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著者	SATO Sennosuke, KURUMADA Akira, KAWAMATA Kiyohiro, SUZUKI Nobuyuki, KANEKO Mitsunobu
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Neutron Irradiation Effects on Thermal Shock Resistances and Fracture Mechanical Properties of Fuel Compacts for the HTTR

Sennosuke SATO[1], Akira KURUMADA[1], Kiyohiro KAWAMATA[1], Nobuyuki SUZUKI[2] and Mitsunobu KANEKO[2]

1; Faculty of Engineering, University of Ibaraki, Hitachi 316.
2; Nuclear Fuel Industries Ltd., Tokai Works, Tokai 319-11.

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To simulate the nuclear fuel for the High Temperature Engineering Test Reactor (HTTR), a fuel compact model using SiC-kernel coated particles instead of UO_2-kernel coated particles was prepared under the same conditions as those for the real fuel compact. The mechanical and fracture mechanics properties were studied at room temperature. The thermal shock resistance and fracture toughness for thermal stresses of the fuel compact model were experimentally assessed by means of arc discharge heating applied at a central area of the disk specimens. These model specimens were then neutron irradiated in the Japan Material Testing Reactor (JMTR) for fluences up to 1.7×10^{21}n/cm^2 (E>29fJ) at 900℃±50℃. The effects of irradiation on a series of fracture mechanical properties were evaluated and compared with the cases of graphite IG-110 used as the core materials in the HTTR.

KEYWORDS : fuel compact, thermal shock resistance, thermal shock fracture toughness, neutron irradiation, HTTR.

1. Introduction

Evaluations of the mechanical, fracture mechanics properties and the thermal shock resistances of the nuclear fuel compact for the High Temperature Engineering Test Reactor (HTTR) developing by Japan Atomic Energy Research Institute (JAERI) were carried out for a safety assessment of the reactor. For the study, a fuel compact model using SiC-kernel coated particles instead of UO_2 particles was trially prepared in the same manufacturing process and was submitted to a series of experimental study for the disk- and rod-type specimens. Then these model specimens were neutron irradiated in the Japan Material Testing Reactor (JMTR) in JAERI up to 1.7×10^{21}n/cm^2(E>29fJ) at 900 ℃ ± 50 ℃ and the changes of these properties were investigated. These data obtained here are compared with the cases of graphite IG-110[1] used as the core materials in the HTTR.

2. Fuel Compact Model

SiC-kernels simulating UO_2-kernels were granulated in advance together SiC powder and binder with solvent, then were sintered. The kernels were over coated successively a low and high density pyrolytic carbon layers, SiC and then a high density pyrolytic carbon layer. Then quite similar coated particles to the real fuel particles were made. The coated particles were about 900 μm in diameter and 2.1 g/cm^3 in density. Subsequent preparation process was quite same with the process of the real fuel compact with UO_2-kernel. Photo.1 shows the microscopic structure of a fuel compact model.

