Development of Titanium Alloy for Lightweight LH_2 Tankage

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An analysis of typical liquid hydrogen (LH_2) propellant tankage demonstrated that a 30–35% weight saving can be achieved by using 5Al-2.5Sn titanium (Ti) alloy as compared with high-strength steel and aluminum alloys. A unique grade of Ti alloy was developed to improve its toughness at −423°F. Evaluation of 22 heats of material showed that, by reducing the O, C, N, and Fe content, toughness could be increased. Two years of industry effort were necessary to develop coil stock (0.013). This cold-rolled material had better emissivity and absorptivity values than stainless steel, thereby reducing LH_2 boiloff. Fusion butt welds and continuous-resistance seam welds proved to be best in LH_2 static and fatigue tests. Significant cost savings were achieved by cold-forming the Ti bulkhead gores as compared with past hot-tooling techniques. A 10-ft-diam, 0.013-gage, 5Al-2.5Sn extra low interstitial (ELI) Ti alloy bulkhead was successfully welded. Titanium diaphragms, subjected to impact while containing liquid oxygen (LO_2), ignited and burned. No reaction occurs with LH_2. Based on the results of this and other related programs, titanium is ready to be used practically in LH_2 tankage.

Introduction

LIQUID hydrogen is now in use as a propellant in upper stages of rockets, and its use for rockets and spacecraft (and possibly for hypersonic airplanes) is likely to grow rapidly. Its biggest disadvantage, of course, is its low density, which leads to large tank volumes and makes tank weight even more important than it is for other propellants. Titanium alloy has three advantages as compared with steel and aluminum alloys for this use: 1) higher strength/weight ratio at cryogenic temperatures (Fig. 1), 2) higher allowable stress for joints, and 3) greater resistance to crack propagation (Fig. 2). Some of the comparisons to be discussed indicate that these factors lead to weight savings from 21 to 42% relative to stainless-steel and aluminum alloys, depending upon tank size and design. Alloy development, fracture toughness testing, joint development, coil stock development, forming, welding, processes and fabrication achievements, radiative properties, and reactivity with oxygen are discussed.

Advantages of Titanium for LH_2 Tankage

Figure 3 shows results of an optimization study on LH_2 storage temperature to make maximum use of strength/weight advantage of Ti. The optimum skin temperature is seen to be between −300° and −320°F.

With respect to joint weights, annealed 5 Al-2.5Sn Ti has excellent fusion weld joint properties (98–100%). Since the material is annealed, little weakening takes place in the heat-affected area. In comparison, aluminum and cold-rolled steel are severely affected by welds, and doublers or built-up sections must be provided at the joints; the multiple joints and bracketry can add ~5% to the weight. Annealed titanium (5Al-2.5Sn), using butt fusion welds or continuous-resistance seam welds, maintains a high tensile efficiency and fatigue life as well as being able to accept weldments on the tank in any area without reducing over-all strength.

Another important property is resistance to crack propagation. A low ratio of notched to unnotched tensile strength indicates that minor defects in material or weld porosity could precipitate catastrophic failure. A tough material will allow the stress to flow around a defective area. Titanium (5Al-2.5Sn) alloy has this property (Fig. 2).

The use of Ti for large-diameter tanks for LH_2-LO_2 was investigated. Since Ti will burn in LO_2 or an O_2-rich atmo-

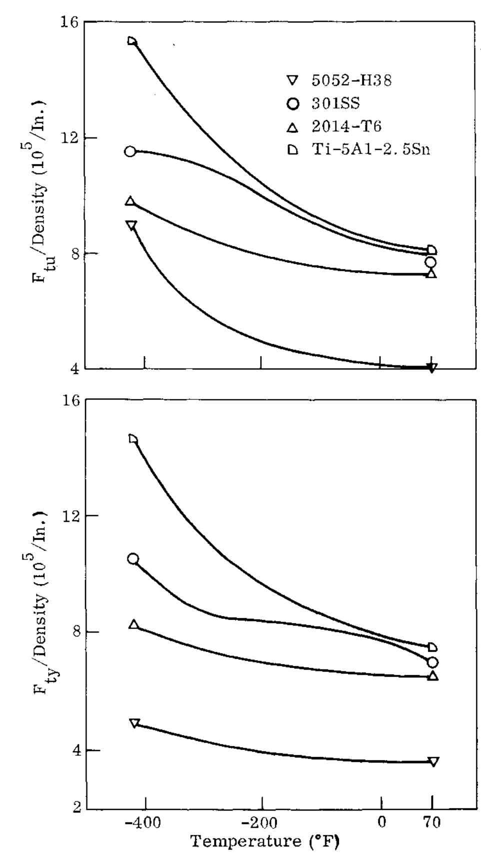

Fig. 1 Strength/density ratios vs temperature.[6]

