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HEAVY WATER ORGANIC COOLED REACTOR

THE EFFECT OF SOME FABRICATION VARIABLES ON THE MECHANICAL PROPERTIES OF SINTERED ALUMINUM POWDER (SAP) SHAPES

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ABSTRACT

Short-time tensile tests of rod, and tensile and tube-burst tests of tubing specimens of SAP alloys were conducted to provide preliminary information concerning the effects of thermal-mechanical history on mechanical properties. Quantitative correlation of the full fabrication processes with mechanical properties was precluded by lack of knowledge of the history of semifinished material. Comparison of effects of final fabrication indicated that mechanical properties of SAP are improved, to a point, during hot compressive working, and then might decrease when a critical degree of working is exceeded. Tube-burst test results indicated that the presence of longitudinal fins on SAP fuel cladding tube neither increases nor decreases its inherent strength in a short-term test. The difference in deformation, and the fracture location in tube-burst tests of cladding tube with fins removed, indicates a difference in mechanical behavior of the tube wall under fins and the tube wall between fins. The difference in behavior is attributed to differences in the mechanical working of the areas.

I. INTRODUCTION

Organic cooled, heavy water moderated reactors offer an attractive concept for producing relatively low-cost power. In a concept such as the Heavy Water Organic Cooled Reactor (HWOCR), it is planned to use natural uranium as a fissile fuel. Because of this, it is necessary to use a low thermal neutron capture cross section material for the structural in-core components. Sintered Aluminum Powder (SAP)* alloys combine the attractive thermal and nuclear characteristics of aluminum with useful strength at organic coolant temperatures. These alloys have been chosen as reference material for HWOCR pressure tube and fuel cladding applications.

The SAP alloys are powder metallurgy products of commercially pure aluminum with additions of Al_2O_3 as a stable dispersion-strengthening agent. Comparison of reported mechanical properties data indicates that differences in material lots, fabrication histories, and testing methods cause an inordinate amount of scatter in the test data.

SAP alloys are, in general, not heat treatable; however, the mechanical properties are somewhat dependent upon fabrication history. It is therefore deduced that the major factor in fabrication effects is the mechanical and thermal history. Hot compressive working is a necessary step in development of shape, strength, and ductility of SAP; however, the thermal-mechanical history of the materials subjected to mechanical tests is seldom reported. This lack of knowledge of fabrication history has prevented a true evaluation of the effects of fabrication on the mechanical properties of SAP reported in technical literature.

One of the purposes of the SAP development work is to establish fabrication techniques which will develop optimum properties in finished structural shapes, with particular reference to products used for the manufacture of HWOCR fuel element cladding and pressure tubes. The scope of the work reported here is of a preliminary nature, being intended to guide development work which will reveal quantitative relationships between fabrication variables and mechanical properties.

*In this report, SAP is used as a generic term for all Al - Al_2O_3 alloys. SAP-type alloys made by Aluminum Company of America (Alcoa) are designated as Aluminum Powder Metallurgy (APM). Specific alloys will be referred to by the appropriate alloy number.

The observed scatter of mechanical properties data for SAP has been attributed to a number of variables other than the fabrication techniques used for specimen stock. As a consequence, it has been impossible to properly define inherent differences in the properties of SAP alloys. Specimens of SAP alloys from a variety of fabrication sources, representing Aluminum Company of America and Aluminum Industries A.G. (AIAG) deliveries during the past four years, were tested in identical final configurations to eliminate the effects of variable geometry on the results. The results of these tests have been used to indicate the relative importance of fabrication variables, specimen configuration, and test methods. Since full knowledge of the production and fabrication histories of these specimens was not available, these factors were largely deduced qualitatively from metallographic examination. Consequently, quantitative comparisons of inherent properties of the alloys studied cannot be derived from the data in this report. It is the aim of the future SAP development work to generate properties data on the materials fabricated under known, controlled conditions, so quantitative comparison of fabrication effects on properties may be made.

