ARV-1 were in good agreement with the results of tests on uranium dioxide. Using the data obtained in this study, a calculation formula for determining the strength of the nuclear fuel material based on the "Brazilian test" results is proposed.

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1. INTRODUCTION

Nitride nuclear fuel has certain advantages over the traditional UO_2 and is considered a promising option for the reactors of the 4th generation. The main advantages of mononitrides include: high melting point, 2797 °C, high density (more than 14 g/cm3) and high thermal conductivity (about 20 W/(m · K) [1]. The post-irradiation studies of the first combined experimental fuel assemblies with mixed nitride fuel (uranium nitride and plutonium nitride) after these assemblies completed their assigned life cycle in the BN-600 reactor at Beloyarsk NPP reported strikingly optimistic if not "phenomenal", especially from a scientific standpoint, results [2]. This report [2] quoted: "no violations of the fuel column integrity were found; the deformation of the shells was surprisingly low. A set of experimental data shows that the condition of the fuel rods with nitride fuel is satisfactory and their life time has not been exhausted”. The electromagnetic compaction, which includes electro-pressing and spark plasma sintering [3-6] is considered as a prospective approach to obtain products made of nitrides of high density uranium and plutonium. Since the development of nitride fuel by electric pulse exposure involves mechanical testing of small samples with thickness up to 10 mm and a diameter of 7-10 mm we strived to further develop and refine strategies to test the strength of nuclear fuel materials. In the present work to assess the strength of these materials we used the method of compressing the sample disc (fuel tablet) in the diametrical plane following the ”Brazilian test” [7] approach.

2. RESULTS AND DISCUSSION

2.1. Testing of brittle discs under the scheme of the “Brazilian test”

A detailed computational analysis of loading small solid disk with compressive force in the diametrical plane (”Brazilian test”) is presented in our prior study [8]. It is shown that the maximum tensile stresses developing upon loading of the sample disk in its diametrical plane lead to brittle fracture of low-plasticity materials. The calculation of destructive voltage can be done according to the formula recommended by the ASTM standard D 3967-95a,

$$\sigma_t = \frac{2P}{\pi t D}, \tag{1}$$

where P is the maximum load on the stamp, compressing the disk, t is the thickness of the disk, D is its external diameter.

Brittle materials: grey cast iron and graphite were selected for testing according to the ”Brazilian test”. Mechanical properties of model materials are shown in table 1.

Table 1: Mechanical and physical properties of the materials studied.

materials	σ^t, MPa	σ^c, MPa	E, GPa
cast iron	104	404	100
graphite ARV-1	13.8	37	7

2.1.1. Testing solid disks made of grey cast iron

Prior results by our group [9] of testing small-size disk made of cast iron confirmed the possibility of applying the formulas (1) to determine the stress of destruction, or the strength of the material in tension. Discs made of grey cast iron were of the following *D* x *t* dimensions: 10x4 and 15x4 mm. Diagram of compression of cast iron disc shown in Fig. 1, *a*.

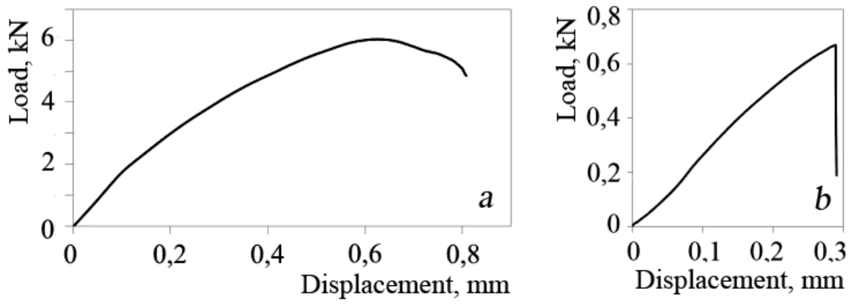

Figure 1: Diagrams of the compression of discs made of cast iron of size 10x4 mm (*a*) and graphite 8x8 mm (*b*).

The initial cracks are formed in the contact region, where maximum shear stresses are observed. The beginning of the crack growth is associated with the maximum load on the sample. Gradual decline in load after the maximum is associated with slow crack propagation and dissociation of one half of sample from each other. We did not find any explosive fracture characteristic of brittle fracture from normal stresses.

