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Fabrication of OWR Gamma Shield Assemblies

by

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ABSTRACT

A procedure has been developed for metallurgically bonding lead to 6061-T6 aluminum plates for use as gamma shields in the Omega West Reactor (OWR).

The procedure used was to plate the 6061-T6 aluminum component with approximately 0.002 in. of silver then bake the assembly to remove volatiles and to diffusion bond the silver plating to the aluminum plates. The plated aluminum component and the lead component were then plated with approximately 0.002 in. of tin. The plates were assembled with the tin plated faces together then pressed at a temperature of 200°C and a load of 0.5 t/in.².

Ultrasonic inspection of the bonded assemblies has indicated that nominally 95 percent of the surface area was bonded.

I. INTRODUCTION

The Omega West Reactor (OWR) thermal column gamma shield is essentially a lead slab approximately 28 in. square and 2-1/8 in. thick, interposed between the reactor core and the thermal column head, in the flow path of the reactor cooling water. Its purpose is to reduce the gamma flux incident upon the thermal column to decrease the amount of gamma heating and, consequently, the temperature of the thermal column.

To maintain the quality of the reactor cooling water, it is necessary that the lead be clad in either aluminum or stainless steel. Aluminum was chosen because of its high thermal conductivity and superior nuclear properties. Prior to the present design, four gamma shields were built and installed and each failed at the lead-aluminum interface on the core side. By "failed" it is meant that the metallurgical bond between the lead and aluminum was destroyed, so that heat transfer to the aluminum cooling surface was no longer adequate to maintain an acceptably low lead temperature. Since modifications are underway to permit operation of the

reactor at substantially higher powers, the need for a radical change in the design of the gamma shield is obvious.

The four unsatisfactory gamma shields were fabricated in essentially the same manner: a welded aluminum "can" was constructed with the top (28 in. by 2-1/8 in.) left open. The inside surfaces of the can were cleaned and tinned with a stannous chloride flux and lead was poured through the top opening, while the can was maintained at a temperature near the melting point of lead by torches. The temperature of the assembly was then reduced slowly until the lead solidified and, finally, the top was welded in place. The reason for the failures has never been made clear, although there is some question as to whether a true metallurgical bond between the lead and aluminum was ever achieved.

The design presently in service was fabricated by casting the lead into two shallow, machined aluminum trays whose inside surfaces were prepared for the bonding and casting processes. After machining the exposed lead surfaces, the two trays

were welded together around the edges, forming a gamma shield with positively-bonded lead-aluminum interfaces at the cooling surfaces, but having an unbonded lead-lead interface at the mating plane of the trays.

The important consideration in the design is the location of the unbonded lead-lead interface; this determines the relative amounts of heat dissipated at the two cooling surfaces, the surface temperatures, and the maximum temperature attained in the lead. Intuitively, the optimum design is the one in which the lead-lead interface is at the point of maximum lead temperature; then no temperature gradient exists across the interface, so that no heat flows across the impedance offered by the inevitable air film at the interface.

A tentative design of this configuration was submitted to Knapp-Mills, Inc., of Wilmington, Delaware, whose patented lead-aluminum bonding process seemed particularly well-suited to this application. Following their concurrence with the soundness of the proposal, detailed design was undertaken.

A few remarks concerning the Knapp Mills process are appropriate at this point. Details of how the lead-aluminum bond was achieved were not made known outside the company and, therefore, cannot be discussed here. The result of the process is an intimate metallurgical bond having an 0.0005-in. layer of nickel, with a trace of phosphorous, at the interface. The shear strength of the bond was given as 16,000 psi; the tensile strength exceeded that of lead. Experiments have shown that there is no measurable heat transfer coefficient across the interface.

The shield presently in service has performed satisfactorily for a period of approximately 8 years; however, temperature profiles indicate that the lead is apparently losing adherence to the aluminum frame.

At the request of Group P-2, CMB-6 initiated a program to fabricate two sets of lead-aluminum gamma shields to replace the existing assembly. This report describes the procedure used for fabricating those assemblies.

