Technical Notes

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Development of 2021 Aluminum Alloy Propellant Tanks

WARREN BERGER* AND ELLIOTT WILLNER†
Lockheed Missiles & Space Company, Sunnyvale, Calif.

ALUMINUM alloy 2021 was developed in 1967 by the Aluminum Company of America (ALCOA) under contract to the NASA Marshall Space Flight Center, Huntsville, Ala., as a high-strength weldable aluminum primarily for cryogenic applications. This Note will describe the salient characteristics of the new alloy and how they were related to the manufacture of a 5-ft-diam, spherical hydrazine tank with an operating pressure of 300 psig and a minimum burst pressure of 600 psig. The tank comprises shear-formed hemispheres welded to an equatorial ring (Y ring) forging. The aft hemisphere features two series of integral, internally threaded lugs for attaching the motor and a protective heat shield. Nominal machined section thicknesses of the tank are 0.15 in. at the membrane, 0.33 in. at the weld lands, and 0.75 in. at each apex. This first commercial application of the alloy saved 20 lb (8%) compared to 2219 aluminum and 100 lb compared to 6061 aluminum.

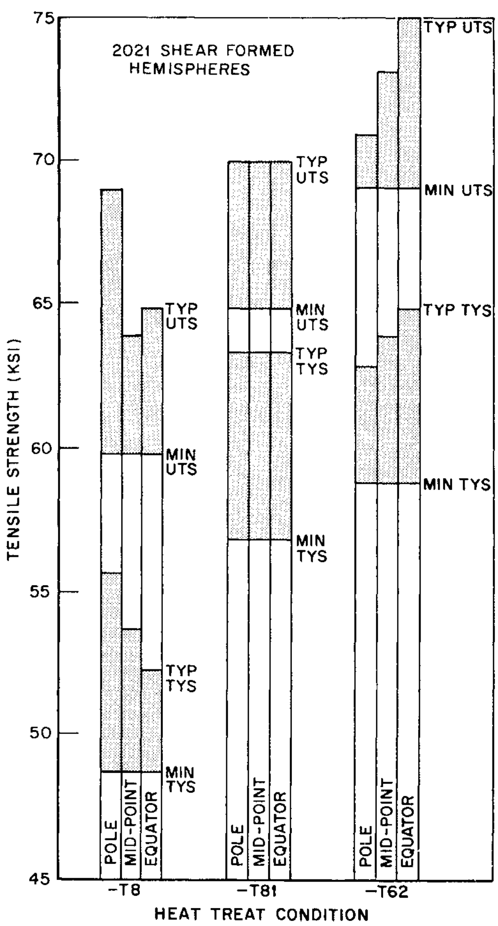

Fig. 1 Typical and minimum mechanical properties of shear-formed 2021-T8, -T81, and -T62 hemispheres.

Table 1 Minimum mechanical properties of aluminum alloys 2021, 2219, and 6061

	Ultimate tensile strength, ksi	Tensile yield strength, ksi	Elongation, %
2021-T62	69	59	3
2021-T81	66	57	3
2219-T87	63	50	5
6061-T62	42	35	9

Material Considerations

Except for minor additions of cadmium (0.15%) and tin (0.05%), the chemical composition of 2021 is identical to 2219 aluminum. Metallurgical and processing aspects of 2021 have been comprehensively examined and reported.[1,2] Table 1 compares mechanical properties of alloys 2021, 2219, and 6061. An important feature of 2021 is that, unlike 2219, its high strength is not dependent on cold work. This characteristic gives 2021 a distinct advantage as a material for shear-forming hemispheres, where the polar region receives little or no cold work. The region of a 2219 shear-formed hemisphere, for comparison, would require using a technique such as explosive shock hardening following solution treating to develop maximum mechanical properties.

Figure 1 gives typical and minimum mechanical properties for the various tempers of fully aged 2021 shear-formed hemispheres. The minor additions of cadmium and tin influence the aging reaction of solution-heat-treated 2021 to provide for maximum strength in the -T62 condition with no cold work. The -T8 properties result from artificially aging 2021 material that has been cold worked after solution-heat-treating. When an intermediate preage (1 hr at 300°F) is performed between solution-heat-treating and cold work, the resultant temper is 2021-T31; full aging then results in 2021-T81.

