

## **Effect of $\text{TiO}_2$ on Sintering Behavior of Mixed $\text{UO}_2$ and $\text{U}_3\text{O}_8$ Powder Compacts**

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### **Abstract**

The effect of  $\text{TiO}_2$  on the sintering behavior of mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  powder compacts has been investigated using the  $\text{U}_3\text{O}_8$  powder made by oxidation of defective  $\text{UO}_2$  pellets. Without  $\text{TiO}_2$ ,  $\text{UO}_2$  pellet density is inversely proportional to  $\text{U}_3\text{O}_8$  content and is below 94 %TD in the  $\text{U}_3\text{O}_8$  range above 15 wt%. Using more than 0.1 wt %  $\text{TiO}_2$ , however, the density decreases slightly with  $\text{U}_3\text{O}_8$  content and thus is higher than about 94 % TD in the whole range of  $\text{U}_3\text{O}_8$  content. The grain sizes of  $\text{UO}_2$  pellets with more than 0.1 wt %  $\text{TiO}_2$  are larger than about 30  $\mu\text{m}$ . Therefore, the  $\text{U}_3\text{O}_8$  powder can be reused without any restriction on its amount in  $\text{UO}_2$  pellet fabrication by sintering the mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compact with the aid of  $\text{TiO}_2$ . Mechanisms for densification and grain growth are proposed and discussed, based on a dilatometry study and an examination of microstructure.

**Key Words :** Key Words :  $\text{UO}_2$  fuel, sintering,  $\text{U}_3\text{O}_8$  recycle,  $\text{TiO}_2$  additive

### **1. Introduction**

The uranium dioxide ( $\text{UO}_2$ ) pellet which has been widely used as a nuclear fuel is manufactured from  $\text{UO}_2$  powder by mixing, pressing and sintering. In the manufacturing process, defective  $\text{UO}_2$  pellets which do not meet the fuel specifications of density and diameter may be produced. Because defective  $\text{UO}_2$  pellets contain expensive enriched uranium, they should be recycled in the manufacture of new  $\text{UO}_2$  pellets. A common recycling method is

as follows [1]. Defective  $\text{UO}_2$  pellets are oxidized to  $\text{U}_3\text{O}_8$  powder, which is then mixed with  $\text{UO}_2$  powder. The powder mixture of  $\text{UO}_2$  and  $\text{U}_3\text{O}_8$  is pressed and sintered in the same way as the  $\text{UO}_2$  powder.

The above recycling method, however, has a problem in that the  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  powder mixture is less sinterable than the  $\text{UO}_2$  powder alone. Generally, a content of  $\text{U}_3\text{O}_8$  powder only up to about 15 wt % is allowed since a larger content of  $\text{U}_3\text{O}_8$  powder makes a deviation from the acceptable density required by fuel specification.

If many defective  $\text{UO}_2$  pellets happen to be made, it will take a long time for them to be recycled. Moreover, the remaining defective pellets will have to be stored for a very long time, if new  $\text{UO}_2$  pellets of which  $\text{U}^{235}$  enrichment is different from that of defective pellets are fabricated before all the defective pellets are recycled. So it is necessary to fabricate  $\text{UO}_2$  pellets from the powder mixture with higher  $\text{U}_3\text{O}_8$  contents.

The effect of  $\text{TiO}_2$  addition on the sintering behavior of  $\text{UO}_2$  powder compacts has been studied [2,3,4], especially from a grain growth point of view. It is well known that  $\text{TiO}_2$  increases grain size very much in  $\text{UO}_2$ . Ainscough et al. [2] reported that  $\text{TiO}_2$  addition enhanced the densification of  $\text{UO}_2$  compacts, and Radford and Pope [4] showed that  $\text{TiO}_2$  addition had an enhancing effect on the densification of  $\text{UO}_2$  compacts at low temperatures but had a negligible effect on the final density. The effect of  $\text{TiO}_2$  addition on the sintering behavior of mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  powder compacts has not been studied until now.

The purpose of this work is to fabricate  $\text{UO}_2$  pellets reusing more  $\text{U}_3\text{O}_8$  powder than by the conventional method. This paper mainly studies the effect of  $\text{TiO}_2$  addition on the densification and grain growth of mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  powder compacts. The paper also describes the pellet microstructure developed by the  $\text{TiO}_2$  addition.

## 2. Experimental Procedures

The  $\text{UO}_2$  powder used in this work was produced through the AUC (Ammonium Uranyl Carbonate) process [5].  $\text{U}_3\text{O}_8$  powder was prepared by oxidizing defective  $\text{UO}_2$  pellets in flowing air at  $400^\circ\text{C}$  for 3 hours. The particle size distribution of  $\text{UO}_2$  and  $\text{U}_3\text{O}_8$  powder was measured by a laser light scattering method, and

their morphology was observed by scanning electron microscopy. The specific surface area of  $\text{UO}_2$  and  $\text{U}_3\text{O}_8$  powder was measured by BET method.