II. MATERIALS AND EQUIPMENT

A. Materials

1. Lead. The lead plates were cast 27 by 29

by 7/8-in. and 1-1/2-in. thick by air melting chemical grade lead (ASTM B-29-55) and pouring into heated graphite molds. The cast plates were then machined on the perimeter to fit the machined 6061-T6 aluminum frames. Machining chips from each of the plates were saved, identified, and analyzed. (See Table I.)

TABLE I
ANALYSIS OF MACHINING CHIPS

Plate No.	Composition, %						
	Ag	Cu	Sn, Sb, As	Zn	Fe	Bi	Pb (by diff.)
1	0.006	0.005	< 0.005	< 0.001	< 0.001	0.050	99.96
2	0.006	0.003	< 0.005	< 0.001	< 0.001	0.050	99.96
3	0.006	0.005	< 0.005	< 0.001	< 0.001	0.050	99.96
4	0.005	0.005	< 0.005	< 0.001	< 0.001	0.050	99.96
ASTM B-29-55 (chem gr)	0.002	0.040	< 0.002	< 0.001	< 0.001	< 0.005	> 99.90

As shown by the chemical analysis, none of the lead plates were of a composition which conformed strictly with ASTM B-29-55 chemical grade. The silver contents in each case were slightly above the typical composition and the copper contents were considerably less than typical. The 0.050% bismuth reported was a factor of six greater than the 0.005% maximum specified by ASTM B-29-55. In spite of these discrepancies the composition was approved by P-2.

2. Aluminum. The aluminum frames were machined from commercial 6061-T6 material. No chemical analysis, physical testing, or nondestructive testing was done on these frames.

B. Equipment

1. 250 Ton Press. The preliminary development work was done using a 250-ton press manufactured by the Hydraulic Press manufacturing Co. The press was equipped with resistance heated platens which were capable of being heated to 275°C. The platens could also be cooled quickly by flowing air or water through channels machined in them.

2. 5000 Ton Press. The full-size assemblies were fabricated using a 5000 ton Lake Erie Press equipped with resistance heated platens capable of being heated to 300°C. These platens were not equipped with channels to enable rapid cooling. Cooling was accomplished by turning off the platen heaters and maintaining the load during cooling.

III. PROCEDURE

A. Preliminary Development

The initial development was done using a shot-gun approach to evaluate the effect of plating 6-in.-square by 1/2-in.-thick aluminum plates with various materials and bonding by heat and pressure to 6-in.-square by 1/2-in.-thick lead plates. The bonds were evaluated by cutting a 1/2-in.-wide strip from one edge of the bonded composite and manually peeling the lead from the aluminum. The results are shown in Table II. Of the four surface treatments used, the tin and cadmium platings appeared to offer the most promising results. The results obtained using the tin preparation on 1100 aluminum were far superior to those obtained using the same preparation on 6061-T6 aluminum alloy. Unfortunately, the aluminum frames for the gamma shield assembly were to be made from 6061-T6 aluminum. The consideration of cadmium for an interface material was discontinued at this point because of the extremely high neutron absorption cross section of cadmium.

Three of these assemblies (2, 3 and 5) underwent ultrasonic inspection to evaluate the bond between the lead and aluminum. The specific ultrasonic inspection technique used was to read the amplitude or intensity of an ultrasonic reflection from the backface of the aluminum component. Using this technique, the bond quality was read as an inverse function of the amplitude of the backface

Fig. 1. Ultrasonic evaluation of bonded lead to aluminum assemblies.

echo. The results shown in Fig. 1 indicate bond qualities very similar to those estimated by the manual peel test. The 1-in.-wide area along one side of each assembly was intentionally left unbonded for evaluation purposes.

