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Ultrasonic Testing of Dispersion Type Fuel Miniplates Manufactured with Hydrided UMo Powder

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ABSTRACT

In order to evaluate the bonding integrity in dispersion fuel plates, the transmission ultrasonic technique is applied. This technique was a development for monolithic fuel type and dispersion fuel type miniplates manufactured with UMo atomized powder. This paper reports the results obtained from the development, analysis and discussions conducted at CCHEN using miniplates manufactured with hydride powder and atomized UMo. In summary, the results for miniplates with a density of $6gU/cm^3$, manufactured with atomized UMo powder, shown an ultrasonic signal strength of 32.84% (UMo-84), related to the initial amplitude of ultrasonic signal. However, for miniplates manufactured with UMo particles obtained by hydriding, the ultrasonic testing presented lower values of ultrasonic signal strength, close to 10.32% (UMo-76). Considering the characteristics of this powder and the miniplates fabrication process, it has been verified that the porosity and brittleness of UMo hydrided particles produce an excessive increase in fine particles. When starting with 61% vol. particles below 45 µm in the UMo fuel powder, this percentage increases up to 93% volume after compacting (UMo-54 miniplate) and 96% vol. at the end of the miniplate manufacturing process, checked by quantitative metallography. According to this analysis, for this study were analyzed miniplates with different percentage of fine, with de 61 wt % at the beginning and then continuing with 7.3 % and 18.4 % of particles below 45 µm. Based on these results, the possibility that the excessive increase in the percentage of fine fuel particles, considering besides the residual porosity present in the meat, could be the main cause for high attenuation of the ultrasonic signal through the meat, are discussed in this paper.

1. Introduction

Since 2003, CCHEN’s fuel fabrication staff has been working in a Fuel Development Program based on UMo alloys. The main challenge has been the powder fabrication, obtained by different techniques, the fuel miniplates fabrication, and the development of methodologies for inspection and evaluation [1].

Non-destructive testing (NDT) plays a key role for the evaluation of miniplates by ultrasonic inspection – UT. The evaluation technique known as through transmission, in which two transducers located opposite one another are used, one as a transmitter and the other as a receiver, is the most widely used [3].

In order to implement this technique and considering the internal behavior of the plates during fabrication, different fuel powder characteristics at the end areas of meat, areas where a lower ultrasonic signal strength by “fishtail” is expected, it was necessary to define inspection criteria [4], in which three inspection zones were defined.

Miniplates with different powder type; hydride powder (dense and porous) and atomized powder with densities between 6-8 gU/cm^3 were evaluated by Ultrasound Testing Technique - UT.

2. Experimental set-up

2.1. Miniplates Fabrication

The miniplates were manufactured blending UMo and Al-Si powders, followed by compacting, assembling (compact, covers and frame), welding, hot-rolling, blister test, cold rolling and QC inspections at each fabrication step. The uranium densities were between 6 and 8 gU/cm^3. The mixture was compacted in a rectangular die of 18 x 22 mm, applying 21 Tons to a 4 cm^2 area.

The UT transmission technique was applied to 21 miniplates with different characteristics. A summary of these miniplates is presented in Tables 1 and 2.

For results analysis purposes, this paper includes the ultrasound evaluation of U_3Si_2 miniplates fabricated with uranium densities of 1.7, 3.4 and 4.8 gU/cm^3, as detailed in Table 3.

Table 1. Miniplates fuel with the hydride powder, dense and porous type

Miniplate Identification	**UMo-74**	**UMo-76**	**UMo-77**	**UMo-78**	**UMo-79**	**UMo-80**	**UMo-81**	**UMo-83**
Uranium type	NU	NU	LEU	LEU	LEU	LEU	LEU	LEU
Hydrided UMo Fuel	Porous	Porous	Porous	Porous	Porous	Porous	Dense	Dense
Fuel powder density [g/cm^3]	16.15	16.15	11.45	11.45	11.45	11.45	16.15	16.15
UMo powder Lot (U-7wt% Mo)	U7Mo HD-NAT L3	U7Mo HD-NAT L3	U7Mo HD-LEU L7	U7Mo HD-LEU L7	U7Mo HD-LEU L7	U7Mo HD-LEU L7	U7Mo HMD-LEU L8	U7Mo HMD-LEU L8
UMo < 45 µm fraction [%]	38.4	38.4	7.3	7.3	7.3	7.3	18.4	18.4
Nominal Loading [gU/cm^3]	7.0	6.0	7.0	7.0	7.0	8.0	7.0	7.0
Real Loading [gU/cm^3]	6.6		6.3	6.3	6.3	6.3	7.53	7.53
UMo Fuel weight [g]	6.18	5.93	6.18	6.18	6.18	6.40	6.18	6.18