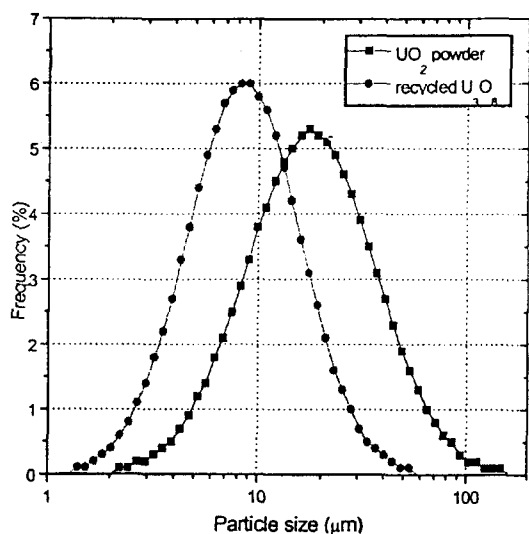
The  $\text{UO}_2$  powder was mixed with the  $\text{U}_3\text{O}_8$  powder in a tumbling mixer together with  $\text{TiO}_2$  powder. The powder mixtures had  $\text{U}_3\text{O}_8$  contents of 10, 20, 30, 40, 60, 80, and 100 wt %, and  $\text{TiO}_2$  concentrations were 0.05, 0.1, and 0.2 wt %, respectively. Powder mixtures were pressed under the pressure of  $3 \text{ ton/cm}^2$  with die-wall lubrication into compacts, which had a density of about  $5.75 \text{ g/cm}^3$ . Powder compacts were heated to  $700^\circ\text{C}$  in hydrogen gas and then held for 1 hour to eliminate lubricant. Subsequently, they were heated to  $1680^\circ\text{C}$  and held for 4 hours prior to furnace cooling. Hydrogen gas had a dew point of  $-30^\circ\text{C}$ , so the ratio of water vapor to hydrogen gas was  $5 \times 10^{-4}$ . The densification rate of the powder compact composed of 60 wt %  $\text{UO}_2$  and 40 wt %  $\text{U}_3\text{O}_8$  was measured with a dilatometer (Netzsch) under the same heating rate and gas atmosphere as those in the above-mentioned sintering condition.

Pellet density was determined by the water immersion method, and pellets were sectioned longitudinally and polished. To observe the grain boundary, thermal etching was carried out at  $1250^\circ\text{C}$  for 1 hour in  $\text{CO}_2$  gas, and the grain size was determined by a linear intercept method. The second phase formed in the  $\text{TiO}_2$ -doped  $\text{UO}_2$  pellet was quantitatively analyzed by electron probe micro analysis.

## 3. Results and Discussion

### 3.1. Effect of $\text{TiO}_2$ on Densification Behavior

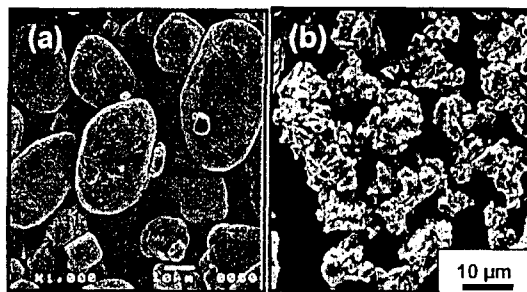
The particle size distribution of  $\text{UO}_2$  and  $\text{U}_3\text{O}_8$



**Fig. 1. Particle Size Distribution of  $\text{UO}_2$  and  $\text{U}_3\text{O}_8$  Powder**

powder is shown in Fig. 1. Both powders have a mono-modal distribution, and the mode which occurs with the greatest frequency is  $17\ \mu\text{m}$  for  $\text{UO}_2$  powder and  $8\ \mu\text{m}$  for  $\text{U}_3\text{O}_8$  powder. The orthorhombic  $\text{U}_3\text{O}_8$  phase has an about 30 % larger lattice volume than the cubic  $\text{UO}_2$  phase, so  $\text{UO}_2$  pellets are spontaneously pulverized by the large stress involved in the oxidation of  $\text{UO}_2$  to  $\text{U}_3\text{O}_8$ . It has been known that the particle size of  $\text{U}_3\text{O}_8$  powder is mainly dependent on the oxidation temperature [6]. As the oxidation temperature increases, the stress involved in the oxidation is so relieved that cracks are less developed in a pellet and the particle size of  $\text{U}_3\text{O}_8$  powder increases. Moreover,  $\text{UO}_2$  pellets cannot be pulverized above a temperature of about  $900^\circ\text{C}$  because of the formation of a crack-free  $\text{U}_3\text{O}_8$  layer[7]. In order to make fine  $\text{U}_3\text{O}_8$  powder, it is important to perform the oxidation of  $\text{UO}_2$  pellets at a temperature as low as possible [6].