A second group of preliminary assemblies was prepared and bonded. These assemblies were made

TABLE II
RESULTS OF INITIAL Pb-Al BONDING EVALUATION

Specimen Number	Component Materials	Intermediate Plated Material	Preheat Temp., °C	Flatten Temp., °C	Pressing Cycle, Description	Results
1	1100 Al and Pb	Ag	310	225	Pressed at ~ 1 t/in. ² ; deformation occurred dropped to 0.5 to 0.7 t/in. ² ; held 20 min cooled under load and removed.	Very poor bond no eutectic formation.
2	1100 Al and Pb	Sn	200	200	As above - held 5 min at 0.5/0.7 t/in. ² cooled under load and removed.	Very good bond excellent eutectic formation.
3	1100 Al and Pb	Cd	250	225	Pressed at 0.5/0.7 in. ² ; held 20 min; cooled under load.	Fair bond - temp may have been too low.
4	1100 Al and Pb	Zn	250	225	As above	No bond.
5	6061-T6 Al and Pb	Sn	200	200	Pressed at ~ 0.3 t/in. ² 5 min; cooled under load.	Fair to poor bond.

TABLE III
EVALUATION OF Pb-Al BONDS

<u>Specimen No.</u>	<u>Surface Prep.</u>	<u>Platen Temp. °C</u>	<u>Pressing Cycle</u>	<u>Ultrasonic</u>	<u>Peel Test</u>
1	Sn plate on Al	200	Heat in platen under no load condition; after 5 min load to 0.25 t/in. ² ; cool under load.	Not done	Fair to good appears to be an oxide film at Al interface.
2	Sn plate on Al pre-tinned Pb with 50-50 Sn-Pb	195	As above	Not done	Poor bond came loose at Al interface; oxide present.
3	Ag plate + Sn plate on Al Sn plate on Pb	190	As above	Not done	Excellent bond failed in solder; both interfaces intact.
4	Ag plate on Al bake out 200°C Sn plate on Al Sn plate on Pb	200	As above	Void areas in center	Excellent in bonded area no bond in center.
5	As above	200	As above but load of 0.35 t/in. ²	Void area in center	Not done

from 12 by 14 by 1/2-in. 6061-T6 aluminum plates and 12 by 12 by 1/2-in. lead plates. The assemblies were evaluated by both peel tests and ultrasonic inspection. The bonding parameters and evaluation results are presented in Table III.

The results of ultrasonically testing assemblies 4 and 5 are presented by Fig. 2A and B. Peel test specimens were cut from both the void area and the indicated bonded area of specimen No. 4 with the results shown in Table III. Assembly No. 5 was repressed at 230°C and a pressure of 0.7 t/in.². At this pressure some deformation occurred in the lead. The results of ultrasonically testing this assembly showed nearly 100% bonding as shown in Fig. 2C.

These data (Table III and Fig. 2) show that of the methods evaluated, the preparation of the aluminum surface by silver and tin plating and the lead surface by tin plating was by far the most satisfactory.

Two full-size mockup assemblies were prepared using this method and pressed at 200°C using the 5000 ton press. The first assembly was pressed using a pressure of approximately 0.6 t/in.²; this pressure proved to be over the yield point of the lead in this assembly and caused considerable extrusion and flattening of the lead plate. The assembly was evaluated ultrasonically and proved to be well bonded except for some areas around the

edges. Peel tests have verified the results of the ultrasonic evaluation.

A. ASSEMBLY NO. 4 - UNMARKED AREAS ARE POORLY BONDED AREAS (~75% BONDED)

B. ASSEMBLY NO. 5 - UNMARKED AREAS ARE POORLY BONDED AREAS (~80% BONDED)

C. ASSEMBLY NO. 3 - 2nd PRESSING (~100% BONDED)

Fig. 2. Ultrasonic results from testing assemblies 4 and 5. B shows the results from the initial pressing, assembly No. 4. C shows the results after repressing at a higher pressure.

The second assembly was fabricated using the same surface preparation but pressed at a pressure of 0.5 t/in.² at 200°C. When no deformation occurred the pressure was gradually raised until a pressure of 1.5 t/in.² was attained. When no deformation and poor lead-tin alloy flow was observed at this pressure, which was more than double the yield stress of chemical grade lead at room temperature, the assembly was allowed to cool and was removed from the press. Subsequent investigation has revealed that, since this lead plate was cast for mockup use, no care had been taken to use chemical grade lead. Closer examination of the lead plate revealed small areas where considerable melting had occurred indicating "impurity pockets." The conclusion was that this assembly could not be considered representative.