II. MATERIALS

The alloys and products used for test specimens in this program are listed in Table 1. The quantities of the material lot are included to indicate the size of the delivery lot represented by the specimens tested. The XAP001 and SAP 930 tubing specimens were produced by a slow hydraulic extrusion at Torrance Brass Foundry (now Torrance Extrusion Corporation) as one fabrication order of 1000 ft. The XAP005 tubing was produced by Alcoa by impact extrusion on a similar 1000-ft development quantity. This run was made at the end of an impact extrusion development program, and is representative of the technology status of their SAP extrusion capability. The ARL tubing was impact extruded

TABLE 1
ALLOY, SHAPE, AND SUPPLIER OF MATERIALS TESTED

Alloy *	Shape	Raw Product Manufacturer	Finished Product Manufacturer
SAP930	7-3/4 in. diameter rod	AIAG (150 lb) [†]	
SAP930	3-1/4 in. diameter rod	AIAG (120 lb)	
SAP930	1.5 in. diameter rod	AIAG (200 lb)	
SAP930	0.4 in. diameter rod	AIAG	TEC (50 lb) [§]
SAP930	Configuration 1 tubing	AIAG	TEC (600 ft)
SAP930	Configuration 2 tubing	AIAG	TEC (400 ft)
XAP001	3-1/4 in. diameter rod	Alcoa (130 lb) ^{**}	
XAP001	1-1/2 in. diameter rod	Alcoa (250 lb)	
XAP001	0.4 in. diameter rod	Alcoa	TEC (50 lb)
XAP001	Configuration 1 tubing	Alcoa	TEC (600 ft)
XAP001	Configuration 2 tubing	Alcoa	TEC (1000 ft)
XAP005	Configuration 1 tubing	Alcoa	Alcoa (1000 ft)
ARL	Configuration 1 tubing	Alcoa	Alcoa (100 ft)

*All materials tested contained a nominal 7 wt % Al₂O₃

[†]AIAG—Aluminum Industrie A.G., Zurich, Switzerland

[§]TEC—Torrance Extrusion Corporation (formerly Torrance Brass Foundry), Torrance, California

^{**}Alcoa—Aluminum Company of America, Pittsburgh, Pennsylvania

Note: Numbers in parenthesis indicate the quantity of material purchased for that particular order.
The amount of tubing is expressed in feet, the amount of rod is expressed in pounds.

a. Configuration 1

b. Configuration 2

Figure 1. Target Design for Fuel Cladding Tubes Used for Testing

from an experimental alloy made by Alcoa Research Lab. The SAP rod was tested as-supplied from Alcoa and AIAG, with the exception of the 0.41-in. diameter rod, which was produced by TEC from 1.5-in. diameter rod supplied by Alcoa and AIAG. Discussions with Alcoa representatives indicated that all of the rod produced by Alcoa was from one size powder compact. Metallographic evidence indicates that the rod stock from AIAG could have been produced from different sized compacts; however, this was not established.

The tubing was extruded from 1.5-in. diameter tube blanks in the temperature range of 600 to 900°F at a final extrusion ratio of approximately 25:1 (Figures 1a and 1b). The procedure used in making the tube blanks was different for each application, and is noted in the tabulation of the data. It is believed that the rod, as received from each of the raw product fabricators, was made in a single extrusion. In the case of the Alcoa material, it is known that, in some cases, a multihole die was used, which would cloud the determination of the actual extrusion ratio from compact to tubing or rod. An example of the evidence used in evaluating the relative amounts of reduction is shown in Figure 2, which is a composite of photomicrographs of areas from a cross section of a 7-3/4 in. diameter SAP 930 rod. The microstructure indicates that only the surface of the rod had received any great amount of work. Figure 3 shows the typical microstructures of the materials tested. It can be seen that the structure of the SAP 930 material from a 3-1/4 in. rod is similar to that of the 7-3/4 in. rod, but the relative coarseness indicates that the 3-1/4 in. rod received a greater degree of working. The photomicrographs of the Alcoa APM 3-1/4 in. rod material indicate that it could have received substantially greater working than the SAP rod of the same size. The metallographic evidence of the amount of working of the Alcoa material is not as pronounced as it is with AIAG SAP. Consequently, direct comparisons of microstructures of the APM and SAP are not meaningful. APM rods of 7-3/4 in. diameter were not available for testing.

Only the 7 wt % Al_2O_3 alloys of the respective suppliers were selected for this study, in order to minimize the number of variables. The sizes, shapes, and fabrication history of the materials tested were dictated by availability. The results of chemical analyses of the test specimens are listed in Table 2.