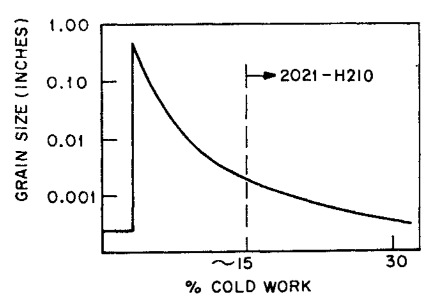

Fig. 2 Effect of solution-heat-treatment on grain size vs percentage of cold work.

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* Senior Manufacturing Research Engineer.
† Materials Engineering Specialist.

A unique temper was developed for the as-received 2021 material to assure freedom from a coarse-grained membrane in the propellant tank after forming and heat treatment. Figure 2 schematically illustrates the consequence of "critical strain" prior to solution heat treatment. There exists a region at a relatively low percentage of strain where the material will recrystallize and coarsen upon exposure to elevated temperature. Beyond this percentage of critical strain, the cold worked region will recrystallize and not coarsen. This principle has been utilized in developing the 2021-H210 temper. The -H210 condition retains an incremental amount of cold work beyond the critical strain to permit stress relieving, annealing, or solution-heat-treatment without grain coarsening.

The compatibility of alloy 2021 with several propellants has been studied. These propellants included nitrogen tetroxide (green), Aerozine-50, and hydrazine. Plate, forgings, and their weldments were stressed up to 90% of their yield strengths using both four-point-loaded bent-beam and tuning fork specimens. The plate was stressed in the long transverse direction and the forgings in the short transverse direction. The time of exposure was 90 days at 140°F in each propellant. In most cases, each parameter was tested either in duplicate or triplicate. No failure attributable to stress-corrosion cracking was observed in any environment at 140°F. A 30-day exposure at 180°F in N_2O_4, following a successful 30-day exposure at 140°F, caused stress-corrosion cracking in two of three base metal forging tuning forks stressed at 75% of yield. Bent-beam specimens loaded to 90% of yield, including their weldments, were unaffected in the same 180°F, N_2O_4 environment. Using fracture toughness parameters, a subsequent series of notched and precracked specimens were uniaxially loaded in tension, with the notches and cracks exposed to hydrazine at 120°F. The stress was periodically modified to simulate a flight mission profile. All specimens passed the profile requirements.

Manufacturing Considerations

Shear-forming was selected for fabricating the hemispheres, following previous practice used in producing 6061 aluminum hemispheres for Agena tanks. The Hufford Spin Forge, a vertical-type machine capable of spinning parts up to 96 in. in diam and 120 in. in height, is used to form the hemispheres in two operations: a preform is made by spinning the flat blank into the shape of a shallow dishpan, and, after thermal treatment, the preform is shear-formed into a hemisphere with material thickness reductions progressively increasing to a maximum of 50%. Two basic methods were considered for the final operation: 1) shear-form the hemisphere from a solution-heat-treated (-T42) preform, or 2) form the hemisphere from a process-annealed preform and then solution-heat-treat it. Method 1, using a -T42 preform, avoids an annealing operation, and only the outside surface of the hemisphere is machined. Since solution-heat-treating and water-quenching are done prior to final forming, the hemisphere inside surface can be used as-formed. This process is currently used to shear form 5-ft-diam tanks from 0.250-in.-thick 6061 aluminum blanks, and has been used for 0.250-in.-thick 2021 aluminum. However, attempts to shear-form 0.70-in.-thick 2021 resulted in fractures at 40–45% thickness reduction. With method 2, which was adopted for production, the preform is in the annealed condition, making final forming easier with less chance of fracturing. Besides the additional manufacturing operations, however, it also has shrinkage and distortion problems associated with solution-heat-treating and water-quenching the hemisphere after final forming.