B. Electroplating Procedures

1. 6061-T6 Aluminum Frames. The aluminum frames were vapor degreased then masked on the backside and perimeter with Scotch Brand No. 470 tape. The masked frame was etched as follows:

- a. Alkaline etch-22.5 g/l NaOH + 15 g/l Na₂CO₃ - 1 min at 140-160°F.
- b. 25 vol% H₂SO₄ - 5 min at 140°F.
- c. 5 vol% HF - 1 min at room temp (70°F).
- d. Pickle - 50 vol% HNO₃ - 1 min at room temp (70°F).

Each step was followed by a thorough rinse in running water.

The aluminum frame was then placed in a zincating solution of 500 g/l NaOH and 100 g/l ZnO at room temperature for two minutes. This was sometimes followed by stripping in 50 vol% HNO₃ and repeating the zincate step to improve adhesion. The aluminum frame was plated in a Rochelle copper strike bath for two minutes at 0.1 asi, followed by a silver strike for one minute at 0.07 amp/in.², and then silver plated to a thickness of 0.002 in.

The masking tape was stripped and the plated aluminum frame was baked-out at 350°C for 2 h and visually inspected for blisters. If acceptable, the frames were again masked with tape and the Ag plated surface scrubbed with MgO. The silver plating was then overplated with 0.002 in. of Sn from a fluoborate bath. A current density of 0.1 to 0.2 amp/in.² was used.

2. Pb Plates. The Pb plates were vapor degreased and masked on the backside. Each piece was pickled for 30 seconds in 50 vol% HNO₃ and the snut residue removed by wiping. The pickled plate was placed in the Sn fluoborate bath for 15 seconds without current, then a current of 0.1 to 0.2 amp/in.² was applied until a plating thickness of 0.002 in. was attained.

C. Fabrication of OWR Shields

The design of the OWR shield was such that two lead-aluminum bonded assemblies were required for each shield. The bonded pieces were assembled as shown in Fig. 3 and joined by welding the aluminum frames together. The interface between the lead plates was not bonded since the maximum temperature from gamma heating occurred here resulting in heat flow in both directions from this plane to the aluminum surfaces. Four bonded assemblies were fabricated by heating and pressing. All of the assemblies needed more than one pressing to attain the required percentage of bonding. The bonding procedure used and the results of ultrasonically inspecting each plate are described below.

1. Plate No. 1 (27 by 29 by 7/8-in.). The assembly was pressed at 200°C and 0.5 t/in.² by holding at temperature and pressure for 20 minutes. The heaters were then turned off and the assembly allowed to cool under pressure. The time required to cool to 150°C was approximately 4 hours. The time required to cool below the eutectic temperature (175°C) was approximately 2 hours. The ultrasonic results presented in Fig. 4A showed generally good

Fig. 3. A sketch showing the manner in which the bonded lead-aluminum assemblies are bonded.

A

ULTRASONIC TRACE AFTER 1st
PRESSING OF ASSEMBLY NO. 1
BLANK AREAS DESIGNATE
UNBONDED AREAS

B

SHIM PLACEMENT ON ASSEMBLY
NO. 1 FOR 2nd PRESSING

C

ULTRASONIC TRACE AFTER 2nd
PRESSING OF ASSEMBLY NO. 1
THE BLANK AREAS DESIGNATE
UNBONDED AREAS

Fig. 4. Ultrasonic traces from production assembly No. 1.

bonding; however, there were areas in each corner where poor bonds were indicated.

The assembly was repressed by placing 0.025-in.-thick aluminum shims in each corner as shown in Fig. 4B and with the same parameters used for the first pressing. The results of ultrasonically inspecting this assembly are shown in Fig. 4C. These results indicated that approximately 97% of the area was bonded with most of the unbonded area being near the outside perimeter of the lead. No additional work was done on this assembly since we felt that increased coverage was probably not attainable using this procedure unless the yield stress of the lead was exceeded.