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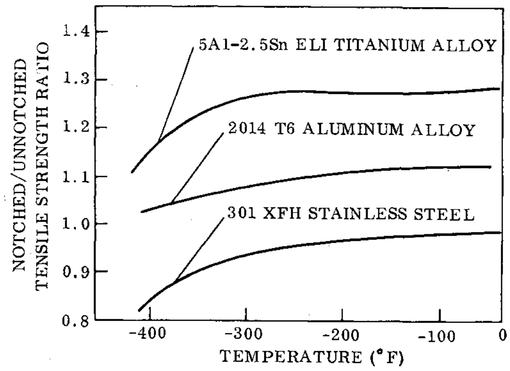

Fig. 2 Notch/unnotch ratio of 5 Al-2.5Sn compared with Al alloy and stainless steel.

Table 1 Weight of typical 10-ft-diam, 30,000-lb tank for LH_2/LO_2 propellant system

Weight, lb	301 SS	5Al-2.5Sn Ti LH_2 tank[a]	5Al-2.5Sn Ti LH_2 + LO_2 tank
Forward bulkhead	112.3	62.3	62.3
Cylindrical section	233.1	155.6	155.6
Aft structure	311.2	311.2	176.0
Secondary structure	155.0	120.0	88.4
Bolt-ons	37.5	37.5	22.4
	869.1	686.6	504.7
% weight saving:	...	21%	42%

[a] LO_2 tank made of steel and brazed to Ti-LH_2 tank with ring at joint indicated in Fig. 4.

sphere when impacted or punctured,[14] the use of Ti for the LO_2 tank section in such a system is questionable. Therefore, in the first study of a 10-ft-diam tank containing 30,000 lb of LH_2/LO_2 propellant (Fig. 4), Ti was considered only for the hydrogen part of the tank. The LO_2 part was assumed to be made of steel, and a brazed ring was used at the steel-titanium interface. Tests indicate that a joint of this type is feasible at LH_2 temperature and is within the present state of the art. In a second study, it was assumed that a protection technique preventing catastrophic oxidation had been developed and that Ti could be used for the full tankage. The resulting weights are shown in the third column of Table 1. The 21% saving for the LH_2 tank in the first case and the 42% saving for the combination are certainly significant.

A lunar logistic vehicle employing 25,141 lb of propellant contained in a separate tank within a 320-in. diam was also considered. Two potential pressure systems are feasible: 1) a low-pressure system using 35 psig, and 2) a high-pressure system of 150 psig. The weight comparisons for Ti vs Al show savings of 33% (Table 2).

Material Development

A number of titanium alloys were evaluated for strength and toughness properties from 78° to −423°F. The results indicated that the Ti 5Al-2.5Sn alloy possessed the best combination of strength, toughness, and fabricability for structural use at −423°F. However, large differences in properties, particularly toughness, were obtained from one heat to another in the commercially produced Ti 5Al-2.5Sn alloy at −423°F. As a result, a more detailed investigation was made.[1]

The first phase of the investigation included the determination of tensile, notched tensile, and fusion-weld tensile properties of seven heats of normal commercial [Aeronautical Material Specification (AMS) 4910] material.[2] From these data, as well as from results obtained by other investigators,[3–5] it was evident that the amount of interstitial elements (C, Fe, O, N, H) present in the material strongly affected the toughness at cryogenic temperatures. The second phase was therefore aimed at making a quantitative determination of the effects of variations in content of impurities, particularly oxygen and iron content, on the properties of the Ti 5Al-2.5Sn alloy from 78° to −423°F. As a result of this phase of the investigation, a new specification,[7] General Dynamics/Astronautics (GD/A) ES 0-71010, was prepared, which limited the iron and inter stitial contents to those of the better-performing materials, such as the seven heats listed in Table 3 and Fig. 5. Thereby achieving a considerable improvement in the toughness of the alloy at −423°F. This also resulted in a decrease in the yield and tensile strengths of the materials at room temperature. Use of the cold temperature (−300°F) allowables in design eliminates the need for high room temperature properties.

The final phase was the evaluation of three heats of GD/A ES 0-71010 for notched tensile and fusion-weld tensile properties as a function of the following factors: 1) temperature from 78° to −423°F, 2) sheet thickness from 0.010 to 0.125, and 3) various tempers, such as mill-annealed (as received), vacuum-annealed, and stretch-formed (Fig. 6).