Matrix (Al+4wt%Si) [g]	1.27	1.52	1.27	1.27	1.27	1.05	1.27	1.27

Table 1. Continuation

Miniplate Identification		**UMo-74**	**UMo-76**	**UMo-77**	**UMo-78**	**UMo-79**	**UMo-80**	**UMo-81**	**UMo-83**
Compact Measures	Length (mm)	22.34	22.44	22.42	22.45	22.43	22.43	22.37	22.38
	Width (mm)	17.89	17.91	17.96	17.97	17.97	17.97	17.93	17.92
	Thickness (mm)	2.75	2.71	2.44	2.49	2.47	2.33	2.55	2.56
Meat Measures	Length (mm)	82.4	85.2	82.7	82.0	82.7	81.5	82.8	82.8
	Width (mm)	19.5	19.0	18.4	18.4	18.3	18.2	18.5	18.0
	Thickness (mm)	0.52	0.69	0.68	0.64	0.63	0.62	0.65	0.67
Miniplate Measures	Length (mm)	170	129.79	130.07	129.84	129.95	129.46	129.93	130.39
	Width (mm)	81	50.64	50.17	50.50	49.85	49.82	49.86	49.99
	Thickness (mm)	1.47	1.45	1.40	1.40	1.39	1.40	1.40	1.40
Cladding thickness avg. [mm]		0.48	0.38	0.37	0.37	0.37	0.39	0.37	0.39
Starting Assembly Thickness [mm]		5.46	5.63	5.56	5.55	5.55	5.55	5.54	5.79
Total Reduction (%)		73.1	74.24	74.8	74.8	74.9	74.8	74.7	75.8
Reduction rate		1:3.72	1: 3.88	1:3.97	1:3.96	1:3.99	1:3.96	1:3.96	1:4.14

Table 2. Fabrication parameters for miniplates based on UMo atomized powder

Miniplate Identification		**UMo-84**	**UMo-85**	**UMo-86**	**UMo-87**	**UMo-89**
Uranium Type		NU	NU	NU	NU	NU
Fuel density [g/cm^3]		12.52	12.52	12.52	12.52	12.52
UMo powder Lot		U7Mo-REP-NAT-L9	U7Mo-REP-NAT-L9	U7Mo-REP-NAT-L9	U7Mo-REP-NAT-L9	U7Mo-REP-NAT-L9
UMo powder < 45 µm [%]		18.56	18.56	18.56	18.56	18.56
Nominal Loading [gU/cm^3]		6.0	6.0	7.0	7.0	8.0
Real Loading [gU/cm^3]		6.6	6.3	6.3	6.3	6.3
UMo Fuel weight [g]		6.18	6.18	6.18	6.18	6.40
Matrix (Al+4wt%Si) [g]		1.27	1.27	1.27	1.27	1.05
Compact measures	Length (mm)	22.34	22.42	22.45	22.43	22.43
	Width (mm)	17.89	17.96	17.97	17.97	17.97
	Thickness (mm)	2.75	2.44	2.49	2.47	2.33
Meat measures	Length (mm)	82.4	82.7	82.0	82.7	81.5
	Width (mm)	19.5	18.4	18.4	18.3	18.2
	Thickness (mm)	0.52	0.68	0.64	0.63	0.62
Miniplates measures	Length (mm)	170	130.07	129.84	129.95	129.46
	Width (mm)	81	50.17	50.50	49.85	49.82
	Thickness (mm)	1.47	1.40	1.40	1.39	1.40
Cladding thickness average [mm]		0.48	0.37	0.37	0.37	0.39
Starting Assembly Thickness [mm]		5.46	5.56	5.55	5.55	5.55
Total Reduction (%)		73.1	74.8	74.8	74.9	74.8
Reduction rate		1:3.72	1:3.97	1:3.96	1:3.99	1:3.96

Table 3. U_3Si_2 Miniplates

Miniplate Identification	**Uranium Type**	**Nominal Loading [gU/cm^3]**	**Cladding thickness**		**Meat Thickness (mm)**	**Miniplate Thickness (mm)**
			Upper side [mm]	**Lower side [mm]**		
PUS-29	UN	1,70	0,61	0,62	0,32	1,55
PE-808	LEU	1,70	0,46	0,46	0,61	1,57
PUS-28	UN	3,40	0,45	0,45	0,65	1,55
PI-801	LEU	3,40	0,46	0,45	0,46	1,55
PAD-07	UN	4,80	0,23	0,23	1,08	1,54
PAD-08	UN	4,80	0,23	0,23	1,11	1,57
PAD-09	UN	4,80	0,37	0,37	0,51	1,29
PAD-10	UN	4,80	0,38	0,38	0,52	1,31

2.2. Equipment Description

Non-destructive testing (NDT) through ultrasonic immersion technique was performed with a Panametrics equipment, Model 5800 Plus with a ScanView Plus software for image view and ultrasonic signals. Figure 1 shown the assembly of the equipment for miniplate scanning, the transducers for ultrasonic inspection were installed in the Z-axis arm; the first transducer, a model V310-SU, 25 [MHz], 3 [mm] diameter, operated as transmitter, and the second operated as receiver and corresponds to V324-SU, 5 [MHz] and 6 [mm] diameter.

