Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

Mechanical resistance of UO_2 pellet by means of free-fall-impact testing

Tae-sik Jung [a*], Seung-jae Lee [a], Jae-ik Kim [a], Young-ho Jo [a], Bo-yong Park [a], Sang-ern Ko [a]
[a]*KEPCO Nuclear fuel, 1047 Daedeokdaero, Yuseong-gu Daejeon 305-353, Republic of Korea*
[*]*Corresponding author: taesik@knfc.co.kr*

1. Introduction

The two major materials challenges in nuclear fuel are extension of the fuel discharged burn-up and reinforcement of fuel assembly safety. Among them, fuel cycle cost is influenced by the former, hence, commercial nuclear power plants can operate in reduced costs to generate electricity by increasing the burn-up[1,2]. However, such operating condition may accompany higher power variation such as load follow operation or elevated power levels and as a result, cause a fuel failure related to a pellet-clad-interaction(PCI)[3].

A fuel rod failed during a power transient can be seen in Fig 1[4]. and conjunction of a chipped pellet with a cladding crack has been observed in commercial reactors through the post-irradiation examinations[5,6]. It revealed that missing-pellet-surface(MPS) was one of the reasons of the fuel failure. The mechanism of this failure mode that MPS induces the asymmetry of the pellet-cladding mechanical system mainly comprises a stress concentration at the inner surface resulting in non-classical PCI.

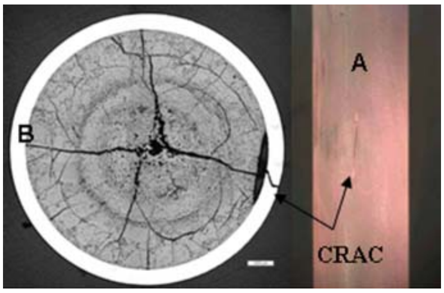

Fig. 1. In ‘A’ post-irradiated fuel rod. In ‘B’ rod cross-section[4].

An integral property of the material strength includes variables such as load mode, imperfections in material, especially pores, and geometry etc. Considering the material strength for failure behavior of ceramics can be described by the equation:

$$\sigma_f = \frac{K_{IC}}{\sqrt{\pi \cdot a \cdot f}}$$

Where ‘σ_f’ is failure stress, ‘f’ is a dimensionless factor describing geometry and load situation, ‘a’ is the critical crack size and K_{IC} is the fracture toughness. The fracture toughness is largely close to material property. It is assumed that by optimizing surface design of UO_2 pellet, the strength arises because theoretical strength is considerably affected by geometry as one of a parameter of factor ‘f’.

Pellet research for design optimization to achieve better resistance to external load should be accompanied with volumetric approach to the improvement of mechanical behavior of pellet being still ongoing.

At this work, the resistance to external load is analyzed varying with the geometry of pellets and angles of impact on UO_2 pellet surface by the free-fall-impact test method. The tested specimens were equivalently produced and sintered for having the same volumetric property such as sinter density and grain size except the surface with different geometry design at the end face and shoulder which includes dish, chamfer and land in dimension and angle.

2. Methods and Results

2.1 Free-fall-impact test

The purpose of the free-fall-impact test is to investigate the resistance of pellets to external load by applying impact from hammer falling down to the shoulder of pellet. With this test, one can lead to chipping on pellet’s surface in quantitative impact energy which could be developed during manufacturing, handling and loading pellets. Hence, with different geometry, pellet types having better resistance to external impact could be distinguished quantitatively measuring the weight of debris chipped from pellets. Additionally, the impact angle to pellet shoulder significantly induces diverse chipping behavior of pellets. Therefore, by varying the geometry and the impact angle, one can geometrically establish the predominant shape of pellet.