Figs. 2(a) and 2(b) show the morphology of



**Fig. 2. Micrographs Showing the Morphology of (a)  $\text{UO}_2$  and (b)  $\text{U}_3\text{O}_8$**

$\text{UO}_2$  and  $\text{U}_3\text{O}_8$  powder, respectively. Each  $\text{UO}_2$  particle has a round shape and a smooth surface, so the  $\text{UO}_2$  powder is well flowing. However, each  $\text{U}_3\text{O}_8$  particle has an angular shape and also has many cracks that were formed during the oxidation, so the  $\text{U}_3\text{O}_8$  powder is not well flowing. The specific surface areas of  $\text{UO}_2$  powder and  $\text{U}_3\text{O}_8$  powder are  $5\text{m}^2/\text{g}$  and  $0.5\text{m}^2/\text{g}$ , respectively, suggesting that the sinterability of  $\text{U}_3\text{O}_8$  powder is much lower than that of  $\text{UO}_2$  powder. The reduced  $\text{UO}_2$  powder, which can be made by reducing the  $\text{U}_3\text{O}_8$  powder, has a specific surface area of  $0.36\text{m}^2/\text{g}$ .

The  $\text{U}_3\text{O}_8$  fraction in the mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compact is reduced to  $\text{UO}_2$  during sintering. According to the work on the kinetics of  $\text{U}_3\text{O}_8$  reduction [8],  $\text{U}_3\text{O}_8$  was reduced to  $\text{UO}_2$  between  $500^\circ\text{C}$  and  $600^\circ\text{C}$  in  $\text{H}_2$  gas for less than 1 hour. Since the densification of mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compacts starts at about  $800^\circ\text{C}$  (see Fig. 5), it is reasonable to suppose that the  $\text{U}_3\text{O}_8$  powder in a powder compact is reduced to  $\text{UO}_2$  powder before significant densification during the sintering in hydrogen. Therefore, from the viewpoint of densification, the mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compact can be regarded as a poorly sinterable  $\text{UO}_2$  compact.

Fig. 3 shows the variation of  $\text{UO}_2$  pellet density as a function of  $\text{TiO}_2$  concentration for

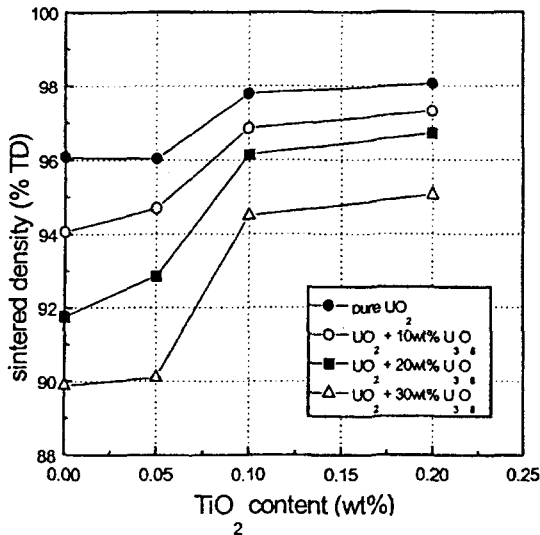


Fig. 3. Variation of  $\text{UO}_2$  Pellet Density with  $\text{TiO}_2$  Content

various  $\text{U}_3\text{O}_8$  contents. In the  $\text{UO}_2$  powder compact (without  $\text{U}_3\text{O}_8$  content), the density is negligibly affected in the concentration range of 0.05 wt %  $\text{TiO}_2$ , increases to the extent of about 2 % TD at 0.1 wt %  $\text{TiO}_2$ , and thereafter remains almost constant. Such a correlation between density and  $\text{TiO}_2$  concentration is readily found in the other compacts with various  $\text{U}_3\text{O}_8$  contents, with the density a little decreased. These relations imply that the densification of mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compacts can be enhanced by the same amount of  $\text{TiO}_2$  concentration as that of the  $\text{UO}_2$  compact. It can be noticed that more than 0.1 wt %  $\text{TiO}_2$  is needed to promote the densification of mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compacts.