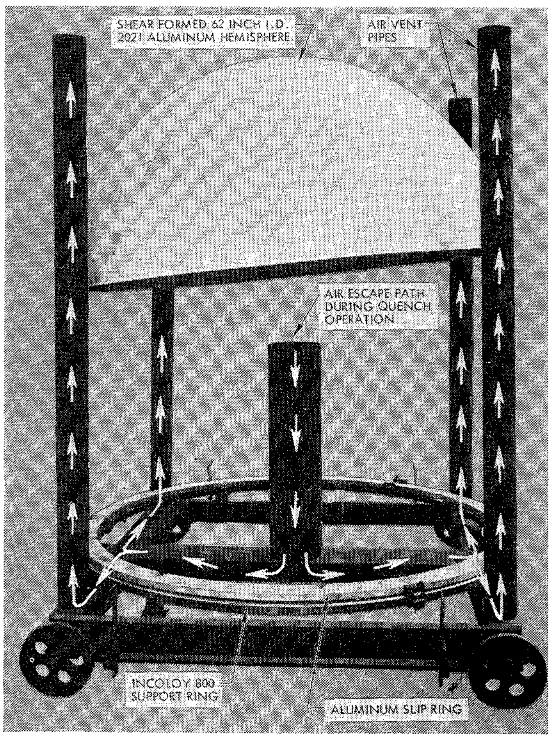

Fig. 3 Heat treat fixture used to solution-heat-treat and water-quench shear-formed 2021 aluminum hemispheres.

The fixture used for solution-heat-treating the hemisphere is shown in Fig. 3. Air trapped in the hemisphere during the quench cycle operation was vented by the large pipe located in the center of the fixture. To minimize distortion the hemisphere was quenched at a controlled rate.

Alloy 2021 increases dimensionally during aging. Since the plate material used in the hemispheres had a different growth rate than the *Y* ring, the components were partially aged prior to machining. This minimized the differential growth rates of the hemispheres and their mating *Y* ring during the post-weld age, and avoided significant stress discontinuities in the completed tank. The partial age treatments were 10 hr at 325°F for the hemisphere and 12 hr at 340°F for the *Y* ring forging. A final post-weld age (12 hr at 340°F) of the completed tank provided freedom from stress-corrosion cracking and increased the ultimate tensile strength of the weldment to allow a minimum design value of 38 ksi.

Tungsten-inert-gas (TIG) d.c. welding with helium was used to weld the two hemispheres to the central *Y* ring. Alloy 2319 was used for the filler wire. Although the 2021 contains only a minor amount of cadmium, an overhead venting system was used as a safety precaution against inhalation of cadmium fumes. A three-pass cast underbead weld procedure was used to join the *Y* ring (forged 2021-T3152 plus partial age of 12 hr at 340°F) to the aft hemisphere (plate 2021-T42 plus 10 hr at 325°F partial age). Welding was done from the inside surface using a steel back-up ring to fix the hemisphere and limit drop-through during the penetration pass. Since the tank closure weld had to be made from the outside surface with no possibility of using a back-up bar, a suspended underbead four-pass weld procedure was developed to join the *Y* ring to the forward hemisphere. The tank was back-filled with argon gas to eliminate oxygen entrapment and maintain cleanliness during welding.

In conclusion, advantages of 2021 for fabrication of space vehicle propellant tankage are: 1) achievement of maximum strength in the -T62 temper without a requirement for intermediate cold work, 2) excellent formability by shear-forming in the process-annealed condition, 3) freedom from stress corrosion in the post-weld aged condition, and 4) compatibility with several propellants.

References

[1] Shultz, R. A., "ALCOA Aluminum Alloy 2021 Green Letter," Technical Information Bulletin GL-210, April 1968, Application

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[2] Westerlund, R. W. et al., "Development of a High Strength Aluminum Alloy, Readily Weldable in Plate Thicknesses and Suitable for Application at −423°F (−253°C)," Final Report on NASA Contract NAS-8-5452, Oct. 1967, Aluminum Co. of America, New Kensington, Pa.

A New Correlation of Parachute Weight Data

KENNETH E. FRENCH*
Lockheed Missiles & Space Company, Sunnyvale, Calif.

Nomenclature

D_0 = parachute reference (constructed) diam, ft or m
F_0 = parachute maximum opening force, lbf or N
k_i = coefficient of proportionality, dimensions as required (i = 1–4)
l_s = line length (from confluence point to canopy skirt), ft or m
N = number of suspension lines
P_c = rated ultimate strength of canopy material
P_s = rated ultimate strength of suspension line, lbf or N
q = dynamic pressure at chute deployment, lbf/ft² or N/m²
S_0 = parachute reference area, ft² or m²
W = weight, lbm or kg

Introduction

IN parachute and parachute system design, it is desirable to be able to rapidly assess nominal parachute weight, to estimate tolerances on the nominal weight, and to calculate weight tradeoffs with respect to variations in such parameters as parachute size and strength. This Note presents a correlation of parachute weight data to assist the designer in performing such tasks.