2. Plate No. 2 (27 by 29 by 7/8 in.). This assembly was pressed using the same parameters described for Plate No. 1. After cooling, the appearance of the plate showed that very little pressure had been applied to the corners of the lead plate; therefore, the corners were fitted with 0.063-in.-thick aluminum shims and repressed using the same settings of temperature and pressure.

The assembly was evaluated ultrasonically with the results shown in Fig. 5. The data definitely showed a nonbonded area near the center of the assembly. This assembly was repressed two more times, once using a 0.063-in.-thick shim in the center of the lead in addition to the corner shims and once after drilling three 1/3-in.-diameter holes into the

unbonded area to allow trapped air to escape. Neither approach made any significant improvement in the bond characteristics. The assembly was repressed one more time using shims over the unbonded areas. After this treatment the unbonded area was larger than before; at this point this assembly was set aside for complete rework.

Fig. 5. Ultrasonic trace of the bond characteristics of production assembly No. 2, second pressing. The blank areas designate unbonded areas.

Fig. 6. The ultrasonic trace from production assembly No. 3, pressing No. 2.

3. Plate No. 3 (27 by 29 by 1-1/2-in.). The third assembly was pressed using the standard 200°C and 0.5 t/in.² parameters then cooled. Shims 0.063-in.-thick were placed on the lead surface and the assembly was repressed using the same settings. The ultrasonic inspection results are shown in Fig. 6. These results show the nonbonded area to be virtually zero; however, during pressing, some extrusion of lead was observed to have occurred around the aluminum pusher block. On closer examination it was found that a crack had formed in the wall of the

aluminum frame during pressing. This crack, shown in Fig. 7, was repaired by welding and this assembly was coupled with assembly No. 1 for the OWR gamma shield. These two assemblies (No. 1 and No. 3) are shown in Fig. 8.

4. Plate No. 4 (27 by 29 by 1-1/2-in.). This assembly was pressed using the standard procedure, cooled, shimmed, and repressed at the same settings. The results of ultrasonically inspecting this assembly are shown in Fig. 9. The data show evidence of some nonbonded areas (~ 3/4-in.-diameter) near the center of the assembly; however, it is doubtful that repressing would have improved the bond significantly unless sufficient pressure was used to cause yielding in the lead. This assembly was stored for future use.

IV. DISCUSSION

The lead-aluminum gamma shield assembly which has been in service for the last eight years in the Omega West Reactor was originally fabricated by melting lead into the aluminum frames. The assembly fabricated by this approach had provided good service for a number of years; however, for various reasons, it was decided to use an entirely different technique for fabrication of these assemblies.

A melting technique seemed more likely to increase the chances of oxidizing the bond interface surface thereby producing a poor bond. In addition, this technique is susceptible to producing "cold-shuts" or voids cast into the lead during the process. Other considerations were that virtually no information was available concerning the surface treatments, preheating techniques, or other process variables used in fabricating the original shield assemblies.

Fig. 7. A crack in the 6061-T6 frame caused by yielding in the lead during pressing. Production assembly No. 3, pressing No. 2.

ASSEMBLY NO 1

ASSEMBLY NO 3

Fig. 8. The surface of the lead plates in assemblies 1 and 3. The photos show where shims were placed to improve bonding in certain areas.

Fig. 9. The ultrasonic inspection trace for assembly No. 4, pressing No. 2.

The technique which seemed more suitable was to cast the lead plates, machine them to size, then using heat and pressure, bond them to the aluminum frames. The first step in developing this process was to evaluate surface preparations and pressing parameters of temperature and pressure. The second step was to develop a nondestructive inspection method to determine the bond quality.

The preparation, pressing, and bond evaluation of the first group of specimens have been described in the procedure, Table II. The selection of the surface preparations used was based on phase diagram information of lead alloy systems.