Fig. 4 shows the variation of  $\text{UO}_2$  pellet density as a function of  $\text{U}_3\text{O}_8$  content. Without  $\text{TiO}_2$  addition, the density decreases linearly with  $\text{U}_3\text{O}_8$  content, and the decreasing rate is about 2 % theoretical density (TD) per 10 wt %  $\text{U}_3\text{O}_8$ . This decrease in density can be ascribed to the low specific surface area of  $\text{U}_3\text{O}_8$  powder. With

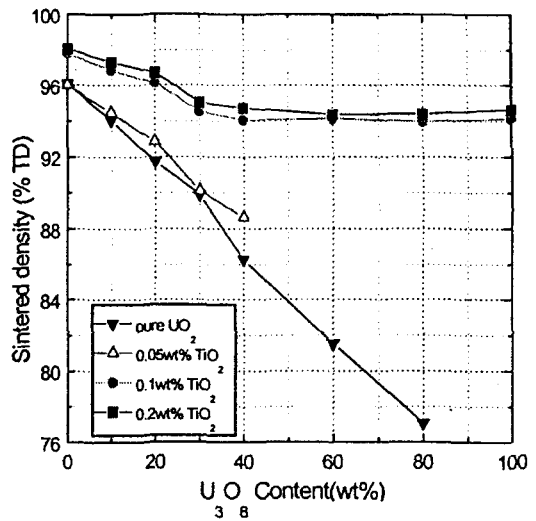
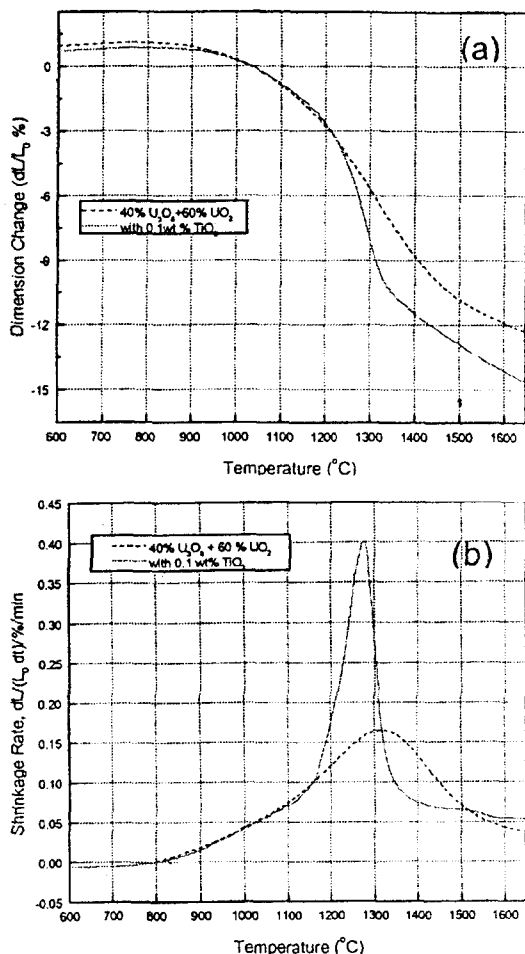


Fig. 4. Variation of  $\text{UO}_2$  Pellet Density with  $\text{U}_3\text{O}_8$  Content

0.05 wt %  $\text{TiO}_2$ , the dependence of density on the  $\text{U}_3\text{O}_8$  content is similar to that without  $\text{TiO}_2$ . With 0.1 wt % and 0.2 wt %  $\text{TiO}_2$ , the density decreases with  $\text{U}_3\text{O}_8$  content only in the  $\text{U}_3\text{O}_8$  range of 40 wt % and remains almost constant beyond that  $\text{U}_3\text{O}_8$  range. The density is about 94 % TD even at 100 wt %  $\text{U}_3\text{O}_8$ . The fuel specification requires the pellet density to be between 93.5 %TD and 96.5 %TD [1], so with more than 0.1 wt %  $\text{TiO}_2$ , the density is in the acceptable range under any  $\text{U}_3\text{O}_8$  content in the mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compact.

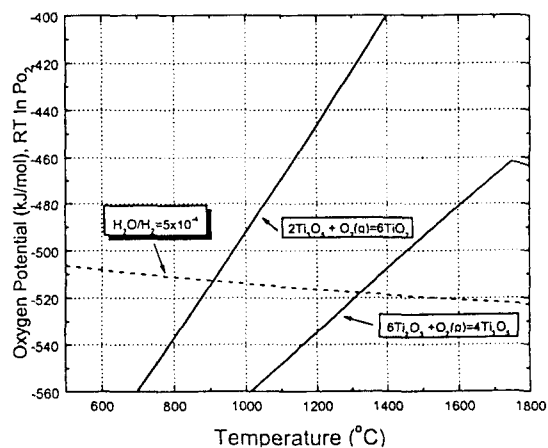
Fig. 4 also shows that the density difference between 'the pellet without  $\text{TiO}_2$ ' and 'the pellet with 0.1 wt %  $\text{TiO}_2$ ' becomes larger as the  $\text{U}_3\text{O}_8$  content increases. The  $\text{UO}_2$  compact is intrinsically sinterable enough to get a pellet density of about 96 %TD so it attains only a small amount of further densification by means of the  $\text{TiO}_2$  addition. However, the sinterability of mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  powder compacts decreases with  $\text{U}_3\text{O}_8$  content, and the amount of further



**Fig. 5. Shrinkage of the Mixed 60 wt %  $\text{UO}_2$ -40 wt %  $\text{U}_3\text{O}_8$  Compact;**  
**(a) Shrinkage Change, (b) Shrinkage Rate**

densification due to the  $\text{TiO}_2$  addition increases with the  $\text{U}_3\text{O}_8$  content. Therefore, it can be concluded that the amount of further densification which can be got by the addition of  $\text{TiO}_2$  appears to increase as the sinterability of a powder compact decreases.

