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THE TENSILE STRENGTH OF SOLID-STATE BONDED ALUMINUM
AND NICKEL-PLATED URANIUM

by

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THE TENSILE STRENGTH OF SOLID-STATE BONDED ALUMINUM AND NICKEL-PLATED URANIUM

H. A. Saller, R. F. Dickerson, and R. J. Carlson

To aid in the evaluation of solid-state bonding techniques for cladding natural-uranium fuel-element cores with aluminum, tensile specimens, 1/4 in. in diameter and 3 in. long, were made and tested. Results show that these techniques are capable of producing satisfactory bonds between aluminum and nickel-plated uranium.

Pressing conditions of 1 min at 950 F and 6000 psi produced consistent bond strengths equal to the yield strength of 2S aluminum. When optimum bonding conditions are used, anodic activation and strike-current density are not critical to bond strength. Nickel plating of the aluminum component of the bond couple reduced the tensile strength by about 50 per cent.

INTRODUCTION

All natural-uranium fuel elements must be clad in a protective jacket of some other material to prevent corrosion and to contain fission fragments. Aluminum is a natural choice for the jacket material since it has very desirable physical properties: low thermal-neutron-absorption cross section, good corrosion resistance, high thermal conductivity, and light weight. In addition, it is plentiful and inexpensive.

A great deal of interest has been expressed in solid-state bonding techniques for cladding uranium with an aluminum jacket. A thin layer of nickel, electrodeposited on the uranium, is favored at present for preventing the formation of the very brittle uranium-aluminum compounds.

Since the bond strength which a cladding technique is capable of producing is important, a study of the bond strength of pressure-bonded aluminum and nickel-plated uranium was undertaken.

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PRODUCTION OF TENSILE SPECIMENS

Equipment

The equipment used to produce tensile specimens consisted of a 20,000-lb-capacity laboratory-type press, a Chromel A resistance-wound vertical-muffle-type furnace and a die of the type shown in Figure 1. Air-hardening die steel was used for the die. Because the total pressures involved were low, the pressure gage on the press was replaced with a 0-to-500-lb Bourdon gage.

Figures 2 and 3 depict the equipment components disassembled and assembled, respectively.

Power was supplied by a Variac V-20-M autotransformer and temperatures were measured by means of a Chromel-Alumel thermocouple and a portable potentiometer.

Materials

The uranium components of the tensile specimens were fabricated from production-grade uranium by rolling, swaging, and drawing. The aluminum components were cut from 1/4-in.-diameter 2S aluminum rod.

Specimen Configuration and Size

Figure 1 shows the aluminum and uranium components of a tensile specimen assembled in the die prior to pressing. The specimens were 1/4 in. in diameter and each component was approximately 1-1/2 in. long.

A specimen length of 3 in. was chosen to minimize the distance through which the ram pressure had to be transmitted. The specimen diameter chosen, 1/4 in., tended to give conservative values because of the greater sensitivity to microscopic defects.

Specimen Preparation

A general outline is given below for the preparation of the uranium and aluminum components of the tensile specimens.

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FIGURE I. CROSS SECTION OF DIE SHOWING ALUMINUM AND URANIUM COMPONENTS IN POSITION FOR PRESSING

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FIGURE 2. PHOTOGRAPH OF DISASSEMBLED EQUIPMENT COMPONENTS

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FIGURE 3. PHOTOGRAPH OF ASSEMBLED EQUIPMENT COMPONENTS

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I. Preparation of Uranium Component

A. Mechanical preparation

1. Fabrication of the uranium to size and shape
2. Grit blasting of the uranium with 50-mesh crushed chilled steel shot at 80-lb open-line pressure

B. Physical and chemical cleaning and activation

1. Degreasing in ethylene trichloride
2. Alkaline cleaning for 2 min
3. Rinsing in water
4. Pickling in 1-to-1 HNO_3 and water
5. Rinsing in water
6. Anodic-etch activating in the following solution for 40 min at 25 amp per sq ft at 100 F:

50 volume per cent H_3PO_4 (85 per cent)

2 volume per cent HCl (38 per cent)

48 volume per cent H_2O

7. Adding of current robber
8. Rinsing in water
9. Pickling in 1-to-1 HNO_3 and water at 80 F for 5 min

C. Electrodeposition of nickel, 0.0003 in. thick, from the following solution in 24 min at a current density of 15 amp per sq ft, a bath temperature of 100 F, and a pH of 5.5:

$\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$ 145 g per liter

$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 75 g per liter

NH_4Cl 15 g per liter

H_3PO_4 15 g per liter

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20 ml per liter

II. Preparation of Aluminum Component

- A. Mechanical preparation of 1/4-in. -round 2S aluminum rod by cutting to length with a water-cooled cutoff wheel
- B. Chemical cleaning by pickling 2 min in a 5 per cent aqueous solution of NaOH at 180 F and then pickling 5 min in 1-to-1 HNO₃ and water at room temperature

General Pressing Procedures

The aluminum and uranium components and the die were assembled as shown in Figure 1. After assembly, the die was loaded into the furnace and the furnace was placed on the bottom die platen. A 50-lb preload was used to exclude all air from the bond interface during heating. The power to the furnace was turned off 25 F below the specimen's nominal pressing temperature and the full bonding load was applied. Thermal inertia of the die and furnace was sufficient to carry the specimen temperature 25 F above the nominal pressing temperature in about 2-1/2 min. After 5 min, the die and specimen were quenched in water.