Fracture Toughness Testing[8]

Center-notched tensile tests were performed in both the longitudinal and transverse grain directions at room and cryogenic temperatures. Calculations were performed for fracture toughness K_c (or critical crack intensity factor) as well as for net fracture stress. Figure 7 shows some of the fracture properties developed from the test program. Although the general trends seem reasonable, some of the individual values are surprising.

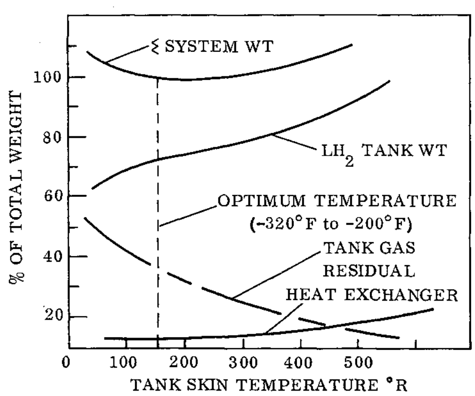

Fig. 3 Optimum LH_2 tank temperature.

Table 2 Weight[a] of tankage for LH_2 for a typical lunar logistics vehicle

Weight, lb	Aluminum 35 psi	Aluminum 150 psi	Titanium 35 psi	Titanium 150 psi
Bulkheads	26	112	18	77
Cylinder	105	450	71	304
Weldments	8	8	6	6
Weld joints	4	17	...	...
	143	587	95	387
% Weight saving	...	...	34%	33%

[a] Based on Al 2219-T84 at −320°F, F_{TU} = 75 Ksi, F_{cy} = 59 ksi, Ti 5Al-2.5Sn at −320°F, F_{TU} = 170 Ksi, F_{cy} = 160 ksi; MS_{Al} = 1.4, MS_{Ti} = 1.25 (ratio of ultimate to yield allows a lower margin of safety to be used on Ti than on Al, resulting in the same structural integrity for both).

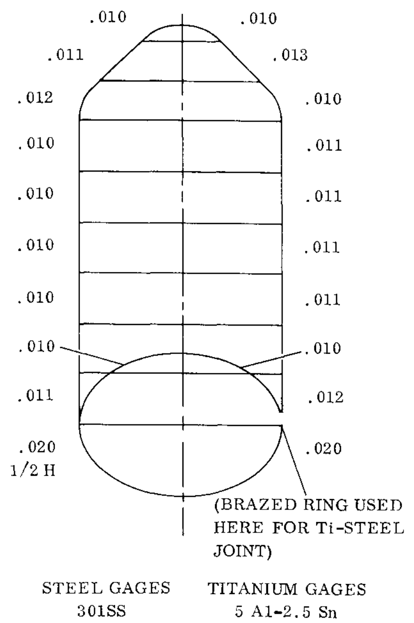

Fig. 4 10-ft-diam, 30,000-lb propellant tank.

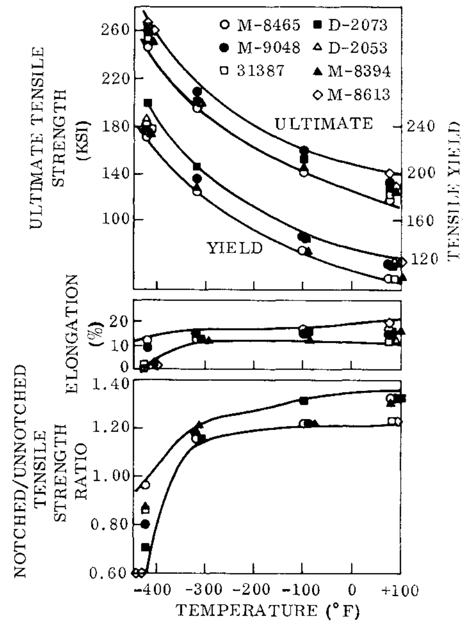

Fig. 5 Strength properties vs temperature (screening materials).

Ultimate tensile strength and yield strength were obtained by using standard tensile coupons. However, in the center-notched specimen, at room temperature, the net fracture stress for longitudinal specimens far exceeded the ultimate tensile strength of the material. In fact, the minimum net fracture stress of the longitudinal specimens was 152 ksi, whereas the highest ultimate tensile strength was 119 ksi.

In several cases, the tests of the center-notched specimens were peculiar in that after a maximum load was reached, crack propagation continued but the load dropped off (decreased). In this case, crack intensity factors (K) were calculated at both the maximum load and at the onset of rapid propagation. The K values at maximum load were larger than at the critical crack length for transverse specimens (at 75° and −100°F). However, the longitudinal specimens were exactly opposite, showing larger critical values of crack intensity factor than the K value at maximum load. Therefore, it was decided to experiment with a specimen under dead loading conditions. The test of the longitudinal specimen at room temperature more or less substantiated the results shown in Fig. 7. A K_c value of 230 was obtained from a critical load of 4400 lb and a critical crack length of 3.15 in. Under dead loading, the crack propagated a finite amount and then stopped. The calculated net stress at the next to last load level was above the yield strength of the material. Finally, when the critical load was applied, the crack propagated rapidly to the critical crack length, stopped momentarily, and then propagated extremely rapidly to failure. Inasmuch as the net fracture stress was far in excess of the ultimate strength, it is suspected that propagation of the crack causes a strain-hardening effect that increases the tensile strength of the material.