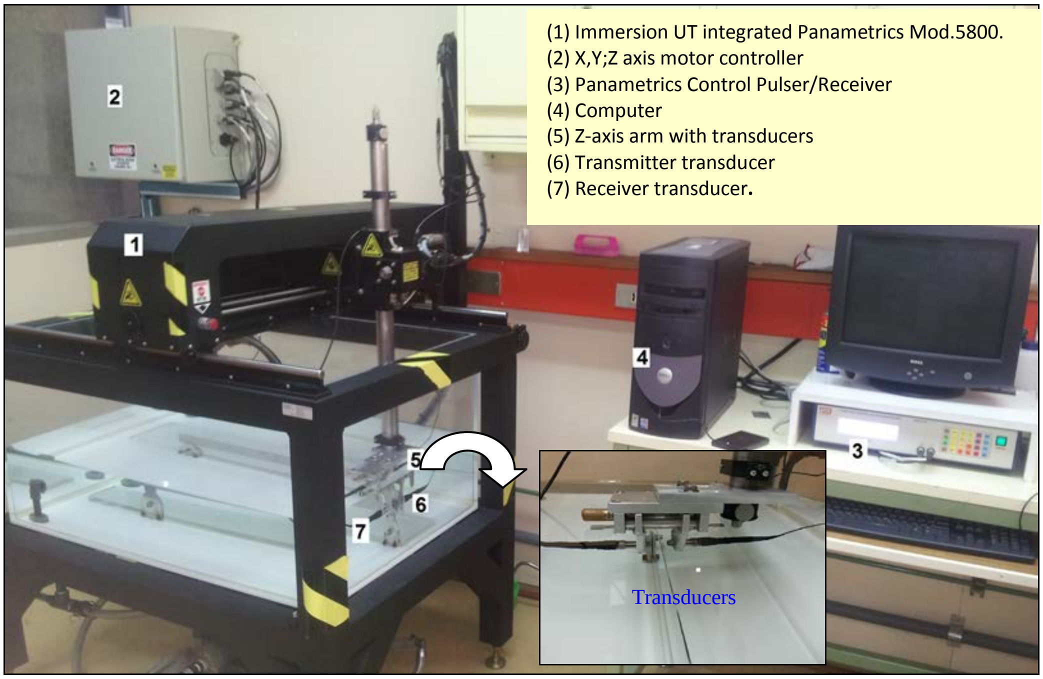

(1) Immersion UT integrated Panametrics Mod.5800.
(2) X,Y;Z axis motor controller
(3) Panametrics Control Pulser/Receiver
(4) Computer
(5) Z-axis arm with transducers
(6) Transmitter transducer
(7) Receiver transducer.

Figure 1. Ultrasonic Testing System in operation at CCHEN**.**

2.3. Ultrasonic Parameters

The configuration of the ultrasonic equipment was adjusted from the parameters of "Gain", "Input Attenuation" and "Output Attenuation", which depends on the “Sensitivity” of the ultrasonic equipment (see Table 4). The ultrasonic signal strength must be adjusted for ultrasonic signal strength of 100% located in the area of cladding, as shown in Figure 2.

Table 4. Ultrasonic Parameters Control

5800PR		**PC Digitizer**	
Mode	Through-Transmission	**Digitizer Frequency**	400 [MHz]
PRF	1000 [Hz]	**Voltage Range**	1[V]
Energy	50 [µJ]	**Offset Voltage**	0 [V]
Damping	36 [Ohm]	**Baseline Alignment**	Center
HPF	1[MHz]	**Coupling**	50 [Ohm] DC
LPF	35 [MHz]	**Amplitude Range**	100
Gain	Related with sensitivity parameters	**Amplitude Unit**	%FSH
Input Attenuation	Related with sensitivity parameters	**Depth Unit**	[mm]
Output Attenuation	Related with sensitivity parameters		

Sensitivity	Related with gain and attenuation

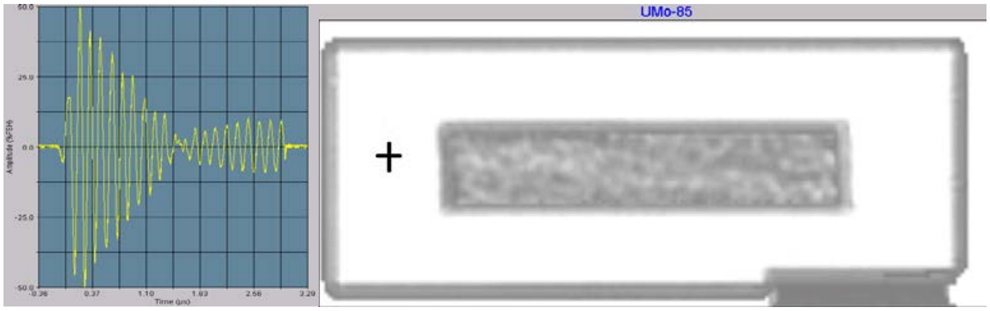


Figure 2. A-Scan and C-Scan of UMo-85 miniplate in clad-clad area (Al-6061 alloy) - 100% ultrasonic signal strength.