4

12

1

1

c. Section 2

4433-2-1

d. Section 3

4433-3-1

e. Section 4

4433-5-1

f. Section 5

4433-7-1

b. Section 1

4433-1-2

a. Locations of Sections

g. Section 6

4433-8-1

Figure 2. Sections from 7-3/4 in. Diameter SAP 930 Rod, Showing Change in Microstructure Across Rod Cross Section

4360-9-2

4360-16-5

1) Transverse to Extrusion Direction

2) Longitudinal to Extrusion Direction

a. 7-3/4 in. SAP 930 Rod

4360-14-2

4360-15-2

1) Transverse to Extrusion Direction

2) Longitudinal to Extrusion Direction

b. 3-1/4 in. SAP 930 Rod

4360-13-2

c. 0.4 in. SAP Rod, Transverse to Extrusion Direction

4360-12-2

4360-10-2

1) Transverse to Extrusion Direction

2) Longitudinal to Extrusion Direction

d. 3-1/4 in. XAP001 Rod

4360-8-2

e. 1-1/2 in. XAP001 Rod, Transverse to Extrusion Direction

4360-11-2

f. 0.4 in. XAP001 Rod, Transverse to Extrusion Direction

Figure 3. Typical Microstructures of Products Tested

TABLE 2
TYPICAL CHEMICAL COMPOSITION OF SAP ALLOYS TESTED

	SAP930	XAP001	XAP005	ARL
Al ₂ O ₃	5 - 7 wt%	5 - 7 wt%	5 - 7 wt%	5 - 7 wt%
C	0.2-0.3 wt%	0.6-0.8 wt%	0.6-0.8 wt%	0.3-0.4 wt%
H	70-100 ppm	70-100 ppm	70-100 ppm	70-100 ppm
Cu	200 ppm	200 ppm	200 ppm	200 ppm
Fe	750 ppm	2000 ppm	300 ppm	300 ppm
Si	0.2-0.4 wt%	0.2-0.3 wt%	0.2-0.3 wt%	0.2-0.3 wt%

Note: Sum total of all other impurities <0.5 wt %

① REDUCED SECTION HAS GRADUAL TAPER FROM ENDS TOWARD CENTER, WITH ENDS $\nless 0.003$ in. LARGER IN DIAMETER THAN CENTER.

3-14-67 UNC

7680-4743

a. Design

b. Orientation of Specimen With Respect to Extrusion Direction of Parent SAP Rod

3-14-67 UNC

7680-4744

Figure 4. Tensile Test Specimens Used for Rod Specimens

III. PROCEDURE

A. SHORT-TERM UNIAXIAL TENSION TESTS

Specimens were selected from each lot of rod and tube, and were machined to the shape depicted in Figure 4a. The orientations of the rod specimens to the rod axis are shown in Figure 4b. The tubing specimens were designed to test the strength of uniform thickness tube wall, without including the effects of the fins (Figure 5a). Figure 5b is a photograph of a tubing specimen and fixtures.

Both tubing and rod specimens were tested on a Baldwin hydraulic tensile-testing machine. The strain rate was controlled at 0.001 in./in. of gauge length per minute to the estimated 0.2% yield, and then at ~300 lb/min until failure. The elevated temperature tests were soaked at least 20 min at the test temperature before commencing each test.

B. SHORT-TERM BIAXIAL TESTS

Specimens for burst testing of tubing were selected and cut to 1 ft lengths. The fins on the end of each tube were removed to the maximum root diameter. The smooth sections at the end of each tube were cold swaged from ~0.4 to 0.375 in. diameter, to facilitate the use of standard tube fittings. Additional specimens had the fins completely removed by machining the test section. Samples of each type of specimen and tube fitting are shown in Figure 6.

The specimens were soaked at the desired test temperature for at least 20 min before testing, which consisted of pressurization with argon gas. The gas pressure at failure was recorded, and the hoop stress formula,

$$\sigma_{\theta} = \frac{PD}{2t} \quad \dots (1)$$

where:

σ_{θ} = Bursting stress (psi)

P = Gas pressure at failure (psig)

▽ CLEAN UP FOR CONCENTRICITY, HOLD TO MAXIMUM ROOT DIAMETER, REDUCED SURFACES TO BE $\sqrt{6}$ OR BETTER.