A. Ag-Pb System

The lead-silver system forms a eutectic of 95.3 wt% Pb and 4.7 wt% Ag at 304°C. To evaluate this system the 6061-T6 Al plate was plated with 0.002 in. Ag and the lead was chemically and mechanically cleaned to remove surface oxides. The assembled parts were preheated to 310°C and pressed between platens which had been preheated to 225°C. A one-inch-wide strip cut from one side of the assembly was evaluated by a manual peel test. The

peel test indicated that the bond was very poor with, at best, a weak diffusion bond being attained. Visual inspection of the interface showed that no eutectic formation had occurred demonstrating that perhaps the assembly had not attained a high enough temperature. Considering the difficulty which might be encountered in heating so close to the melting point of lead, it was decided that the evaluation of this system should be discontinued if one of the other systems looked promising.

B. Sn-Pb System

The lead-tin system forms a eutectic of 38.1 wt% Pb - 61.9 wt% Sn at 183°C. Near eutectic compositions of lead-tin alloys are commonly used as soft soldering alloys; therefore, this alloy system seemed to be a natural. The system was evaluated by plating an 1100 Al plate and a 6061-T6 aluminum plate with 0.002 in. Sn and joining to Pb plates using the parameters previously described in the procedure (Table II).

Both assemblies were then evaluated by peel testing a 1-in.-wide strip cut from one edge of each specimen. The bond between the lead and 1100 Al was very good as evaluated by the peel test. Inspection of the interface revealed that good eutectic formation had occurred, this was shown during pressing by extrusion of some liquid phase from the interface. The bond between the lead and 6061-T6 Al was rather poor. The eutectic had indeed been formed; however, it appeared that there was a dark film between the eutectic and the aluminum which prevented the formation of a good bond.

C. Cd-Pb System

This system was evaluated simply because the phase diagram appeared promising. The use of cadmium in a system of this nature is not advisable because of the high neutron absorption cross section of the material (2450 barns/atom). The lead-cadmium system forms a eutectic of 82.6 wt% Pb - 17.4 wt% Cd at a temperature of 248°C. An 1100 Al plate was plated with 0.002 Cd, assembled with a lead plate from which the surface oxides had been removed and the assembly was preheated to 260°C. The plates were pressed together at 225°C and a loading of 0.5 to 0.7 t/in.². A peel test evaluation showed the bond to be of fair quality, somewhat better than that obtained with the tin-

plated-6061-T6 aluminum. Examination of the bond interface showed that a eutectic had formed but the distribution was spotty, at least along the edges.

D. Nondestructive Inspection

The nondestructive inspection method used to evaluate the bond was the pulse-echo technique described in the procedure. As shown by Fig. 1 of the procedure, this method was easily able to distinguish between the well bonded areas and those areas which intentionally were left unbonded. The well bonded areas produced a backface-echo intensity of 10 to 25% of the intensity from an unbonded standard aluminum plate. Those areas which were intentionally left unbonded produced backface-echo intensities of 90 to 100%.

Additional work done on the first full-size mockup assembly also showed excellent correlation between the ultrasonic inspection results and mechanical testing. When inspecting this assembly the equipment was calibrated and set to record any area of > 50% backface-echo intensity as a poorly bonded area. The results showed an area of poor bonding around the edge of the assembly (75 to 90% intensity). Peel tests established that indeed a poor bond had been achieved in these areas. All of the peel tests done using specimens from the interior of the assembly showed good bonding to have occurred.

Some additional evaluation was done to determine the effect of changing the detection level on the inspection equipment. The final pressing of assembly No. 2 was inspected ultrasonically. The equipment was set to detect backface-echo intensities of > 30%, > 50% and > 80% for three separate inspection runs on the same assembly. The results are shown in Fig. 10. The traces with the gate level at 30% and 50% are essentially identical. The trace with the gate level at 80% shows many of the same unbonded areas but indicates generally more extensive bonding; however, the standard procedure in the program was to consider all intensities of < 50% as indicating well bonded areas. The results shown in Fig. 10 when correlated with the previous ultrasonic and peel test results, indicate that the use of a 50% gate level was valid and perhaps even on the conservative side.