2.4. Data Analysis

For data analysis, three inspection region were considered in the meat of miniplates, as shown in Figure 3, this due to the dispersion observed at the end of meat (see Zone 1 and Zone 3 in Figure 3) produced by the rolling process, and the “fish tail” effect shown in Figure 9, resulting in a decreasing of the ultrasonic signal strength in these areas. Furthermore, is necessary to define evaluation criteria depending on the location of the ultrasonic signal strength to determine the characteristic echo present in miniplates; the main definitions for ultrasonic inspection are:

Debond Indication: When the response measured does not exceed a given value of ultrasonic signal strength. Indications that are caused by "edge effects" or surface defects present in the cladding are not considered
Edge Effects: The interface between the cladding and meat produces a large dispersion of the ultrasonic signal strength. It is necessary to define the ultrasonic signal strength produced in an edge effect.
Flat-line: Through Transmission signal is diffused due high attenuation.
Indication: Response of or evidence from a discontinuity in a material.
Indication size: Indications are sized by locating the edge of the indication (which shall be determined by finding where the signal amplitude of the echo from the indication drops by 50%), finding the location of the edge at several points, mapping the boundary of the indication, and calculating the area from these results. [2].

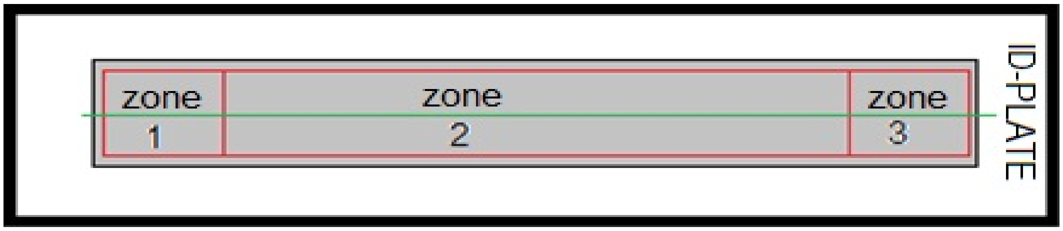


Figure 3. Location of areas for analysis of miniplates

3. Results

Figure 4 shows A-Scans for the reference echoes of signals strength in the clad-clad area with a 100 %, and various echoes of ultrasonic signal strength in the meat. The value of Sensitivity was adjusted to a range between 64.1 and 65.4 [dB].