3. Experimental Methods

3.1 Mechanical and fracture mechanics properties

Bending strength σ_b was examined for simplify supported disk specimen by

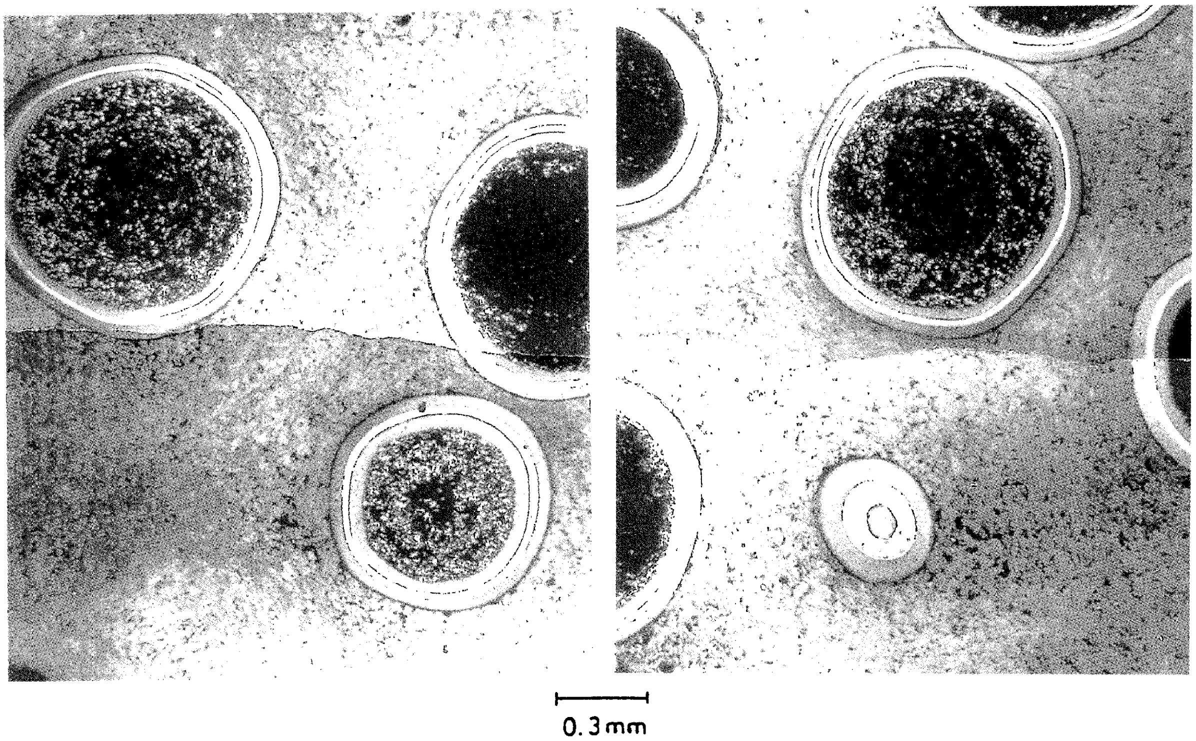

Photo.1 Microscopic structure of a fuel compact model.

a ring anvil and the center loading of a ball indentor, considering the Hertzian contact pressure distribution. Then regular 3-point bend test was also carried out using lod specimen.

Diametral compressive strength σ_{Ht} was measured for disk specimen using circular anvils considering the Hertzian contact pressure distribution[2].

Mode I and mode II fracture toughness values, K_{IC} and K_{IIC} were measured for disk specimens with a central slit 2c in length by means of diametral compression considering the Hertzian contact pressure distribution by anvils[3]. The central slit was machined by a thin dental ceramic saw and an ultrasonic machine. The tip radius was under about 50 μm.

The other, Young's modulus E, electric resistivity ρ, impact fracture energy E_C, thermal diffusivity κ, Rockwell hardness H_{R15X} were also measured.

3.2 Thermal shock resistance and thermal shock fracture toughness

The thermal shock resistance $\triangle$[4] synthesized the tensile strength σ_t, thermal conductivity k, Young's modulus E and thermal expansivity α was measured by determination of the critical electric power W to occur cracking at outer periphery of the disk specimen by following equation[4],

$$\triangle \equiv \sigma_t k/E\alpha = S_* \beta W/\pi h(a/R)^2 \quad (1)$$

where S_* is the specific value of nondimensional maximum thermal stress in nondimensional thermal diffusion time τ =0.25 and is function of (a/R) and Biot number in surrounding atmospher. β is heating efficiency for the thermal shock testing apparatus.

Then the thermal shock fracture toughness ∇[5] was also evaluated by means of determination of the critical electric power W to initiate cracking from the tip of the edge slit of disk specimen. Thermal shock fracture toughness ∇ is expressed as following equation[5],

$$\nabla \equiv K_{IC} k/E\alpha = F_1\sqrt{\pi c}\,\beta W/\pi h(a/R)^2 \quad (2)$$

where F_1 is the nondimensional stress intensity factor which is functions of (a/R) and (c/R) and is calculated from the thermal stress distribution in τ =0.25. And c is a depth of the edge slit.

Table 1 Neutron irradiation conditions in JMTR.