Fig. 5(a) shows the densification (shrinkage,  $L/L_0$ ) of the mixed 60 wt %  $\text{UO}_2$ -40 wt %  $\text{U}_3\text{O}_8$  compact as a function of temperature. The compacts with and without  $\text{TiO}_2$  start to densify at about 800 °C, and undergo similar



**Fig. 6. Oxygen Potentials of Titanium Oxides and Hydrogen Gas with Moisture as a Function of Temperature**

densification up to about 1200 °C. However, the compact with  $\text{TiO}_2$  densifies to a larger extent above 1200 °C than the compact without  $\text{TiO}_2$ . The densification difference between the two compacts, which is made during heating to about 1350 °C, seems to remain almost constant even at higher temperatures. This densification difference suggests that  $\text{TiO}_2$  addition enhances the densification of the mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compact mainly in the intermediate sintering stage.

Fig. 5(b) shows the densification (shrinkage) rates as a function of temperature. It can be readily seen that the compact with  $\text{TiO}_2$  densifies with a high rate in a short range of temperature, but the compact without  $\text{TiO}_2$  densifies with a low rate in a broad range of temperature. The two densification rates increase gradually with temperature and are equivalent up to 1150 °C, but they become greatly different from each other above 1150 °C. The compact with  $\text{TiO}_2$  densifies more rapidly between 1150 and 1300 °C than the compact without  $\text{TiO}_2$ . Therefore, the added  $\text{TiO}_2$  seems

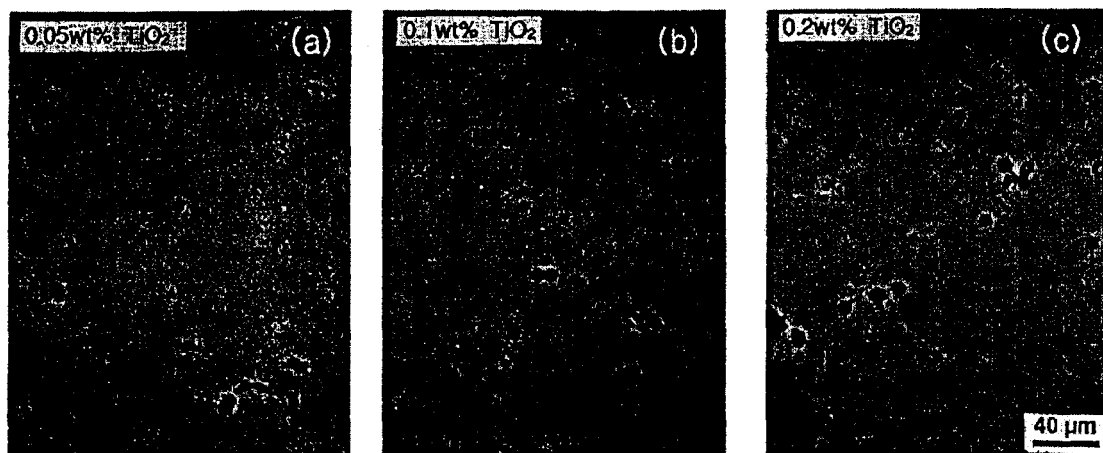


Fig. 7. Microstructures of  $\text{UO}_2$  Pellets with  $\text{TiO}_2$  Additions;  
(a) 0.05 wt%, (b) 0.1 wt%, (c) 0.2 wt%  $\text{TiO}_2$ .

to be working in the above temperature range.

The oxygen potentials of titanium oxides and hydrogen gas with a dew point of  $-30^\circ\text{C}$  are calculated with the HSC software [9], and the results are shown as a function of temperature in Fig. 6. A stable form of titanium oxide is dependent on temperature under hydrogen gas.  $\text{TiO}_2$  is stable below  $900^\circ\text{C}$ , and  $\text{Ti}_3\text{O}_5$  between  $900$  and  $1300^\circ\text{C}$ , and  $\text{Ti}_2\text{O}_3$  above  $1300^\circ\text{C}$ . Since the mixed  $\text{UO}_2\text{-U}_3\text{O}_8$  compact with  $\text{TiO}_2$  densifies with a higher densification rate between  $1150$  and  $1300^\circ\text{C}$  than the compact without  $\text{TiO}_2$  (see Fig. 5(b)), it is reasonable to suppose that the influential titanium oxide is mainly  $\text{Ti}_3\text{O}_5$ . The above temperature range is much below the  $\text{UO}_2\text{-TiO}_2$  eutectic melting point ( $1600^\circ\text{C} - 1620^\circ\text{C}$ ) [2], so liquid phase sintering is not related with the enhancement of a densification rate.