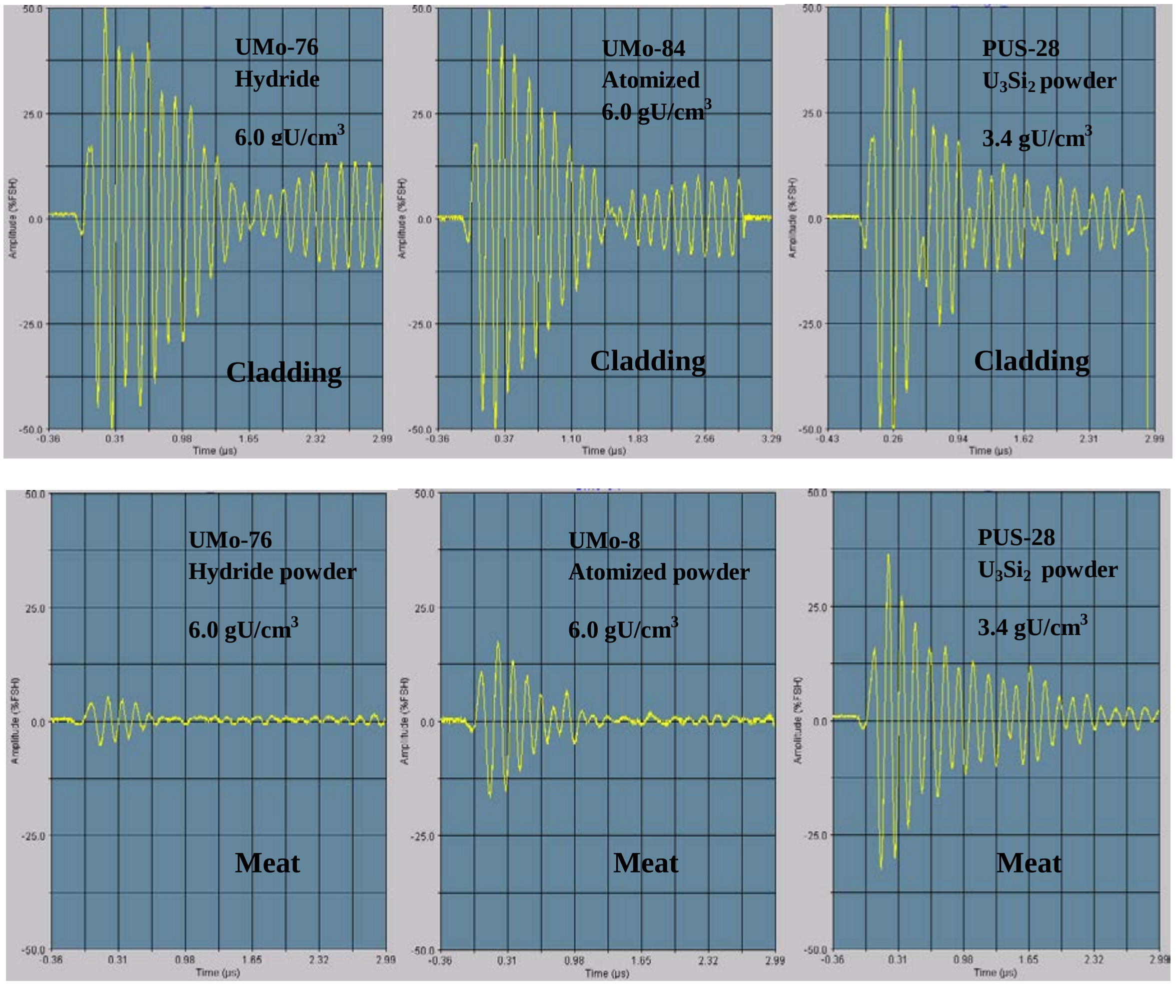
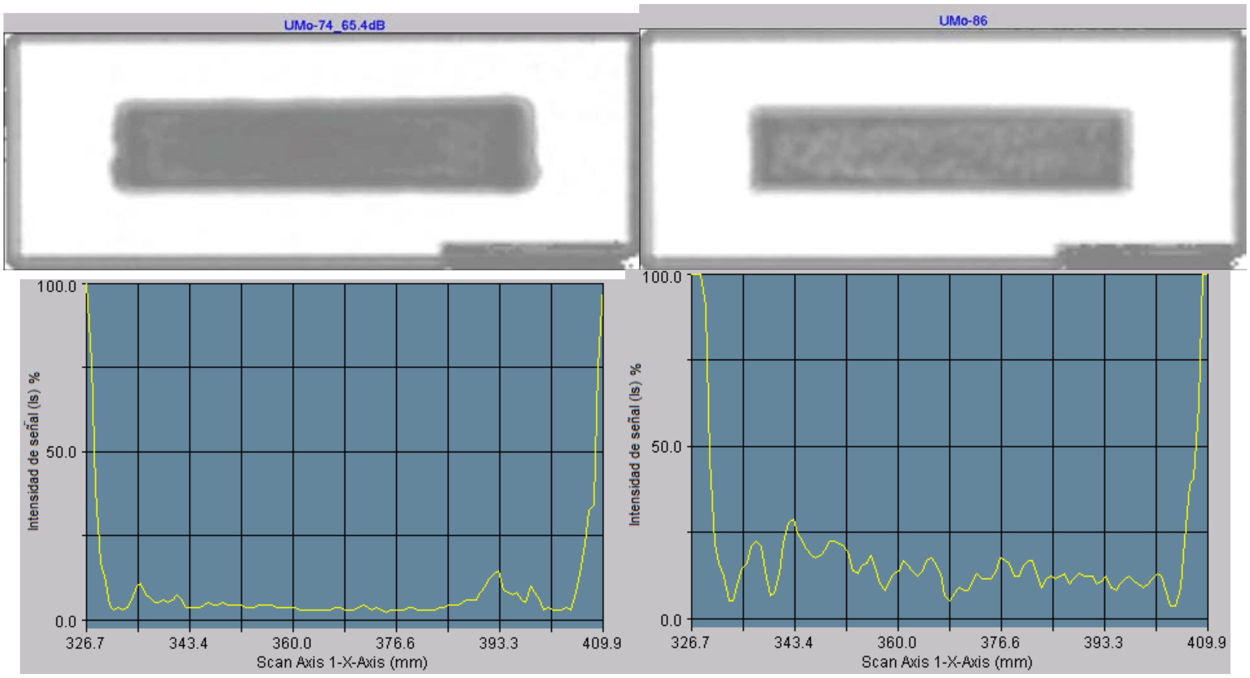


Figure 4. Ultrasonic signal strength A-Scan characteristics- Located in the clad-clad area and meat



(a) (b)

Figure 5. C-Scan View and A-Scan View with a lineal intensity profile
(a) UMo-74 hydrided miniplate (b) UMo-86 atomized miniplate

Figure 6 shows the C-scan View of UMo-74 miniplate and PE-808 fuel plate, where the gray scale in the meat reveals a discontinuity, in this way the A-Scan View shows a total loss of ultrasonic signal strength.

