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ABSTRACT

Fabrication porosity in U_3Si_2-Al dispersion fuel plates and rods has been systematically studied for comminuted and atomized U_3Si_2 powders. A minimum amount of porosity is formed when the maximum fuel particle size is reduced and 40 - 50% of fines are included in the fuel powder. Atomized (spherical) fuel particles are particularly suited to the extrusion process.

INTRODUCTION

There are basically two aspects to the development of high uranium density LEU dispersion fuels. The first challenge is the discovery or development of a uranium compound or alloy with the highest possible uranium density that can be fabricated in a dispersion, and has acceptable irradiation behavior. To date, the highest density qualified compound is U_3Si_2 used in comminuted powder form, however, recently atomized (spherical) powder has become available which may possibly allow higher fuel volume loadings to be fabricated[1].

This second aspect - the maximum volume fraction of fuel particles in the core - is the main subject of this paper.

During rolling of plate type fuel or extrusion of rod or tube type fuel, a certain amount of porosity is formed. This is primarily due to fracturing of the fuel particles in response to the rolling or extrusion force. The amount of porosity can be substantial, for example, for a currently considered maximum commercially acceptable fuel-volume loading of 45% the porosity is 10%. This leaves only 45% matrix aluminum in the core. As the ductile aluminum provides the dispersion core with uniform flow behavior during rolling or extrusion, it appears that the maximum practical fuel loading of 45% is reached when the aluminum becomes a minor - largely discontinuous component of the dispersion. It seems reasonable to conclude that a reduction or elimination of the fabrication porosity would result in a higher practical maximum fuel loading. A much higher loading of ~ 53 Vol. % (~ 6 $gUcm^{-3}$) has indeed been achieved by a proprietary process[6].

Several factors affect the formation of porosity, some of these are examined in this paper.

Experimental Details

Both hot-rolled mini-plates and extruded rods were fabricated with comminuted and atomized (spherical) powder. The U_3Si_2 particle size was between 88 and 74 mm for the rolled plates and between 106 and 63 mm for the extruded rods. Several plates with fines only (maximum U_3Si_2 particle size of 44 mm) were rolled. The maximum fuel particle volume fraction was 50%. Pure aluminum powder was used as core matrix and type 6061 aluminum as cladding material. The rolling schedule consisted of nine passes of 20% reduction at 500°C. The extrusion ratio was (32.6:1) at 450°C with a maximum extrusion force of 105 kg cm^{-2}. The final fabrication porosity measurements were obtained by the Archimedean immersion method, they are listed in Table I. Data from miniplates fabricated previously in the RERTR program were used as well[3].

Fuel Particle Size and Shape

Metallographic examination of dispersion fuel cores reveals that fabrication porosity is primarily caused by cracking of fuel particles and the separation of the particle fragments during the core deformation. Larger particles are more prone to multiple fractures and contribute proportionally more to the formation of porosity. This is shown in Fig. 1, where the fabrication porosity as a function of fuel volume fraction in rolled plates, having maximum comminuted particle size of 150 mm and 88 mm, is compared. Presently no comparable data exists for spherical powder, but the trend of larger particle size and higher porosity is expected to be similar.

The effect of shape per se, however, is pronounced. As shown in Fig. 2, the porosity in 50 Vol. % rolled-plate and extruded-rod samples with comminute powder is roughly the same. The use of spherical powder, however, result in somewhat higher porosity in the plate sample but drastically lower porosity in the extruded sample. The answer to this widely different behavior can be found in the metallographic sections shown in Fig. 3 and Fig. 4.

The comminuted particles predominately fracture perpendicular to the rolling or extrusion direction. This is particularly clear in cross sections of an irradiated U_3Si_2 plate made with depleted uranium shown in Fig. 5. Because negligible swelling took place in the depleted fuel, the crack patterns in the fuel particles are preserved and consolidated by radiation enhanced sintering. The reason for this is that the rhombic shaped U_3Si_2 particles (see Fig. 6) align themselves during compacting of the core so that during the rolling deformation stage the preferred fracture planes tend to be aligned as well. This alignment, or preferred orientation, is clearly evident from the x-ray diffraction patterns shown in Fig. 7. It is also clear that no such alignment takes place with spherical particles. Indeed, spherical particles fracture randomly under the planar stress imposed by the rolls, evidently causing more porosity. The force on spherical particles in a circular extrusion die is more uniform leaving the particles largely intact, thus generating less porosity.