Specimen	Capsule number	Neutron flux ($n/cm^2s, E>29fJ$)	Temperature (℃)	Neutron fluence ($n/m^2, E>29fJ$)
Fuel compact model	87M-33u	3.28×10^{14}	900 (850～950)	1.7×10^{25}
Graphite IG-110	80M-31u	1.10×10^{14}	925 (850～1000)	$(1.1\text{-}1.5)\times10^{25}$

3.3 Neutron irradiation

Table 1 shows the neutron irradiation conditions of fuel compact model specimens in JMTR. Those for graphite IG-110[2] used as the core materials in the HTTR are also shown. As both of these conditions are similar and close to the actual situation in the HTTR, a comparison of irradiation effects can be made between the two.

4. Experimental Results and Discussions

Table 2 summarizes the mean values of experimental results for the fuel compact model and graphite IG-110 specimens before and after neutron irradiation. Values in the parentheses show the ratio of "after" and "before" values. The results for the fuel compact model are explained briefly comparing with graphite IG-110 as follows.

4.1 Mechanical properties

Dimensional change of the fuel compact before and after neutron irradiation was about 0.58% in shrinkage. Young's modulus E, compressive strength σ_c, bending strength σ_b, diametral compressive strength σ_{Ht} of the fuel compact model were all smaller than those of IG-110. Photo.2 (1) and (2) show typical fractures in the bending strength σ_b and the diametral compressive strength σ_{Ht} tests of a fuel compact model disk specimens. Among them, values of σ_c and σ_{Ht} are considerably smaller than IG-110. Therefore coated particles and defects on the interfaces of the fuel compact model are considered to be sensitive for shearing stresses.

Rockwell hardness H_{R15X} of the fuel compact was about 70-80% of IG-110. This difference is smaller comparing with the cases of mechanical strengths. But impact fracture energy E_c was only about 20-30% showing considerably weak tendency to dynamic stresses.

4.2 Fracture mechanics properties

The mode I fracture toughness K_{IC} of the fuel compact was about 80-90% of IG-110 together with before and after neutron irradiation, but the mode II fracture toughness K_{IIC} was showed some large difference of about 70% or less than that of IG-110. K_{IC} and K_{IIC} increased together to 1.45 and 1.26 times respectively due to neutron irradiation. They are quite similar to 1.29 times for the case of IG-110. The ratios of fracture toughnesses (K_{IIC}/K_{IC}) for the fuel compact were 1.06 and 0.92 before and after irradiation, respectively, and were smaller than 1.23 of the case of IG-110. (K_{IIC}/K_{IC}) means the ratio of the pure shearing strength and the tensile strength of the material and .is noteworthy that shearing strength is slightly larger than the tensile strength, but becomes inversely smaller due to neutron irradiation. Photo.3 (1) and (2) show typical fractures in the mode I and the mode II fracture toughness tests of a model fuel compact disk specimens.

Table 2 Mean values of experimental results for a fuel compact model before and after neutron irradiation and their comparisons with graphite IG-110.

Material		Fuel compact model		graphite IG-110	
Irradiation	N*	before	after	before	after
Bulk density γ (g/cm^3)	4	1.82	1.84 (1.01)**	1.75	1.75 (1.00)**
Dimensional change (%)	4	-	- (-0.58)	-	- (-0.04)
Young's modulus E (GPa)	4	6.89	9.97 (1.45)	7.80	11.8 (1.51)
Compressive strength σ_c (MPa)	4	25.7	35.9 (1.40)	70.5	89.2 (1.27)
Bending strength σ_b (MPa)	4	12.6	17.6 (1.40)	38.7	47.6 (1.23)
Diametral compressive strength σ_{Ht} (MPa)	2	6.43	9.10 (1.42)	15.3	18.5 (1.21)
Electric resistivity ρ ($\mu\Omega$cm)	4	2097	4241 (2.02)	1150	1927 (1.68)
Rockwell hardness H_{R15X}	7	49.3	63.4 (1.29)	71.0	78.0 (1.10)
Impact fracture energy E_c (J/cm^2)	2	0.12	0.09 (0.75)	0.41	0.42 (1.02)
Mode I fracture toughness K_{IC} (MPam$^{1/2}$)	4	0.62	0.90 (1.45)	0.78	1.01 (1.29)
Mode II fracture toughness K_{IIC} (MPam$^{1/2}$)	4	0.66	0.83 (1.26)	0.96	1.24 (1.29)
K_{IIC}/K_{IC}		1.06	0.92	1.23	1.23
Thermal diffusivity κ (mm^2/s)	2	34.3	21.9 (0.64)	48.5	26.0 (0.54)
Thermal shock resistance $\triangle$ (W/mm)	7	9.65	4.18 (0.43)	31.9	21.7 (0.68)
Thermal shock fracture toughness ∇ (W/mm$^{1/2}$)	7	25.8	14.0 (0.54)	34.4	26.8 (0.78)
Equivalent crack size $Ce_1=(K_{IC}/\sigma_t)^2/\pi$ (mm)		3.47	3.36 (0.97)	0.13	0.14 (1.08)
$Ce_2=(\nabla/\triangle)^2/\pi$ (mm)		2.28	3.57 (1.57)	0.37	0.49 (1.32)