3-14-67 UNC

7680-4745

a. Design

7629-5114

b. Specimen and Gripping Fixtures (High-temperature extensometer not shown)

Figure 5. Tensile Test Specimens Used for Finned Cladding Tube Tests

7500-51717

Figure 6. Specimens Used for Burst Testing

D = Mean diameter of tubing wall (in.)

t = Wall thickness (in.)

was used to calculate the stress to cause failure.

The pressure testing system was not originally built for controlled pressurization rate, and extreme variations in the specimen loading rate occurred. Specifically, the SAP 930 and XAP001 were tested first, and loading rates varied from 250 to 1000 psig/min. The XAP005 was tested after system improvements had been made, and the loading rate varied from 250 to 500 psig/min. This loading rate varied not only from specimen to specimen, but also during each test.

IV. RESULTS AND DISCUSSION

A. EFFECTS OF FABRICATION ON MECHANICAL PROPERTIES

1. Behavior of SAP

It has been shown, by other investigators, that fabrication variables affect the mechanical properties of SAP.^(1, 2) Data previously reported in technical literature presented a pattern of behavior that permitted qualitative evaluation of the effect of the amount of mechanical reduction (from the powder compact to the product tested) on mechanical properties. The results indicated that:

- 1) Mechanical properties of SAP were enhanced, to a degree, with increasing hot compressive working
- 2) Severe working caused a decline in the mechanical properties of the material.

It has been proposed that the rise and eventual decline of properties with increasing work is due to the predominance of one of two competing mechanisms (homogenization, and formation of microcracks or fissures). This theory attributes improvement of properties in initial stages of mechanical working to the predominance of beneficial homogenization. The subsequent decline in properties with additional working represents predominance of the weakening effect of microcrack formation. The evidence, and the theory, led to the belief that development of consistently good mechanical properties depended on determining the optimum amount of mechanical working from powder compact to finished product. The theory would also predict that inherent differences in response to working would be dependent on oxide content; consequently, the optimum amount of work would vary with alloy composition. An additional result of these observations and hypotheses was a warning against indiscriminate compilation of mechanical properties data for determination of inherent differences between alloys.

The mechanical test results presented in this report show a "normal" wide scatter, when combined without regard to fabrication history. While the full history (from powder compact to test specimen) is not known, the known portion of the histories may be used to assess the validity of the argument for controlling the amount of mechanical working.

a. SAP 930, Longitudinal to Extrusion Direction

3-14-67 UNC

7680-4746

b. XAP001 Rod, Longitudinal to Extrusion Direction

3-14-67 UNC

7680-4747

Figure 7. Ultimate Strength vs Test Temperature

2. Short-Time Tensile Test Results

The relative amounts of mechanical working of the sample material are as follows:

- 1) The specimens from a 7-3/4 in. SAP 930 rod represented the least amount of working. (Metallography of the 3-1/4 in. rod showed that it was produced with slightly more reduction.) The reduction ratio is estimated to be approximately 2:1.
- 2) The specimens from a 3-1/4 in. rod of SAP 930 represented a slightly greater reduction ratio; it was assumed to have been produced from the same size compact as the 7-3/4 in. rod, with a reduction ratio of approximately 9.5:1. The XAP001 3-1/4-in. rod was believed to have represented approximately the same reduction.
- 3) The specimens from 0.41-in. rod represented an increase in reduction ratio over those of the larger bars. The reduction ratio was approximately 600:1.
- 4) The tubular specimens produced from the 1-1/2-in. rod represented a reduction ratio of 1150:1.

The mechanical test results for specimens taken from solid SAP 930 rods showed that the increasing reduction ratio increased ultimate tensile strength (Figure 7a and Table 3). The 3-1/4 in. rod material had tensile strengths from 4.5 to 6.0% higher than the 7-3/4 in. rod material at room temperature, and 33 to 45% higher at 900°F. The 0.41 in. rod had ultimate tensile strengths at room temperature approximately 13 to 13.5% higher than those of 7-3/4 in. rod material, and 57 to 66% higher strength at 900°F.