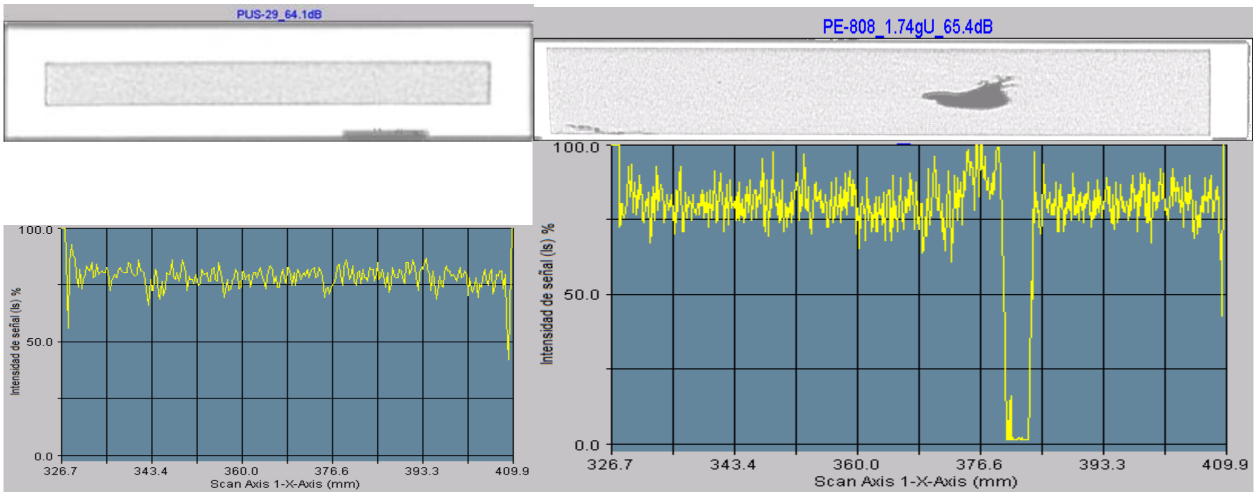


Figure 6. A-Scan View and C-Scan View – U_3Si_2 fuel plate

Table 5. Results of ultrasonic signal strength of the hydride powder with miniplates

Miniplate Identification		**UMo-77**	**UMo-78**	**UMo-79**	**UMo-80**	**UMo-81**	**UMo-83**
Uranium Type		LEU	LEU	LEU	LEU	LEU	LEU
Hydrided UMo Fuel (U-7 wt % Mo)		Porous	Porous	Porous	Porous	Dense	Dense
Nominal Loading [gU/cm^3]		7.0	7.0	7.0	8.0	7.0	7.0
Fuel density [g/cm^3]		11.45	11.45	11.45	11.45	16.15	16.15
Porosity %		1.9	3.0	3.8	4.1	12.3	13.6
% Ultrasonic signal strength	Zone 1	12.42	9.47	14.61	7.76	6.67	9.91
	Zone 2	26.00	36.39	33.61	12.61	3.89	3.89
	Zone 3	12,64	19,16	15.24	10.41	14.15	12.66

Table 6. Results of ultrasonic signal strength of atomized powders

Miniplate Identification		**UMo-84**	**UMo-85**	**UMo-86**	**UMo-87**	**UMo-89**
Uranium Type		UN	UN	UN	UN	UN
Hydrided UMo Fuel (U-7wt% Mo)		Atomized	Atomized	Atomized	Atomized	Atomized
Nominal density (gU/cm3)		6.0	6.0	7.0	7.0	8.0
Fuel density [g/cm^3]		12.52	12.52	12.52	12.52	12.52
Porosity %		9.1	7.8	7.6	6.9	13.1
% Ultrasonic signal strength	Zone 1	26.57	30.76	11.74	16.06	3.51
	Zone 2	32.84	31.06	14.64	22.47	3.03
	Zone 3	28.31	30.92	9.68	16.8	3.32

Table 7. Results of ultrasonic signal strength of U_3Si_2 powders in fuel plates and miniplates

Miniplate Identification		**PUS-29**	**PE-808**	**PUS-28**	**PI-801**	**PAD-07**	**PAD-08**	**PAD-09**	**PAD-10**
Uranium Type		UN	LEU	UN	LEU	UN	UN	UN	UN
Powder Fuel Type		U_3Si_2	U_3Si_2	U_3Si_2	U_3Si_2	U_3Si_2	U_3Si_2	U_3Si_2	U_3Si_2
Nominal Loading [gU/cm^3]		1.7	1.7	3.4	3.4	4.8	4.8	4.8	4.8
Fuel density [g/cm^3]		12.16	12.16	12.16	12.16	12.16	12.16	12.16	12.16
Porosity %		0.5	2.6	3.7	5.3	12.5	12.8	12.2	12.5
% Ultrasonic signal strength	Zone 1	78.54	81.47	72.72	75.64	61.70	60.51	68.83	68.15
	Zone 2	77.63	81.52	72.30	74.80	61.96	62.12	69.95	69.00
	Zone 3	77.43	82.52	71.55	74.65	60.30	59.78	69.39	65.84