There is a separate size class, called "fines," that need to be considered. Fines have a maximum size of 44 mm; they are included in the core mix to minimize the amount of fuel to be recycled. Because of this small size, fines are less susceptible to fracturing, but they nevertheless generate fabrication porosity. At higher volume fractions, they are rather numerous and act as a dispersion hardening agents in the matrix aluminum. During rolling or extrusion porosity is more likely to be formed at the fine particle - aluminum interface in contrast to the fracture type porosity associated with large particles.

Fuel Powder - Porosity Optimization

Functions based on geometric and simplified metallurgical considerations were fit through the data shown in Fig. 1 and Fig. 2. A Separate function for fines was derived

The resulting relations between maximum particle size, particle shape, fraction of fines on one hand and porosity on the other are shown in Fig. 8.

The curve shown in Fig. 8 is based on the hypothesis that the porosity caused by cracking of larger fuel particles and that due to fines alone are additive. To test this hypothesis, two plates with 50 Vol. % U_3Si_2 consisting of 40% fines were rolled. As shown in Table I and Fig. 8, the porosity using this coarse - fine mixture is indeed lower than for either coarse or fine powder alone.

Conclusions

The fabrication porosity generated in the core of dispersion fuel plates and rods is an indicator of uniform plastic flow during fabrication.

As such fabrication porosity can be used as a measured parameter in optimizing highly loaded dispersion fuel.

It has been shown that a minimum of fabrication porosity is achieved by a reduction in maximum fuel particle size, and a high fraction (~40 - 50%) of fuel particle fines.

Atomized (spherical) particles are expected to approach similar upper limits than comminuted particles in rolled plates, but exceeds comminuted powder loading limits in extruded rods. Optimized rolling or extrusion parameters as well as homogenous blending and pressing of cores should be common practice but some refinement may still yield gains in maximum practical loading.

Finally, a most important consideration, not presented explicitly in this paper, is the match of compressive flow properties of core and cladding. A good match has the effect of making the fuel plate or rod deform as a single material. For example, replacing the pure aluminum matrix powder with Al-6061 (a harder alloy) powder increased the fabrication porosity when Al-6061 was also used as cladding material. Use of a stronger cladding alloy on the other hand reduces the porosity[4], as illustrated in Fig. 9.

In summary, we are confident that plate or rod type U_3Si_2-Al dispersion fuel with a volume loading of up to 55% (6 gU/cm^3) can be produced with either comminuted or atomized powder, through careful tailoring of the fabrication and materials specifications.

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TABLE 1
DISPERSION FUEL CORE POROSITY, %

Volume Fraction of U_3Si_2	U_3Si_2 Particle Size, mm	Comminuted (c) Atomized (s)	Plate (Rolled)	Rod (Extruded)
15	88 - 74	S	0.9	
15	88 - 74	C	1.0	
15	106 - 63	S		1.3
15	106 - 63	C		1.0
15	< 44	S	3.0	
15	< 44	C	3.7	
50	88 - 74	S	16.5	
50	88 - 74	C	12.3	
50	106 - 63	S		3.5
50	106 - 63	C		13.0
50	< 44	S	8.2	
50	< 44	C	11.9	
50	88 - 74 (40% < 44)	S	8.1	
50	88 - 74 (40% < 44)	C	9.7	

TABLE 2
COMPARISON OF HOT-ROLLED PLATES WITH 6061 CLADDING

Loading Vol. %	U_3Si_2	Porosity Comminuted	Atomized
50	150 - 44 mm	18 (extrapolated)	
50	88 - 74 mm	12.3	16.5
50	88 - 74 mm (40% < 44mm)	9.7	8.1
50	< 44mm	11.9	8.2