2.1.2. Testing solid disks of graphite

Discs of graphite were of the following *D***t* dimensions: 8x4, 8x8 and 8x12 mm. Characteristic diagram of the compression of the graphite disc 8x8 mm in the diametrical plane shown in Fig. 1, b. The destruction of the graphite disc happens dynamically at a maximum load, along the close-to-linear section of the graph and is accompanied with division of the sample into up to several fragments. Similar to how it happened in the cast iron – the initial cracks in the graphite 8x8 mm sample were found in the contact region, which apparently served as a source of sample destruction. Table 2 shows the breaking strength of the graphite samples calculated using formula (1) and formula

$$S_0 = \frac{P}{tD}. \tag{2}$$

The average value of the resistance of graphite to fracture, calculated according to the formula (1) showed dependence on sample thickness (10% growth in resistance corresponding to two times increase in thickness). It was approximately 2 times lower than the “true” material resistance (see table. 1). This difference between the specific sample resistance and the resistance as defined by the nature of the material is likely to be associated with more fragile condition of graphite as compared to cast iron evident

TABLE 2: The resistance of graphite to destruction.

The sample	the size of the sample	P, N	σ_t, MPa	S_0, MPa
1	8x4	307	6,1	9,6
2	8x8	660	6,6	10,3
3	8x8	695	6,9	10,9
4	8x8	595	5,9	9,3
5	8x12	1100	7,4	11,5
6	8x12	1108	7,4	11,5

from the charts of compression observed in samples built from these materials (Fig. 1, a, b).

2.2. Testing analog fuel tablets

There is a central hole in fuel tablets, designed to drain the reactor gases. Accordingly tests were performed on disks with a central hole.

2.2.1. Test disks made of grey cast iron and having a central hole

Cast iron disks had the following dimensions: diameter – 7,2 mm, thickness – 4 mm, central hole diameter d = 1,2 mm. The destruction of a disk with a hole occurs along the vertical diameter similar to the disk without the hole. The crack originates on the contour of the central hole at the point of intersection with the vertical diameter and extends along the diameter of the complete separation of the specimen. Table 3 presents the results of tests on cast iron disc specimens with a central hole. The resistance of the material to destruction σ_{th} and S_1 were calculated according to the formula

$$\sigma_{th} = 2P/(\pi(D-d)t) \tag{3}$$

and

$$S_1 = P/((D-d)t). \tag{4}$$

The fracture resistance of cast iron specimens was 1.5 times less than the true fracture resistance pertinent to the material (see table. 1).This effect of the reduction of the resistance of the material to fracture observed in the test samples was associated with the concentration of stresses at the central hole.

Table 3: The resistance of cast iron to destruction.

sample	the size of the sample	P, N	σ_{th}, MPa	S_1, MPa
1	7.2x4	3103	83	130
2	7.2x4	2555	68	107
3	7.2x4	3040	80	126
Average values			77	121

2.2.2. Test disks made of graphite with central hole

Tested graphite disks were of the following three sizes: the diameter of all disks was 8 mm, thickness 4, 8 and 12 mm. Diameter of central hole was 1 mm for all disks. Table 4 shows the results of the tests.

Table 4: The resistance of graphite to destruction for discs with a central hole.

sample	the size of the sample	P, N	σ_{th}, MPa	S_1, MPa
1	8x4	321	7.3	11.5
2	8x4	283	6.5	10.2
3	8x4	233	5.3	8.3
4	8x8	479	5.5	8.6
5	8x8	514	5.8	9.1
6	8x12	611	4.7	7.4
7	8x12	820	6.2	9.7
8	8x12	710	5.4	8.5

The compression diagram for graphite samples with a central hole is linear up until the point of brittle fracture, similar to observed in samples without holes. The samples collapsed in a completely brittle way in the diametrical plane of the disk. The destruction was found to originate from the central hole. In some samples we observed several additional cracks, along with the central. This is typical for the brittle fracture associated with a large number of fragments.

The average tear resistance of samples with a central hole as derived using the formula (3) was almost 2,5, and with formula (4) – 1,5 times less than true tear resistance (see table 1). Compared with cast iron, having a central hole in the graphite sample reduces the breaking stress more than 1,5 times. This can be explained by the fact that graphite is a more fragile material than cast iron and therefore more sensitive to stress concentrations. Breaking stress for brittle materials such as graphite, as defined by the formula (4), is 1,5 times less than the true strength of the material as defined by tensile tests according to GOST 1497. Therefore, graphite can be considered as a model material of the nuclear fuel uranium dioxide and uranium nitride.

Analysis of tests done on specimens with a hole shows a slight decrease in the breaking stress (about 10%) associated with doubling the thickness of the sample. Fig. 2 shows the dependence of the average values of S_0 and S_1 from the thickness for the graphite specimens with and without a central hole.