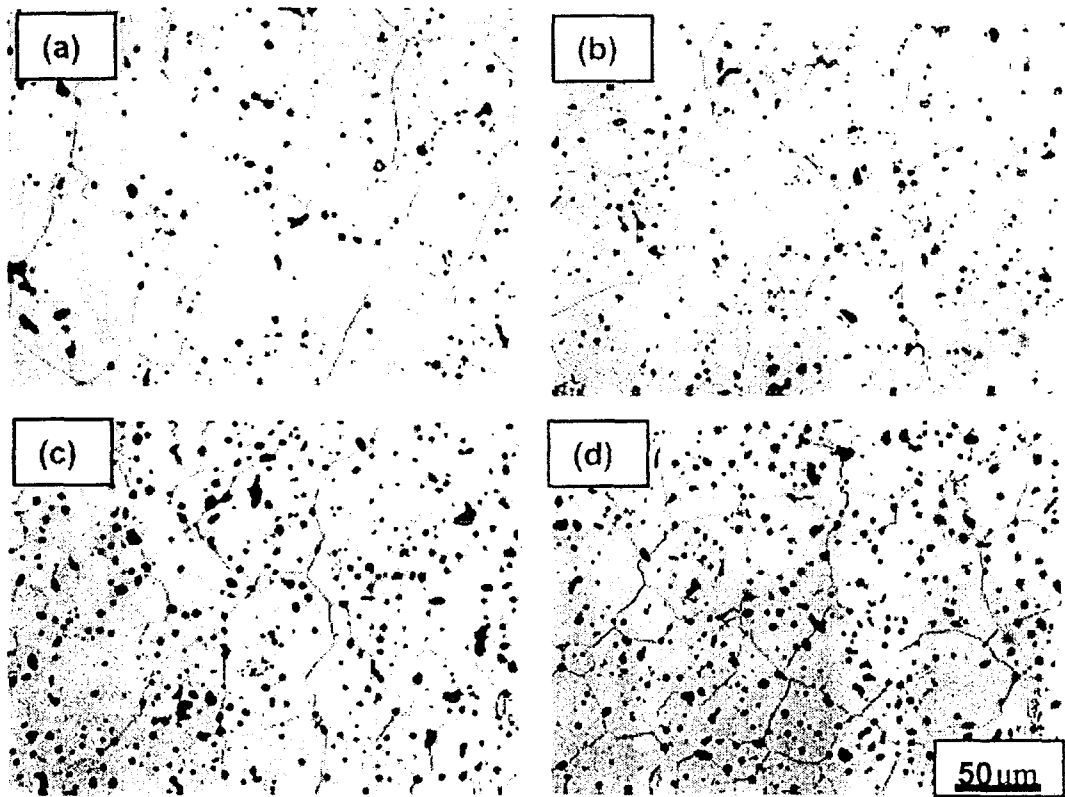
$\text{Ti}_3\text{O}_5$  may be an oxide compound in which a titanium ion has valences of 3+ and 4+. If a titanium ion with a valence of 3+ is dissolved substitutionally in  $\text{UO}_2$ , only the oxygen vacancy may be newly formed so that the increases in uranium diffusion is not expected. If titanium

ions with valences of 3+ and 4+ are dissolved interstitially in  $\text{UO}_2$ , uranium vacancy may be newly formed so that densification is expected to be enhanced as a result of the increase in uranium diffusion. It can be proposed that  $\text{Ti}_3\text{O}_5$  is dissolved interstitially in  $\text{UO}_2$  to accelerate a densification rate.

### 3.2. Effect of $\text{TiO}_2$ on Microstructure

Figs. 7(a), 7(b) and 7(c) show the microstructures of the  $\text{UO}_2$  pellets made of the  $\text{UO}_2$  compacts with 0.05 wt %, 0.1 wt %, and 0.2 wt%  $\text{TiO}_2$ , respectively. It can be readily seen that pores decrease substantially in number as the  $\text{TiO}_2$  concentration changes from 0.05 wt % to 0.1 wt %. The pore structure of the pellet with 0.1 wt %  $\text{TiO}_2$  seems to be similar to that with 0.2 wt%  $\text{TiO}_2$ .