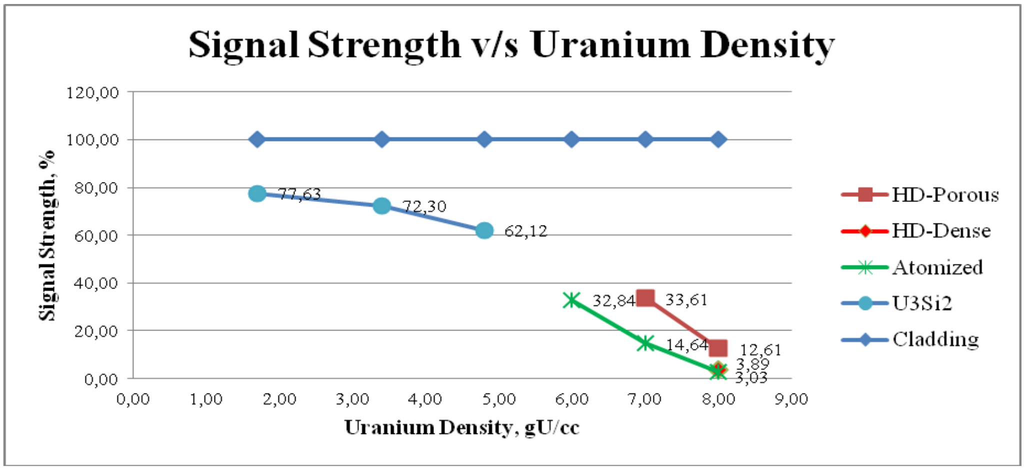


Figure 7. Variation of Ultrasonic signal strength vs. Uranium Density

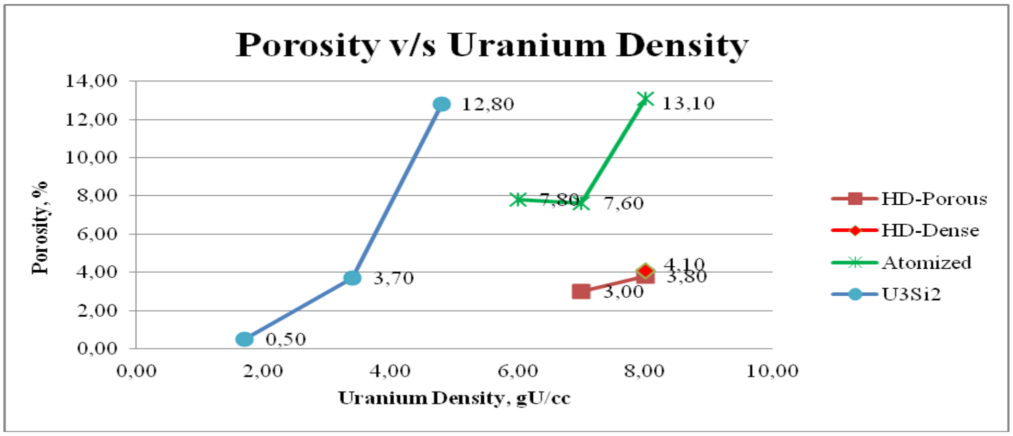
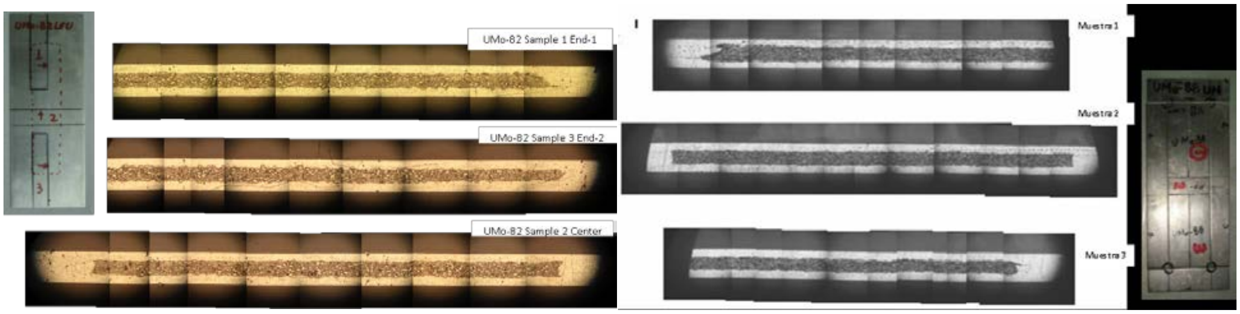


Figure 8. Variation of porosity vs. Uranium Density

Samples extracted from UMo-82 and UMo-88 miniplates shown in Figure 9 (a) and (b), fabricated with hydride UMo powder, revealed defects typically associated to high density dispersion type fuel miniplates as “fish tail” in both miniplates ends (samples 1 and 3) and a light effect of thickening at both sides of the meat (dog-bone). In sample 2, taken from the center of the miniplates, the presence of typical defects of dispersion type miniplates was found; and these defects are mainly due to the movement of fuel particles during the manufacturing process.