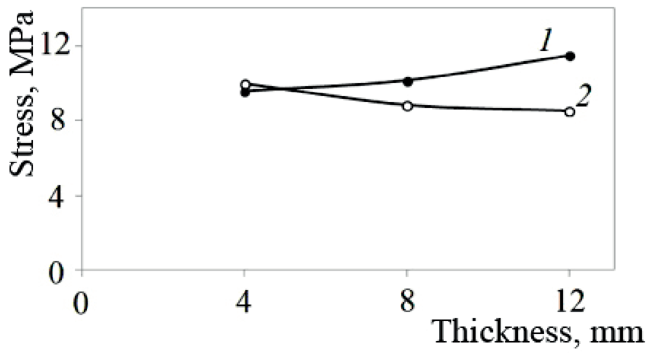

Figure 2: Dependence of the average values of S_0 and S_1 from the thickness of the graphite specimen without central hole (1) and with a central opening (2).

The results, given in table 4, indicate that when the thickness of the samples made of graphite is equal to 5 mm, fracture resistance, estimated by the formulas (2) and (4), is 1,5 times less than the true resistance of the material to rupture and is the same both for solid samples and for the samples with a central hole. These results can be used to produce formulas for estimation of the strength of the material under tension using the data obtained in tests of nuclear fuel samples according to the "Brazilian test" approach. That is, the true tensile strength of the material could be evaluated according to the formula

$$\sigma_B = \frac{1,5P}{tD} \tag{5}$$

for testing solid samples of nuclear fuel without central hole or

$$\sigma_B = \frac{1,5P}{t(D-d)} \tag{6}$$

for testing specimens with central hole.

2.3. Testing of samples of nuclear fuel

Fuel pellets of uranium dioxide were tested according to the ”Brazilian test” scheme. Sample dimensions were: diameter 8,3 mm, thickness 10 mm, central hole diameter of 1,1 mm. Fig. 3 shows the diagram of compression (*a*) and the photograph of typical fractures observed in the samples (*b*). Note almost linear increase in load preceding the brittle fracture of samples much similar to the one observed in tests on graphite specimens.

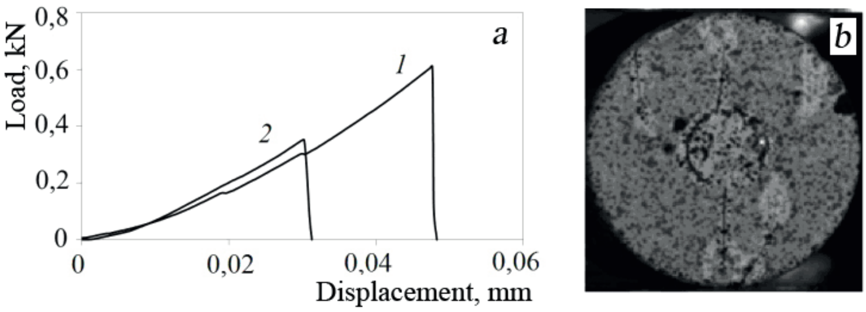

Figure 3: Diagrams of the compression (*a*) and the photograph of fracture (*b*) of the fuel tablets of uranium dioxide.

We observe a completely brittle nature of sample fracture in the diametrical plane of the disk in the zone of tensile stresses. The destruction originates from the central hole. Note the similarity of the destruction for both the graphite specimen and the real fuel pellets and the resemblance in diagrams of compression observed up to the point of full destruction of the specimen. Table 5 shows the results of the tests performed on fuel pellets. Rupture resistance of uranium dioxide was determined according to the formula (6).

Table 5: The results of the test fuel pellets.

sample	the size of the sample	P, N	S_1, MPa	σ_B MPa
1	8.3x10	612	8.5	12.7
2	8.3x10	351	4.9	7.35

The presented results are of course insufficient to establish the true value of the tensile strength of uranium dioxide, but they allow to at least approximate the order of magnitude of this value. The levels of destructive stress for the fuel pellets are within the order of magnitude agreement with the values of the breaking stress of the graphite samples. And accordingly the estimated level of strength agrees with the true strength of graphite ARV-1. This supports the possibility of using graphite ARV-1 as a

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material for modeling the behavior of uranium dioxide. Thus, we showed the possibility of testing the nuclear fuel (fuel pellets) according to the ”Brazilian test” with indirect assessment of the strength of brittle material.

3. CONCLUSION

The results of testing solid samples made of cast iron and graphite, with and without a central hole show lesser strength of brittle materials compared to the strength of the same materials at break determined in the tensile tests. The use of graphite ARV-1 as a model material for nuclear fuel (uranium dioxide) in the determination of the rupture resistance is justified. The possibility of testing nuclear fuel (fuel pellets) according to the “Brazilian test” with an indirect estimate of the material brittle fracture resistance is demonstrated. The formula for indirect evaluation of tensile strength of brittle components of the nuclear fuel based on results of the tests done according to the “Brazilian test” approach (as applied to disc specimens with a central hole or without it) is proposed.

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