Figs. 8(a), 8(b), 8(c) and 8(d) show the microstructures of the 0.1 wt %  $\text{TiO}_2$ -doped  $\text{UO}_2$  pellets made from  $\text{UO}_2$ , 80 wt %  $\text{UO}_2\text{-20 wt % U}_3\text{O}_8$ , 40 wt %  $\text{UO}_2\text{-60 wt % U}_3\text{O}_8$ , and  $\text{U}_3\text{O}_8$  compacts, respectively. It can be seen that the pores increase in number significantly with the



**Fig. 8. Microstructures of 0.1 wt %  $\text{TiO}_2$ -doped  $\text{UO}_2$  Pellets Made from the Compacts Comprising (a)  $\text{UO}_2$ , (b) 80 wt%  $\text{UO}_2$ -20 wt%  $\text{U}_3\text{O}_8$ , (c) 40 wt%  $\text{UO}_2$ -60 wt %  $\text{U}_3\text{O}_8$ , (d)  $\text{U}_3\text{O}_8$**

**Table 1. Compositions of Matrix and a Second Phase in the 0.1 wt %  $\text{TiO}_2$ -doped  $\text{UO}_2$  Pellet**

Elements	matrix (atomic %)	second phase (atomic %)
U	31.445	21.830
Ti	0.134	9.837
O	68.422	68.331

$\text{U}_3\text{O}_8$  content in the  $\text{U}_3\text{O}_8$  range of 60 wt %. However, pores increase in number slightly with the  $\text{U}_3\text{O}_8$  content beyond 60 wt%  $\text{U}_3\text{O}_8$ .

Figs. 9(a) and 9(b) show the second phase found in the  $\text{UO}_2$  pellet with 0.1 wt%  $\text{TiO}_2$ . Fig. 9(a) shows that a second phase having a very

small dihedral angle is precipitated on the grain boundary, suggesting that the second phase was once a liquid phase during sintering. The formation of a liquid phase was previously reported by Ainscough et al. [2]. The profile of titanium concentration across the second phase shows that the second phase has a higher titanium concentration than the matrix (see Fig. 9(b)). The quantitative analysis of titanium, uranium and oxygen was performed by EPMA, and the results are shown in Table 1. The matrix has a titanium concentration of 0.134 atomic %, which is equivalent to 0.125 wt %  $\text{TiO}_2$  addition. The dissolved titanium can be derived from  $\text{Ti}_2\text{O}_3$  in the temperature range between 900°C

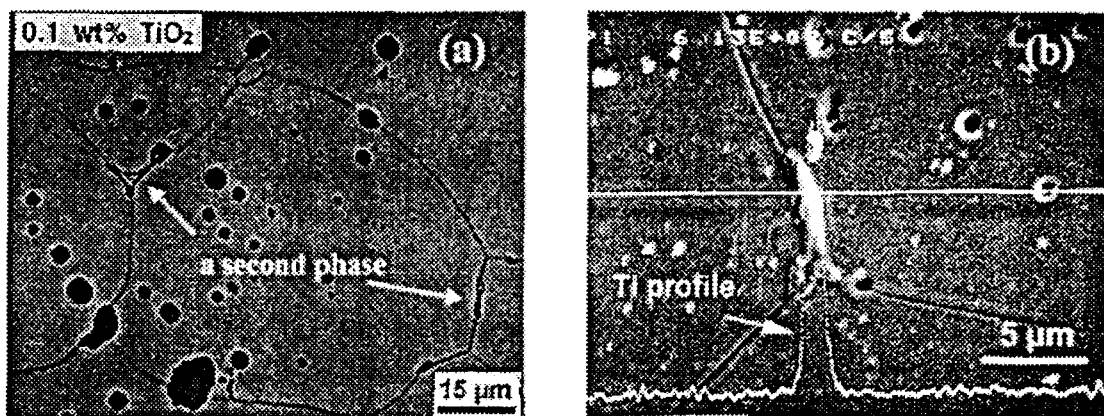


Fig. 9. Micrographs Showing the Second Phase Formed on the Grain Boundary

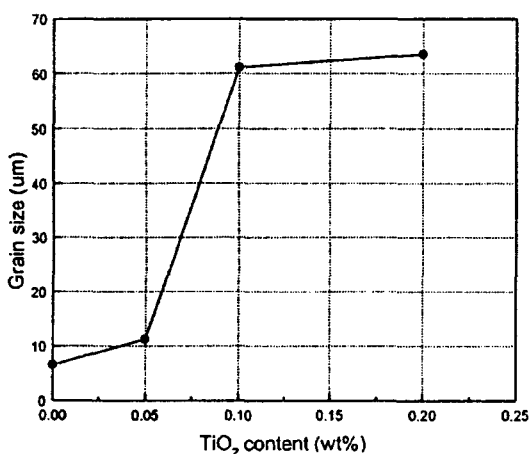


Fig. 10. Variation of the Grain Size of UO<sub>2</sub> Pellets with TiO<sub>2</sub> Content

and 1300°C, and from Ti<sub>2</sub>O<sub>3</sub> above 1300°C, as shown in Fig. 6.