A typical time-temperature curve for the 5-min period during which the specimen was under full bonding load is shown in Figure 4. Figure 5 shows a completed tensile specimen and Figure 6 a typical microstructure of the bond zone.

Variations from the above general procedures are indicated in the tables.

RESULTS OF TENSILE TESTS

The tensile specimens were pulled on a standard tensile-testing machine and standard procedures were used. Figure 7 illustrates the three principal types of specimen failure. Specimen A failed between the nickel and aluminum before any deformation was evident in the aluminum. This type of failure indicates either that bonding temperature and pressure were too low or that techniques were faulty.

*Proprietary wetting agent manufactured by the Harshaw Chemical Company.

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FIGURE 4. TYPICAL TIME-TEMPERATURE CURVE FOR 5 MINUTE FULL LOAD PRESSING PERIOD

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FIGURE 5. PHOTOGRAPH OF COMPLETED TENSILE SPECIMEN

Aluminum

Nickel

Uranium

250X

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FIGURE 6. TYPICAL MICROSTRUCTURE OF BOND ZONE

2.25X

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FIGURE 7. PHOTOGRAPH OF THREE PRINCIPAL TYPES OF SPECIMEN FAILURE

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Specimen B failed in the aluminum component, indicating that the tensile strength of the bond was at least as great as that of the aluminum.

Specimen C also failed between the nickel and aluminum. In this case, however, appreciable deformation occurred in the aluminum near the bond interface. This deformation may have caused a change in direction of the forces at the interface and this may, in turn, have caused the failure at the bond. The tensile strengths of the bonds in specimens which failed in this manner were at least very near the yield strength of the aluminum.

A few specimens were made with high-alloy aluminum components instead of the usual 2S aluminum components. Such specimens failed between the nickel and uranium and had tensile strengths ranging from 18,000 to 30,000 psi. These results indicate that the nickel-uranium bond has a tensile strength of at least 18,000 psi.

Effect of Bonding Temperature and Pressure

The first series of specimens was designed to survey the effect of bonding temperatures and pressures. Temperatures were varied from 800 to 950 F and pressures were varied from 3000 to 6000 psi. Table 1 is a compilation of data from this series of experiments.

Tensile strengths indicated to the right and below the dotted line in Table 1 are equal to or greater than the yield strength of 2S aluminum. In this range, variation of pressing pressure and temperature has little or no effect on the resulting tensile strength when 2S aluminum is used as one component of the diffusion couple.

Effect of Variations in Anodic Activation and Strike- Current Density

The second series of specimens was designed to determine the effect of variations in anodic activation prior to electroplating and the effect of strike-current density during electroplating. Relatively low bonding temperature and pressure, 850 F and 4000 psi, were chosen for this series because it was felt that these conditions would be more sensitive to the effects of variations in activation and strike-current density than higher bonding conditions would be. The data from this series of specimens are presented in Table 2.

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TABLE 1. EFFECT OF PRESSING PRESSURES AND TEMPERATURES ON TENSILE STRENGTH

Pressing Pressure, psi	Tensile Strength, psi			
	800 F	850 F	900 F	950 F
3000	3,240	1,600	4,600	9,100
	3,540	4,000	6,400	8,300
	1,120	5,900	3,800	-
	-	-	5,200	-
4000	8,060	5,000	7,000	10,000
	900	4,200	11,900	12,600
	-	4,240	11,800	10,900
	-	4,200	-	11,800
	-	4,180	-	11,800
5000	3,700	4,600	7,400	10,800
	4,280	4,800	7,700	12,600
	-	5,400	7,000	11,100
	-	-	-	7,920
6000	5,900	6,900	11,200	10,800
	5,900	9,100	11,860	11,400
	4,900	7,240	10,400	-
	-	-	11,000	-
	-	-	8,600	-

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TABLE 2. (Continued)

Activation Current Density, amp per sq ft	Time, min	Tensile Strength, psi, at Indicated Strike-Current Density ^(a) , amp per sq ft			
		120	60	30	None
25	120	600	-	-	Did not bond
	-	4600	-	-	6100
	-	2900	-	-	4300
35	100	-	Did not bond	8700	-
	-	-	1900	8240	-
	-	-	5800	7200	-

(a) Total calculated thickness of nickel is 0.0003 in. Total strike time is 30 sec.