* Number of specimens after neutron irradiation.

** Values inside the parentheses show the ratio of "after irradiation" and "before irradiation" values.

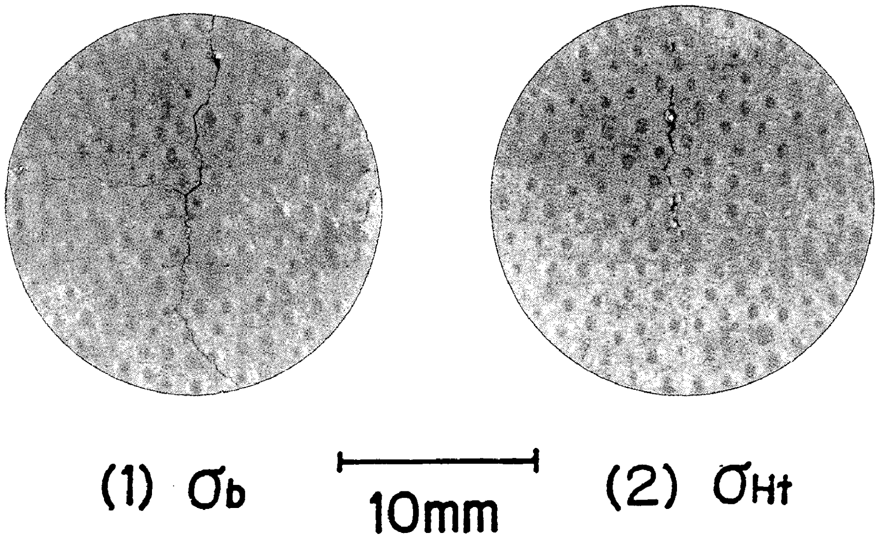

Photo.2 Typical fractures in (1) the bending strength σ_b and (2) the diametral compressive strength σ_{Ht} tests of a model fuel compact disk specimens.

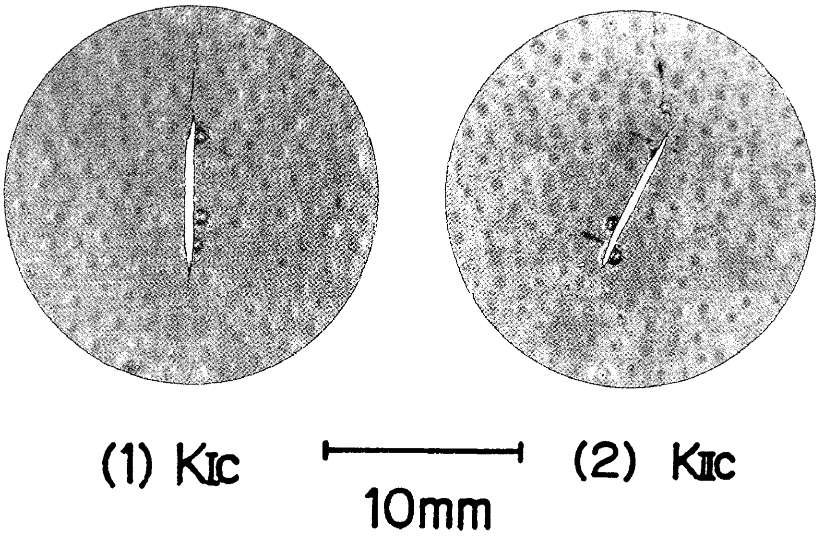

Photo.3 Typical fractures in (1) the mode I and (2) the mode II fracture toughness (K_{IC} and K_{IIC}) tests of a model fuel compact disk specimens.