The yield strength of the specimens from SAP 930 rods showed a similar improvement with increasing reduction ratio. The 3-1/4 in. rod material showed a yield strength at room temperature 13.5 to 30% higher than the 7-3/4 in. rod material; at 900°F, its yield strength was 26 to 41% higher. The 0.41 in. rod yield strength was 42 to 55% higher than that of the 7-3/4 in. rod at room temperature, and 47 to 55% higher at 900°F.

The elongation at fracture of the 3-1/4 in. SAP 930 rod material was higher than that of the 7-3/4 in. rod material at all temperatures tested; the elongation of specimens from 0.41 in. rod was higher than that of the 3-1/4 in. rod material at all temperatures.

TABLE 3

RESULTS OF TENSILE TESTS ON SAP 930 AND XAP001 ROD

Specimen	Test Tempera- ture (°F)	0.2% Yield (1 in. gauge length) (lb/in. ²) (x 10 ⁻³)	Ulti- mate Strength (lb/in. ²) (x 10 ⁻³)	Elong. (1 in. gauge length) (%)	Red. in Area (%)	Specimen	Test Tempera- ture (°F)	0.2% Yield (1 in. gauge length) (lb/in. ²) (x 10 ⁻³)	Ulti- mate Strength (lb/in. ²) (x 10 ⁻³)	Elong. (1 in. gauge length) (%)	Red. in Area (%)	
SAP 930						XAP001						
0.41 in. diameter longitudinal	RT	24.8	37.4	17	38	0.41 in. diameter longitudinal	RT	28.7	39.1	20	42	
	600	14.5	16.4	20	52		RT	27.9	39.2	16	39	
	600	14.6	16.4	20	55		400	22.0	24.4	18	50	
	700	10.9	13.8	14	42		600	16.6	18.2	22	48	
	700	12.4	13.4	14	33		600	16.5	18.3	20	53	
	900	9.0	9.8	8	27		700	14.0	15.3	18	48	
	900	8.6	9.4	4	9		700	14.2	15.4	17	51	
3-1/4 in. diameter longitudinal	RT	16.6	34.7	10	17	3-1/4 in. diameter longitudinal	900	9.6	10.3	6	18	
	RT	21.6	35.0	17	20		900	10.3	10.4	5	12	
	400	16.4	20.5	14	23		0.41 in. diameter longitudinal	RT	30.7	42.2	17	37
	600	12.7	14.8	15	23			RT	29.8	41.6	15	29
	600	12.6	14.8	14	24			400	26.2	28.4	19	38
	700	11.6	12.4	11	20			600	17.8	19.6	22	54
	700	11.2	12.3	8	14			600	17.5	19.6	23	50
900	7.4	8.0	2	2	700	15.1		16.2	19	50		
3-1/4 in. diameter transverse	900	8.1	8.7	4	8	700	15.1	15.9	16	49		
	RT	16.6	28.6	10	13	900	10.6	11.0	9	38		
	RT	16.5	28.9	12	16	900	10.9	11.1	9	32		
	600	8.9	11.4	10	12	1.5 in. diameter longitudinal	RT	27.5	38.5	15	24	
	600	9.0	11.2	7	13		RT	27.3	38.2	17	23	
	700	7.8	9.1	5	3		400	21.4	24.8	12	28	
	700	7.5	9.0	4	2		600	16.0	18.1	17	37	
900	5.2	6.0	3	1	600		16.2	18.4	17	32		
900	5.6	6.1	2	1	700		14.0	15.0	14	23		
7-3/4 in. diameter longitudinal	RT	15.9	33.2	8	7	700	13.4	15.0	13	29		
	RT	19.5	33.0	8	8	900	9.8	10.0	2	1		
	400	16.2	18.8	15	2	900	9.5	9.7	3	2		
	600	10.6	12.2	4	4	3-1/4 in. diameter longitudinal	RT	30.3	38.2	18	35	
	600	10.2	12.6	5	2		RT	29.5	38.6	18	39	
	700	8.7	9.2	2	1		400	23.6	24.2	15	41	
	700	8.4	9.1	2	1		600	14.7	17.8	20	54	
900	5.8	5.9	2	1	600		16.4	18.3	25	48		
900	5.9	6.0	2	1	700		13.9	15.0	13	39		
7-3/4 in. diameter transverse	RT	17.0	29.6	9	9	700	14.0	15.0	24	48		
	RT	15.9	29.6	10	11	900	9.9	10.6	4	20		
	600	8.7	11.0	5	10	900	9.8	10.4	5	14		
	600	9.0	11.3	5	6	3-1/4 in. diameter transverse	RT	21.6	35.5	8	6	
	700	7.7	9.1	3	6		RT	22.3	35.4	13	18	
	700	7.2	8.6	4	5		400	18.6	21.9	12	20	
	900	5.0	6.1	3	3		600	13.7	16.7	13	19	
900	5.1	6.0	4	4	600		13.4	16.4	13	24		
					700		11.7	13.2	8	14		
					700	11.4	13.1	4	13			
					900	8.1	8.6	2	21			
					900	7.8	8.2	2	1			