In general, toughness variation with temperature was as expected for the longitudinal specimens.[12, 13] The critical crack extension force decreases with a decrease in temperature. The toughness in the transverse direction is somewhat erratic over the test temperature range. The critical crack intensity factor shows a substantial increase at −320°F, although this peak is eliminated in a plot of the crack intensity factor at maximum load. Critical crack length decreased with a decrease in temperature for both longitudinal and transverse sheets, as was anticipated. R. Kemp of NASA Lewis Research Center is currently conducting biaxial notched cylinder tests of titanium (5Al-2.5Sn) ELI alloy, high-strength steels and aluminums alloys at LH_2 temperatures. His Ti work to date is unpublished.

Titanium Tank Joint Development[9]

The use of annealed Ti increases the potential methods of joining the material, since the heat-affected zone of the weld

Table 3 Condition and chemical analyses of heats of Ti-5Al-2.5Sn alloy tested[1]

Heat no.	Thickness, in.	Temper	Rockwell hardness, 15N	Supplier	Al	Sn	Fe	C	H_2	N_2	O_2
M-8465	0.040	Mill anneal	78	TMCA	5.8	2.4	0.09	0.017	0.0108	0.010	0.103
M-9048	0.027	Mill anneal	78	TMCA	5.4	2.5	0.21	0.021	0.015	0.010	0.17
31387	0.020	Mill anneal	78	React. metal	5.6	2.6	0.24	0.03	0.010	0.015	0.12
D-2073	0.063	Mill anneal	80	crucible	4.9	2.4	...	0.03	0.0061	0.03	0.16
D-2053	0.016	Mill anneal	81	TMCA	5.3	...	0.37	0.026	0.028	0.017	...
M-8394	0.032	Mill anneal	78	TMCA	5.6	2.2	0.04	0.015	0.013	0.009	0.17
M-8613	0.040	Mill anneal	80	TMCA	5.14	2.53	0.018	0.038	0.0084	0.023	0.167
M-9048	0.035	12% cold roll	80	TMCA	5.4	2.5	0.21	0.021	0.015	0.010	0.17
M-8465	0.024–0.032	20–40% cold roll	80–83	TMCA	5.8	2.4	0.09	0.017	0.0108	0.010	0.103
			GD/A specification ES0-71010[7]		5.0/5.8	2.2/2.8	0.25 max	0.05 max	0.015 max	0.04 max	0.12 max

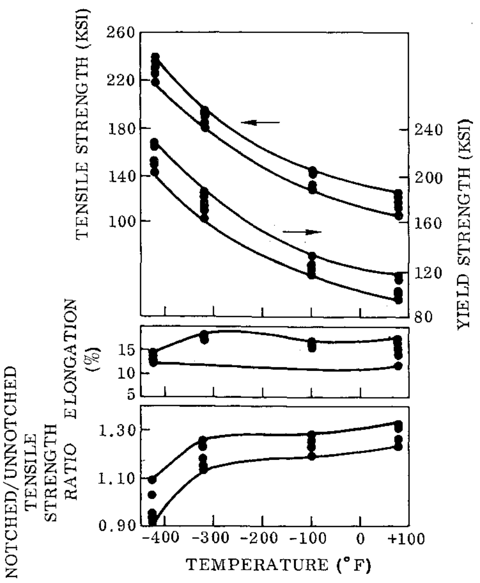

Fig. 6 Strength properties vs temperature for three heats of Ti 5 Al 2.5Sn (GD/A specification 0-71010).

has less effect on the joint than in aged aluminum or work-hardened steel. Three potential joining problems exist: 1) the tank longitudinal joint, 2) the tank circumferential joint, and 3) the attachment of weldments to the tank. Typical joints tested at $-423°F$ are shown in Fig. 8.

Tests at room temperature, $-320°$, and $-423°F$ proved that the best joint in annealed 5Al-2.5Sn is a heliarc butt-weld. The butt-weld joints were stressed for 2000 fatigue cycles at maximum operating stress level ($F_{TU}/1.25 = F_{oper.}$) at $-423°F$ without failure. With a spot-welded doubler added over the butt-welded joint, failure occurred in 557 cycles in the spot-weld area with leakage occurring after only 50 cycles.