4.3 Thermal diffusivity and electric resistivity

Thermal diffusivities κ of the fuel compact before and after irradiation were about 70% and 84% of graphite IG-110, respectively. The ratio for before and after irradiation was 0.64.

Electric resistivities ρ of the fuel compact before and after irradiation were about 1.8 times and 2.2 times those of IG-110, respectively. The ratio between values before and after irradiation was about 2.0 and was larger than the value of IG-110 of about 1.7. Increasement of electric resistivity of graphite by neutron irradiation is known due to large decrease of the mobility of electron by increase of the scatting center for the carrier.

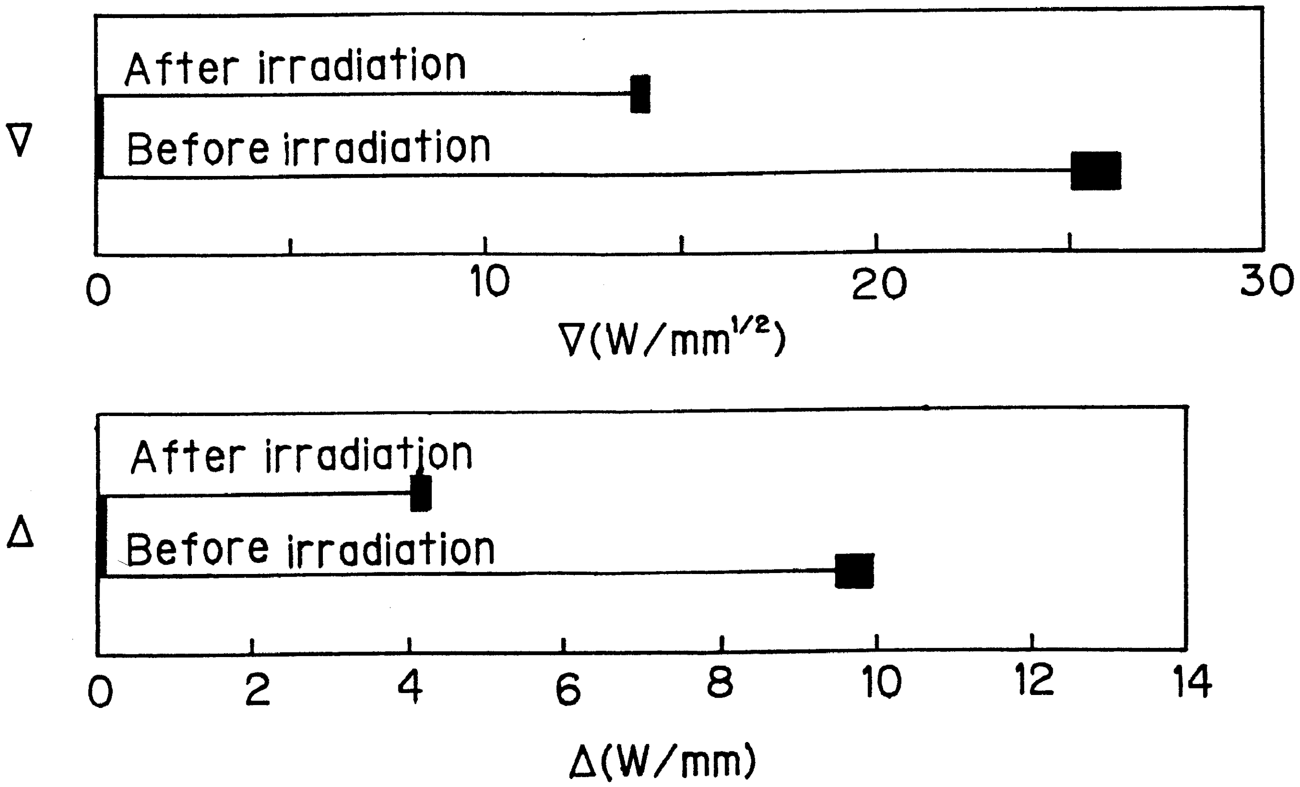

Fig.1 Thermal shock resistance △ (down) and thermal shock fracture toughness ▽ (upper) for a fuel compact model.