The mechanical test results on specimens from XAP001 solid material, representing extrusion reduction ratios of 11:1 (3-1/4 in. rod), 54:1 (1-1/2 in. rod), and 720:1 (0.41 in. rod), showed only slight differences in tensile properties (as shown in Figure 7b and Table 3). It is not known whether the greater response to mechanical working of SAP 930 properties than those of XAP001 was caused by inherent differences, or whether it could be accounted for by unknown extrusion variables, such as temperature.

The mechanical properties of samples of SAP 930 tubing, with an estimated total reduction ratio from the compact higher than the 0.41 in. rod, showed equal or higher strength, but lower elongation at fracture (Figure 7a and Table 4). A similar comparison of properties of 0.41 in. rod and the tubing configurations of XAP001 shows that one configuration of finned tubing had lower strength and elongation at fracture than the rod material. The other configuration, with a comparable reduction ratio, showed approximately the same strength, but lower elongation at fracture than the 0.41 in. rod (Table 4).

It is believed that the differences in response of mechanical properties of the SAP 930 and XAP001 tubing under similar relative reduction ratios does not represent inherent differences in behavior during working, but unknown variations in extrusion conditions other than reduction ratio. Factors which might also affect the properties of the material during extrusion are temperature of extrusion and amount of reduction in the final extrusion. Tensile test specimens of the tubing showed a visibly smaller deformation in the tube wall where fins were removed than occurred in the wall between fin locations. This observation indicates that product configuration can also influence the mechanical properties of the material, through uneven distribution of mechanical working.

3. Short-Time Tube-Burst Test Results

The short-time tube-burst tests (see Table 5) were performed on a wide variety of products; specific sets of results may be used for comparison of specific properties when only one major variable is different. At room temperature, the burst strength of the SAP 930 was highest, on the average; at 600°F and above, the SAP 930, XAP001, and XAP005 burst strengths were approximately equivalent, on the average. The XAP005 test results displayed less scatter than those of the SAP 930 and XAP001, which could be attributable to improvement in control of pressurizing rate during testing.