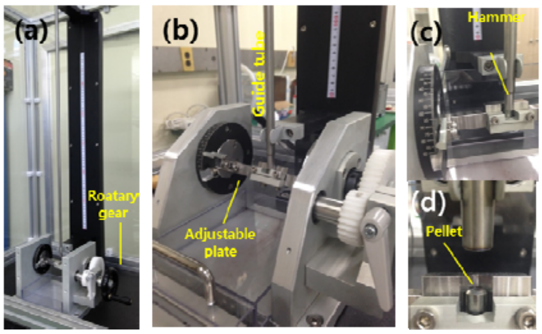

Fig. 2. Free-fall-impact test. (a) Rotary gear (b) Adjustable plate, Guide tube (c) Hammer (d) Pellet

Free-fall-impact test apparatus(see Fig. 2) was developed at the KEPCO NF Material Development laboratory in Daejeon and the research of mechanical chipping behavior of UO_2 pellets with different geometry and impact angle was performed. The impact angle can be rotated with the Rotary gear connected to the Adjustable plate holding a pellet and the Hammer induces the same amount of impact energy to pellets through the Guide tube as shown in Fig. 2.

2.2 Experimental procedure

The schematic sequence of sintering pellets and measuring characteristics process is shown in Fig. 3. Zinc-sterate(lubricant, 0.2wt.%)-added dry conversion(DC) UO_2 powder was pressed('P', 'K' type having different end face, shoulder shape and dimension) and apparent density was about 5.91 ~6.13 g/cm^3 of green pellets.

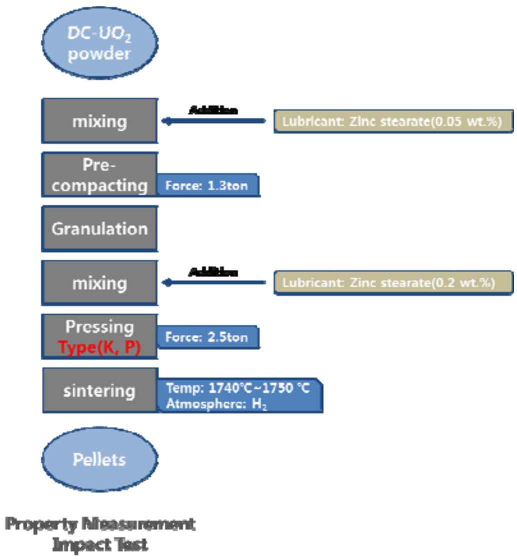

Fig. 3. Pellet production and property measurement schematic sequence diagram.

After sintering in H_2 atmosphere at 1730~1740℃ for 4h grinding was performed on the surface of pellets. Density was measured by buoyance method using water and the microstructure was analyzed.

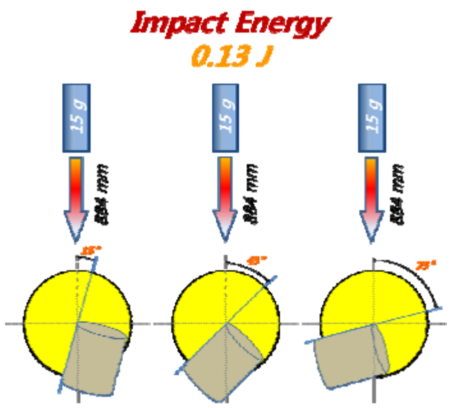

Fig. 4. Scheme of the free-fall-impact test.

Ten samples per angles were impacted for the tests impact angles of 15°, 45° and 75°(see Fig. 4). The hammer was dropped from 884mm high and weighed 15g corresponding to impact energy of 0.13J.

2.3 Results and discussion

As shown in Table 1, two types of pellets have almost same characteristics as a result of equivalent powder and sintering process.

Fig. 5. shows weight loss behavior as weight loss ratio with angle and pellet type. One can apparently find that the chipping behavior varies with the impact angle as well as pellet surface shape.

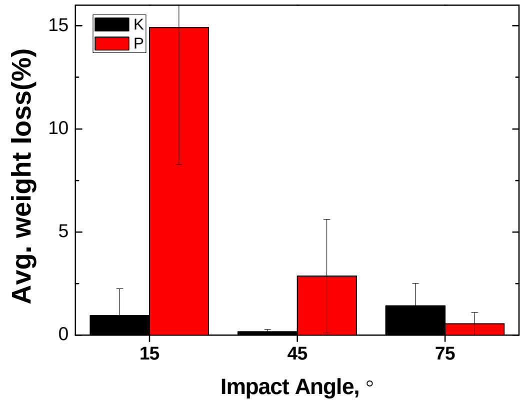

Fig. 5. Free-fall-drop test results of pellet type K, P.