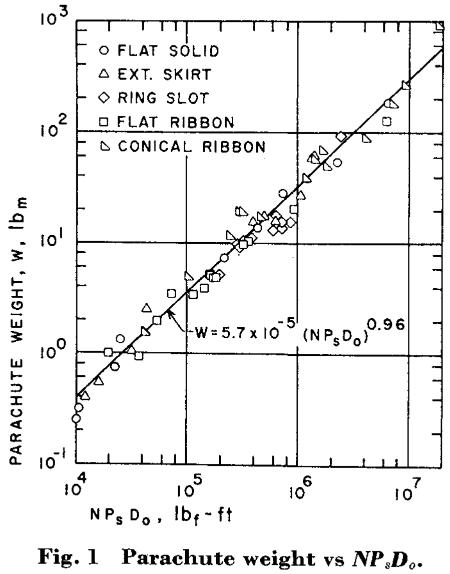

Fig. 1 Parachute weight vs NP_sD_o.

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* Staff Engineer, Advanced Design Department. Associate Fellow AIAA.

Rationale

Parachute weight can be considered to consist of two major parts: suspension line weight and canopy weight. Total suspension line weight will depend on the number, length, and material of the suspension lines. Canopy weight will depend on canopy area and material. Also, material weight is approximately proportional to material strength

Table 1 Parachute weight and configuration data

Type of chute	D_0, ft	N	P_s, lbf	l_s/D_0	W, lbm	Use[a]
Flat solid	1.75	6	1,000		0.31	
	5	8	250		0.25	
	7.5	8	375		0.75	1
	10	10	250		1.31	
	24	24	375		7.5	
	28	28	550		14	2
	44	44	375		29	
	64	64	550		55.12	3
	100	100	550		186	
Ext. skirt	6	8	250		0.4	1
	8	8	250		0.54	1
	11.5	10	375		2.56	
	24	24	550		10.66	2
	32	36	550		16.25	4
	35	30	550		16	
	37.1	36	375		18	4
	44	44	550		27.5	
	67	52	375		58.75	
	67	56	375		63	
Ring slot	10.86[b]	12	1,500	0.83	5.31	4
	14	20	2,250		15.5	
	15	20	1,000		9.5	5
	16	20	1,000		11	
	16	16	1,500		11.19	
	16	20	2,250		14	
	16	20	2,250		16	
	16	24	2,250		16	
	20	20	1,500		13.28	5
	29.6[b]	24	400	0.90	9.88	4
	29.6[b]	24	900	1.00	18	4
	70	64	550		95	
Flat ribbon	3	12	1,500		2	
	3.4	8	1,000		0.94	
	4.33	16	2,500		5	
	6	6	550		1	6
	6	16	1,500	1.33	4	
	6.05	8	1,500		3.5	4
	9	16	2,500		10.5	
	11	28	3,000	1.00	21	
	11.5	10	1,000		3.5	1
	11.5	14	1,000		5.25	
	11.5	14	1,000		5.1	5
	15	16	750		5	
	16	20	1,000		10	
	43.5	48	3,000		129	
Conical ribbon	4.82	14	1,500		5	4
	5.58	18	4,500		17.5	4
	5.88	18	3,000		19.25	4
	6.86	8	750		1.56	4
	10.83	18	1,500		19.25	4
	12.5	16	9,000	1.12	50	
	13.3	18	1,000		11.75	4
	17	24	10,000	1.12	90	
	17.8	22	3,000		39	4
	20	30	12,000		180	
	29	32	1,500		57.3	4
	35	32	1,500		69	4
	48	48	4,000	0.92	266	
	76	80	3,000		900	

[a] Use code: 1 = flare descent, 2 = personnel, 3 = balloon payload recovery, 4 = aerospace vehicle recovery, 5 = aircraft landing brake, and 6 = antispin.
[b] Conical ring slot parachute.