A double-resistance seam weld took 370 cycles to failure. This type of joint is applicable for the circumferential tank joints where the hoops are "stove-piped" in thin tank construction. The joint specimens were tested at twice the stress level of a circumferential joint. Therefore, a double-seam weld would be expected to take sufficient cycles to match the 2000 cycles of the maximum stress, longitudinal butt weld.

Single spot welds are prone to fatigue failure, and should be avoided in titanium tank construction Bracketry pres-

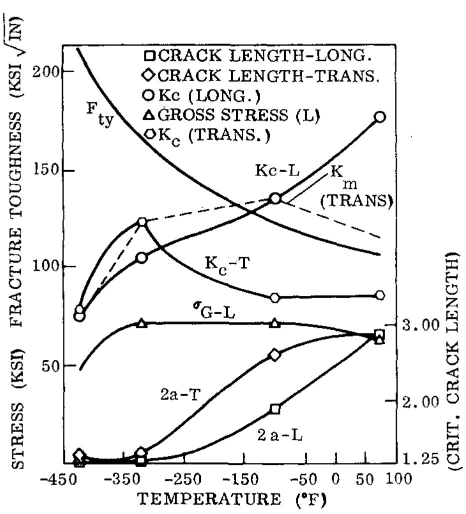

Fig. 7 Typical Ti joint LH_2 tests specimens.[8]

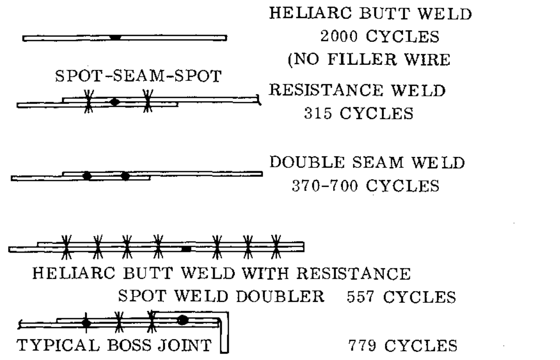

Fig. 8 Toughness of 5 Al-2.5Sn Ti at cryogenic temperatures.[9]

surization bosses and duct inlets should be attached with continuous seam welds or should be heliarc butt-welded into the tank. Double-seam welds on outlets improved fatigue life considerably over spot-welded, doubler weldments. Two seam-weld joints went 779 cycles at $-423°F$ before failure occurred at the edge of the seam weld.

Coil Stock Development

In order to build thin-gage, minimum weld tankage, coil stock (continuous roll of material) is required. GD/A requested two titanium producers, Republic Steel and Titanium Corporation of America (TMCA), to supply coil stock to meet GD/A's specification. A major development program over a $2\frac{1}{2}$-yr period was required to achieve a reproducible coil of thin-gage 5Al-2.5Sn.

Republic Steel produced the first coil of Ti 5Al-2.5Sn, 18 in. wide. A second order was placed for 24-in.-wide stock, 0.014 in. The material was reduced to 0.020 in. when it was destroyed in mill rolling because of an insufficient in-process anneal. The program at Republic proved that a large hot band (the initial hot-rolled form of the coil) could be made and that cold rolling was feasible for reducing the material. A maximum of a 15% reduction was possible between cold rolls before annealing was required. The anneal was done in an open-line annealing furnace with a pickling and cleaning process at the end of the line to remove the oxide. The coil was also sent through a continuous sander to remove the more stubborn oxide. As the thickness decreased below 0.020 in., vacuum-pit annealing was used since the in-line furnace handling was too rough for the material. The 0.020-in. thickness appears to be a major break point in processing Ti 5Al-2.5Sn. It is also the point at which the cost of the material starts to rise sharply.

The second order for coil stock was obtained from TMCA and was of excellent quality. At present, GD/A has 220 lb of 0.013-in., 26-in.-wide 5Al-2.5Sn titanium. This material is in a continuous coil, enabling the maximum stressed hoops of a 10-ft tank to be made with one weld in the longitudinal direction.

The development that Republic and TMCA went through to produce coil stock 5Al-2.5Sn was a major step in titanium production. Formerly, only low-strength pure titanium had been produced in coil, whereas alloy titanium could only be supplied in sheet stock with a limitation of 114 in. in length.

Titanium Manufacturing Processes and Bulkhead Fabrication

In order to build a titanium bulkhead, a considerable amount of research was required in the fabrication and processes area. The areas of forming and welding were refined to provide the high quality of workmanship required for the LH_2 tank construction.