TABLE 4

TENSILE TEST DATA - SAP FINNED TUBING

Alloy	Configu- ration	Test Temper- ature	0.2% Yield (lb/in. ²) (x 10 ⁻³)	Ultimate Strength (lb/in. ²) (x 10 ⁻³)	Elongation (%)	Alloy	Configu- ration	Test Temper- ature	0.2% Yield (lb/in. ²) (x 10 ⁻³)	Ultimate Strength (lb/in. ²) (x 10 ⁻³)	Elongation (%)
SAP 930	1	RT	33.1	44.8	9	XAP005- 61S	1	RT	29.1	40.15	6
		RT	34.5	45.3	5			RT	25.5	34.75	12
		600	16.5	18.75	6			600	17.6	19.45	9
		600	20.5	22.6	5			700	13.2	13.5	-
		700	17.5	18.8	3			900	9.4	9.8	5
		700	17.9	19.0	4			900	9.8	10.1	5
		900	12.0	13.2	3						
		900	12.8	13.5	-						
XAP001	1	RT	21.4	33.5	12	ARL	1	RT	24.3	34.15	8
		RT	26.0	39.8	14			RT	25.0	34.3	8
		600	12.0	13.85	6			600	15.4	17.7	3
		600	11.7	13.4	6			600	15.5	16.6	-
		700	10.5	11.3	5			700	12.7	14.0	3
		700	10.8	11.25	4			700	11.7	12.9	4
		900	8.4	8.5	-			900	9.2	9.8	3
		900	8.5	8.9	-			900	9.6	10.5	2
XAP005- 71S*	1	RT	26.1	34.2	9	SAP 930	2	300	22.5	26.7	10.5
		RT	24.8	31.5	8			300	21.1	26.6	9
		600	15.1	16.8	6			600	14.8	17.5	7.5
		600	14.3	15.2	5			600	13.9	16.6	9.5
		700	11.9	12.6	4			700	11.6	13.6	7
		700	11.6	12.21	-			700	11.9	13.5	5.5
		900	8.9	8.7	-						
		900	8.3	8.9	3			850	9.9	11.1	4
XAP005- 71H	1	RT	24.4	32.6	10	XAP001	2	850	9.6	11.1	2.5
		RT	26.45	32.9	5			300	24.7	28.8	7
		600	15.1	16.3	8			300	24.5	30.0	9
		600	14.4	15.5	6			600	17.2	19.1	7.5
		700	12.1	12.85	3			600	15.5	18.2	8
		700	12.4	12.83	4			700	13.8	15.6	7
		900	10.1	10.5	3			700	13.6	15.0	7
		900	9.9	10.0	3						
XAP005- 72H	1	RT	26.4	36.65	10			850	10.6	11.7	3
		RT	30.5	35.5	7			850	10.9	12.0	4
		600	15.5	17.0	6						
		600	15.6	16.9	10						
		700	13.7	14.1	-						
		700	13.4	13.8	-						
		900	10.2	10.7	3						
		900	9.9	10.6	3						

*-71 = Powder lot, as designated by Alcoa

S = Tubing extruded and supplied straight (without helical twist)

H = Tubing extruded with helical twist

no letter = Tubing extruded straight; helix later introduced by cold twisting

AI-CE-36

TABLE 5
BURST TEST DATA - SAP FINNED TUBING

Alloy	Test Temperature (°F)	Burst Stress (lb/in. ²)(x 10 ⁻³)	Alloy	Test Temperature (°F)	Burst Stress (lb/in. ²)(x 10 ⁻³)
XAP001	RT	34.6	SAP 930	800	7.3
	RT	33.6		1000	6.0
*	RT	34.0		1000	5.2
*	RT	28.5		1000	4.6
*	600	13.4	*	1000	6.2
	600	9.8			
	600	17.8	XAP005-71S†	RT	33.6
	600	16.1		RT	32.6
*	700	15.2		600	15.1
	700	9.7		600	15.1
	700	8.6		700	13.0
	700	12.1		710	12.5
*	700	10.7		920	7.0
*	800	9.0		930	6.7
*	800	7.8			
*	800	7.5	XAP005-71H	RT	35.8
	800	8.2		RT	34.0
	800	7.8		600	17.0
	800	7.3		600	15.7
	1000	3.6		690	12.5
	1000	8.1		700	12.1
	1000	7.9		900	7.6
	1000	7.4		900	7.6
*	1000	3.5	XAP005-72H	RT	34.3
*	1000	9.0		RT	34.0
*	1000	7.9		600	16.6
*	1000	7.5		600	16.0
SAP 930*	RT	39.2		600	15.5
*	RT	37.0		700	11.5
	RT	39.6		710	11.8
	RT	35.6		900	7.9
	300	27.8		900	7.9
	400	20.4	XAP005-61S	RT	37.0
*	600	18.0		RT	35.3
*	600	12.8		600	18.7
	600	15.4		610	16.0
	600	13.9		700	14.8
	700	13.8		700	14.6
*	700	17.8		700	14.2
*	700	10.2		900	7.9
*	800	11.4		900	7.9
*	800	8.2	ARL	RT	37.0
	800	8.2		RT	35.0
	800	8.7		600	14.4
	800	8.0		600	14.1
	800	7.7		700	13.8
				700	13.3
				890	8.7

*The fins on these specimens were machined off prior to testing.