Fig. 10 shows the effect of TiO<sub>2</sub> addition on the grain size of the UO<sub>2</sub> pellet made from the UO<sub>2</sub> compact. The grain size is slightly increased by the addition of 0.05 wt % TiO<sub>2</sub> but is enormously increased up to about 60 μm by the addition of 0.1 wt % TiO<sub>2</sub>. Fig. 11 shows the grain sizes of UO<sub>2</sub> pellets made from (UO<sub>2</sub> - U<sub>3</sub>O<sub>8</sub>) compacts with 0.1 and 0.2 wt % TiO<sub>2</sub>.

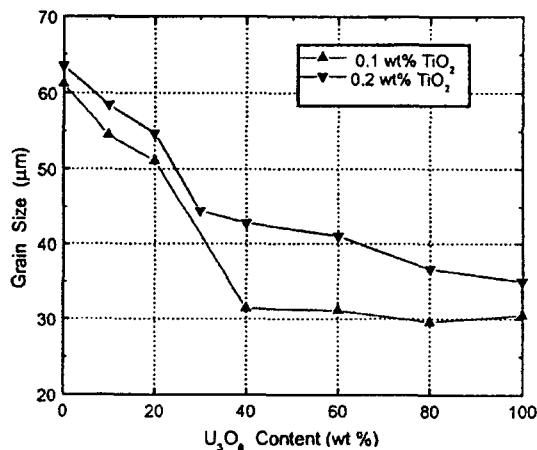


Fig. 11. Variation of the Grain Size of UO<sub>2</sub> Pellets with U<sub>3</sub>O<sub>8</sub> Content.

The dependence of grain size on U<sub>3</sub>O<sub>8</sub> content shows two different behaviors according to the U<sub>3</sub>O<sub>8</sub> content. In the range of about 40 wt % U<sub>3</sub>O<sub>8</sub>, the grain size decreases significantly with U<sub>3</sub>O<sub>8</sub> content, but in the range of above 40 wt % U<sub>3</sub>O<sub>8</sub>, it decreases slightly. Such decreasing behavior is probably attributed to the change in pore number in the respective range. Fig. 8 implies that pores increase in number significantly with U<sub>3</sub>O<sub>8</sub> content in the range of



low  $\text{U}_3\text{O}_8$  contents but increase slightly with  $\text{U}_3\text{O}_8$  content in the range of high  $\text{U}_3\text{O}_8$  contents. An increase in the pore number can yield a small grain size since grain growth in  $\text{UO}_2$  is retarded by pores [10,11].

A powder compact is subject to densification rather than grain growth before a final sintering stage during sintering. A final sintering stage begins with the closure of open pore channels, and it is known that a powder compact is densified to at least 90 % TD to reach a final sintering stage. Fig. 5(a) suggests that the compact with  $\text{TiO}_2$  densifies to 90 % TD above the temperature of about 1500°C, so the role of  $\text{TiO}_2$  addition in grain growth could be negligible below 1500°C. Accordingly, the dissolved  $\text{Ti}_3\text{O}_5$ , which mainly enhances the densification of a compact between 1150 and 1300°C, is not likely to influence grain growth. It is found that a liquid phase is formed on the grain boundary during sintering. The increase in grain size may be ascribed to the presence of a liquid phase, since material transport can be substantially enhanced through the liquid phase.

#### 4. Conclusions

$\text{TiO}_2$  is added to the powder mixture of  $\text{UO}_2$  and  $\text{U}_3\text{O}_8$ , and the powder mixture is then pressed and sintered to fabricate  $\text{UO}_2$  pellets. Without  $\text{TiO}_2$ , the  $\text{UO}_2$  pellet density decreases very much with  $\text{U}_3\text{O}_8$  content so that it becomes lower than 94 % TD for more than 15 wt%  $\text{U}_3\text{O}_8$ . However, with more than 0.1 wt %  $\text{TiO}_2$ , the density decreases slightly with  $\text{U}_3\text{O}_8$  content in the  $\text{U}_3\text{O}_8$  range of 40 wt% and then does not decrease any more. So the density is higher than 94 % TD in the whole range of  $\text{U}_3\text{O}_8$  content. The amount of densification which can be got by  $\text{TiO}_2$  addition appears to increase as the sinterability of powder compacts decreases. The

addition of  $\text{TiO}_2$  enhances the densification of a mixed  $\text{UO}_2$ - $\text{U}_3\text{O}_8$  compact between 1150°C and 1300°C, so it is proposed that  $\text{Ti}_3\text{O}_5$  is interstitially dissolved in  $\text{UO}_2$  to accelerate the densification rate. The grain size is enormously increased by the addition of more than 0.1 wt %  $\text{TiO}_2$ , mainly because a liquid phase is formed on the grain boundary during the sintering.

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