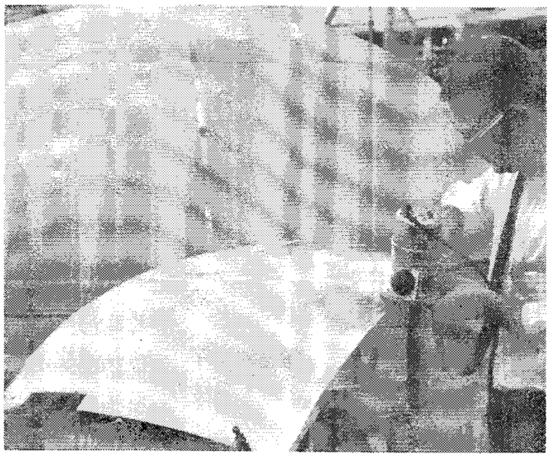

Fig. 9 Preparation of butt-weld joint.

Forming

The bulkhead gores were cold-formed on the same radial draw tool, and dies were used for the Atlas bulkheads. The annealed 5Al-2.5Sn titanium with the low interstitial oxygen and low iron content readily formed cold. The formed gores held their shape, and no springback or "memory"-type distortion was encountered over a six-month period. The gores match the die better than work-hardened stainless steel. No trouble was encountered in matching up the gores after trimming, in tolerances, or in distortion during welding.

Welding

A considerable improvement in titanium welding was required to insure porosity-free welds. At −423°F, porosity that would normally be acceptable at room temperature would severely reduce fatigue life. It was found that careful preparation of the material faces to be welded, with the exposing of a fresh unoxidized face of titanium immediately prior to welding, does provide porosity-free welds. The straight-line welder and bulkhead-gore welder used in the Atlas for tank fabrication were qualified for titanium with changes in improved gas quality, gas coverage (increased), and the copper backup bar. A higher degree of cleanliness was required in all of the operations. Welding schedules were successfully developed for three gages (0.012, 0.013, and 0.014) of material on all of the welding machines required to build a tank.

Production workers were used in all of the fabrication steps to insure that the shop procedures and processing specifications would be established and understood. Production tooling was also used with relatively minor modification. Based on this experience, titanium bulkheads, the most difficult portion of the tank, could be currently reproduced in production. Figures 9–11 illustrate some of the steps in the fabrication of the 10-ft-diam, ellipsoidal ($a/b = 1.4$) bulkhead.

Radiative Properties of Annealed Cold-rolled 5Al-2.5Sn Titanium[10]

The emittance, reflectance, and solar absorptivity of twelve titanium samples were determined to provide information for the thermodynamic evaluation of the boiloff rate of LH_2 in titanium tankage. The samples were subjected to different surface treatments in order to evaluate the influence of environmental effects on the radiative properties of the metal. The best combination for a space vehicle LH_2 tank would have a high emittance at low temperature and a low solar absorptivity. Ten of the specimens and the test results are shown in Table 4. It might be noted that cold-rolled Ti has far better radiative properties than the dull gray, sheet-stock titanium commonly used in aircraft. Titanium coil stock is slightly better in radiative characteristics than highly reflective cold-rolled 301 stainless steel.

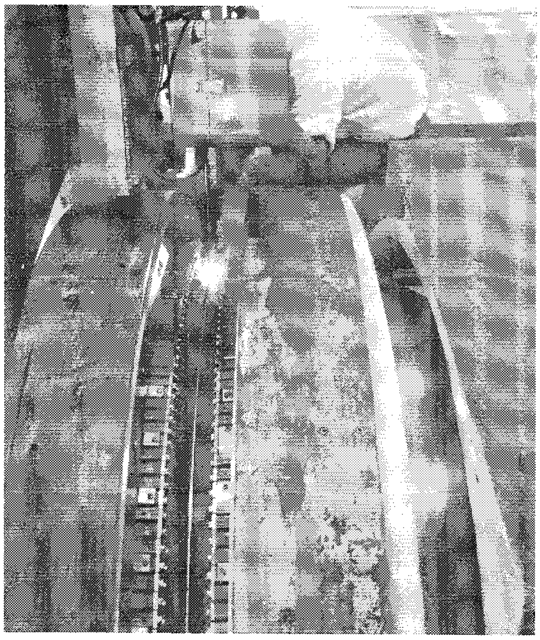

Fig. 10 Fusion butt welding of the Ti gores.

Titanium-Oxygen Reactivity Study

A program[14] was conducted at Astronautics to investigate the likelihood of occurrence of the catastrophic oxidation of titanium alloy sheet under conditions, which simulate certain cases of accidental failure of the metal while it is in contact with liquid or gaseous oxygen. Three methods of fracturing the metal were used; they consisted of 1) mechanical puncture, 2) tensile fracture of welded joints, and 3) perforation by very high-velocity particles.