TABLE 3
COMPARISON OF ORR DEMONSTRATION PLATES[5]

Loading, Vol. %	U_3Si_2 Particle Size	Porosity	Cladding
46, C	90 - 40 mm (40% < 40 mm)	4	AG3NE
43, M	150 - 40 mm (17% < 40 mm)	7	AlMg2
41, B & W	150 - 44 mm (18% < 44 mm)	10	6061

Figure 1. Effect of U3Si2 Particle Size on Fabrication Porosity in Hot-Rolled Dispersion Cores

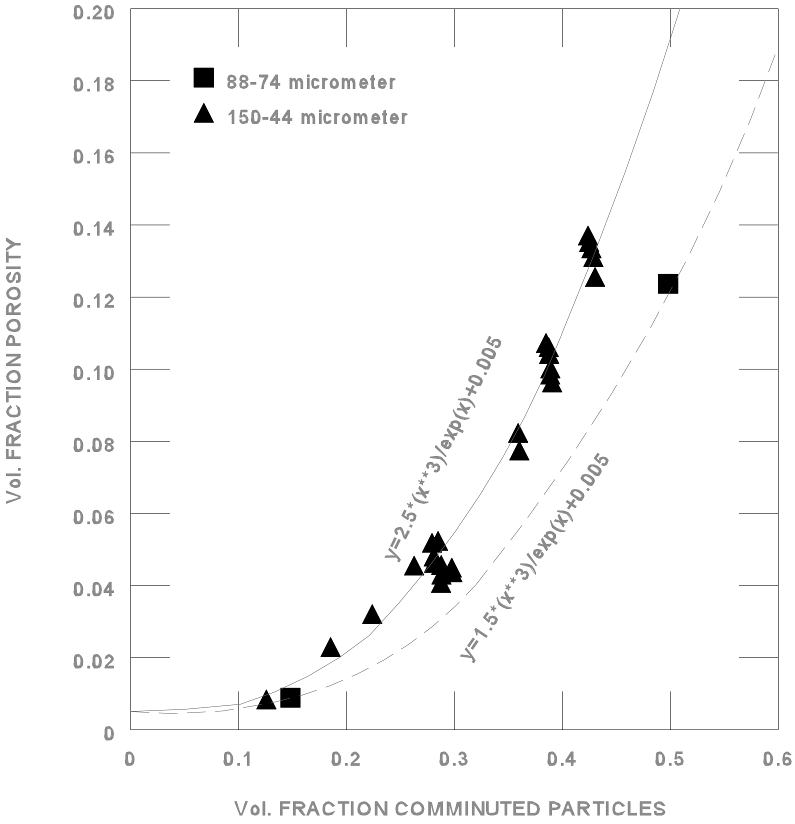
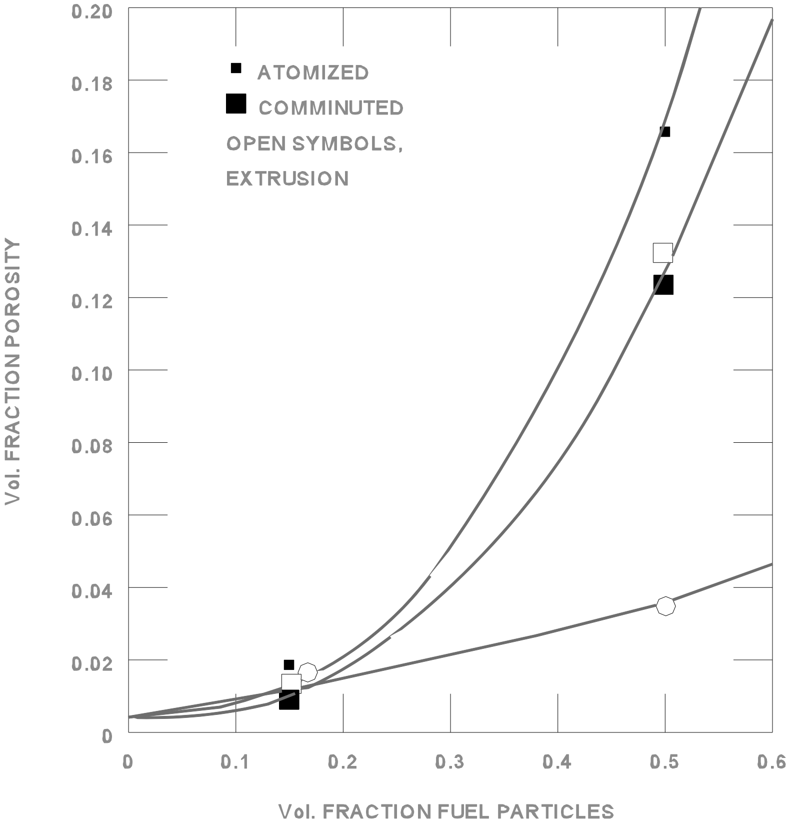