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The results of this series of specimens were too erratic to show any trends with regard to the effect of variations in activation and strike-current density. However, these data may be regarded as further proof that a temperature of 850 F and a pressure of 4000 psi is insufficient to yield reproducible bond strengths in times less than 5 min.

The third series of tensile specimens was a repetition of the second, except that the specimens were bonded at a higher temperature and pressure (950 F and 6000 psi). Data from this series of specimens are shown in Table 3.

The third series of specimens again failed to show any effect of strike-current density or variation in activation on tensile strength. On the contrary, this series of specimens indicated quite strongly that variations in strike-current density and activation within the limits used in this experiment have little or no effect on tensile strength.

Effect of Bonding Time

The fourth series of tensile specimens was designed to determine the effect of bonding time on tensile strength. These specimens were all bonded at 950 F and 6000 psi. The results of this series of tests are reported in Table 4.

This series of specimens illustrates clearly that any bonding time between 1 min and 5 min (5 min was used in previous experiments) will produce uniformly high tensile strengths. Except in the case of one specimen, even 30 sec yielded relatively high tensile strengths.

Effect of Nickel Plating Both Components

The fifth and final series of specimens was designed to compare the tensile strength of nickel-plated aluminum bonded to nickel-plated uranium with that of unplated aluminum bonded to nickel-plated uranium. The series consisted of five specimens with nickel-plated aluminum and one control specimen with unplated aluminum. All of the specimens were

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TABLE 3. EFFECT OF VARIATIONS IN ANODIC ACTIVATION
AND STRIKE-CURRENT DENSITY ON TENSILE
STRENGTH

Activation Current Density, amp per sq ft	Time, min	Tensile Strength, psi, at Indicated Strike-Current Density ^(a) , amp per sq ft			
		120	60	30	None
25	10	12,200	-	-	12,400
	-	12,300	-	-	12,500
	-	12,600	-	-	12,400
35	14	-	11,800	12,500	-
	-	-	12,500	12,600	-
	-	-	12,600	12,800	-
45	22	-	12,300	11,300	-
	-	-	12,400	5,400	-
	-	-	12,400	12,500	-
25	60	12,400	-	-	12,300
	-	11,800	-	-	12,400
	-	11,800	-	-	12,600
35	57	-	12,300	12,400	-
	-	-	12,400	12,100	-
	-	-	11,400	11,500	-
45	56	12,600	-	-	10,200
	-	12,200	-	-	11,200
	-	12,500	-	-	11,300
25	120	12,400	-	-	12,400
	-	12,400	-	-	11,300
	-	10,300	-	-	12,200
35	100	-	11,700	12,600	-
	-	-	11,900	12,700	-
	-	-	12,400	10,700	-

(a) Total calculated thickness of nickel is 0.0003 in. Total strike time is 30 sec.

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TABLE 4. EFFECT OF BONDING TIME
ON TENSILE STRENGTH

Bonding Time, min	Tensile Strength, psi
4	12,400
	11,000
	12,700
	12,700
	10,800
3	12,800
	8,700
	12,400
	12,800
	12,800
2	10,000
	9,800
	12,900
	12,800
1	12,800
	12,900
	12,700
	12,500
	11,200
	12,900
0.5	10,700
	12,400
	10,200
	12,100
	5,300

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bonded at 950 F and 6000 psi for 5 min. Table 5 is a compilation of data from this series.

TABLE 5. EFFECT OF NICKEL PLATING BOTH COMPONENTS ON TENSILE STRENGTH

Specimen	Tensile Strength, psi
Nickel-plated aluminum	7,300
Nickel-plated aluminum	6,800
Nickel-plated aluminum	7,700
Nickel-plated aluminum	7,700
Nickel-plated aluminum	7,200
Unplated aluminum	12,400

From this series of specimens it may be deduced that, at least as far as tensile strength is concerned, it is a decided disadvantage to use nickel-plated aluminum in conjunction with nickel-plated uranium in solid-state bonding work.

The tensile strengths recorded in Tables 1 through 5 were limited by the tensile strength of 2S aluminum. It is quite possible that, when aluminum alloys, instead of 2S aluminum, are used with nickel-plated uranium in solid-state bonding work, pressing conditions other than those indicated above might prove advantageous.

CONCLUSIONS

This study of the tensile strengths obtained in tensile-strength testing of the bond between aluminum and nickel-plated uranium leads to the following general conclusions.

- (1) Bonding temperature must be at least 950 F if the bonding pressure is 5000 psi or less. At 6000 psi, 900 F will produce uniformly strong bonds.

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- (2) Bonding pressures must be at least 4000 psi to yield uniformly high tensile values at 950 F.
- (3) Bonding times of 1 min or more are satisfactory.
- (4) Anodic activation and strike-current density are not critical if required minimum bonding temperature and pressure are maintained.
- (5) Nickel plating of the aluminum component as well as the uranium component substantially reduces the tensile strength of the resulting bond.

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