The results of tests provide further evidence of the reactivity of titanium with liquid and gaseous oxygen. The evidence indicates that the rapid fracturing of titanium sheet while it is in contact with oxygen initiates the catastrophic oxidation reaction. Initiation occurred when the speed of the fracture was some few feet per second, as in both the drop-weight puncture tests and the static tensile fracture

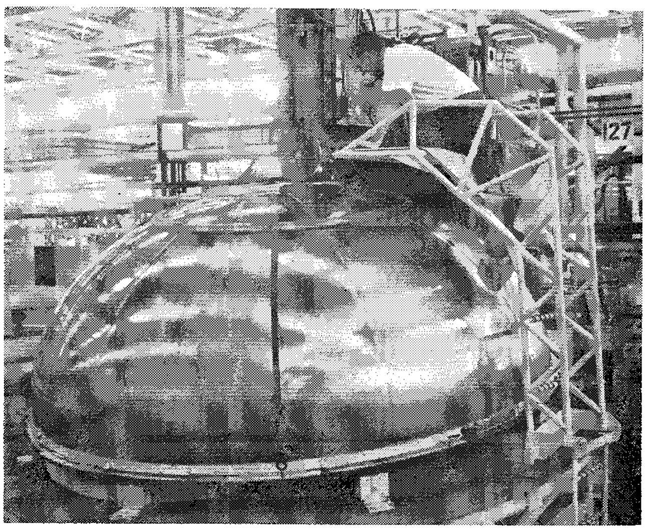

Fig. 11 Resistance seam welding of cap.

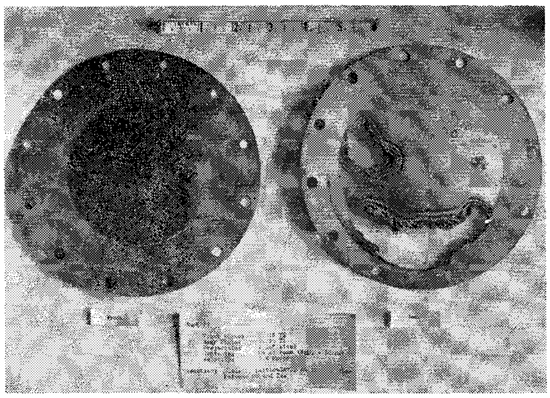

Fig. 12 Titanium alloy diaphragms after typical high-velocity puncture.[8]

tests of welded joints, as well as when the speed was several thousand feet per second, as in the simulated micro-meteoroid penetration tests[11] (Fig. 12). Figure 13 illustrates the same impact on steel. The slow propagation of a crack, however, did not initiate the reaction. Failure occurred in all of the specimens with burning in the titanium specimen only. Gaseous oxygen pressure-surge tests conducted by Astronautics resulted in no reaction.

The physical and chemical properties of titanium alloys are such as to explain, in part at least, their higher sensitivity to the oxygen reaction. Titanium has 1) low thermal conductivity and low heat capacity on a volume basis, resulting in the development of a high temperature and slow heat dissipation for a given heat input; 2) a low ignition temperature in an oxygen atmosphere; 3) a highly exothermic titanium-oxygen reaction, thus ample heat is generated to sustain the reaction; and 4) titanium oxides in which the products of the reaction are highly soluble in the molten metal at the reacting interface, thereby maintaining sufficient contact of unprotected titanium metal with oxygen to allow the reaction to proceed with little or no retarding effect on the oxide layers.

In the work conducted at Battelle Memorial Institute, fresh titanium surfaces were made by fracturing or gouging the metal under LO_2. In only a few instances, there was evidence of a reaction at the fractured surfaces. Reaction did occur at pin-grip holes on the specimens because of compressive impact as the specimen halves rebounded against the pins. In tensile fracture tests, in high-pressure gaseous oxygen, they found that reaction occurred at the fracture surface. Occurrence of the reaction appeared to be dependent upon both pressure and temperature. They obtained no reactions below 75 psig between $-300°$ and $+75°F$. They

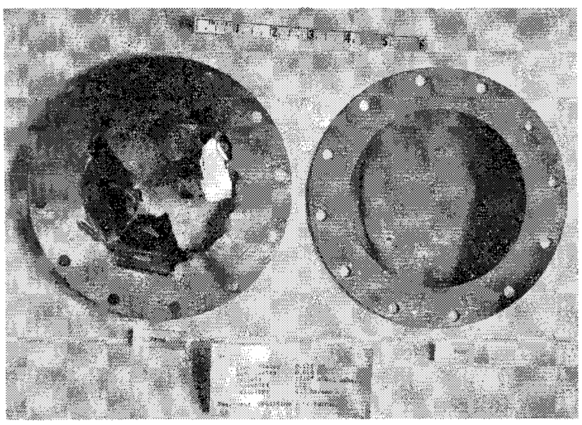

Fig. 13 Stainless-steel diaphragms after high-velocity puncture test.[8]

concluded that the reaction occurs only when the oxygen is in the gaseous state and is above some threshold pressure, which is dependent upon its temperature. Thus, according to the hypothesis, heat must be generated at a local spot to gasify LO_2 in order to initiate a reaction.