Figure 2. Fabrication Porosity in Hot-Rolled and Extruded Dispersion Cores with 88 - 74 µm U3Si2 Particles



SCANNED IMAGES FOR FIGURES 3-6 WOULD INCREASE THE SIZE OF THIS FILE BY ABOUT 2.5 MEGABYTES AND REQUIRE A LONG TIME TO DOWNLOAD. PLEASE CONTACT DR. GERARD HOFMAN AT THE ADDRESS SHOWN BELOW TO OBTAIN A FAX OF HIS PAPER INCLUDING FIGURES 3-6.

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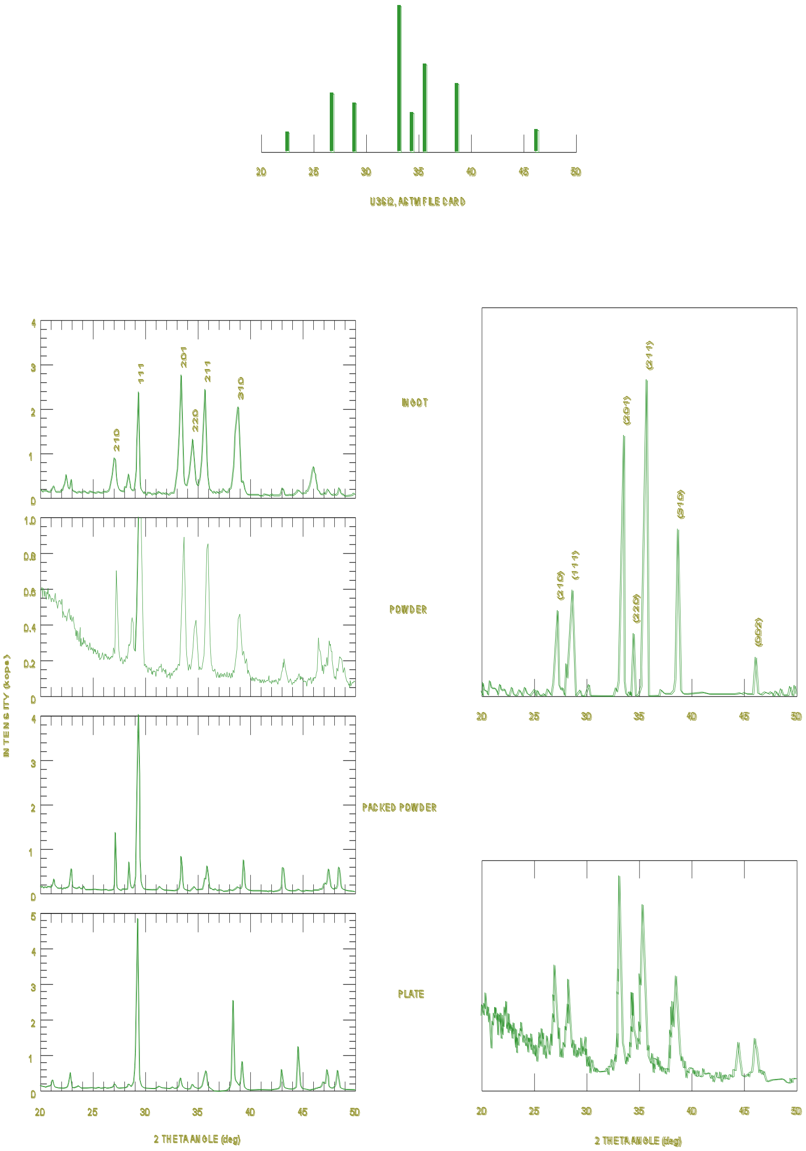
Fig. 3. Microstructures of Hot-rolled Cores Containing 50 Vol. % Comminuted and Atomized U_3Si_2 Powder