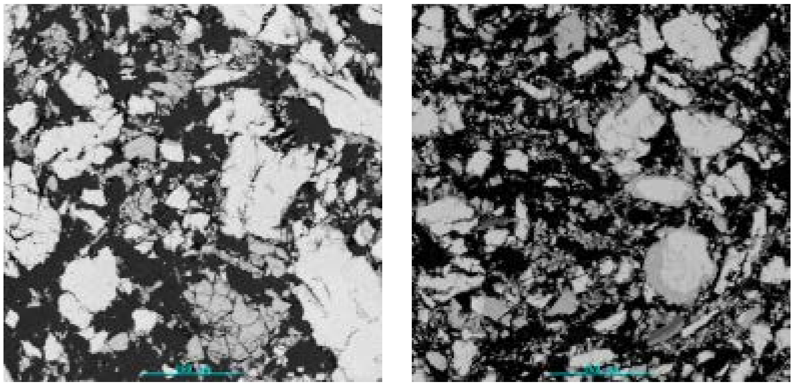
Metallographic inspection revealed meat consistency and did not show defects like micro cracks, fracture and/or coalescence of residual porosity. However, the fluctuation in the dispersion could influence the ultrasonic signal strength, because the dispersion is highly dependent on the relationship between the grain size and the wavelength. A number of particles move to the ends of miniplates and form stray particles.



(a) (b)

Figure 9. (a) UMo-82 Miniplate 7.0 gU/cm^3 (b) UMo-88 Miniplate 8.0 gU/cm^3

According to the quantitative metallography of UMo-54 miniplate, performed after compacting and at the end of miniplate manufacturing process, the percentage of fine powders below 45 µm increased up to 93% vol. after compacting an to 96% vol. at the end of the cold rolling. It is a matter for discussion if this increasing could affect the ultrasonic signal strength.



(a) (b)

Figure 10. UMo -54 LEU miniplate (a) As compacted (b) after rolling

4. Discussions

Since the inspections of the first miniplates fabricated with hydride UMo powder, for under irradiation qualification, emerged the difficulty for evaluation and the bonding assurance for these miniplates applying rejection/acceptance criteria defined for other types of fuel, such as monolithic or dispersed based on atomized UMo powder. After an unsuccessful first UT evaluation, CCHEN’s fuel staff decides to apply some changes in manufacturing variables such as particle size and size distribution, decreasing the fine fraction of particles and improvements in some fuel miniplates fabrication procedures. As a consequence of these modifications, new ultrasonic signal strength values were obtained, which are discussed in the following paragraphs.

The results in Table 4 show the difference for ultrasonic signal strength in relation with the type of hydrided UMo powder used for miniplate fabrication. Higher values were obtained with porous hydride powder and uranium densities of 6gU/cm^3 and 8gU/cm^3. However, dense hydride UMo powder exhibits ultrasonic signal strength relatively low for a 7gU/cm^3 uranium densities, around 3% in zone 1 of the fuel meat.

Table 5 presents ultrasonic signal strength for atomized powder, whose behavior was inversely proportional to the density of uranium analyzed, from 6 to 8 gU/cm^3. However, the ultrasonic signal strength variation throughout the entire meat resulted more homogenous, and this was seen in the three zones selected for analysis, not exceeding a 5% variation in the entire meat. The miniplates made of hydride powder showed a marked variation of the ultrasonic signal strength, with a variation greater than 15%.

Table 6 shows results that are inversely proportional to the density of uranium, 1.7 to 4.8 gU/cm^3 with attenuation values between 60 and 80%, showing a uniform variation in the three zones, with variations not exceeding 2% of the signal strength. Exceptions to this rule are the PAD-09 and PAD-10 miniplates 4.8 gU/cm^3 with 69% attenuation of ultrasonic signal strength because these miniplates had lower thickness, as shown in Table 3.

The residual porosity calculation shown in Figure 6 was made by the Archimedes method, in order to have a correlation of this variable with the data obtained from ultrasonic signal strength, and considering that this parameter could be affected by the residual porosity in the meat.

5. Conclusions

Ultrasonic inspection of a variety of dispersion fuel miniplates made with different kinds of powder, allows to validate the implementation of a proper technique for the evaluation of the cladding/meat bonding in fuel miniplates, in which the approval or rejection criteria must be defined according to the type of fuel, the uranium density, meat geometry and characteristics of the fuel powder used.

6. Acknowledgements

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