A

B

C

- A. ULTRASONIC TRACE WITH GATE LEVEL AT 30 %. BLANK SPOTS REPRESENT THOSE AREAS FROM WHICH THE BACK FACE-ECHO WAS >30 % OF THE STANDARD UNBONDED SPECIMEN**
- B. ULTRASONIC TRACE WITH GATE LEVEL AT 50 %**
- C. ULTRASONIC TRACE WITH GATE LEVEL AT 80 %**

Fig. 10. Ultrasonic inspection results from assembly No. 2, final pressing, using three different detection levels.

E. Metallography

Although some metallography was done on bonds made during the preliminary evaluation work, the value of such metallography is certainly questionable. Smearing from polishing in the lead and at the soft bond interface was so extensive that most of the metallographic detail was either hidden or

distorted. Despite these difficulties the results of the metallography which was done are presented for what they may be worth.

Cross sections of two areas of a bond between 1100 Al and Pb using a 0.002 in. Sn electroplate at the intermediate material are shown in Fig. 11. The first cross section (Fig. 11A) shows an area

A. APPARENTLY GOOD BOND BETWEEN 1100 Al AND Pb. INTERFACE IS Pb-Sn EUTECTIC. 1100 Al IS AT THE TOP, Pb AT THE BOTTOM. (100x)

B. APPROXIMATELY .030 INCH WIDE UNBONDED AREA IN 1100 Al TO Pb BOND. (100x)

Fig. 11. Lead to 1100 aluminum bond made by forming a lead-tin eutectic at the interface.

that was shown by ultrasonic inspection to be 100% bonded. The area does seem to be well bonded with what appears to be a thin (~ 0.0005 in.) layer of Pb-Sn alloy along the interface.

Another area of the same assembly was shown by ultrasonic inspection to have less bonding although the ultrasonic intensity was still approximately 20%. Metallography of this area showed a few small unbonded areas one of which is shown in Fig. 11B. This unbonded area was estimated to be 0.030-in.-wide.

Two areas of another assembly bonded with Cd as the intermediate material are shown in Fig. 12. Figure 12 shows a well bonded area with a continuous layer of Cd-Pb alloy at the interface. The interfacial layer contains considerable porosity which may account for the generally higher ultrasonic intensities (10 to 25%) than were shown by the bond shown in Fig. 11. Fig. 12B shows an unbonded area that was detected by ultrasonic inspection. The lack of bonding is between the Cd-Pb alloy and the Pb plate. The bond between the Cd-Pb alloy and 1100 Al appears to be excellent in both areas.

V. SUMMARY AND CONCLUSIONS

A satisfactory procedure for fabricating metallogically bonded Pb-Al plate assemblies has been developed. These assemblies have been fabricated for use as gamma shields in the Omega West Reactor.

The bond surface was prepared by plating the 6061-T6 Al frames with approximately 0.002 in. Ag and baking the frame at 375°F to remove any volatiles and improve the bond. The plated Al frames and the Pb plates were both plated with approximately 0.002-in. Sn. The bond was formed by assembling the plates, plated faces together, and hot pressing at a temperature of 200°C and a loading of 0.5 t/in.².

The bonded assemblies were inspected with the use of ultrasonics to determine bond quality. In general, the unbonded area in each assembly was estimated to be less than 5%.

The procedure used appears to be generally satisfactory; however, the results indicated that better bonding may have been achieved by increasing the pressing load to a value over the yield point of the Pb. In order to do this the rough machined Al frames would have required heavier sidewalls to sustain the hydrostatic loading from pressing. The sidewall of the Al frame failed on the only assembly in which yielding of the Pb did occur. The bonding in this assembly was essentially 100%.

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A. AN APPARENTLY WELL BONDED AREA IN AN 1100 Al-Pb TEST ASSEMBLY (100x)

B. POORLY BONDED AREA IN AN 1100 Al-Pb TEST ASSEMBLY (100x)

Fig. 12. Lead to 1100 aluminum bond made by forming the cadmium-lead eutectic at the interface.

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