Fig. 4. Microstructure of Extruded Cores Containing 50 Vol. % Comminuted and Atomized U_3Si_2 Powder (SEM).

Fig. 5. Postirradiation Microstructure of Fuel Plate Containing 45 Vol. % Depleted U_3Si_2.

Fig. 6. Scanning Electron Micrograph of Comminuted U_3Si_2 Powder.

Figure 7. X-Ray Diffraction of Comminuted and Atomized Powder Plates. Observe the strong variation between finished fuel plates indicating an orientation of comminuted U3Si2.



(a) Comminuted powder

(b) Atomized powder

Figure 8. Fabrication Porosity as Derived for Variable Fraction of Fines and Measured Data for 40% Fines in Hot-Rolled Plates with Comminuted and Atomized U3Si2 Powders

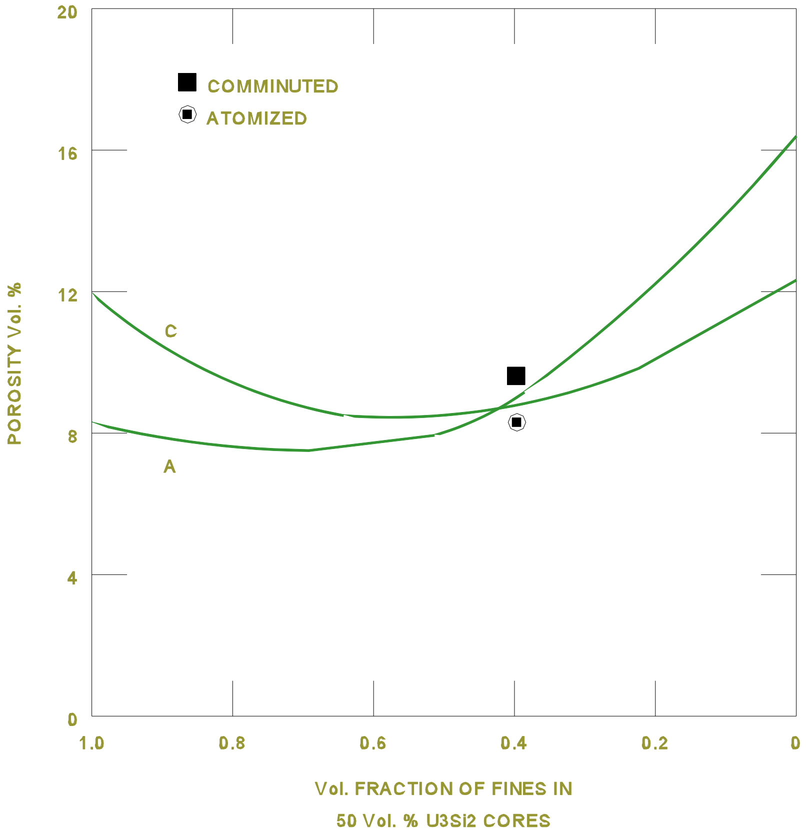


Figure 9. Effect of Matrix Aluminum Powder and Aluminum Claddings on Fabrication Porosity in Hot-Rolled Dispersion Cores