†-71 = Powder lot, as designated by Alcoa

S = Tubing extruded and supplied straight (without helical twist)

H = Tubing extruded with helical twist

no letter = Tubing extruded straight; helix later introduced by cold twisting

Some of the SAP 930 and XAP001 tubes were burst tested after the fins had been removed by machining. Removal of the fins avoided influencing the burst pressure of the material with the mechanical notch of the fin. It was found that the burst strength of specimens with fins removed was not significantly different from the strength of specimens with fins left intact. This behavior indicates that the material is not appreciably notch sensitive (the calculated stress concentration factor of the fin on hoop stress was $K_t = 1.5$) under short term loading.

The specimens with fins removed showed greater deformation in sections which originally lay between fins than in the portion which was originally under the fins (Figure 8). The nonuniform strain implies that, during the extrusion of finned tube, the nature of the mechanical working of the tube wall under the fins is different from that of the normal tube wall between fins. The result of the difference in working of the fin area is apparently an increase in yield strength.

The fractures produced by the tube-burst test were located in the tube wall adjacent to the transition from the tube wall to the fins; this occurred whether or not the fins had been removed. The fractures ran parallel to the fin (and extrusion direction) in specimens with fins removed, even when the tubes were twisted after extrusion.

3-14-67 UNC

7680-4748

Figure 8. Sketch of Fuel Cladding From a Tube-Burst Test (Extruded fins removed)

The average burst stresses for fracture of SAP 930, XAP001, and XAP005 in the tube-burst tests were approximately 80 to 86%, 83 to 89%, and 96 to 99%, respectively, of the average ultimate tensile stress obtained for the same tubing materials during uniaxial tensile tests. The lowest values of burst stress for fracture of SAP 930, XAP001, and XAP005 were 76 to 79%, 73 to 85%, and 94 to 103%, respectively, of the lowest values of ultimate tensile stress of the same tubing materials. The highest values of burst stress for fracture of SAP 930, XAP001, and XAP005 were 80 to 94%, 87 to 91%, and 92 to 105%, respectively, of the highest values of ultimate tensile stress of the same tubing materials. The XAP005 tube-burst strengths exhibited less scatter than those of the SAP 930 and XAP001. It is believed that this was a result of improvement in the testing technique, rather than an inherent difference in the materials.

4. Fractography

The fracture surfaces of the bar specimens had the appearance which would be expected from the fracture ductility shown by the mechanical test data. The fracture surfaces of the bars with little reduction in area are of the cleavage type, as shown in Figure 9a. The fractures in Figure 9b show specimens which received more reduction. The cleavage-type fracture in these specimens appeared at high and low temperatures, the cup and cone nature was evident in the mid range.

4-14-67 UNC

7629-5113@

a. 7-3/4 in. Rod

Figure 9. Relationship Between Fracture Appearance of SAP 930 Specimens and Ductility at Fracture

3-14-67 UNC

7629 5116@

b. 3-1/4 in. Rod

Figure 9. Relationship Between Fracture Appearance of SAP 930 Specimens and Ductility at Fracture

V. SUMMARY

While quantitative correlation of short-term mechanical properties of SAP and its fabrication history was not obtained, the results of these tests show that the thermal-mechanical history of SAP has an effect on its short-term mechanical properties. It appears that the mechanical properties improve, up to a point, during hot compressive working; and then they might decrease, as some level of working is exceeded. The optimum degree of working has not been established from these data, because only the final steps in the fabrication history of the specimens were known.

The tube-burst test results indicated that the presence of longitudinal fins on a SAP tube neither increases nor decreases its inherent strength in a short-term test. Removal of these fins by machining does not change the burst strength. The hoop stress to cause the tube to burst is less than the stress required to fracture the tube when stressed uniaxially longitudinally. The equation, $\sigma_{\theta} = (PD/2t)$, appears equally valid to determine the stress in a longitudinally finned tube or a tube with fins removed, when stressed by internal pressure for a short-time burst test. The difference in deformation, and the fracture location, in a tube-burst test of cladding tube with fins removed indicates a difference in mechanical behavior of the tube wall under fins and the tube wall between fins. The greater deformation of the material lying between fin locations indicates that it has lower yield strength. The crack location in the tube wall at the location of fins indicates either that the deformation of the wall between fins imposes high bending stresses or that the portion of the wall lying under the fins has a lower ultimate tensile strength than that of the tube wall between fins.

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