4.4 Thermal shock resistance and thermal shock fracture toughness

Fig.1 shows the ranges of the thermal shock resistance △ and the thermal shock fracture toughness ▽ which were obtained by equations (1) and (2) calibrated β for critical electric powers in the thermal shock testings, respectively. These mean values were entered as the values of △ and ▽ in Table 2. Photo.4 shows typical fractures in the thermal shock resistance and the thermal shock fracture toughness tests of a model fuel compact disk specimens. Photo.5 shows typical fractographs of a fuel compact model. (1) and (2) general view, (3) fuel particle and (4) matrix.

The values of △ and ▽ of the fuel compact are about 1/3 and 3/4 comparing with the values of graphite IG-110, respectively. The △ and ▽ after neutron irradiation decreased together about 50% from the before values. These degradations are considerably larger than the value of about 70% of IG-110.

5. Conclusion

In replacing UO_2 by SiC in the kernels, a fuel compact model for the HTTR was prepared by dispersing coated particles in a representative graphite matrix, and by following the same process route as that for the real fuel compact. Mechanical and fracture mechanics properties, as well as resistances against thermal shocks were then investigated. The results were compared with those of the core graphite IG-110 for the HTTR. Effects of neutron irradiation by JMTR were also compared. Although the number test specimens was small, especially for the after irradiation case, the obtained values of experimental results are tabulated in Table 2 with their mean value. These results can be summarized as follows ;

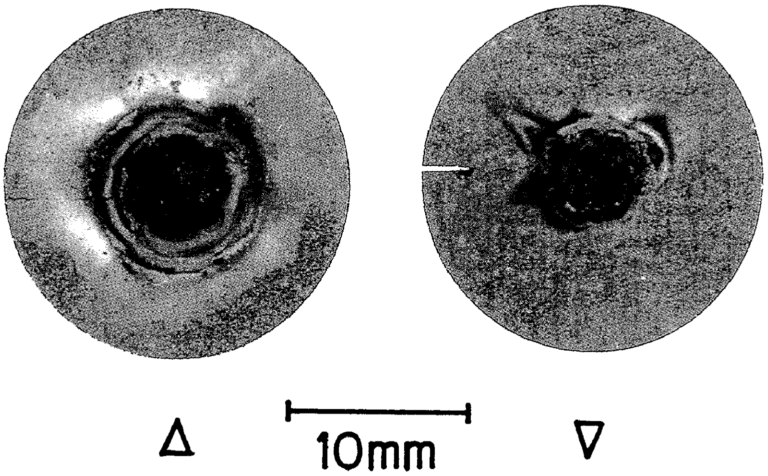

Photo.4 Typical fractures in the thermal shock resistance (left) and the thermal shock fracture toughness (right) tests of a model fuel compact disk specimens.