It may be concluded logically that the localized frictional heat of rapid fracture and/or spontaneous oxidation (exothermic) of minute particles emanating from the fracture cause initiation of the reaction. Under conditions of slow fracture, however, the small heat generated may be adequately dissipated and the reaction is not initiated.

In recent work conducted by the NASA Marshall Space Flight Center, stainless-steel, aluminum, and Ti alloy sheet specimens were placed in contact with LO_2 and detonated by primacord or other explosive materials. A variety of test configurations was used. Some of these subjected the reactants to only a shock wave, whereas others created mechanical rupture. The test results indicated that both the titanium and aluminum alloys reacted with oxygen when the reaction was initiated by the explosive; the titanium, however, reacting with much greater frequency than the Al alloys.

The accidental puncturing or similar rupturing of thin-walled, pressurized oxygen tanks on missiles and space vehicles will usually constitute loss of function, and may sometimes cause their catastrophic destruction by explosive decompression regardless of the type of material used for their construction. In the case of LO_2 tanks constructed of titanium alloys, the added risk is incurred on catastrophic burning of the tanks. If a protective coating is developed or tank history can be predicted to indicate a lack of impact along with high fatigue life at operating stress levels, titanium in LO_2 tanks may still be feasible. This problem applies only to LO_2; LH_2 and titanium do not react.

Table 4 Radiative properties of titanium[10]

No.	Ident. and treat.[a]	Sample temp., °K	Σ/α	Emittance, Σ	Solar absorptivity, α	Reflectance
1	T,B,A	100	4.07	0.123	...	...
		300	4.21	0.119	0.501	0.499
		500	3.63	0.138	...	...
2	T,D,A	100	3.82	0.143	...	...
		300	4.04	0.135	0.546	0.454
		500	3.43	0.159	...	...
3	T,B,A,W	100	3.32	0.165	...	...
		300	3.68	0.149	0.548	0.452
		500	3.32	0.165	...	...
4	T,D,A,W	100	3.20	0.167	...	...
		300	3.20	0.167	0.535	0.465
		500	2.85	0.188	...	...
5	T,E	100	3.00	0.157	...	...
		300	3.36	0.140	0.471	0.529
		500	3.06	0.154	...	...
6	T,E,W	100	2.64	0.204	...	...
		300	2.69	0.200	0.538	0.462
		500	2.60	0.207	...	...
7	T,C,W	100	2.78	0.182	...	...
		300	2.82	0.180	0.507	0.493
		500	2.61	0.194	...	...
8	T,B,A,S	100	3.12	0.169	...	...
		300	3.36	0.157	0.527	0.473
		500	2.99	0.176	...	...
9	T,B,E,S	100	3.32	0.151	...	...
		300	3.53	0.142	0.501	0.499
		500	3.09	0.162	...	...
10	S,A,W	100	2.57	0.198	...	...
		300	2.86	0.178	0.509	0.491
		500	2.81	0.181	...	...

[a] T = Ti-5Al-2.5Sn (cold-rolled), A = as received, S = 301 × FH steel, E = electropolished, B = bright side (outside tank), C = chem. polished, D = dull side (inside tank), W = weathered, and S = salt sprayed.

Conclusions

Four major factors make titanium (5Al-2.5Sn) alloy extremely attractive for thin-gage LH_2 tankage: 1) approximately (30–35%) weight saving in LH_2 tankage is possible by using Ti-5Al-2.5Sn instead of the high-strength aluminum and steel alloys; 2) titanium alloy (5Al-2.5Sn) ELI is basically a tougher, more crack-resistant material than the existing high-strength steels and aluminums at LH_2 temperature; 3) the annealed Ti alloy material may be fusion-welded readily, resulting in an excellent joint with high fatigue life (2000 cycles at LH_2 temperature); and 4) the material is available in thin-gage coil stock, may be cold-formed in large radii (30 ft), and has been successfully fabricated in large-scale (10-ft-diam) tankage components. Large-scale tankage, fabrication, and testing must still be done, but basically, titanium alloy is ready to supply a better, lighter material for LH_2 propellant vehicles.

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