On the pellet type P, as decreasing degree of angle, weight loss ratio drastically went up whereas the ratio of type K did not depend on it. It seemed that type K has higher resistance to external impact on pellet surface than type P.

Fig. 6. Impacted pellets having facet surface (a) type P (b) type K of 15°, 45°, 75° respectively in order from up to down.

As shown in Fig. 6(a), for type P impacted on 15°, chipped area on surface shows broken whole end face including circumferential face. With tilting to 45° and 75°, chipping area was changed to circumferential edge. Apparently, there not seems to see large-cracked area or facet surface for type K at every impacted angle as shown in Fig. 6(b).

Table. 1. Pellet type 'K' and 'P' properties and free-fall-impact test results.

pellets characteristics and test results	Pellet type					
	K			P		
Diameter (mm)	10.100 ± 0.001			10.100 ± 0.001		
Length (mm)	12.66 ± 0.04			12.58 ± 0.03		
Bulk density (g/cm^3)	10.55 ± 0.01			10.53 ± 0.02		
Theoretical density[a] TD(%)	96.25 ± 0.20			96.16 ± 0.30		
Grain size (㎛)	11.40 ± 0.15			11.36 ± 0.36		
Impact angle (deg)	15	45	75	15	45	75
Avg. Weight loss (%)	0.94±1.31	0.16±0.11	1.42±1.09	14.91±6.64	2.86±2.75	0.55±0.55

[a] Theoretical UO_2 density of 10.96g/cm^3

3. Conclusions

Missing-pellet-surface(MPS) on UO_2 pellet is inevitable behavior during manufacturing, handling and burning in reactor and brings about non-classical PCI behavior that could damage fuel rod integrity. For this reason, the free-fall-drop tester was developed by KEPCO NF Material Development laboratory in Daejeon for quantitatively investigating the mechanical behavior of UO_2. The free-fall-impact test is performed by dropping hammer on pellet shoulder with certain impact energy and at various angles. The result is quantitatively measured with weighing chipped debris.

Two types of pellets, P and K which have different shoulder geometry were impacted with varying impact angle. The P pellets were increasingly chipped as decreasing impact angle whereas the K pellets did not have any correlation with impact angle. A possible explanation for this is the fact that geometry factor for resistance to external load is significantly critical since the other characteristics of two types of pellets clearly appeared equivalent.

With this apparatus the development of geometry of UO_2 could be performed by measuring weight loss tendency at certain angle so that optimization for UO_2 geometry design to reduce chipping by external load can be achieved.

REFERENCES

[1] K.W. Song, Y.H. Jeong, K.S. Kim, J.G. Bang, T. H. Chun, H.K. Kim, K.N. Song, Nuclear Engineering Technology 40 (2008) 21-36.
[2] Very High Burn-ups in Light Water Reactors, OECD NEA report NAEA No. 6224, 2006
[3] Fuel failure in water reactors: causes and mitigation, IAEA-TECDOC-1345, 2002
[4] H.H.S. Santana et al, Applied Radiation and Isotopes 69 (2011) 1159-1161.
[5] Yagnik, S.K. et al., "Assessment of BWR Fuel Degradation by Post-irradiation Examinations and Modeling in the DEFECT Code", Proc. 1997 International Topical Meeting on LWR Fuel Performance, pp. 329-336, Portland, Oregon, 2-6 March 1997.
[6] Groeschel, F., G. Bart, R. Montgomery, S. K.. Yafnik, "Failure Root Cause of a PCI Suspect Liner Fuel Rod", *IAEA Technical Meeting on Fuel Failure*, Bratislava, Slovakia, 17-21 Jung 2002.