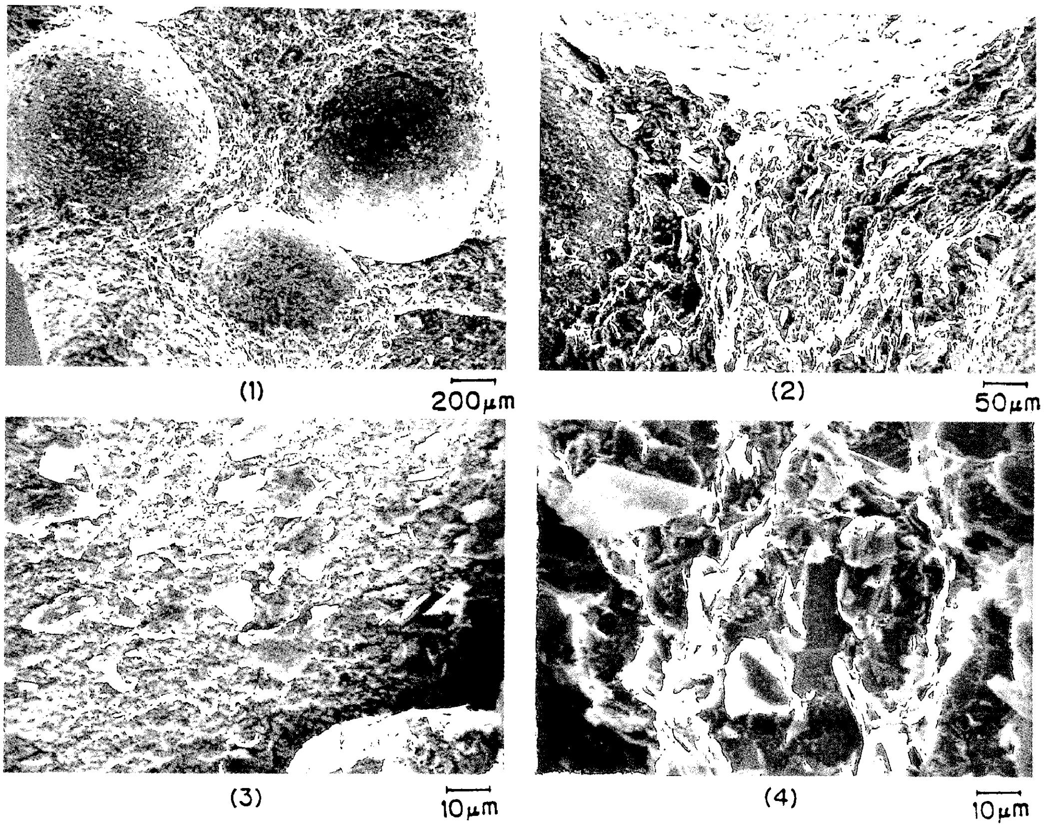

Photo.5 Typical fractographs of a fuel compact model.
(1) and (2) general view, (3) fuel particle and (4) matrix.

(1) Mechanical properties ; The mechanical strength of the fuel compact is about 1/2-1/3 that of graphite IG-110. Judging from the relatively small difference between Young's moduli, the enclosed coated particles appear to act as one concentrated source of structual sensitivity.

(2) Fracture mechanics properties ; Fracture toughness values of the fuel compact are about 70-90% of those for IG-110. The difference is small, compared to that of mechanical strength. This implies that the enclosed coated particles become dispersed inclusions or defects, thus having a tendency to moderate the stress singularities at the crack tips.

(3) Thermal diffusivity and electric resistivity ; Thermal diffusivities of the fuel compact are about 70 % and 84 % respectively of IG-110 for before irradiation and after irradiation. Assuming an identical specific heat, and judging from the difference in specific gravity, the difference in the thermal conductivities can be expected to be small. The electric resistivity is about 2 times that of IG-110.

(4) Thermal shock resistance and thermal shock fracture toughness ; Thermal shock resistances of the fuel compacts are about 1/3 and 1/5 respectively of IG-110 for before and after irradiation. The degradation of thermal shock resistance and thermal shock fracture toughness due to irradiation is about 43% and about 54%, respectively. The differences are not as significant as those of the thermal shock resistances. These circumstances resemble the characteristic differences of mechanical strengths and fracture toughnesses between the fuel compact and IG-110. This is an indication that the defects have plenty of room to grow before reaching the final fracture. The equivalent crack sizes calculated from the thermal shock tests are about 2.3 mm before irradiation and about 3.6 mm after irradiation. They are considerably larger than the value of about 0.4 - 0.5 mm for IG-110. Such large equivalent crack sizes of the fuel compact tend to substantiate the fact that the crackings found in the fuel safety experiment of the Nuclear Safety Research Reactor (NSRR) under abnormal conditions did not lead to fuel fracture.

(5) Thermal stresses of the fuel compact under the normal operating condition based on the design of HTTR and abnormal condition in a high energy pulse irradiation test in the NSRR were estimated using proper physical properties. These results can be concluded that the fuel compact is sufficiently safe since the thermal stress under the normal operating condition is well below the thermal shock resistance $\triangle$. However, the thermal shock stresses in the pulse experiment by the NSRR exceed $\triangle$ in all directions, substantiating that reticulate cracking occurred on the surface of the fuel compact.

(6) Thermal shock testing of matrix material containing no coated fuel particles was also carried out. It was revealed that both the thermal shock resistance and the thermal shock fracture toughness reduce to about one-half as a result of the presence of coated fuel particles.

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